Extended Lambertson for FFA
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Background

The existing Lambertson is 230 cm long. The Hall B beam passes through a 17.78 mm thick plate at linac (reference) height with the A beam 15-19 mm above and the C beam 15-19 mm below, A and C beam locations dependent on pass. In order to deal with the possible 22 GeV beam from the FFA energy upgrade concept the Lambertson must be extended and the B plate increased in thickness as it is already in saturation (TN-15-005). The dipoles designed for the upgrade (TN-21-051) would have 380 cm long steel so that length was chosen rather than 460 cm. The B plate thickness was increased to 24 mm thickness. The transport recombiner has NOT yet been redesigned and must accommodate the increase. It is believed that the septum magnet concept (TN-22-037) will allow the additional spread given the pole width chosen. The height of the A line is 22 mm above the linac; C line is 22 mm below the linac. I assume herein that the A and C beams enter 20 mm above/below the B beam. The Lambertson must provide a 1.6° bend. The dispersion so generated will be closed with a 200 cm dipole after three quadrupoles (TN-22 -016, -022).

Discussion

The choices above were somewhat but not completely arbitrary. A Hall B plate thicker than 24 mm would have rendered the design of the transport recombiner much more difficult. The slope of the A and C beams coming out of the recombiner now is such that they will change by ~6 mm over the 380 cm length (28921-D-0065). The gap from B plate to the pole in this design is 26 mm so an entrance at 20 mm absolute, 8 mm above (below) B plate edge, allows for the 6 mm change. Correctors stronger than the MBDs now installed, aka the MCG (TN-21-033) procured for the MOLLER beam line, will be needed after the Lambertson to flatten the beam and get it to nominal height. The pole is 6 cm wide; I have not calculated how thick the vacuum vessel needs to be to withstand atmospheric pressure. If a substantially greater pole gap is needed, everything below will change.

The present Lambertson has five single layer pancakes of four turns each, five cooling water circuits. My thermal calculations for the present Lambertson contradict reality if the 3 mm diameter hole on the drawing is correct: I calculate that the water should be boiling as it exits each pancake, which it is not since the thermal interlocks allow operation. Since more amp-turns are needed as the length increased only 65% and the energy doubled, I chose Luvata 8157 as the conductor. 9.5 mm square, 5.7 mm diameter hole, 1 mm corner radius, net copper 61.6 mm^2. Five pancakes of five turns each. Current density in copper 7.5 A/mm^2 at 22 GeV, well within reason. Five turns implies ~40 m conductor length per pancake including ends. Pancake resistance 13 mΩ at 60 C. 11524.8 AT in 25 turns yields 461 A and 2760 W per pancake. Using http://www.pressure-drop.com/Online-Calculator/ one sees that 60 cc/sec of water would drop 5.6 bar in pressure in a straight tube of 5.7 mm ID, 40 m length. Our LCW is 35 C at 7 bar. Exit water will be ~81C at 1.4 bar, acceptable. In the model the coil is assumed to be 49 mm square, allowing for insulation and potting.

The AT quoted above and below bend a 22 GeV beam 1.607° versus 1.6° desired. Close enough. Current density over the full coil pack 4.8 A/mm^2. Some of the images below were taken from a simulation with 4.95 A/mm^2. Given the scales, invisible.

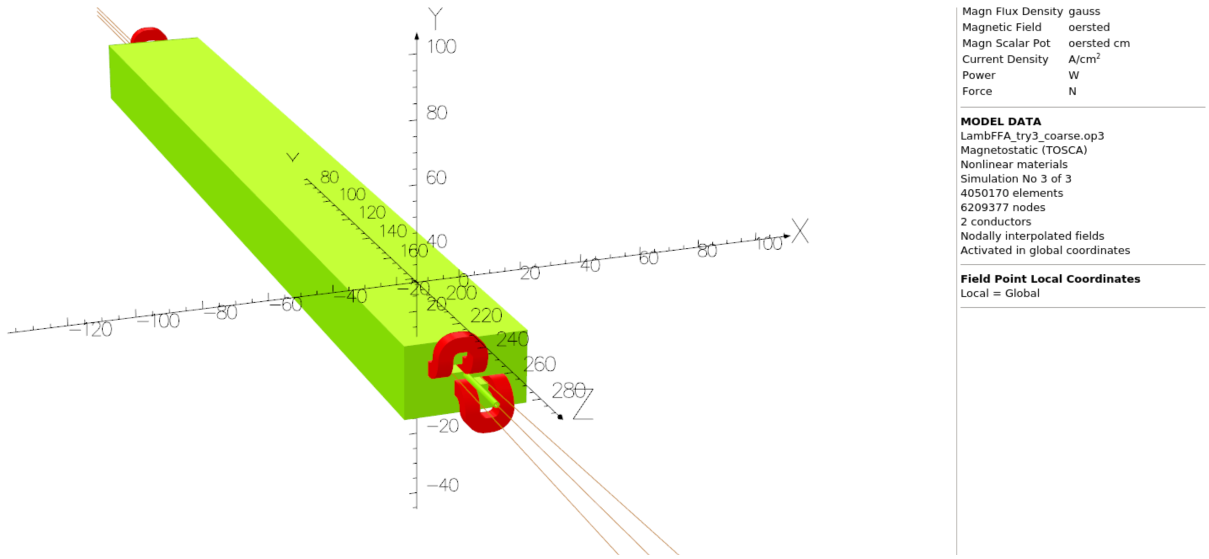

Figure 1. Three 22 GeV beams entering the model at the upper left and beams to A, B and C exiting at center right. Stable heights as it's too much of a pain to include the launch angles, unknown now.

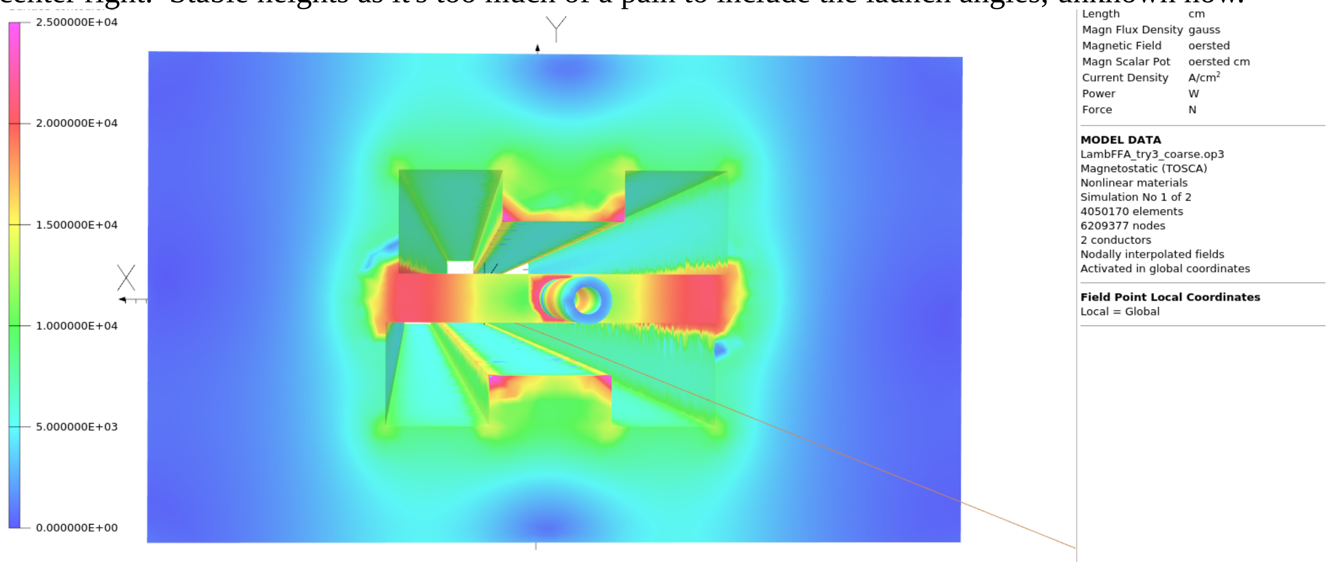

Figure 2 Perspective view of entrance of model, with C beam entering 3 mm to right of pole center

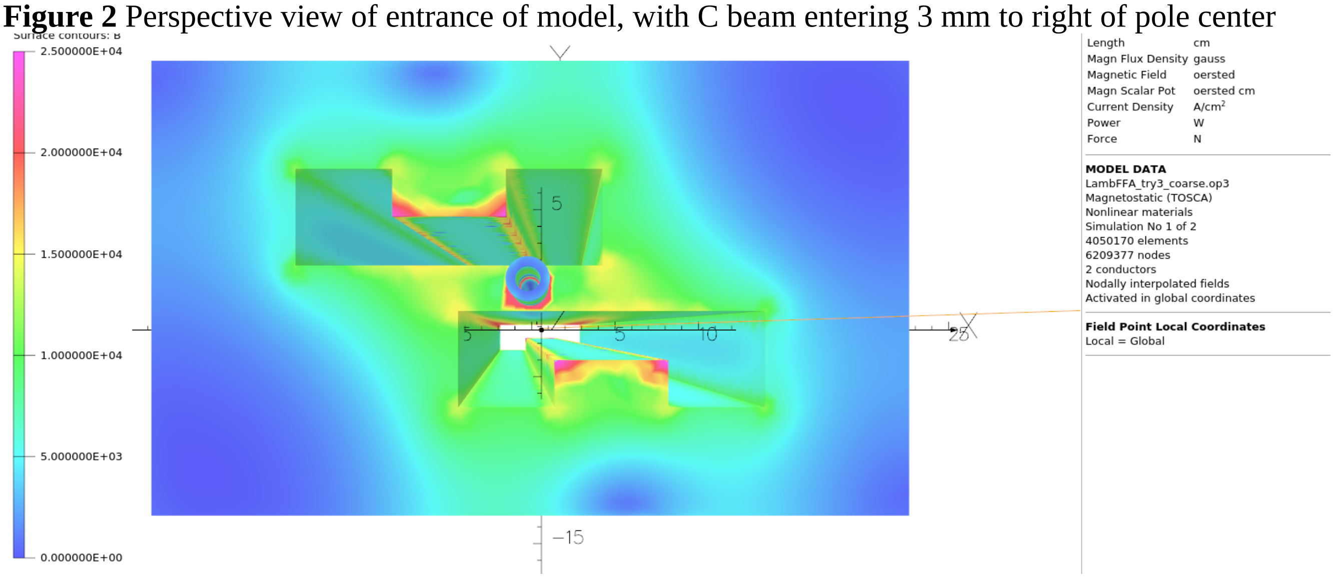

Figure 3 Perspective view of exit of model with C beam at right. Field on surface of steel in Gauss.

The existing Lambertson has A and C beam channels angled at 0.64°. After trying 0.8° and looking at my 2015 model of the existing Lambertson I decided that 0.6° was likely a better choice for this longer unit. The three figures below show a 1 mm wide array of 22 GeV particles passing over the C pole. A curved channel and curved coil would be better but the modeling effort involved is not warranted at this stage of the FFA effort.

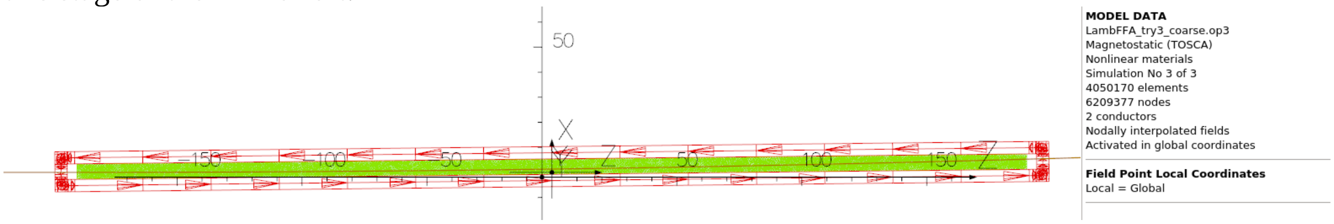

Figure 4. Barely visible beam passing over the pole.

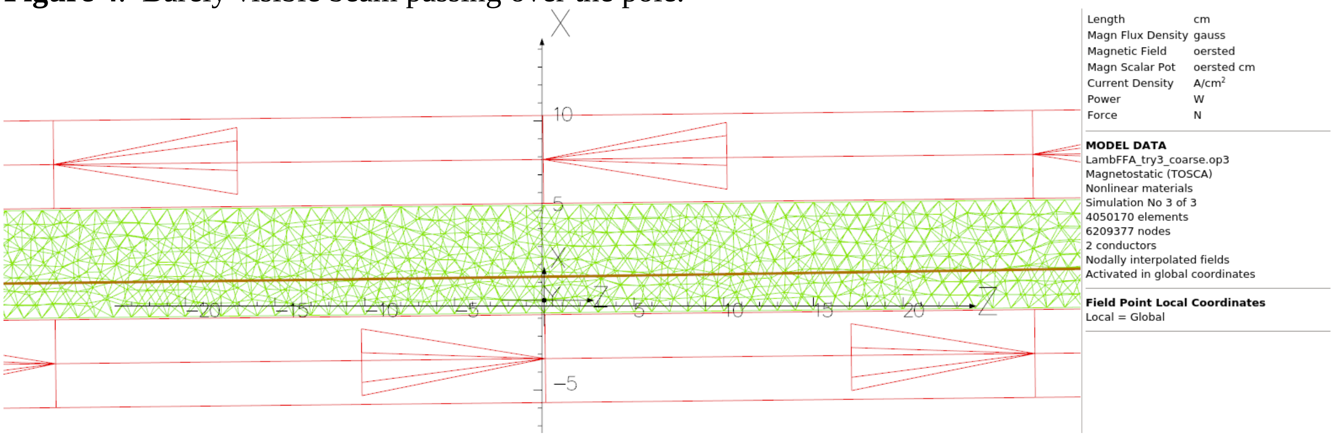

Figure 5. 1 mm array over the pole at the center of the model. Pole is 6 cm wide.

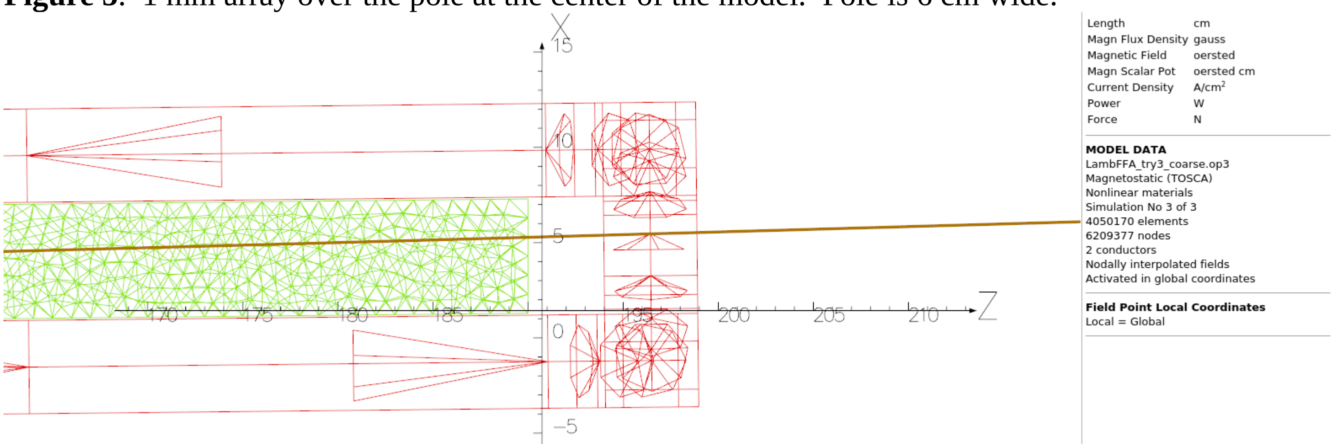

Figure 6. 1 mm array over the pole at the exit of the model. Offsets from pole center are adequately balanced center vs exit with the 0.6° angle chosen. There's a 1 mm gap between coil and pole although it's not visible at this magnification.

This model has 1 cm voxels for the A and C beam volumes and 0.5 cm voxels for B beam. These are sufficient for the images above. The first simulation took 8 hours and subsequent ones at similar J 3.5 hours as coil calculations from the first are used. Simulations with voxels small enough to be used for Fourier harmonic calculation, given sampling theorem, will increase duration to 3-6 days. In 2015 I ran 25 simulations, all combinations of Halls A and C at passes 1 to 5, and calculated harmonics for all three beams. For the first four passes in the FFA configuration one will still be able to choose to have one hall's beam extracted on a given pass so 12 combinations must be calculated. The FFA working group has assumed that A/B/C will all receive the same energy extracted from the splitter so six more are needed with A and C coils at same setting if 22 GeV is the ultimate energy.

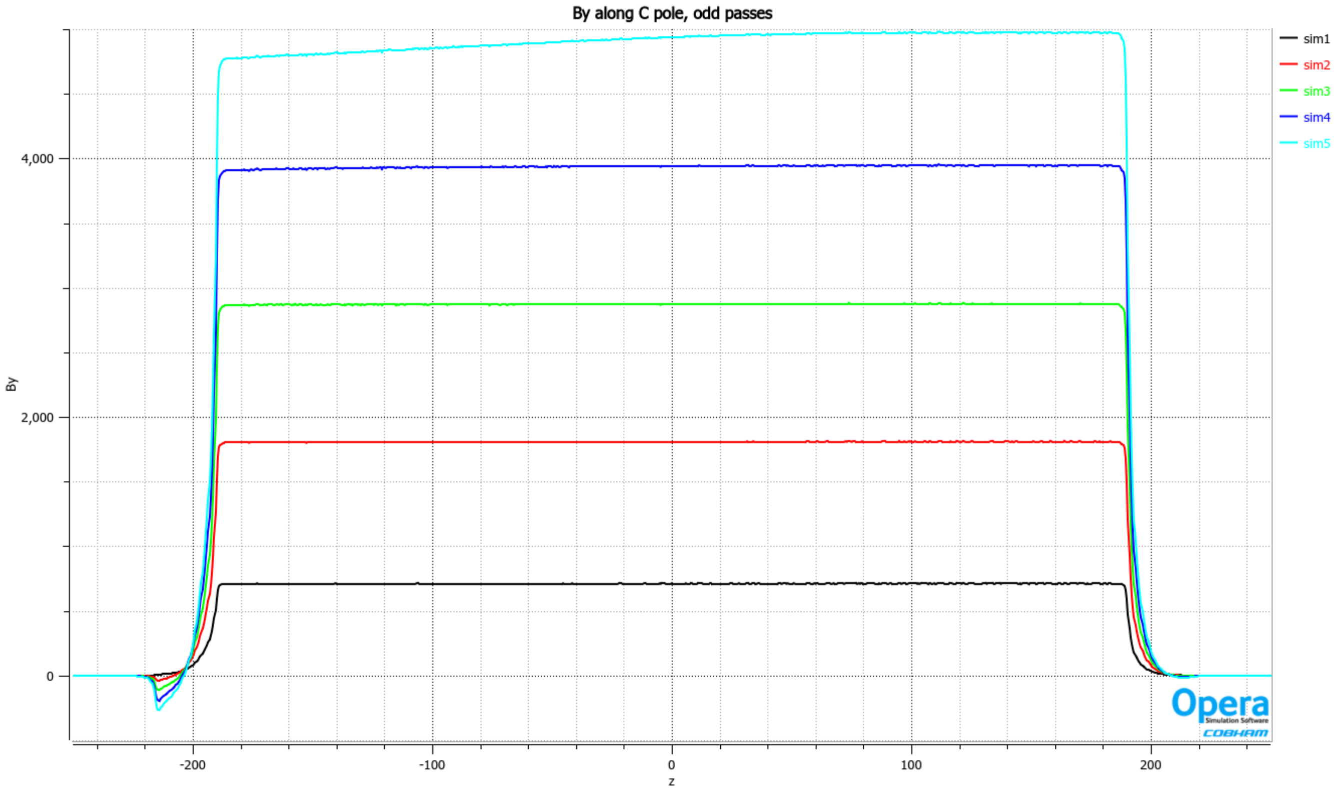

Figure 7. Fields along the center of the C pole for the odd passes through the Lambertson. For pass 9 (sim5, 19.92 GeV) one sees that as the beam moves farther from the A coil, the field increases due to reduced saturation seen in Figure 3. Field along A pole behaves exactly the same except for sign.

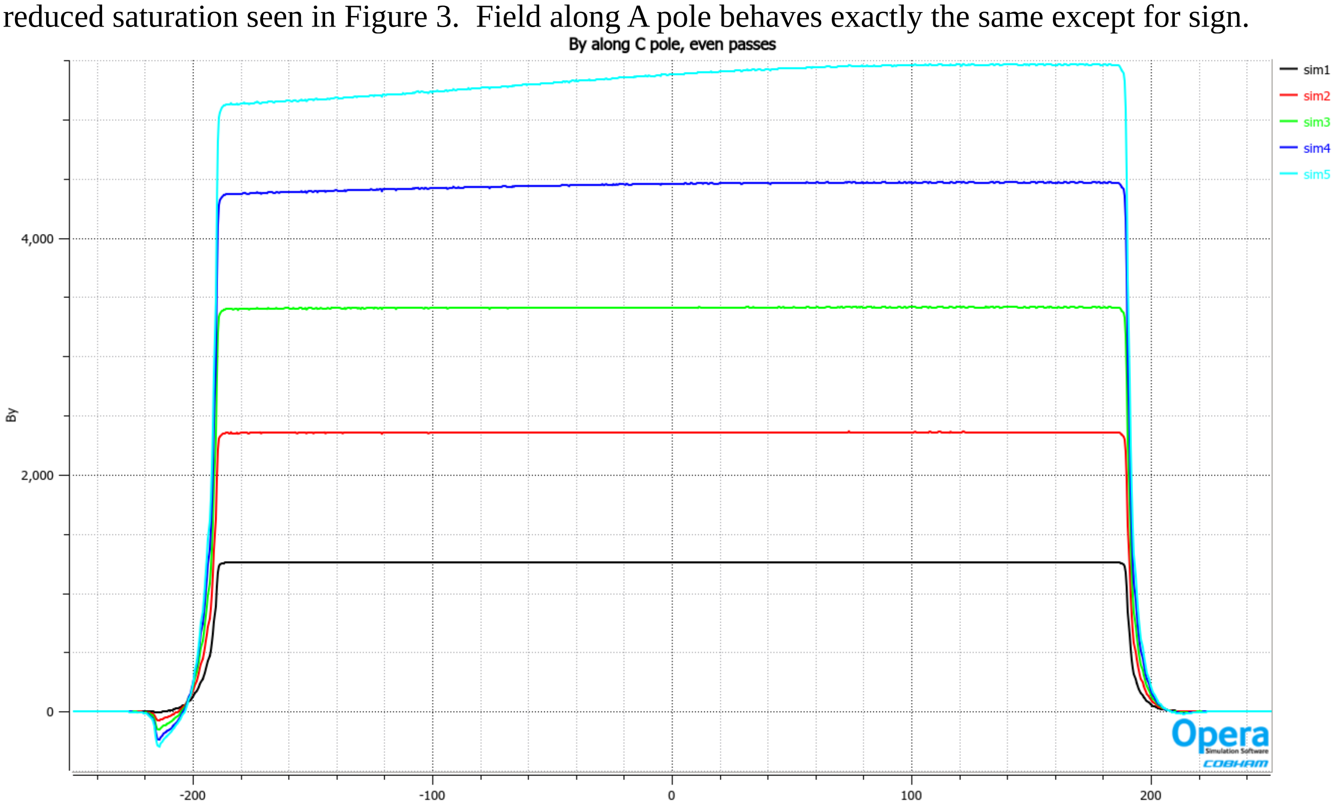

Figure 8. Field along C pole for the even passes through the Lambertson. One sees saturation effects for pass 8 (sim4, 19.89 GeV) and pass 10 (sim5, 21.88 GeV). Sims 1 and 2 in Figures 7 and 8 are non-physical as one can't have both beams at the same energy in the first four passes; but no saturation seen.

The beam air volumes in the model discussed on pages 1-3 have been made rectangular. Enough simulations have since been run at smaller current densities to determine what drive multipliers are appropriate for each of the beam energies.

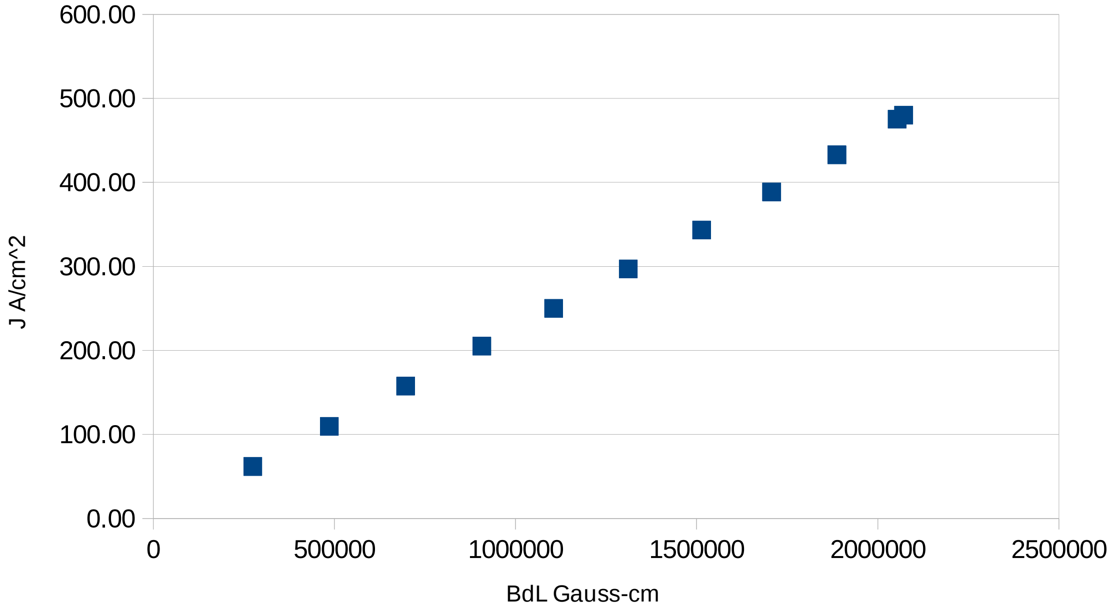

Figure 9. The results of eleven cases at varying drive values are plotted. It's plotted in this manner so I could fit a third order polynomial to the results to calculate drive values needed for the BdL Optim requires for each energy. This polynomial was found to be less accurate than desired in reproducing the actual J's used in creating the values above so simple linear scaling of each value was used to get the drive value appropriate for each energy given BH curve used.

The model has been rebuilt and solved with sufficient voxels to get accurate Fourier expansion of fields in all three beam paths. Having calculated harmonics for the eighteen required models, I cast about for a way to describe the harmonic content given the wide range in excitation. Remembering that three decades ago multipoles were often quoted in "units", parts in 10000 of the dipole field, I decided to try that on the harmonics. I found the results quite uniform. I took absolute values in creating the table below. What is shown here is the scale of the inhomogeneity, independent of excitation. These values are for the A and C beam paths. A good accelerator dipole will have one or two units of sextupole (cos2) and well under a unit of decapole (cos4). It will not have any skew (sin) terms. This is not a good dipole. But then septa never are.

Table One: Harmonic content in A and C beam paths in units

UNITS aka parts in 10^4 of dipole, absolute values used

	Cos1	Sin1	Cos2	Sin2	Cos3	Sin3	Cos4	Sin4
mean	60.2	164.6	79.5	46.4	17.4	34.7	8.1	0.8
standard deviation	1.1	7.6	3.3	0.2	0.1	1.6	0.8	0.2

The number of poles is 2*(N+1) aka cos1 is normal quadrupole, cos2 normal sextapole, etc.

For the Hall B aperture, because there is not supposed to be a dipole field, another way of looking at harmonic content proved fruitful. In the table below I show the units of harmonics in the B aperture as a function of the summed fields in the A and B apertures. One sees that the harmonic content is nearly constant as a function of excitation at lower fields but increases as the beam energies for A and C go above 9 GeV and the 24 mm plate encompassing the B beam path begins to saturate.

Table Two: Harmonic content in B beam path in units of |A|+|C|

	Hall B	UNITS aka parts in 10^4 of sum of |A| and |C| dipoles						
dipole sum	Cos1	Sin1	Cos2	Sin2	Cos3	Sin3	Cos4	Sin4
742438.86	0.29	-1.99	0.01	0.07	-0.39	0.69	0.00	0.03
742466.93	0.29	-2.00	0.00	-0.07	-0.39	0.72	0.09	0.02
948803.26	0.29	-2.00	0.02	0.10	-0.40	0.68	-0.01	0.13
948830.31	0.29	-2.02	0.00	-0.11	-0.37	0.73	0.13	0.04
1154930.97	0.30	-2.02	-0.01	-0.07	-0.40	0.67	0.13	0.31
1155004.76	0.30	-2.05	0.03	0.06	-0.35	0.73	-0.03	-0.01
1155416.09	0.30	-2.02	0.03	0.12	-0.39	0.67	-0.03	0.24
1155442.11	0.30	-2.05	-0.01	-0.13	-0.34	0.73	0.15	0.05
1361435.77	0.31	-2.05	-0.01	-0.11	-0.40	0.67	0.16	0.41
1361487.47	0.31	-2.05	0.02	0.05	-0.39	0.66	0.03	0.37
1567565.10	0.32	-2.12	0.02	-0.01	-0.31	0.74	0.07	0.03
1567564.79	0.32	-2.12	0.04	0.06	-0.31	0.74	0.00	0.01
2162623.27	0.35	-2.17	0.02	-0.06	-0.39	0.64	0.14	0.71
2569281.07	0.37	-2.23	0.02	-0.07	-0.39	0.62	0.16	0.85
2970210.03	0.38	-2.29	0.02	-0.08	-0.39	0.62	0.17	0.93
3745397.03	0.42	-2.45	0.02	-0.10	-0.39	0.62	0.17	0.99
4109254.70	0.47	-2.78	0.02	-0.10	-0.38	0.63	0.17	1.00

Summary

A conceptual design for the Lambertson needed for 22 GeV CEBAF has been completed. Looking at Figures 4-6 one might conclude that a cost analysis of straight versus curved slots and coils should be made. IFF the incremental cost of curved slots/coils is small should a matching simulation be created. It will be time consuming to build and is not necessary at this stage of the project concept.

Model information (updated 9/29)

All cells quadratic except background. Voxel sizes below are for final Fourier analysis, 1 cm was used for A and C in August to keep solution time down. Hall B voxels 0.5 cm for the early models.

outer_air level 60, size 16 cm
x,y 100 cm square z [-500,500]

inner_air 70, 4
x,y 50 cm square, Z [-250,250]

A_inner_return 85, 2
x try [-20,20] y [1.2,12] z [-190,190]
coil slot starts x [-8.1,8.1] y [1.2, 6.30] z [-200,200] rotate angle 0.6° offset 2.3 cm appropriately. Want centered beam to enter to left of pole center in A slot so when it exits to the right it's not too far off to the right from pole center. Opposite for C hole.

B_plate 90, 0.25
x try [-20,20] y [-1.2,1.2] z [-190,190]

C_inner_return 85, 2
x try [-20,20] y [-12,1.2] z [-190,190]
coil slot starts x [-8.1,8.1] y [-1.2, -6.30] z [-200,200] rotate angle 0.6° offset 2.3 cm appropriately. Want centered beam to enter to right of pole center so when it exits to the left it's not too far off to the left from pole center

coil_air 75, 1
reduce with new angle y[-18,18] Z [-215,215] likely x [-15,15]

A_pole 90, 0.25
6 cm wide y [3.8, 6.3] z [-195,195] rotate, offset, trim flush

C_pole 90, 0.25
6 cm wide y [3.8, 6.3] z [-195,195] rotate, offset, trim flush

A_beam_air 95, 0.25
1.1 cm radius hole starts x,y,z [0, 2.5, -210] ends z 210 then rotate 0.6° and offset. Was rebuilt rectangular given beam path shown in Figures 4-6. 5 cm wide by 2.6 cm high. Very large voxel count.

B_beam_air 97, 0.125
1 cm diameter hole x,y 0,0 z [-220,220]. Diameter 1.1 cm inside the steel tubes below.

C_beam air 95, 0.25
1.1 cm radius hole starts x,y,z [0, -2.5, -210] ends z 210 then rotate 0.6° and offset Was rebuilt rectangular given beam path shown in Figures 4-6. 5 cm wide by 2.6 cm high. Very large voxel count.

Z_pos_tube 96, 0.25
(x,y) (0,0) z [215, 190] diameter 1.9 cm, wall 0.4 cm, commercially available

Z_neg_tube 96, 0.25

(x,y) (0,0) z [-215, -190] diameter 1.9 cm, wall 0.4 cm, commercially available

A coil origin x -2 when centered, offset appropriate direction theta 0.6° phi 180 psi 180

3.1	1.3
4.9	4.9
191	3
0	2

Default current density 1000 A/cm^2. Drive values multiply this.

C coil similar except YP1 negative and origin offset appropriate.

Table: drive values used for the fine-mesh models.

pass	drive	energy
1	0.0605	2850
2	0.1073	5049
3	0.1541	7244
4	0.2010	9439
5	0.2452	11510
6	0.2915	13670
7	0.3374	15800
8	0.3835	17890
9	0.4301	19920
10	0.4769	21880

There were convergence issues with models with low currents in some of the coils. The software vendor was consulted. I learned that there is a default parameter of minimum face size of 10^{-6} cm^2. The mesh generator then produced sufficiently peculiar elements that iterating as the BH curve rolled over took very long and in a few cases crashed the program. 3DS tech support suggested changing this to 10^{-3} cm^2. The models in the accompanying spreadsheet with JB in their names were meshed with this setting rather than the smaller one used for the initial set of simulations. I will likely use a setting of 10^{-4} cm^2 in the future as my default as it's easier to figure out what the smallest tetrahedron will be.