JLAB-TN-08-080

J(BdL) curves for CEBAF dipoles from 3D magnetostic models

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Abstract

Sixteen iron configurations now used in CEBAF or planned for the 12 GeV upgrade have been modeled in Opera 3D, magnetostatic software from Vector Fields. Sufficient cases were run to obtain polynomial fits, first or fifth order as needed, to J(BdL). Cases within 2% of the BdL values for the upgrade were also used to determine multipoles along the beam orbits through the magnets for accelerator simulation. Multipoles are addressed in another note. Here I present all of the BdL(J) data and the resulting polynomial fits. For the last few magnets I show effective length as a function of central field, demonstrating that the rule of thumb that adds 1.65*gap to the steel length to get effective length is appropriate only at low fields. Comparisons with the AM/AM magnet measurements suggest errors in the BH curve above 10 kG.

This TN was sent to the 12 GeV Project team for review July 17, 2008. Comments received from the team on Nov. 13, 2008, are given in the appendix.

Results

For each steel configuration I will provide a brief description, a list of the locations at which this configuration is used, results, and one or two graphs. This note describes a work in progress. The results shown represent perhaps 4000 hours of CPU time. See tech notes 08-022 and 08-024 for background on magnetic modeling. The former includes a comparison with measured field versus current showing the accuracy of these models above a few kG. Below that hysteresis effects which are not in the B-H curve cause an offset.

All of the BdLs given here are straight down the middle of the magnet. Since the accelerator modeling tools we use assume hard edge magnets of integer centimeter length and they include both the nominal field of this magnet and the beam path length through it, it is easy to convert between straight line BdL and the BdL along the curved path through the magnet. Note that the curved path BdL is not accurate either because it doesn't take into account end effects.

The common dipole B fields are set by the field needed for first and second pass beam and have curved path lengths significantly longer than their nominal lengths of one meter. One can still use the curve shown here via the B field in the Optim and elegant decks and 100cm length.

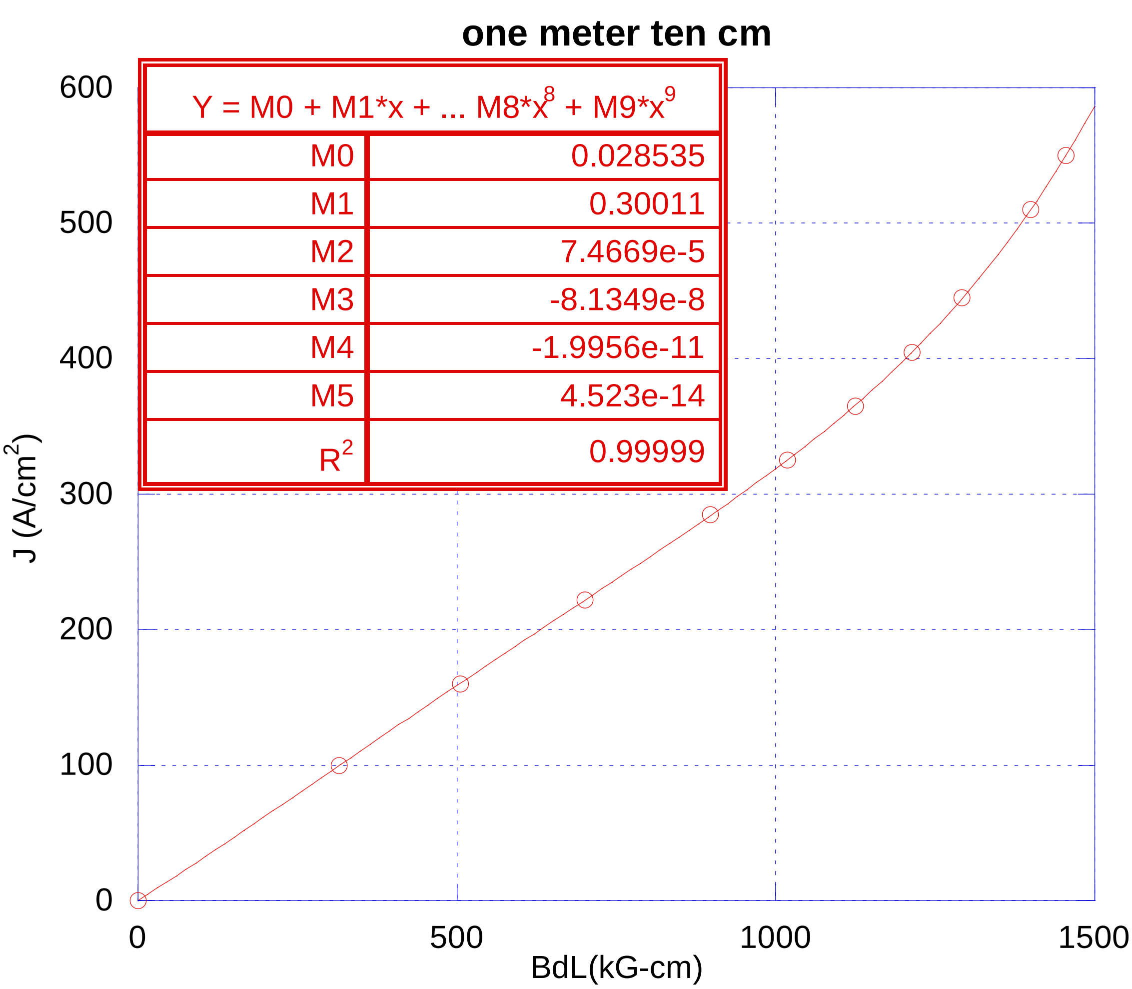
The arc dipoles have steel one, two, three or four meters long. The spreader/recombiner dipoles have shorter steel, assuming the rule of thumb mentioned in the abstract. Most are ~4cm short of their nominal length.

Coil areas given are for one of the two coils, assumed symmetric about the bending plane. To compute total amp-turns, multiply J by twice this area.

One meter dipole with 10 cm poles and "H" steel

This dipole is used in pairs in the spreaders/recombiners to move between final and intermediate heights. Iron length is 96.088 cm. Poles are 4" wide. Return leg is 3.65" wide in CEBAF. Additional return steel of minimum thickness 1.5" will be added for 12 GeV.
Coil area 4.655 x 7.05 cm^2

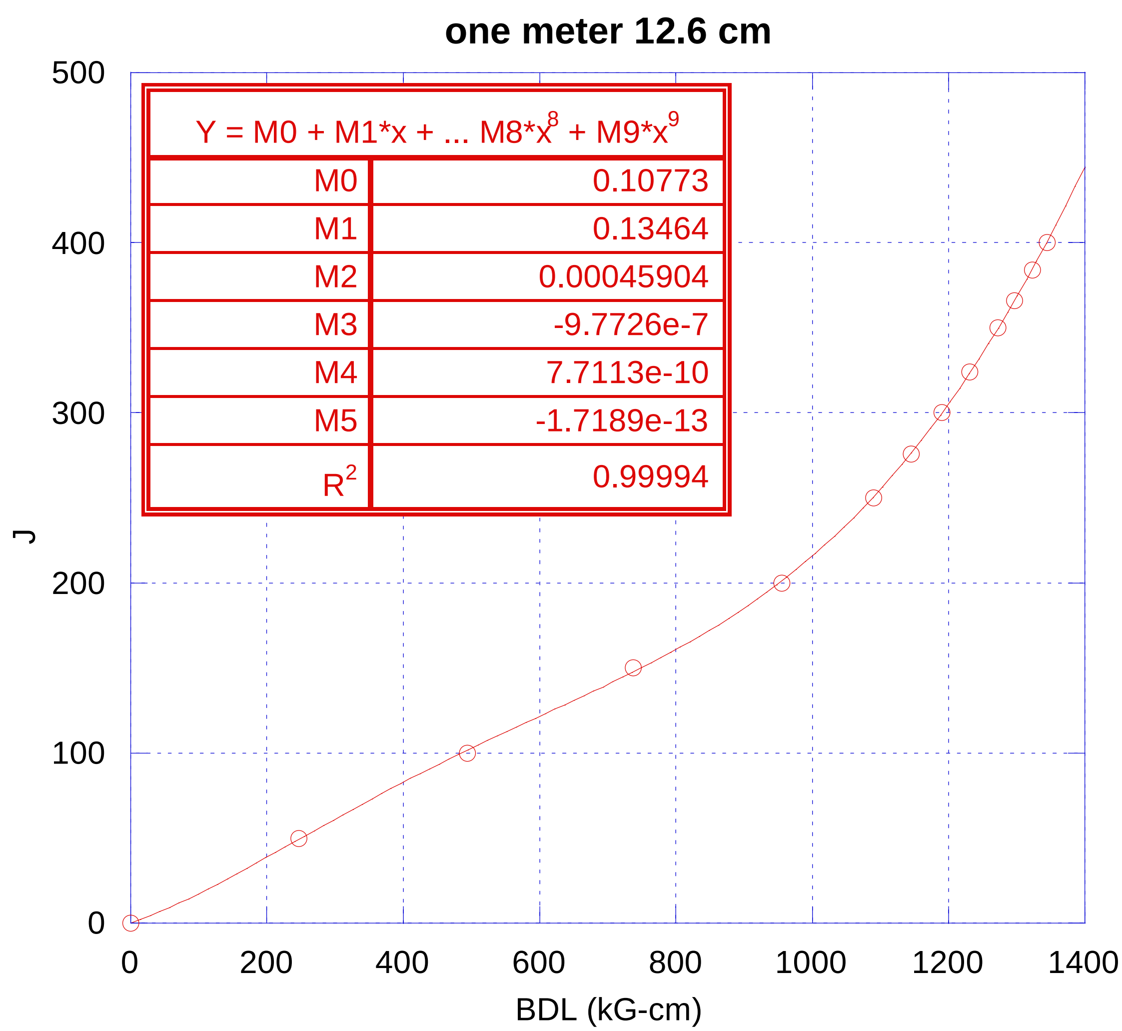
BdL(kG-cm)	J	fomula	formula/J
0	0	0.028534	0.0000
316.062242	100	99.71581057	0.9972
505.63911	160	160.539922	1.0034
701.014052	222	221.9165805	0.9996
897.670894	285	284.1585742	0.9970
1018.388628	325	325.2563262	1.0008
1125.1418	365	365.925436	1.0025
1214.37653	405	404.9576261	0.9999
1292.32476	445	444.370195	0.9986
1400.06258	510	509.9499619	0.9999
1455.638432	550	550.1863691	1.0003



One meter, 12.6cm pole, as now (AI)

This steel configuration is used in 1S/R, 2S/R and A(10) S/T in CEBAF. It will not be used in arc 10 or the fifth pass extraction line in the upgrade. It will be used with and without additional return steel. This page shows the current configuration. **Coil area 5.3 x 9.6 cm^2**

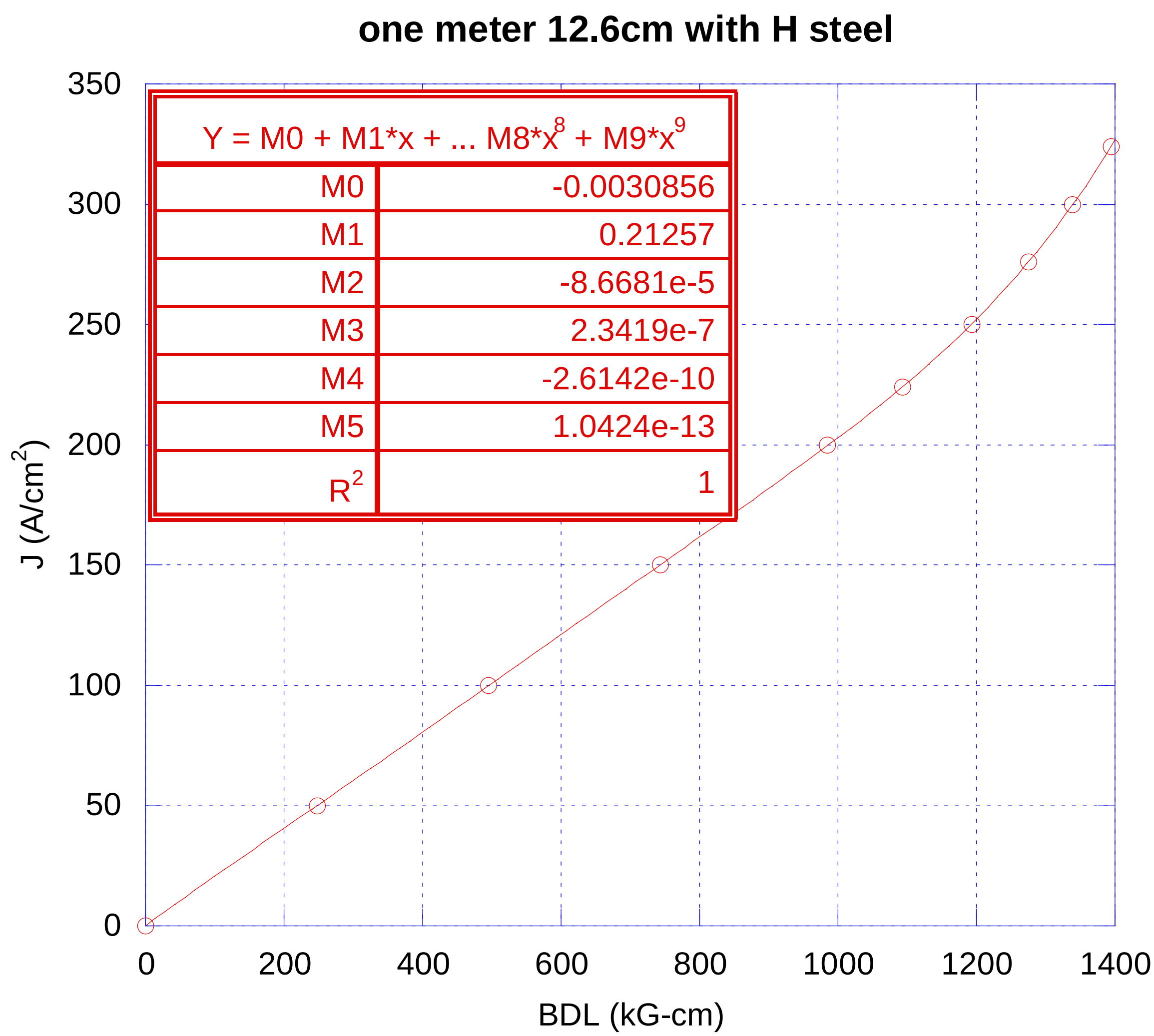
BDL (kG-cm)	J	formula	formula/J
0.000	0		
246.956	50	49.345	0.987
493.912	100	101.681	1.017
737.592	150	147.724	0.985
955.357	200	201.184	1.006
1090.597	250	251.019	1.004
1144.859	276	276.212	1.001
1189.764	300	299.664	0.999
1230.933	324	323.377	0.998
1272.349	350	349.471	0.998
1296.488	366	365.748	0.999
1322.582	384	384.248	1.001
1344.893	400	400.819	1.002



One meter, 12.6 cm with "H" steel

see description on previous page

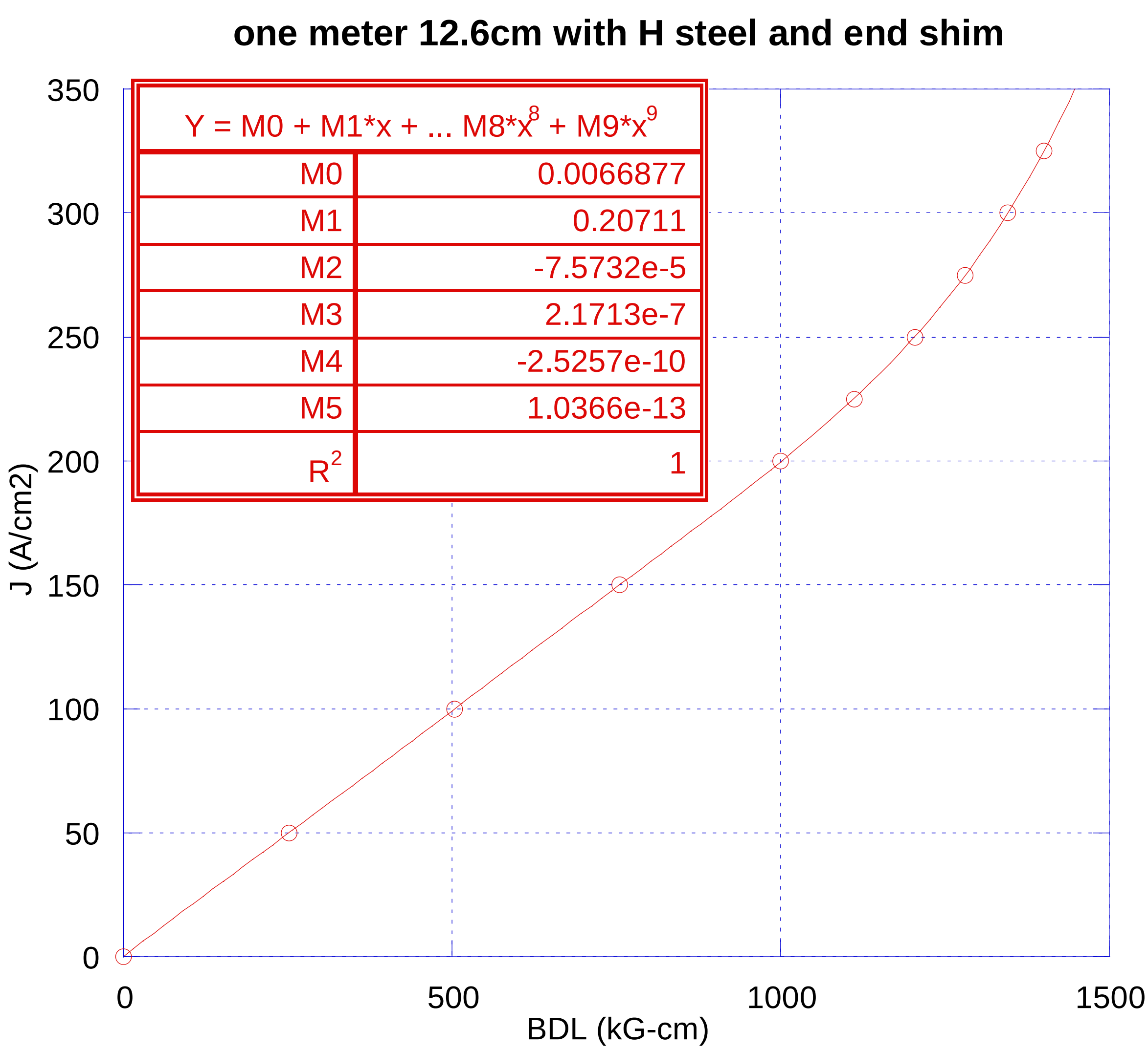
BDL (kG-cm)	J (A/cm2)	formula	formula/J
0.000	0	0	
247.807	50	50.024	1.0005
495.613	100	99.909	0.9991
743.625	150	150.200	1.0013
984.792	200	199.611	0.9981
1093.385	224	224.182	1.0008
1193.086	250	250.257	1.0010
1274.990	276	275.899	0.9996
1338.974	300	299.772	0.9992
1394.629	324	324.132	1.0004



One meter, 12.6 cm with "H" steel and 1cm shims on each end

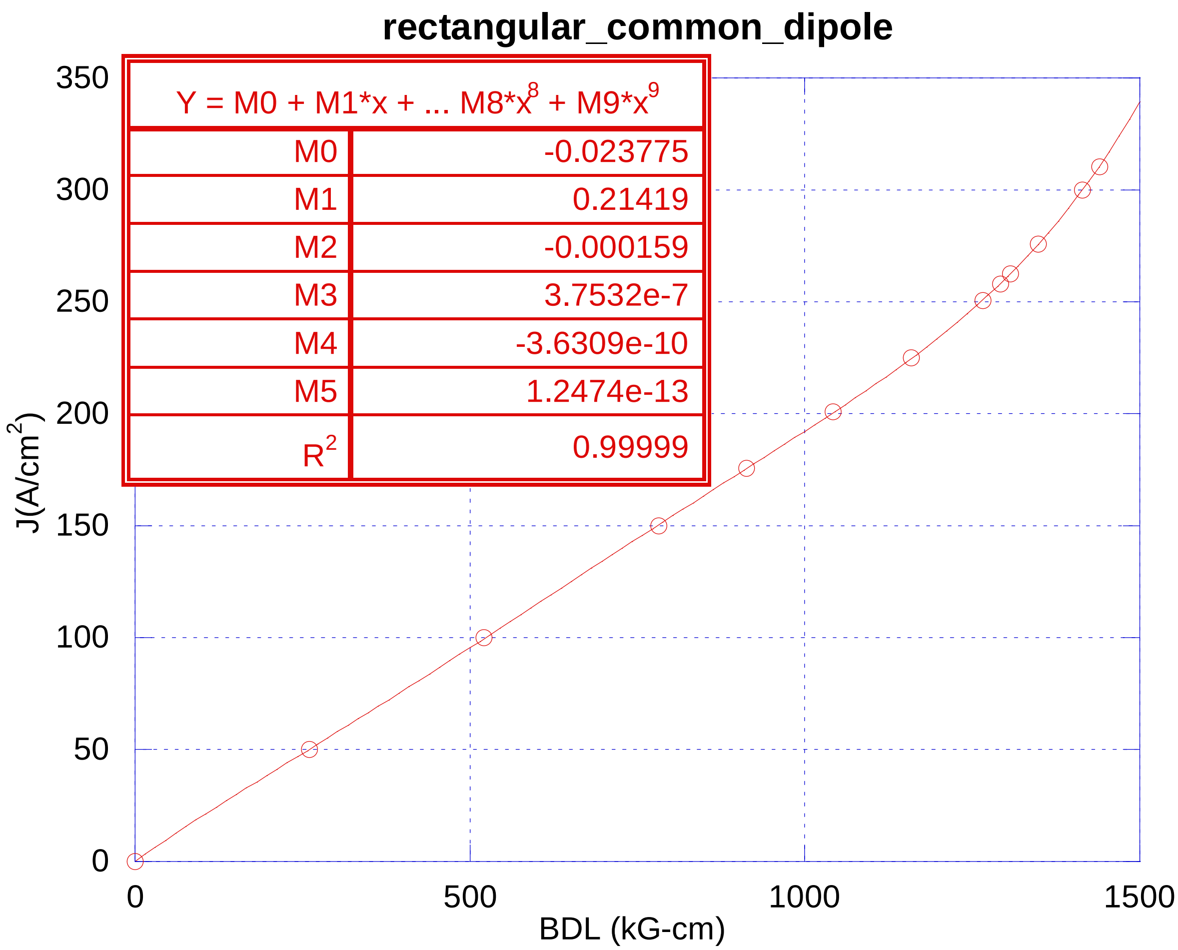
Shims 1cm in length(Z), 5cm in height and full pole width added to pole of previous model. In reality, one would taper the shim over the height and perhaps round the nose to reduce saturation effects. I didn't spend the couple of additional hours needed to model this.

BDL (kG-cm)	J (A/cm2)	formula	formula/J
0.000	0	0	
252.077	50	49.966	0.9993
504.155	100	100.056	1.0006
754.996	150	150.014	1.0001
1000.390	200	199.690	0.9985
1112.019	225	225.299	1.0013
1204.522	250	250.228	1.0009
1280.827	275	274.867	0.9995
1345.197	300	299.683	0.9989
1401.313	325	325.220	1.0007



Rectangular common dipole with added return steel
coil area 8.241 x 9.5 cm^2

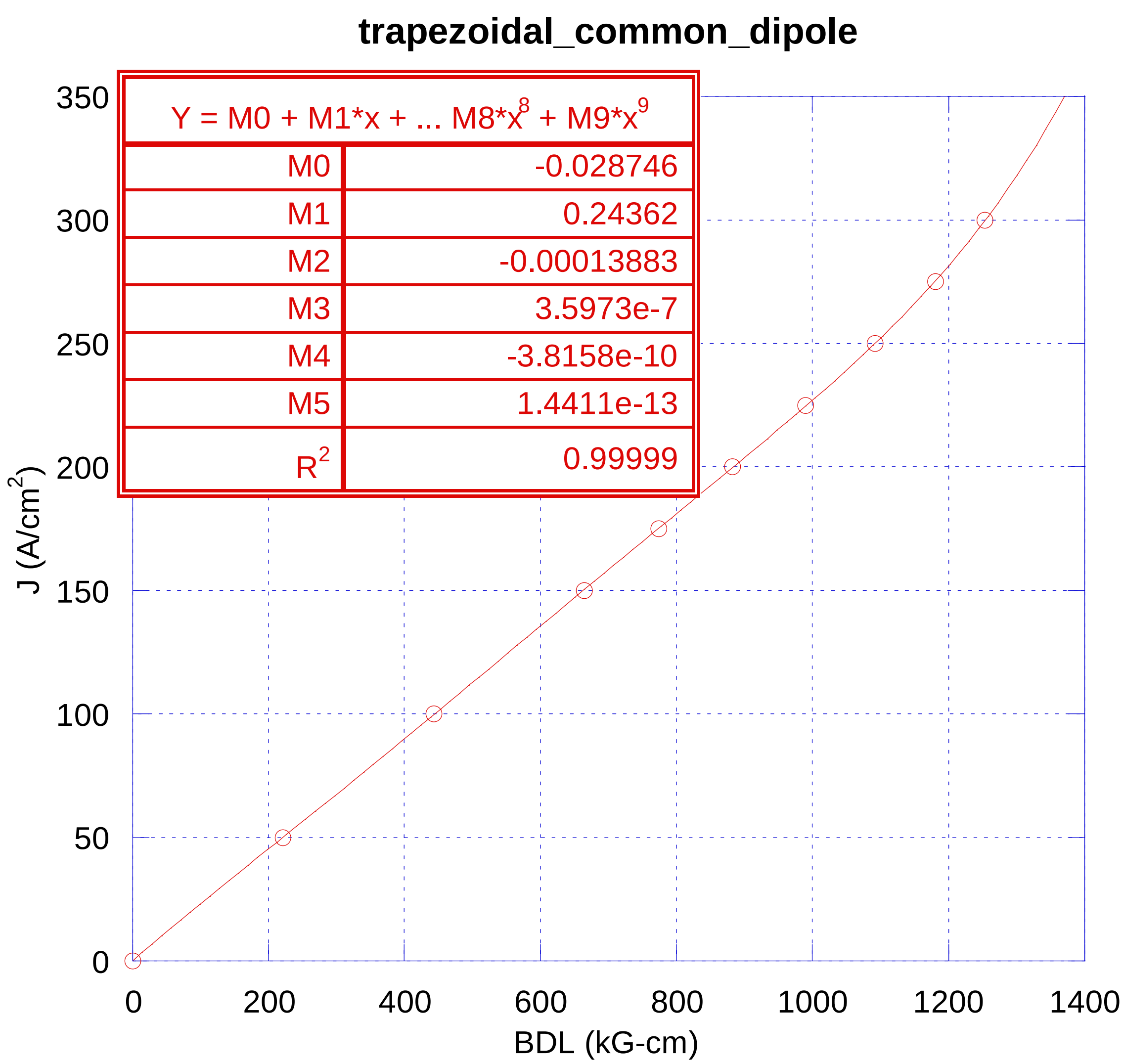
BDL (kG-cm)	J(A/cm^2)	fomula	formula/J
0.000	0		
260.767	50		
521.535	100		
782.302	150	150.504	1.0034
913.693	175.5	175.491	0.9999
1043.025	201	200.385	0.9969
1159.375	225	224.671	0.9985
1265.948	250.5	250.826	1.0013
1307.471	262.5	262.689	1.0007
1349.128	276	275.873	0.9995
1414.231	300	299.695	0.9990
1292.501	258	258.278	1.0011
1440.181	310.5	310.503	1.0000



Trapezoidal common dipole with ~6" additional return steel

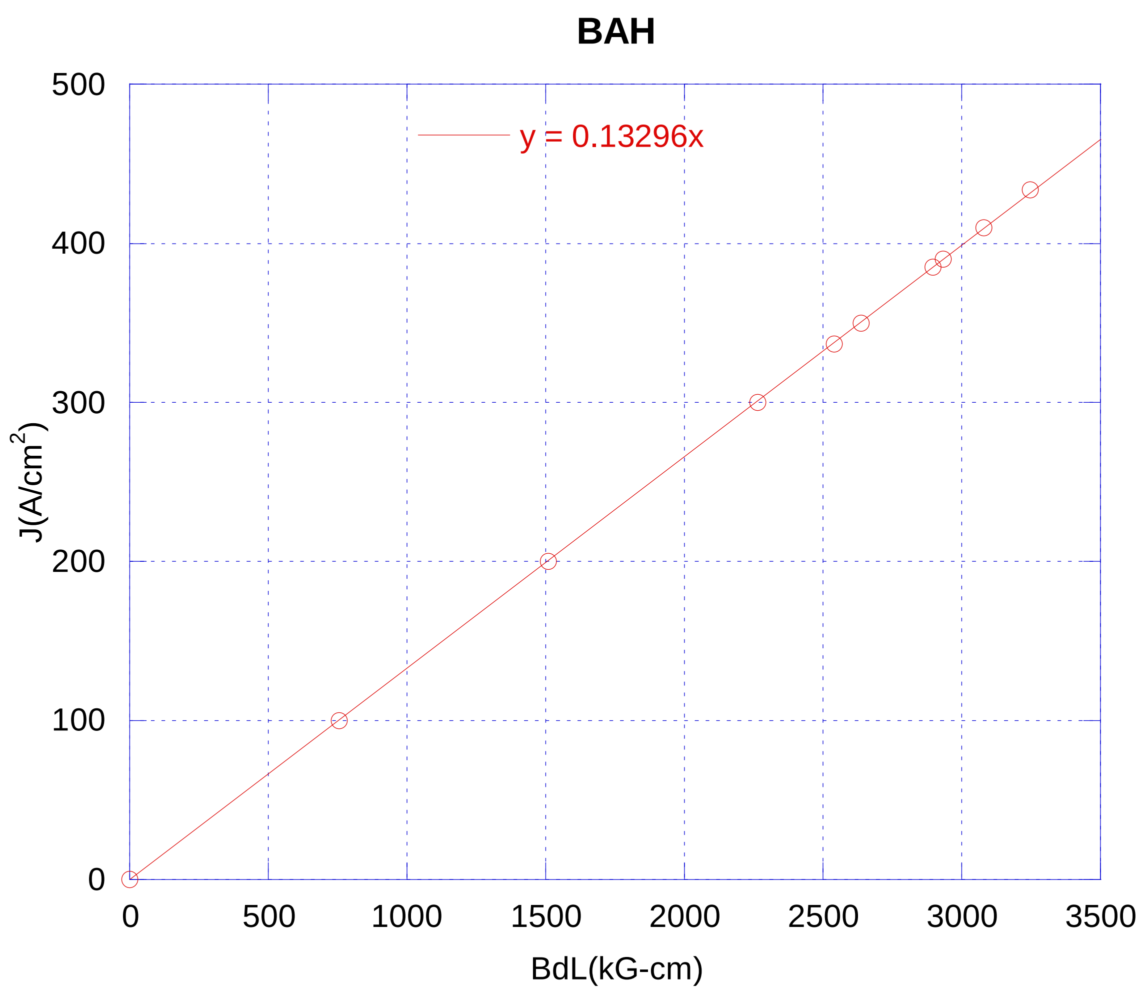
Coil cross-section 16.05 x 5.296 cm^2. The results below are for the dipole without the hole drilled in the return steel for the first pass beam. I made a number of models with such a hole. I found that a 66mm diameter hole with a beam pipe of 2" nominal, schedule 40 carbon steel pipe has the same BdL(J) as without the hole for the nominal J. The carbon steel pipe reduces the field which the first pass beam experiences to ~120 G-cm, about a factor of fifty.

BDL (kG-cm)	J (A/cm2)	fomulaJ	formula/J
0.000	0		
221.384	50	50.164	1.0033
442.768	100	99.634	0.9963
664.152	150	150.299	1.0020
773.930	175	175.234	1.0013
882.806	200	199.849	0.9992
989.861	225	224.603	0.9982
1091.940	250	250.046	1.0002
1181.203	275	275.444	1.0016
1253.868	300	299.772	0.9992



3m arc dipole with H steel
coil cross section 5.384 x 7.7 cm^2

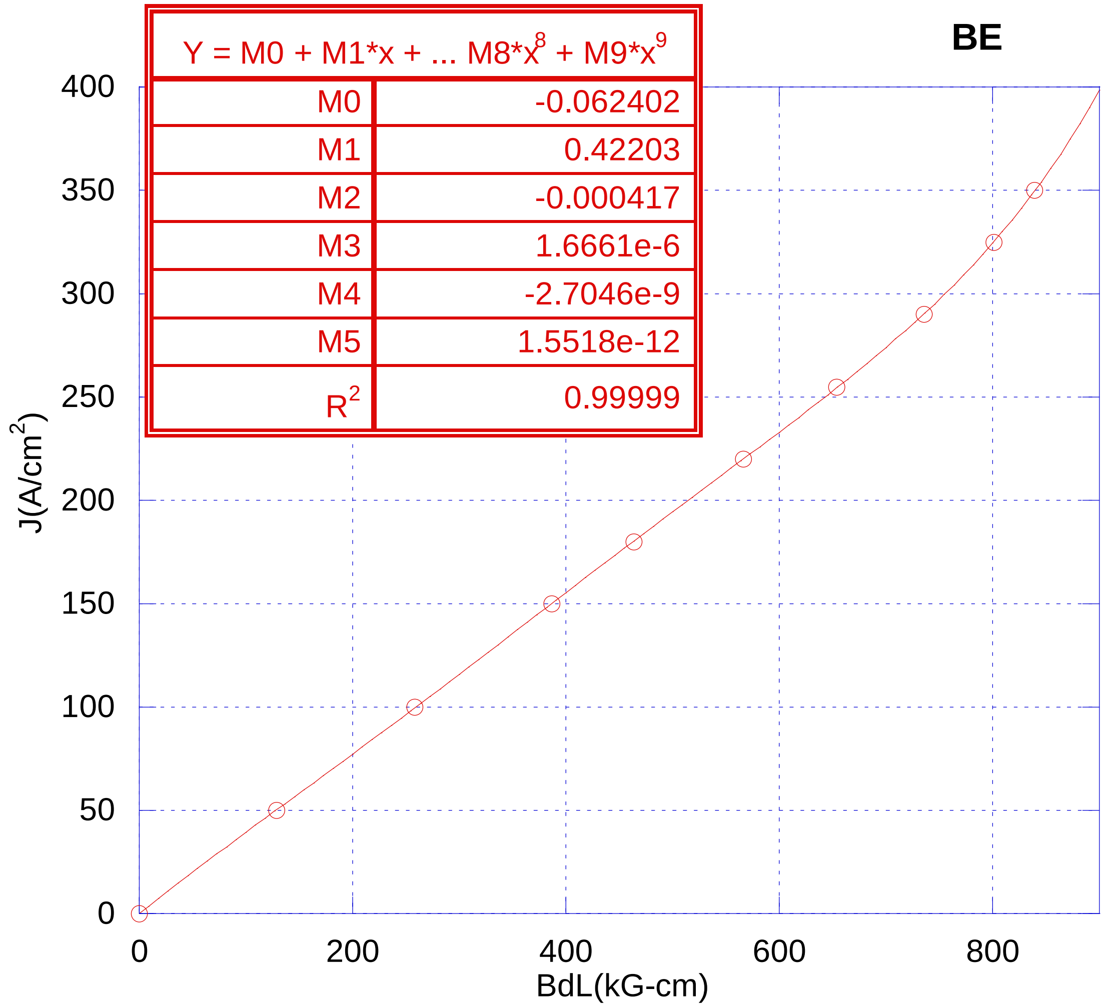
BdL(kG-cm)	J(A/cm^2)	fomulaJ	formula/J
0	0	0	
754.847	100	100.364	1.0036
1509.693	200	200.729	1.0036
2264.540	300	301.093	1.0036
2541.441	337	337.910	1.0027
2638.285	350	350.786	1.0022
2896.970	385	385.181	1.0005
2933.597	390	390.051	1.0001
3078.712	410	409.346	0.9984
3248.045	434	431.860	0.9951



1 m arc dipole, as now (BE, BN, BQ)

Used in arc 1, arc 3 and hall B now. All but arc 1 will get H steel for upgrade. **Coil cross-section 5.384 x 4.7 cm^2** BQ in extraction has same steel, too, and won't get H steel.

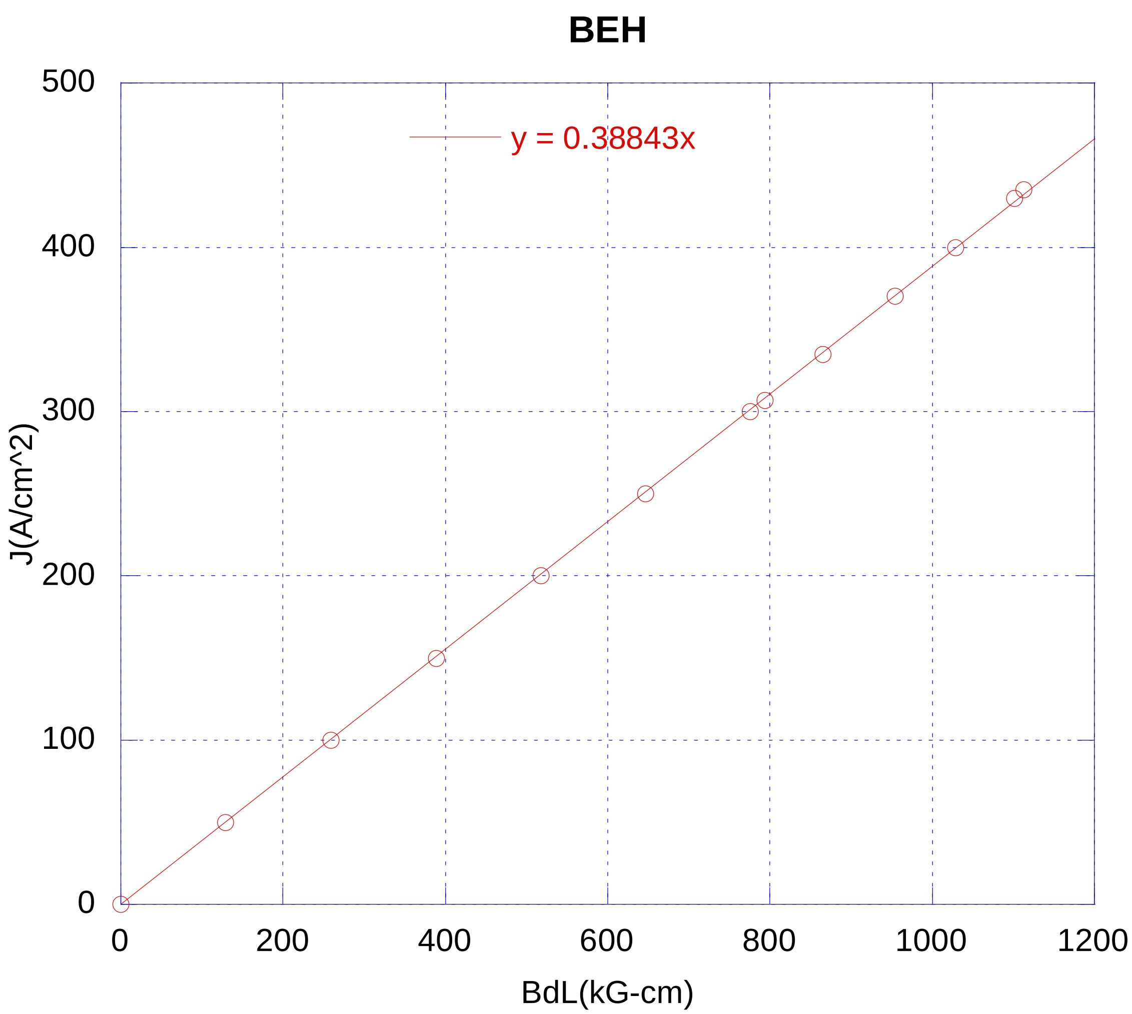
BdL(kG-cm)	J(A/cm^2)	fomulaJ	formula/J
0	0		
128.973	50	50.313	1.0063
257.946	100	99.446	0.9945
386.919	150	150.150	1.0010
464.083	180	180.463	1.0026
566.068	220	219.916	0.9996
653.686	255	254.392	0.9976
735.668	290	290.276	1.0010
801.624	325	325.380	1.0012
839.350	350	349.696	0.9991



One meter arc dipole with H steel

Otherwise as on previous page. Data begins to diverge from straight line after 400A/cm^2 but not enough to worry about.

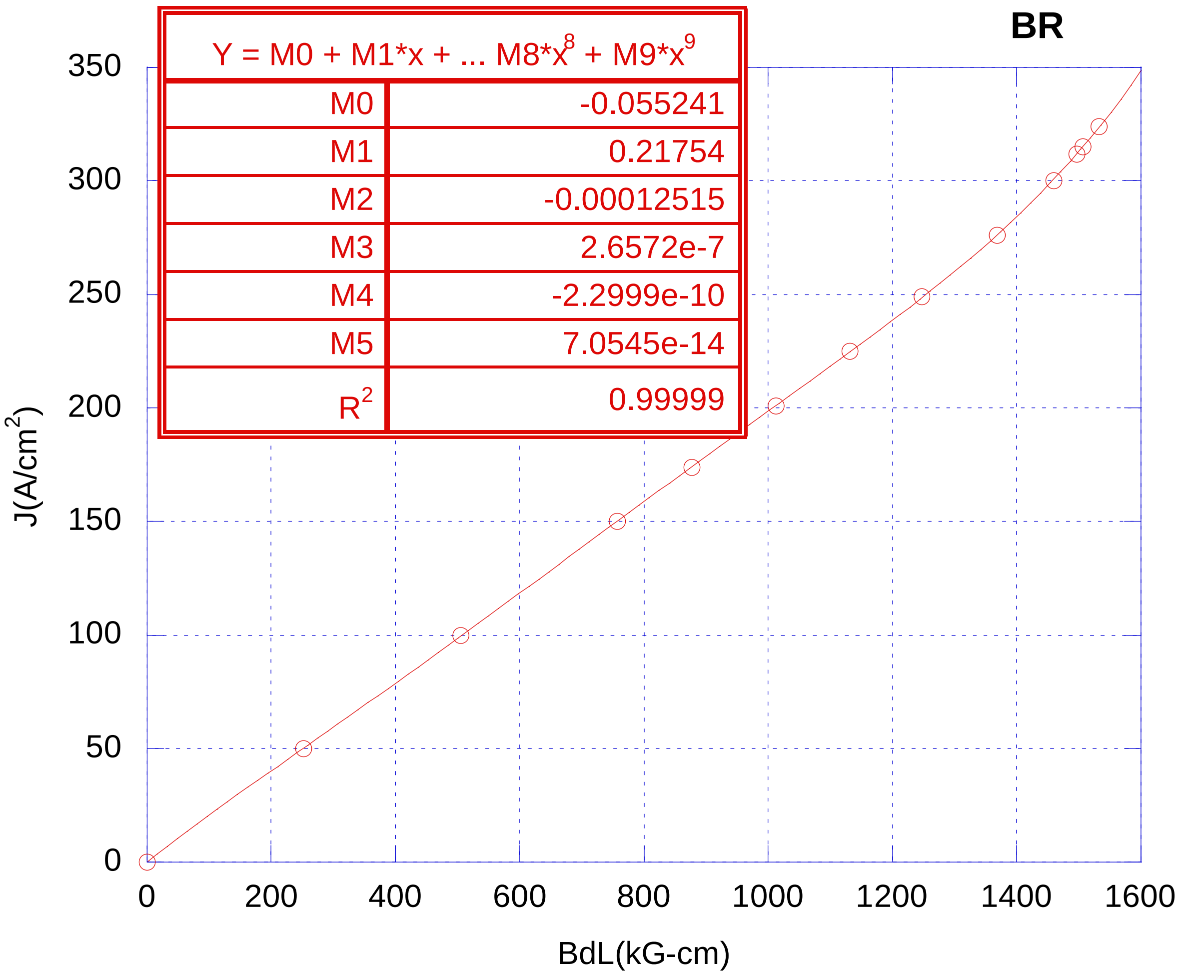
BdL(kG-cm)	J(A/cm^2)	fomulaJ	formula/J
0	0	0	
129.488	50	50.297	1.0059
258.975	100	100.594	1.0059
388.567	150	150.931	1.0062
517.849	200	201.148	1.0057
646.995	250	251.312	1.0052
775.808	300	301.347	1.0045
793.969	307	308.401	1.0046
865.586	335	336.220	1.0036
954.338	370	370.693	1.0019
1029.128	400	399.744	0.9994
1101.111	430	427.704	0.9947
1112.680	435	432.198	0.9936



Arc 2 dipole (BR)

Coil cross-section 5.384 x 4.7 cm^2

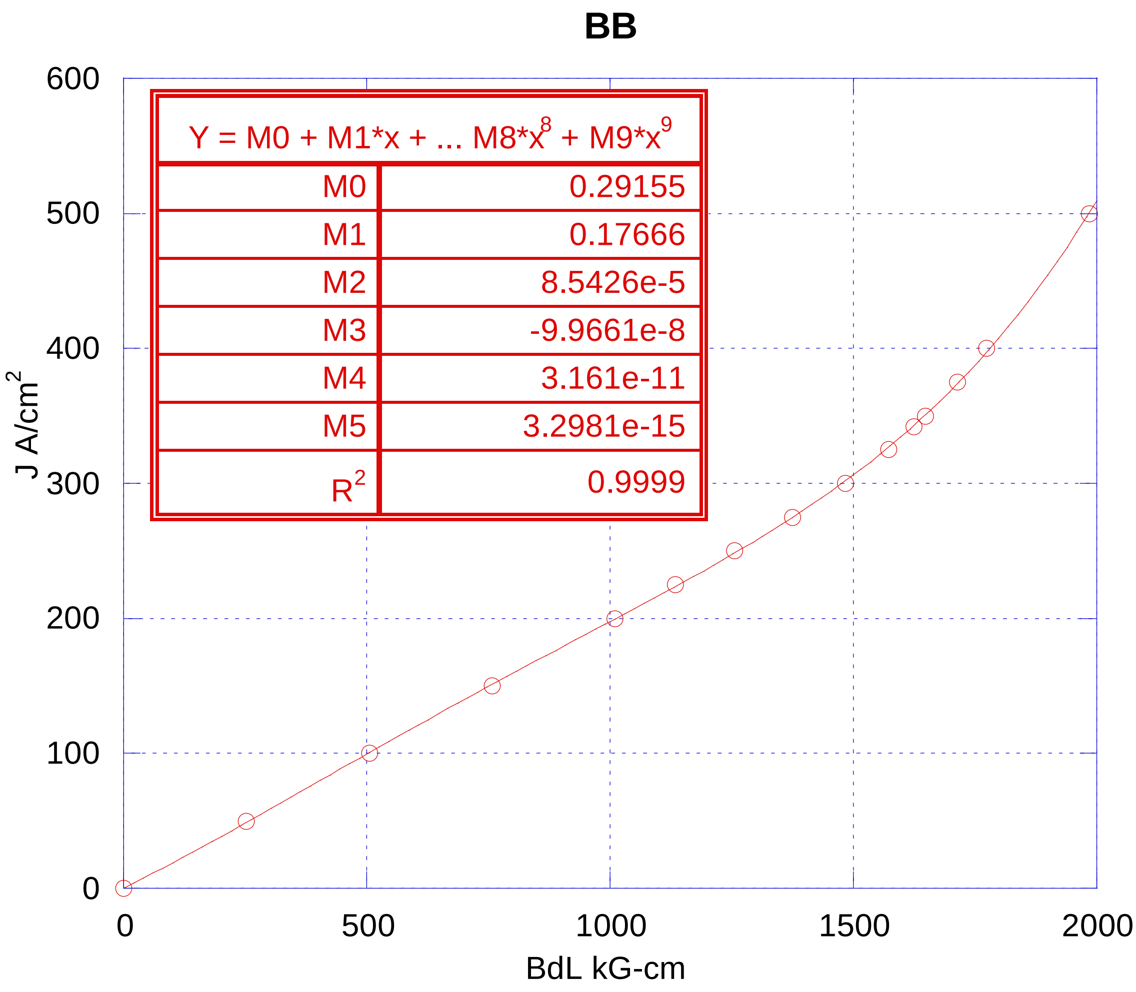
BdL(kG-cm)	J(A/cm^2)	formula	formula/J
0	0		
252.409	50	50.292	1.0058
504.818	100	99.430	0.9943
757.226	150	150.231	1.0015
877.793	174	174.410	1.0024
1012.643	201	201.102	1.0005
1131.225	225	224.595	0.9982
1247.285	249	248.513	0.9980
1368.826	276	276.314	1.0011
1459.323	300	300.517	1.0017
1497.462	312	312.048	1.0002
1532.828	324	323.630	0.9989
1506.511	315	314.925	0.9998



2m arc dipole (BB, BP)

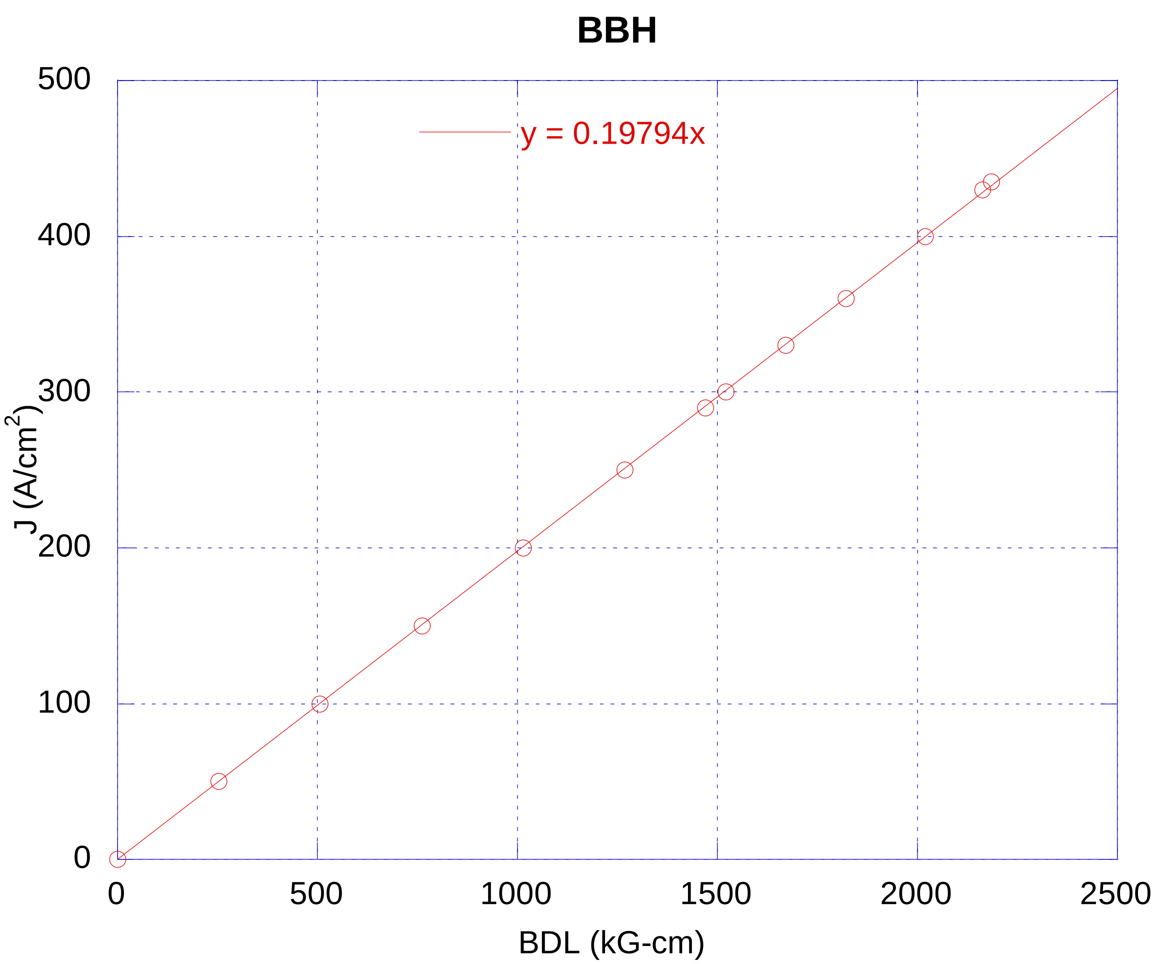
Coil cross section 5.384 x 4.7 cm^2

BdL kG-cm	J A/cm^2	formula	formula/J
0	0		
252.856	50	48.944	0.9789
505.713	100	100.765	1.0077
758.288	150	151.195	1.0080
1009.605	200	199.464	0.9973
1134.103	225	223.623	0.9939
1256.940	250	248.645	0.9946
1375.730	275	274.997	1.0000
1483.738	300	301.852	1.0062
1572.823	325	326.892	1.0058
1624.863	342	343.035	1.0030
1647.622	350	350.497	1.0014
1713.554	375	373.658	0.9964
1774.354	400	397.290	0.9932
1985.550	500	500.794	1.0016



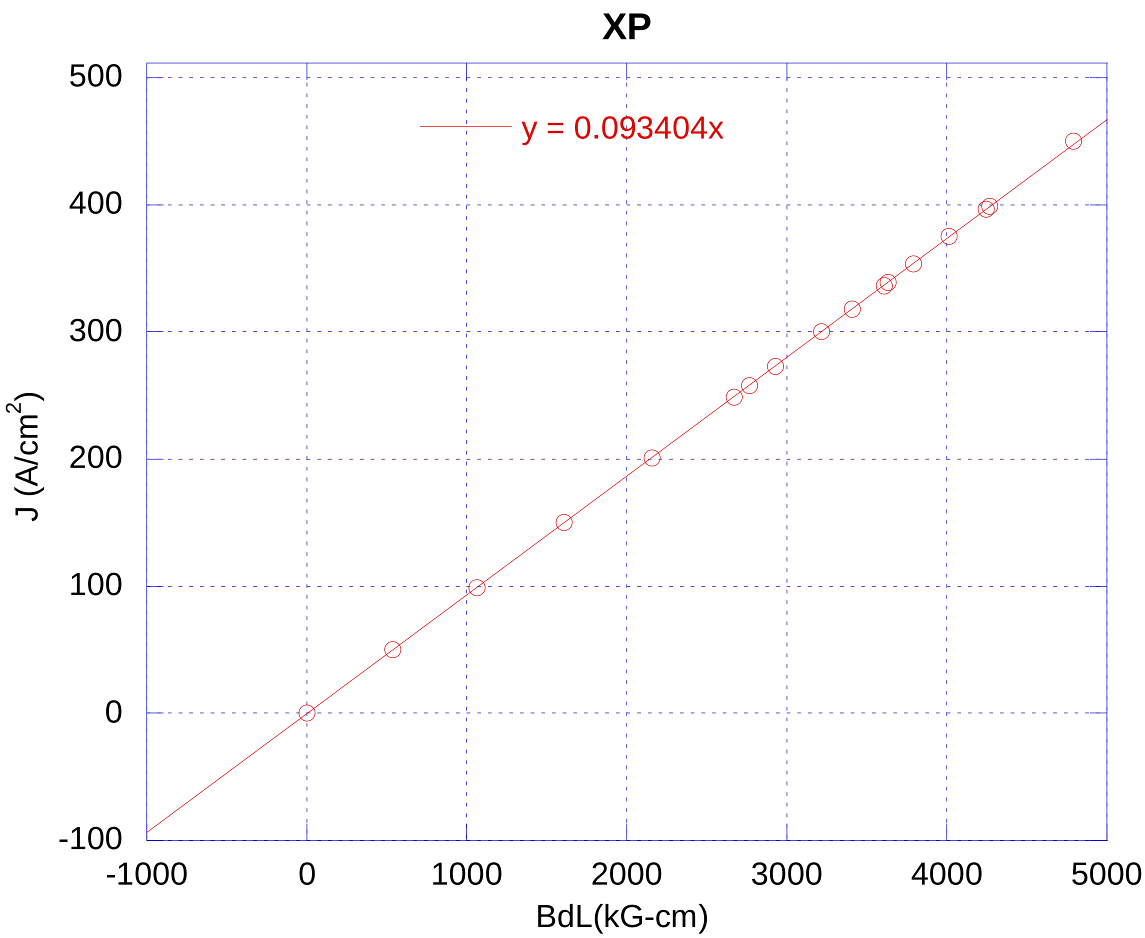
2 m arc dipole with H steel
Otherwise as on previous page. Note modest departure from linear fit for two highest points.

BDL (kG-cm)	J (A/cm2)	formula	formula/J
0	0	0	
253.849	50	50.247	1.0049
507.698	100	100.494	1.0049
761.527	150	150.737	1.0049
1015.234	200	200.955	1.0048
1268.546	250	251.096	1.0044
1471.027	290	291.175	1.0041
1521.447	300	301.155	1.0039
1672.307	330	331.016	1.0031
1822.291	360	360.704	1.0020
2019.529	400	399.746	0.9994
2162.828	430	428.110	0.9956
2185.955	435	432.688	0.9947



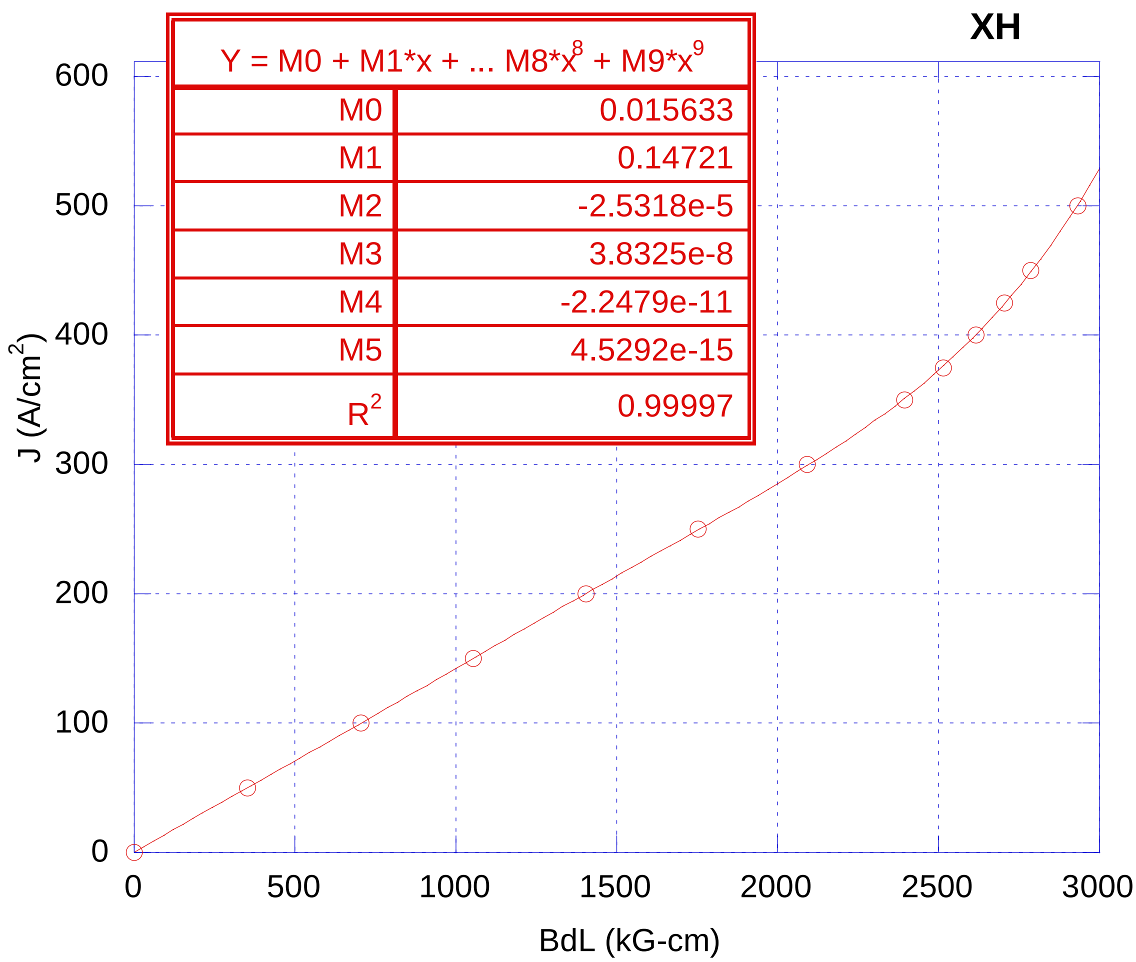
4m Dipole
Coil cross section 5.4 x 5 cm^2. Note modest departure from line at highest current.

BdL(kG-cm)_	J (A/cm2)	formula	formula/J
0.000	0	0	
536.635	50	50.124	1.0025
1062.537	99	99.245	1.0025
1609.854	150	150.367	1.0024
2156.986	201	201.471	1.0023
2671.500	249	249.529	1.0021
2767.884	258	258.531	1.0021
2767.845	258	258.528	1.0020
2928.436	273	273.528	1.0019
3217.094	300	300.489	1.0016
3409.220	318	318.435	1.0014
3632.934	339	339.331	1.0010
3792.347	354	354.220	1.0006
4014.764	375	374.995	1.0000
4267.475	399	398.599	0.9990
4791.597	450	447.554	0.9946

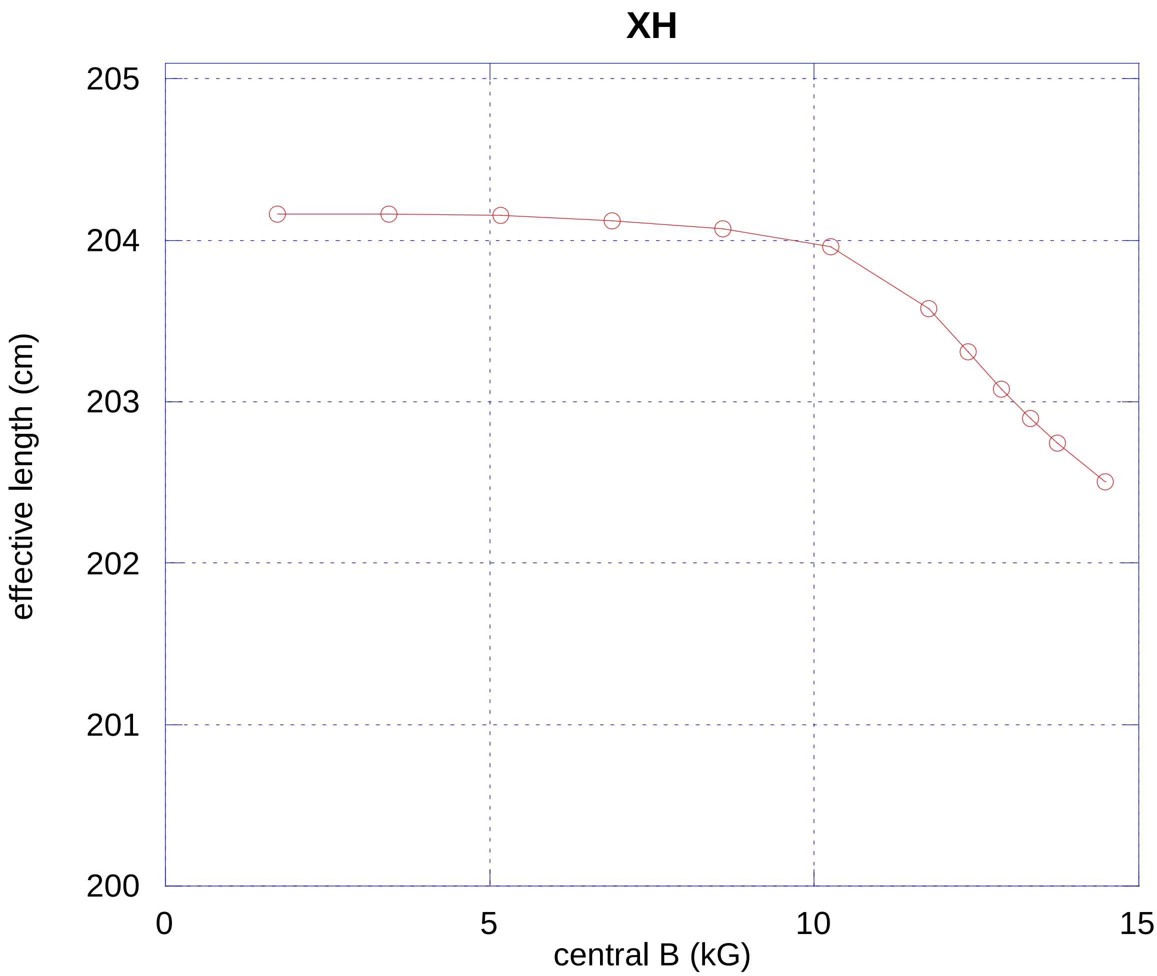


Arc 10 S/R/T C dipole for 12 GeV, 2m steel, 13 cm pole, 13.5cm return steel
This is a suggested replacement for ME's XH design. It has about 10% less steel. **Coil cross-section is 5x7.2 cm^2.**

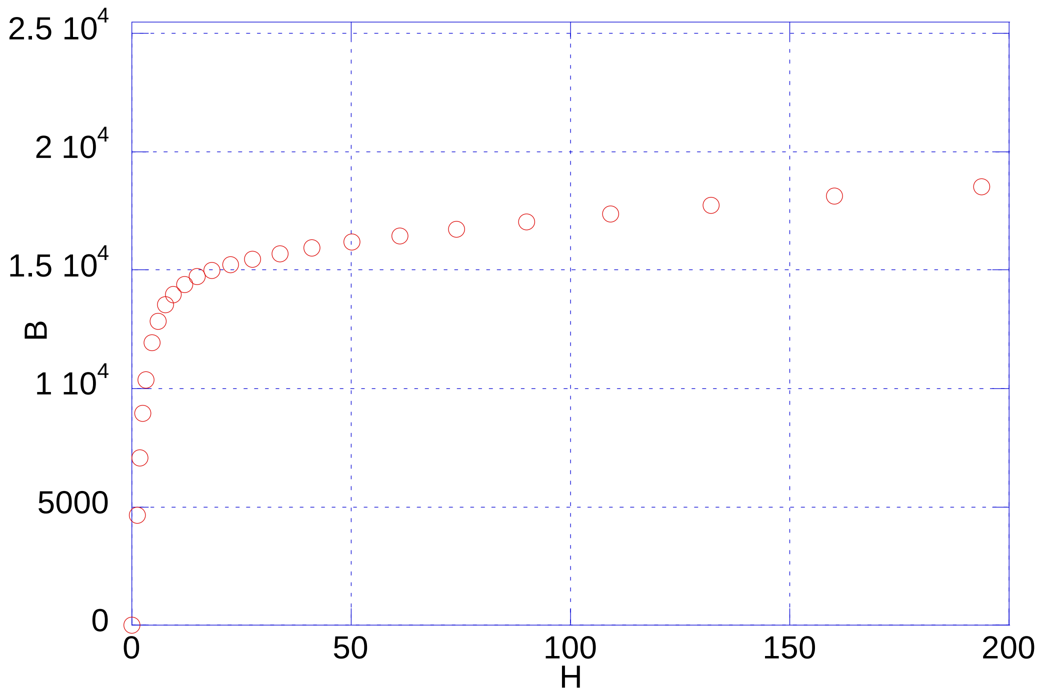
Bdl(kG-cm)	J(A/cm2)	formula	formula/J	central B(kG)	effective length (cm)
0.000	0				
351.917	50	50.036	1.0007	1.724	204.164
703.788	100	99.707	0.9971	3.447	204.163
1055.313	150	150.263	1.0018	5.169	204.153
1405.691	200	200.462	1.0023	6.887	204.121
1753.171	250	249.452	0.9978	8.591	204.071
2092.453	300	299.063	0.9969	10.259	203.961
2395.425	350	351.241	1.0035	11.767	203.577
2515.033	375	376.170	1.0031	12.370	203.310
2616.046	400	400.116	1.0003	12.882	203.080
2705.450	425	424.074	0.9978	13.334	202.895
2786.829	450	448.588	0.9969	13.745	202.745
2934.090	500	500.952	1.0019	14.489	202.506



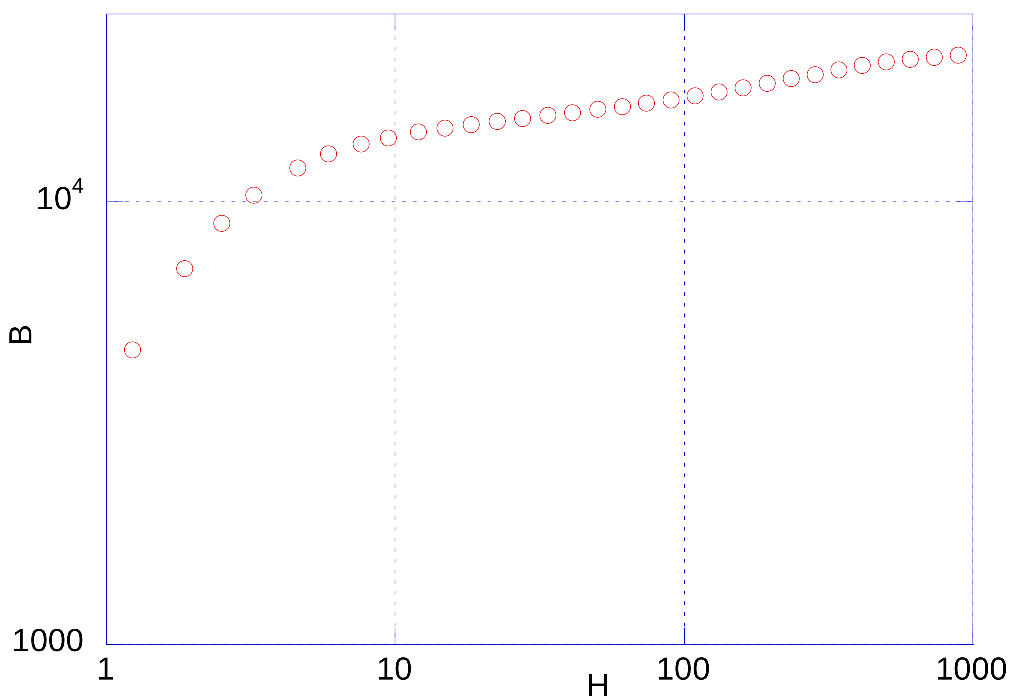
Arc 10 S/R/T 2m dipole (cont)



Steel length 200cm



Jlab SR BH curve on linear (above) and log-log axes (below)



AM and AN dipoles

These dipole models are important because they are the only one operating in 6 GeV CEBAF at fields in excess of 10 kG. Fields at 6 GeV are ~7-14 kG. Mike Tiefenback pointed out that they provide an important test of the BH curve used in the model and of my assumption that coil configuration used in the model does not matter, as found in the BA dipole at fields below 6 kG.

As shown below, coil configuration does matter in these magnets with long poles, 13.7 and 16 cm respectively. Further, with modeled coils matching reality within 1mm, measured BdL departs from modeled BdL ~10 kG in a similar manner in both magnets. This suggests that the BH curve provided and used by ME is not accurate above 10 kG. Current difference between EPICS field map and the AM model at 92% of peak field planned for 12 GeV in one S/R design is about 5A, one fourth of the shunt range. If this is due to the BH curve as hypothesized all of the models shown in this paper will be uncertain above 10kG at the level of several amps.

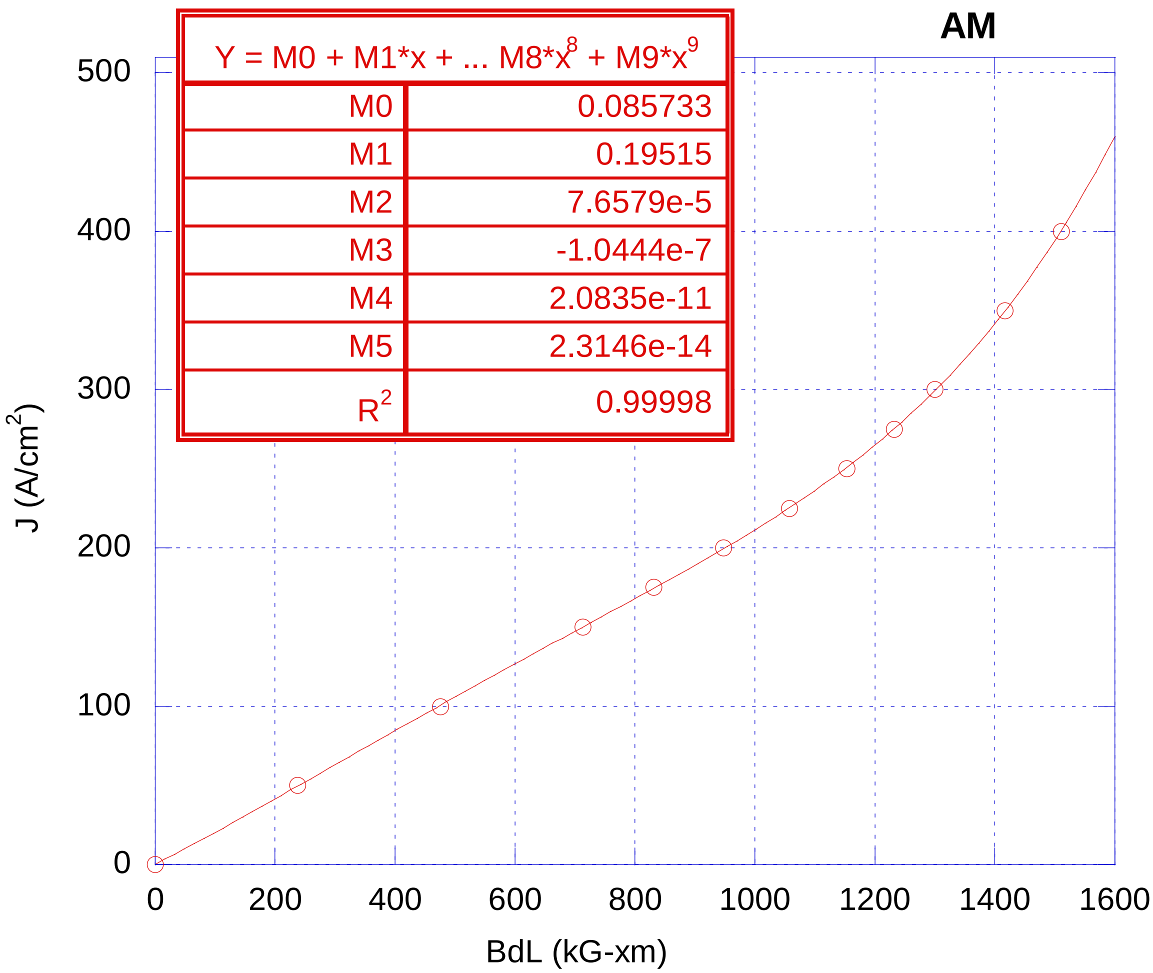
AM dipole - rollover magnet in arc 3

Coil cross section 5x10 cm^2. Steel 96.088 cm long. "Shunt adders" needed for 6 GeV

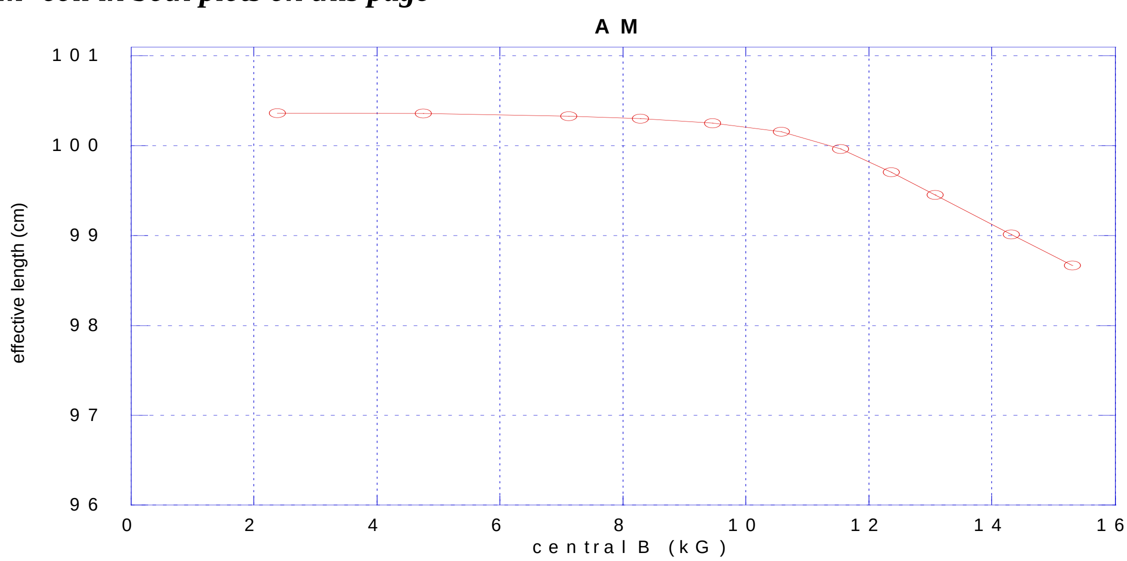
BDL(kG-cm)	J(A/cm^2)	formula J	formula/J	central B (kG)	effective length
0	0			0	
238.119	50	49.571	0.9914	2.373	100.360
476.153	100	100.732	1.0073	4.745	100.357
713.391	150	150.032	1.0002	7.111	100.326
831.139	175	174.341	0.9962	8.287	100.297
947.417	200	199.350	0.9967	9.450	100.251
1058.455	225	225.490	1.0022	10.568	100.152
1153.673	250	250.993	1.0040	11.541	99.962
1232.186	275	275.201	1.0007	12.358	99.707
1300.544	300	299.397	0.9980	13.077	99.450
1417.044	350	349.474	0.9985	14.312	99.010
1510.909	400	400.356	1.0009	15.313	98.667

coil cross section 5x11.7cm^2

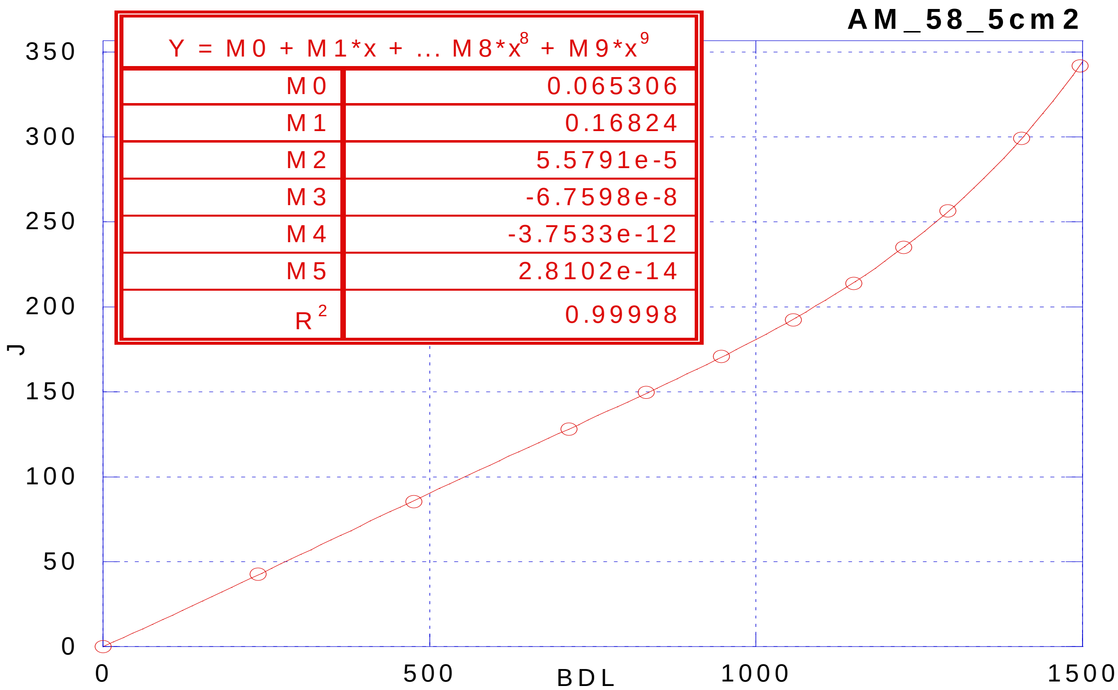
BDL/2	BDL	J	formula	formula/actual	Bcenter	effective length	amp-turns
0.000	0.000	0.0					0.000
119.007	238.014	42.7	42.367	0.992	2.370	100.411	2497.950
238.246	476.492	85.5	86.081	1.007	4.746	100.408	5001.750
356.782	713.564	128.2	128.188	1.000	7.109	100.376	7499.700
415.719	831.439	149.6	149.033	0.996	8.286	100.346	8751.600
473.556	947.111	170.9	170.419	0.997	9.443	100.298	9997.650
528.535	1057.070	192.3	192.807	1.003	10.550	100.195	11249.550
574.967	1149.934	213.7	214.459	1.004	11.499	100.004	12501.450
613.129	1226.258	235.0	235.051	1.000	12.293	99.751	13747.500
646.546	1293.092	256.4	255.849	0.998	12.997	99.490	14999.400
703.036	1406.071	299.1	298.786	0.999	14.197	99.040	17497.350
748.073	1496.146	341.9	342.139	1.001	15.160	98.690	20001.150



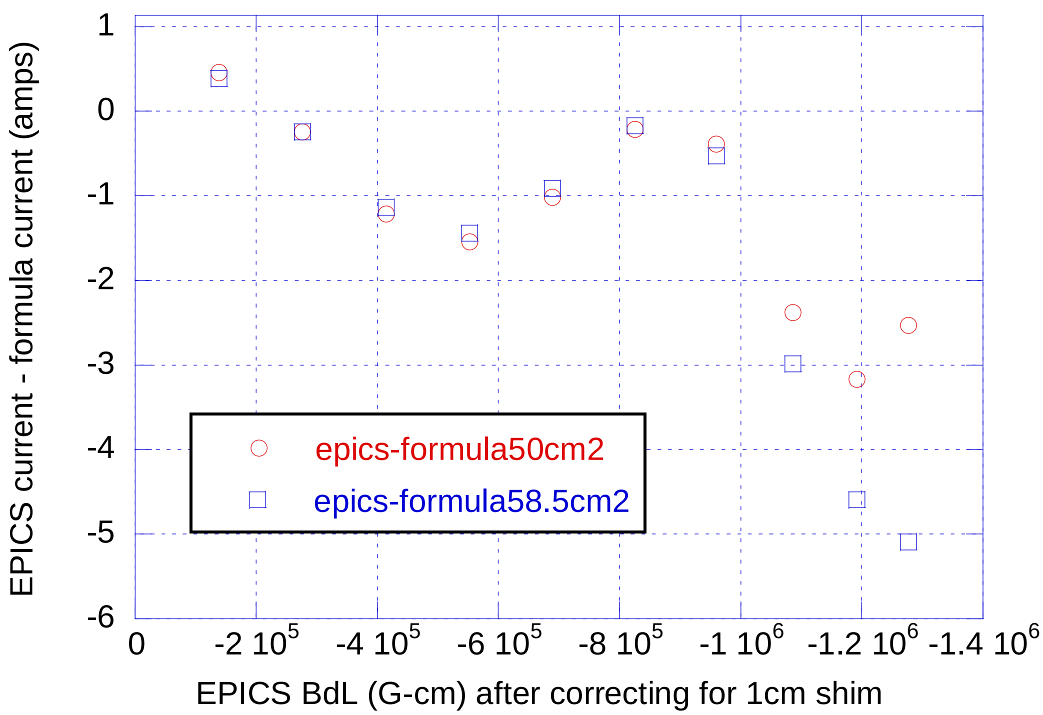
50cm² coil in both plots on this page



Steel length 96.088 cm. Hence lower limit on Y axis.



58.5 cm² coil used for plot above.



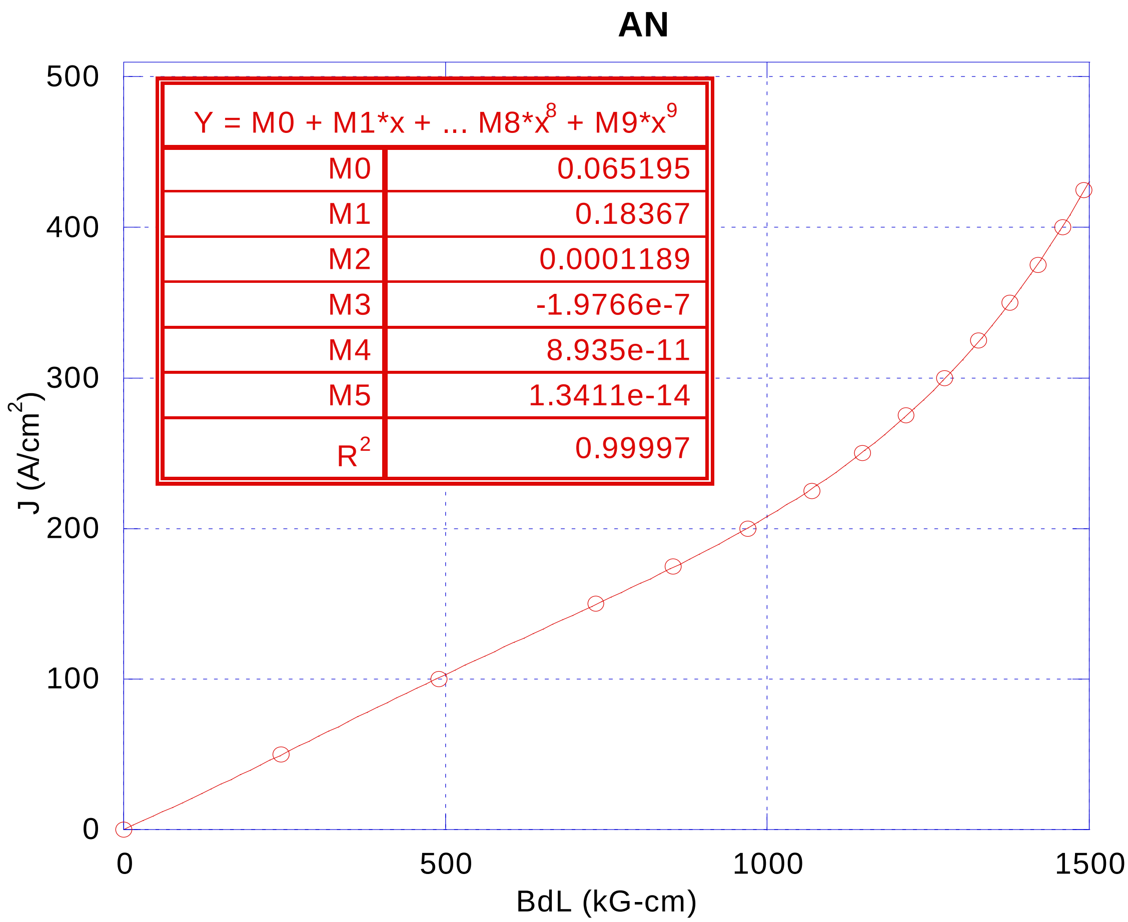
Comparison of currents from EPICS map to models for two coil sizes. 58.5 cm² more accurately reflects reality. Note the abrupt change in current difference after the ~10kG (10^6 G-cm) point. At low fields the length of the coil doesn't matter because the pole isn't saturated. At higher fields some of the flux from the longer coil is outside the pole gap proper, requiring more current for a fixed BdL. At ~13 kG the discrepancy with measurement for the "real" coil is 5A.

AN dipole - rollover magnet in arc 5
Coil cross section 5x10 cm^2. Steel 96.088 cm long. "Shunt adders" needed for 6 GeV

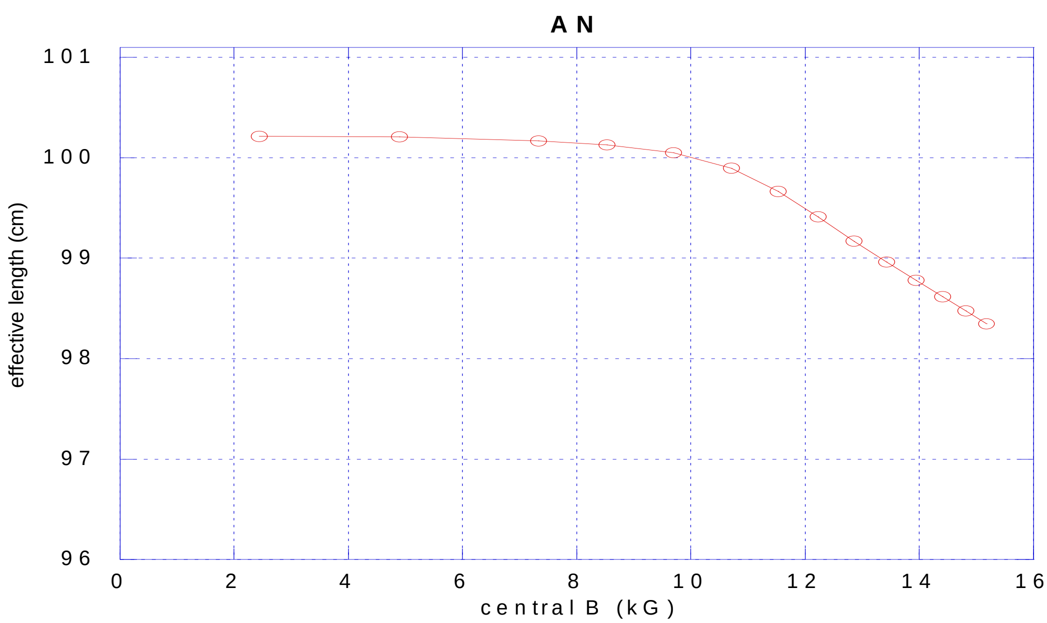
BDL (kG-cm)	J (A/cm2)	formula	formula/J	central B (kG)	effective length (cm)
0	0			0	
244.972	50	50.209	1.0042	2.445	100.213
489.849	100	101.443	1.0144	4.888	100.207
733.498	150	150.051	1.0003	7.323	100.168
853.744	175	174.675	0.9981	8.526	100.129
969.666	200	200.823	1.0041	9.692	100.051
1069.232	225	226.876	1.0083	10.704	99.895
1148.260	250	251.170	1.0047	11.521	99.666
1215.285	275	275.143	1.0005	12.225	99.411
1274.912	300	299.703	0.9990	12.856	99.170
1328.707	325	324.973	0.9999	13.427	98.961
1377.156	350	350.653	1.0019	13.942	98.777
1420.579	375	376.330	1.0035	14.405	98.617
1458.969	400	401.356	1.0034	14.816	98.475
1492.170	425	424.920	0.9998	15.172	98.348

AN with 70 cm^2 coils   5x14 cm^2

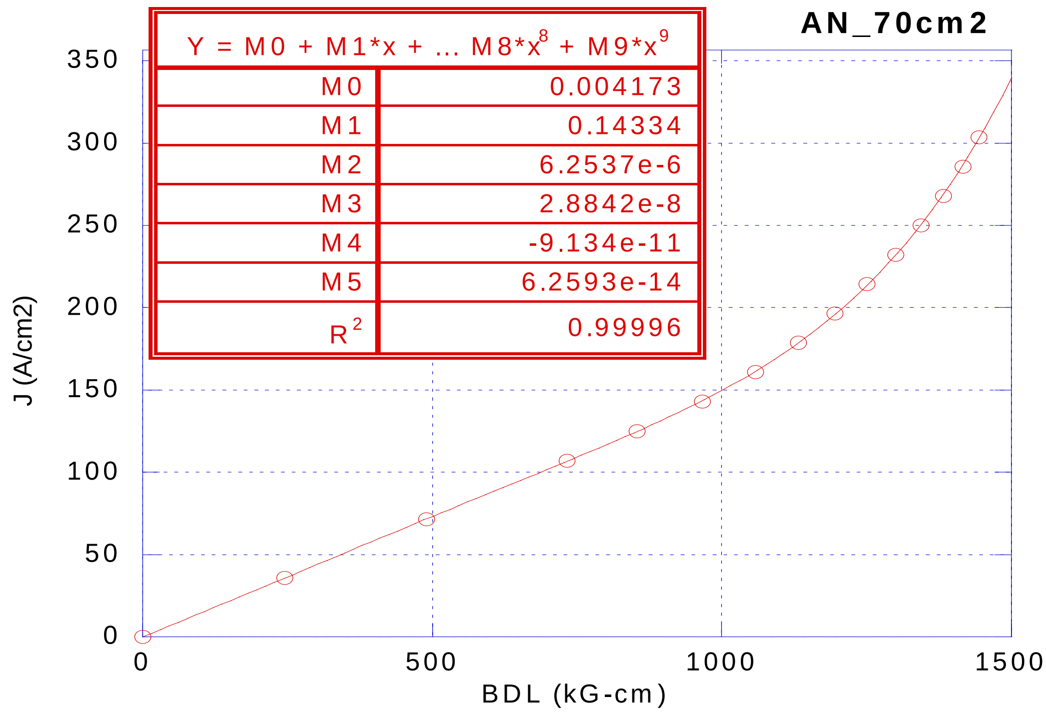
BDL (kG-cm)	J (A/cm2)	formula	formula/actual	central B (kG)	effective length (cm)	amp-turns
0	0					0
245.007	35.7	35.663	0.9990	2.443	100.305	2499
489.891	71.4	71.583	1.0026	4.884	100.299	4998
733.305	107.1	106.752	0.9967	7.314	100.256	7497
853.317	125.0	124.731	0.9979	8.515	100.212	8750
966.470	142.9	143.507	1.0042	9.653	100.126	10003
1058.458	160.7	161.370	1.0042	10.587	99.977	11249
1132.275	178.6	178.404	0.9989	11.350	99.759	12502
1195.023	196.4	195.521	0.9955	12.009	99.507	13748
1250.606	214.3	213.288	0.9953	12.599	99.262	15001
1299.961	232.1	231.575	0.9977	13.125	99.042	16247
1344.003	250.0	250.255	1.0010	13.596	98.850	17500
1382.676	267.9	268.773	1.0033	14.011	98.686	18753
1415.803	285.7	286.406	1.0025	14.367	98.546	19999
1443.702	303.6	302.654	0.9969	14.667	98.431	21252

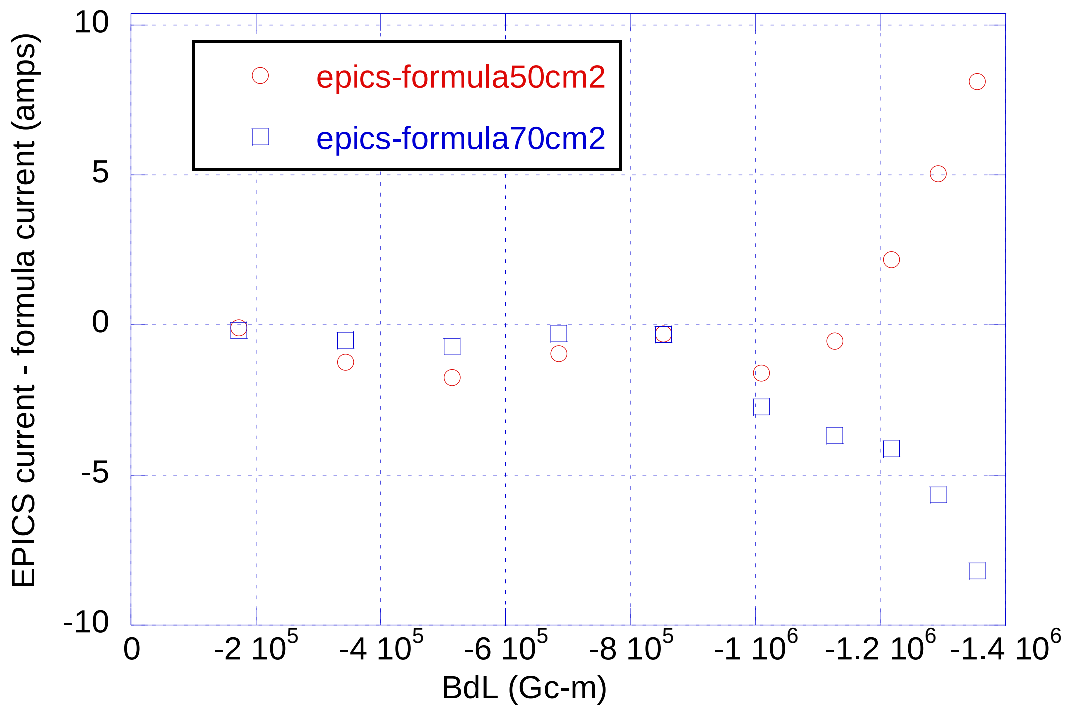


50cm² coil used in both plots on this page

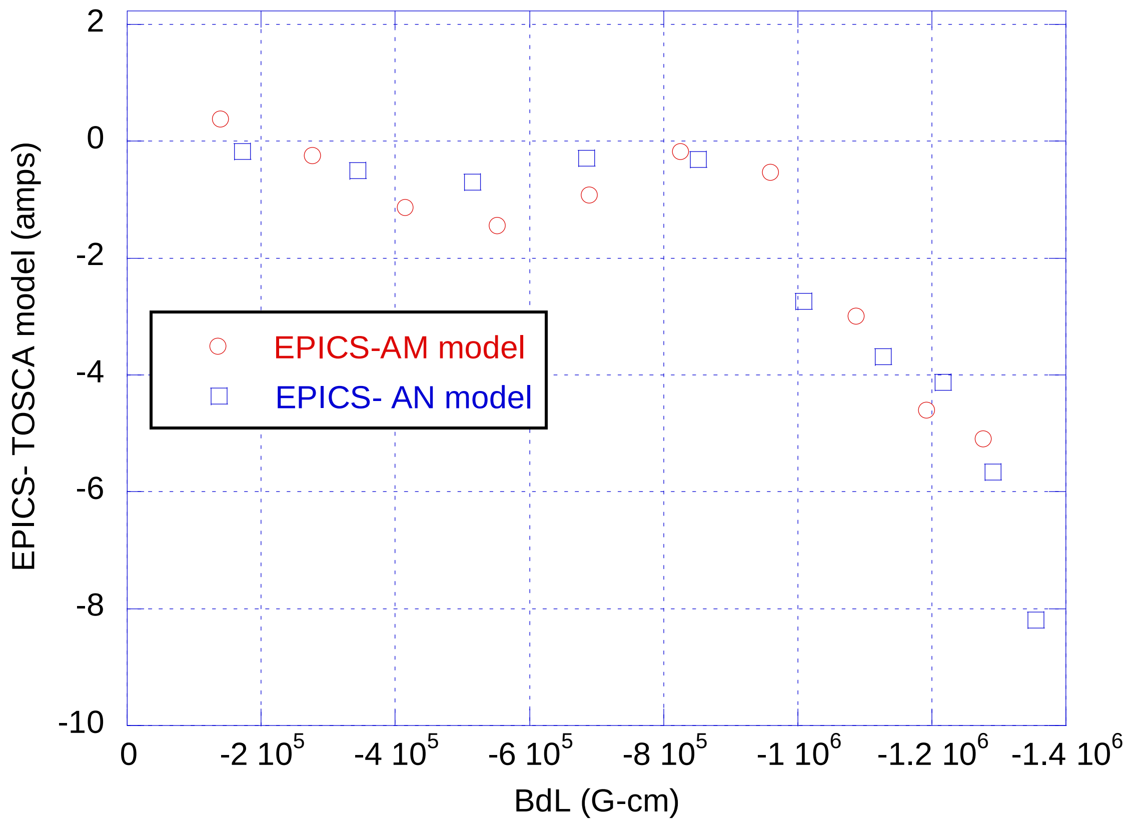


Steel length 96.088 cm. Hence lower limit on Y axis.





Here the first distinct difference between measurement and model is ~10kG or 1E6 G-cm. The short coil (10cm long) couples better to the gap and so suggests less current is needed than measured. The long coil (14cm long, 70cm^2) matches physical reality so the discrepancy here between measurement and model is likely due to the BH curve. Note that the long coil is a better match at low fields.



Combining the graphs for the AM and AN models with realistic coils, one sees a dramatic change in agreement with measurement around 1E6 G-cm or ~10kG.

Conclusions

Three dimensional magnet models are necessary for calculating J(BdL) fits at the fields needed for the 12 GeV upgrade. Coil configurations must be close to reality if fields above 10kG are to be calculated accurately. The BH curve is suspect above 10 kG per comparisons with EPICS field maps for the AN and AM magnets.

Vector Fields software allows the needed relationships to be obtained with acceptable time and capital expenditure. These relationships may be used to calculate shunt currents as a function of turns count for each of the arc magnet ensembles. A spreadsheet which accomplishes this at 5% energy intervals from 50-100% is available from the author.

Appendix - comments from the 12 GeV Project team

J(BdL) curves

- General: H-iron thicknesses being used in the Project team's designs have changed from what was being used when the document was drafted. The document needs to identify the vintage (a date) for the thicknesses that were used in the simulations.
- Pg 18, 2nd paragraph: The 3rd sentence asserts that the B-H curve is wrong above 10.5kG. It could well be wrong, but 10.5 kG (which is the gap field if I'm reading the stuff right) is not the value of interest. The saturation depends not on the gap field but on the field in the iron. The AM and AN saturate "early" specifically because the field in the pole root is significantly higher than the gap field. The objection on this paragraph is removed if the words "above 10.5kG" are removed.
- Pgs 18-20: The two different coil sizes are confusing. Why is anything other than the real coil cross-section (which the document doesn't identify) being used? The document needs to explain why the comparison is being done before it starts listing results from said comparison.
- Pgs 21-23: Same comments as for 18-20
- Pg 20 & 23: Unclear what is meant by "flux from the longer coil is outside the pole gap proper" or "shot coil couples better to the gap". Without knowing how the actual iron and copper configurations differ between the short and long coil cases, the validity of the statements can't be ascertained. Specifically, the statement is incorrect for some iron/copper configurations and thus over-general; this could result in some readers reaching the wrong conclusion.
- Pg 24: Same comment about what field is important for the saturation. Objection is removed if "above 10 kG" is removed.