Lambertson Final Design Review Responses
Dave Johnson
November 20, 1995

Recommendation 1

Recommendation: There should be readily available a concise statement of the accelerator physics requirements for the fringe field.

Response (D. Johnson): The paper presented at the 1995 PAC, titled "Design of the Fermilab Main Injector Lambertson", was included in section 2 of the Final Design Review books for reference. In this paper, the motivations and specifications for the physical apertures and design bending field were discussed in terms of its usage in the Main Injector and Tevatron. Additionally, specifications and motivations for field uniformity in the bending region, leakage dipole field and skew quad fields in the field free region were also given. It should be pointed out that the requirements are not hard limits but rather guidelines to minimize any effect on the beam.

A summary of the fringe field requirements is given below:

- DIPOLE: The orbit distortion is proportional to $\sqrt{\beta_{lam}\beta_s}$ times the integral dipole field. Since the lattice functions in the MI are about a factor of two less than the Tevatron, the specification on the leakage dipole field is based upon the Tevatron requirements. At 150 GeV/c we want an orbit distortion caused by the Lambertsons to be less than 2 mm rms. An integrated dipole field of 0.0114 T-m per Lambertson (4 Lambertsons) produces an orbit distortion of 2mm rms distortion in the current B0/D0 injection lattice. Therefore, we would like to like to limit the dipole integral (body+ends) per Lambertson to be less than 0.0114 T-m.

- QUADRUPOLE: The leakage gradient generates a skew quadrupole field. This effectively changes the coupling constant given by $\kappa = \frac{1}{\beta\rho}\frac{\beta}{4\pi}\int\frac{d\beta_x}{dx}dl$. For the Tevatron, a change in the coupling constant of .005 is acceptable. To achieve this criteria the integrated gradient (body+ends) per Lambertson should be kept below 0.1 T$m^{-1}m$.

- SEXTUPOLE: The primary effect of the sextupole field on the beam is to alter the chromaticity. The magnitude of the chromaticity change is given by $\delta\xi = \frac{N}{4\pi}\beta DS$ where S is in units of $[m^{-2}]$. The Lambertsons in the MI are in a region of zero dispersion, hence this effect is not important. For the Tevatron, we would like to keep the change in chromaticity under 1 unit. This requires an integrated sextupole field of less than $0.018m^{-2}$ or 9 T$m^{-2}m$ per Lambertson.

Recommendation 2

Recommendation: In the most recent metal model the saddle coil bent toward the zero field channel can be electrically disconnected and the other coil powered to twice the design current. This configuration is close to the design configuration, and measurements of the fringe field should be able to confirm the computer prediction.

Response (D. Johnson): This recommendation also addressed the computer modeling of the end field configurations. The paper titled "Three-Dimensional End Effects in Iron Septum Magnets", also presented at the 1995 PAC was included in section 2 of the Final Design Review book. It should be explicitly pointed out that the intent of the computer model was not to obtain an absolute agreement with prototype measurements but rather guide the prototype development and understand the important parameters in reducing the integral end field. To this end, the computer model has been successful in guiding us to the final configuration.

The committee's recommendation of shorting half the saddle coil (the half saddle toward the field free region) and running the magnet at twice the current was followed. This resulted in the measurement of prototype configuration ILP001-13. The results of the magnetic tests are presented below and confirm the predictions of the computer model to the expected accuracy.

The body and end fields for this configuration were measured by a "point scan" method using a hall probe. The field was measured at 0.5 inch intervals from -16 inches outside the outer core to +6 inches inside. This was done for the bending region as well as 3 positions in the field free region. The harmonic probe/software did not work so there are no harmonics data for this configuration.

Figure 1 shows the measured field shape (solid line) for ILP001-13 and the computer model's predictions of the field shape through the end plates. The end of the outer core and the start of the 4.3 inch inner core extension is at zero. The fields at positive distances measure the leakage fields into the field free region in the body of the magnet. The outside edge of the mirror plate is located at approximately 7.8 inches and is generally less than 15 Gauss. The discrepancy in the field shape between the prototype measurement and model is not unexpected due to small differences between the model and prototype, the small magnitude of the field, the number of nodes used in the calculation, and the requirement that the field go to zero at -15 inches in the model.

Figure 2 shows the measured dipole end field integral (from 0 to -16 inches) for the prototype and model. The model was expected to predict a smaller integral due to clamping the field to zero at z=-15 inches (as seen in Figure 1). The measurements agree to within 10% for the y=1.68 inch data and within 50% for the y=2.53 inch measurement. The maximum integrated end dipole field at the nominal field of 1.072T is approximately 4.3 Gauss-meter.

Figure 3 shows the dipole end field integrals as a function of distance from the septum between the field and field free region for the computer model and configuration ILP001-13. The integrals for the computer model were calculated by integrating the dipole field from -15 to 0 inches for various distances from the septa. The dipole end field of the prototype was measured for only three distances from the septa due to the geometry of the hall probe. The field was integrated from -16 to 0 inches for each of the three data sets and plotted. The gradient was calculated for comparison in both the computer model and the prototype only in the region between 1.68 and 2.53 inches. The two straight lines indicate the data used to calculate the gradient.

Figure 4 shows the dipole field integral (body+end) with the accelerator physics limits discussed in recommendation 1 superimposed. Also included is the end dipole field integral for a single y (at 1.68 inches) position. The corresponding field in the bending region for each current is noted as well as the nominal design field of 1.072 T (at 3930 Amps). It should be noted that the main contribution to the integral is due to the body leakage field and that the contribution from the ends is a factor of 10 less than that of the body (which was the desired result). Additionally, it should be remembered that the integrated dipole field due to leakage in the body for the production Lambertsons is expected to be less than that of the prototype. This is due to a modified field free region geometry (smaller opening angle and larger septa radius) and better (higher permeability) steel around the field free region. Therefore, the data from the prototype (at the nominal 150 GeV/c excitation) is on the order of a factor of two better than the specification (0.0114 T-m) and the production magnet results are expected to be even better through the reduction of the leakage field in the body.

Figure 5 shows the measured gradient (body+end) along with the limits from the recommendation 1. This curve was calculated taking the derivative of the total field integral between 1.68 and 2.53 inches from figure 4. The results indicate the measured gradient is about a factor of 10 less than the accelerator requirement of 0.1 T$m^{-1}m$.

Recommendation 3

Recommendation: Even if the test in Recommendation 2 is very encouraging, the committee recommends that the project plan to build and test one article of the present design before committing to production.

Response (G. Pewitt): Although we have confidence in the mechanical and magnetic design, based upon simulations, calculations, and prior Lambertson experience, the project plan called for the construction of the first article prior to purchasing all components for the production of the full quantity. The exceptions are that we have bought steel and copper conductor for all the magnets, and we have ordered long lead items such as insulators. We have also placed orders for a complete lot of vacuum flanges.

In summary, I believe that we have satisfied the intent of this recommendation.

Recommendation 4

Recommendation: A comprehensive test plan should be developed for assessing the performance of the first article.

Response (D. Johnson): A comprehensive test plan is being constructed between the Main Injector Department and MTF. This plan will include measurements in both the field and field free region to confirm the quality of the magnetic field in each region. The required measurements and accuracy of measurements, originating in the MI Department, has been discussed at the Main Injector Magnet Physics (MIAP) meeting and transmitted to MTF to construct a detailed run plan and determine hardware and software needs to accomplish the requests. This test plan should be in place well before the arrival of the first article.

Recommendation 5

Recommendation: In the tunnel at the present time there are problems with metal chips generated by tunnel activities falling into the ends of saddle coils of B3 magnets and being worked into the coils by coil flexing. Verify that this problem is not an issue for the present Lambertson magnet design.

Response (N. Chester): In the Lambertson design, as with any saddle coil design, if the ends are left unprotected it is possible that chips can collect between the back of the coil and the outside surfaces of the cores. Because the coils are to be glued in place with epoxy and will fill the entire core pocket, it is unlikely that chips, etc. could work their way into the magnet body.

However, to protect the ends of the coil from allowing contaminants to accumulate, as the final magnet assembly with flux catcher is completed a barrier that attaches around the ends of the flux catcher plate is planned for design. By extending up and perhaps over the core body, this barrier will effectively prevent contaminants from being able to fall behind the coils.

Recommendation 6

Recommendation: The reviewed design has vacuum pump-out ports on both "sides". The pumping capacity on the coil/dipole channel side is not well utilized. Consideration should be given to simply blanking off these ports with corresponding savings in pump-out hardware cost and complexity.

Response (D. Johnson): It was recognized early on that the effectiveness of the ion pumps on the coil side of the inner core would not be as effective as those on the field free side, however based on prior Lambertson experience, these were included to provide help with any potential outgassing from the laminations in this area. Special cleaning, handling, and assembly procedures for the inner core components have been established to minimize outgassing.

The (reduced) effectiveness of this set of ion pumps was reiterated by the review committee. As a result two actions have/will be taken. First, the back 3/16" of the ion pump lamination packs (on both inner core sides) are sheared to increase conductance to the tiebar and "v-notch" channels. Secondly, we plan to test the effectiveness of these pumps by doing a blank off test on the first article to see if they are indeed needed to reach Tevatron vacuum requirements of 5E-9 torr.

Recommendation 7

Recommendation: The field configuration's sensitivity to mirror plate alignment with respect to the extended coil should be investigated.

Response (D. Johnson): The mechanical design of the mirror plate and its assembly to the magnet will assure transverse alignment to within tens of mils. The longitudinal "gap" is determined by the vacuum end plate thickness plus vacuum gap which will be known to within 60 mils or better. The effect of the gap width on the end field simply determines the peak field on the face of the mirror plate and inner core end plate. The end field dipole integral scales with the inner core extension plus vacuum gap thickness (i.e. 4.8 inches) so any misalignment on the order of 10 mils will have little or no effect on the integral.

Recommendation 8

Recommendation: Baking the inner coil to temperatures approaching 450^o C will generate substantial stresses in welds at tie bar locations due to different thermal expansion of lamination steel and stainless steel tie bars. The committee felt that these stresses and their potential for cracking welds is not sufficiently understood.

Response (N. Chester): A thermal stress analysis on the weld between the stainless spacer bar and the inner core laminations was done to assure ourselves that the risk of weld fatigue is small. This analysis will be reviewed for accuracy and completeness and to determine what additional modeling might be performed. Once done, a summary report will be distributed to committee members for review and comment. In addition, during the bakeout stage of fabrication of the first inner core, tests and measurements will be made to substantiate analytical results.

Recommendation 9

Recommendation: Although not a subject of this review, the committee senses that tunnel installation/alignment issues may not have been identified and systematically addressed.

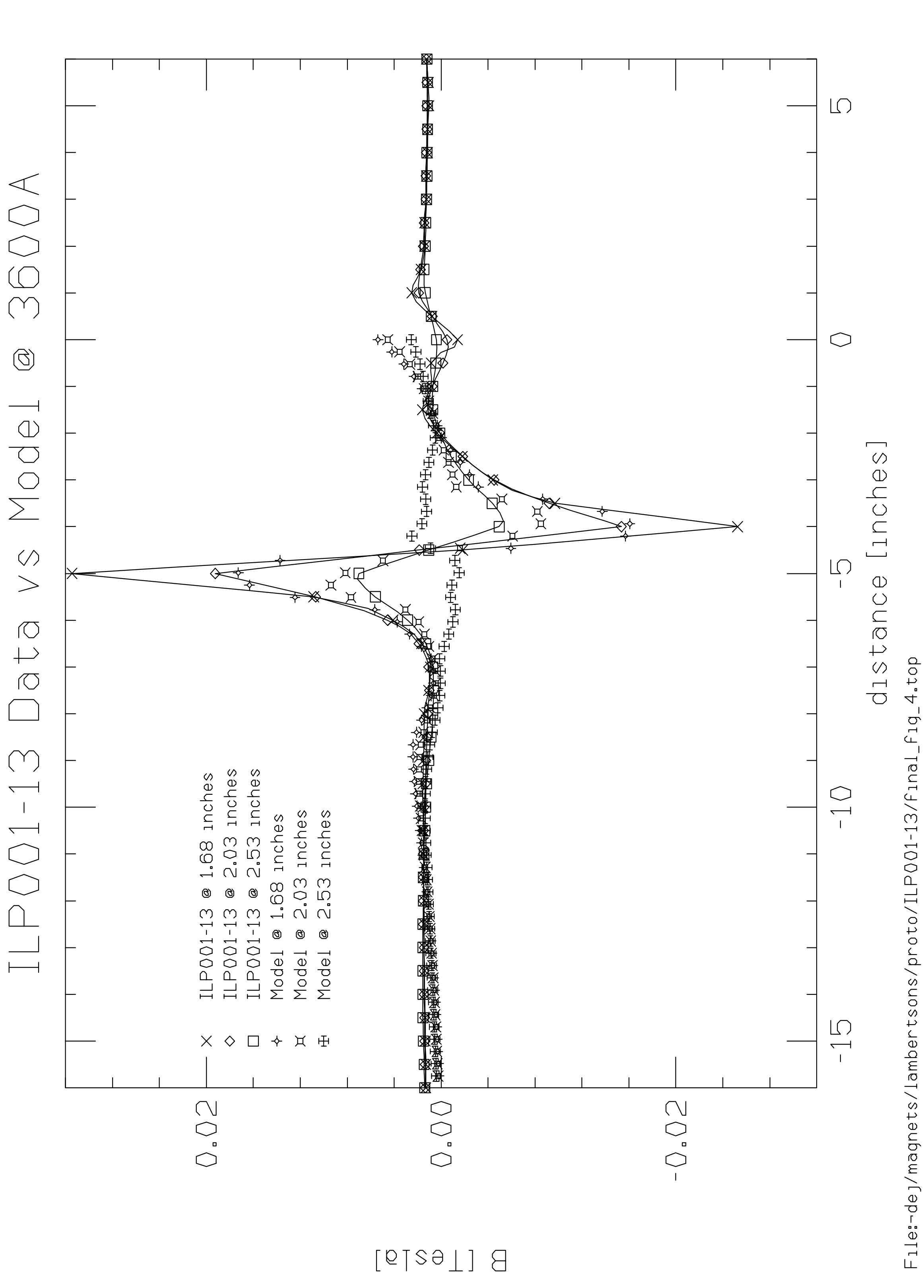
Response (P. Martin/D. Johnson): The integration of the Lambertsons into the Main Injector and Tevatron are being addressed. Mike May has the responsibility for the integration of the Lambertsons into the accelerators. We have discussed many, if not all, the issues related to integration of the Lambertson at our regular Wed. Lambertson meeting. Below are the current issues and their status.

- MAGNET TRANSPORT: This issue has not been fully addressed, however, we are aware that this will require some attention but don't feel that this will present any serious difficulty.
- ELECTRICAL AND COOLING: The connections of the Lambertson to the power supply/bus and water have been coordinated with EE Support and AD Mech Support groups and their requirements have been integrated into the magnet manifold design.
- MAGNET SUPPORT: The Lambertson will utilize a four point support due to the aspect ratio of the Lambertson and some of the MI installations will require roll angles

up to 12.9 degrees. Conceptual design of the supporting fixtures has been completed and final design is underway for both the Main Injector and Tevatron installations.. Included in the design for the Tevatron installation is the provision of radial motion control of a Lambertson girder such that all the Lambertsons move together. No remote motion control is being provided for the Main Injector installation.

- ALIGNMENT: The alignment of the Lambertsons has been discussed with the Alignment group and fiducials are being provided for installation purposes. At time of final assembly the relative position of the septa to the fiducials, located on the outer core, will be determined and recorded. These fiducials are standard access holes, specified by the alignment group, to witness marks on the outer lamination sides and top which will accommodate either laser tracking detectors or optical tooling.

- VACUUM CONNECTIONS and Z/N Parts: The lattice design has been modified to incorporate the new Lambertson end length and specifically includes spool pieces to be used to connect the magnet to the MI or Tevatron vacuum systems. Preliminary design for the Lambertson-Lambertson spool pieces and Lambertson-Tevatron interface have been done and the conceptual designs and some preliminary layouts have been done for several cases of MI to Lambertson interfaces. These interface designs will require more work.



ILP001-13 Data vs Model @ 3600A
ILP001-13 @ 1.68 inches
ILP001-13 @ 2.03 inches
ILP001-13 @ 2.53 inches
Model @ 1.68 inches
Model @ 2.03 inches
Model @ 2.53 inches
B [Tesla]
0.02
0.00
-0.02
-15
-10
-5
0
5
distance [inches]
File:~dej/magnets/lambertsons/proto/ILP001-13/final_fig_4.top

Figure 1:

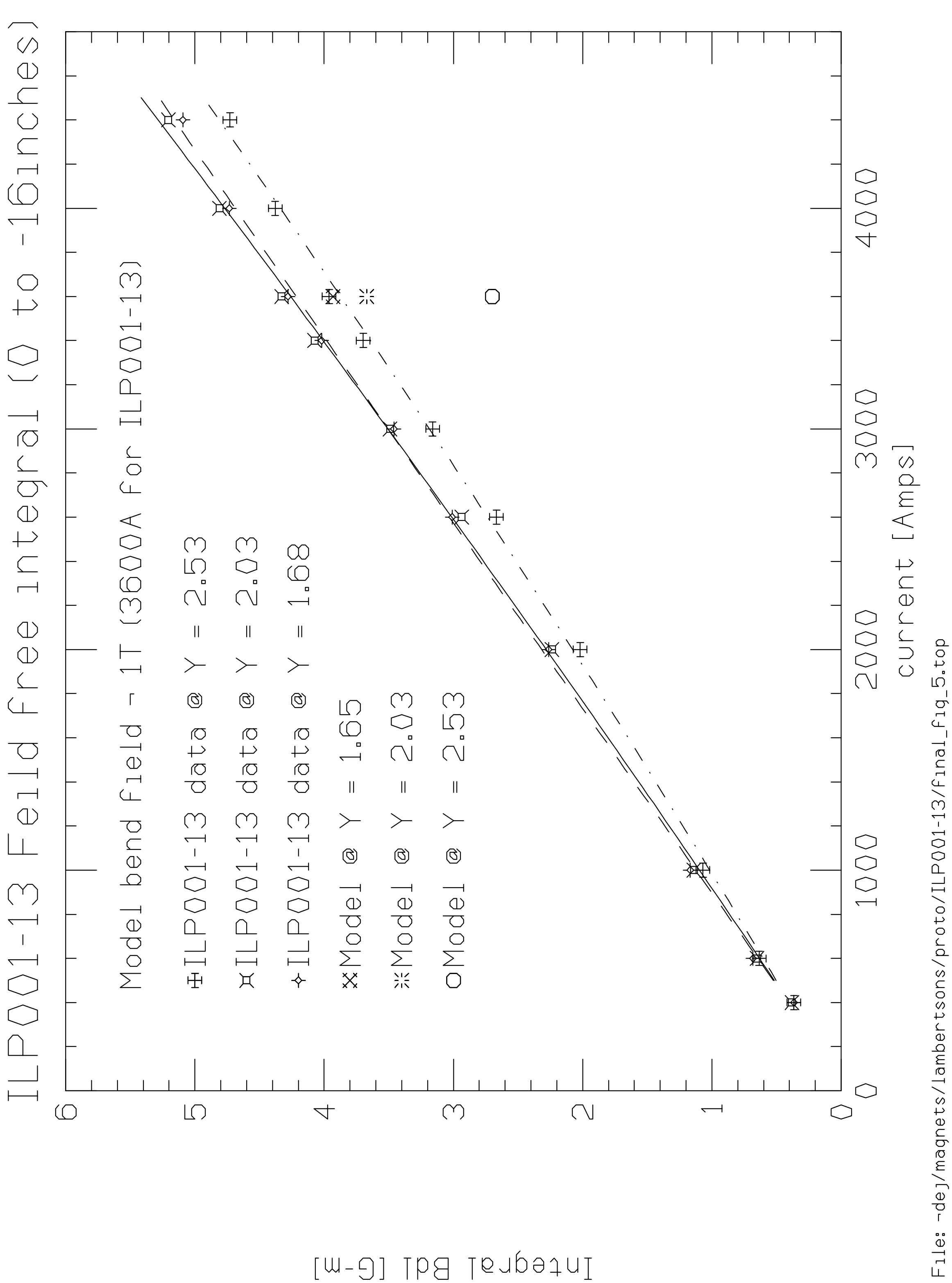
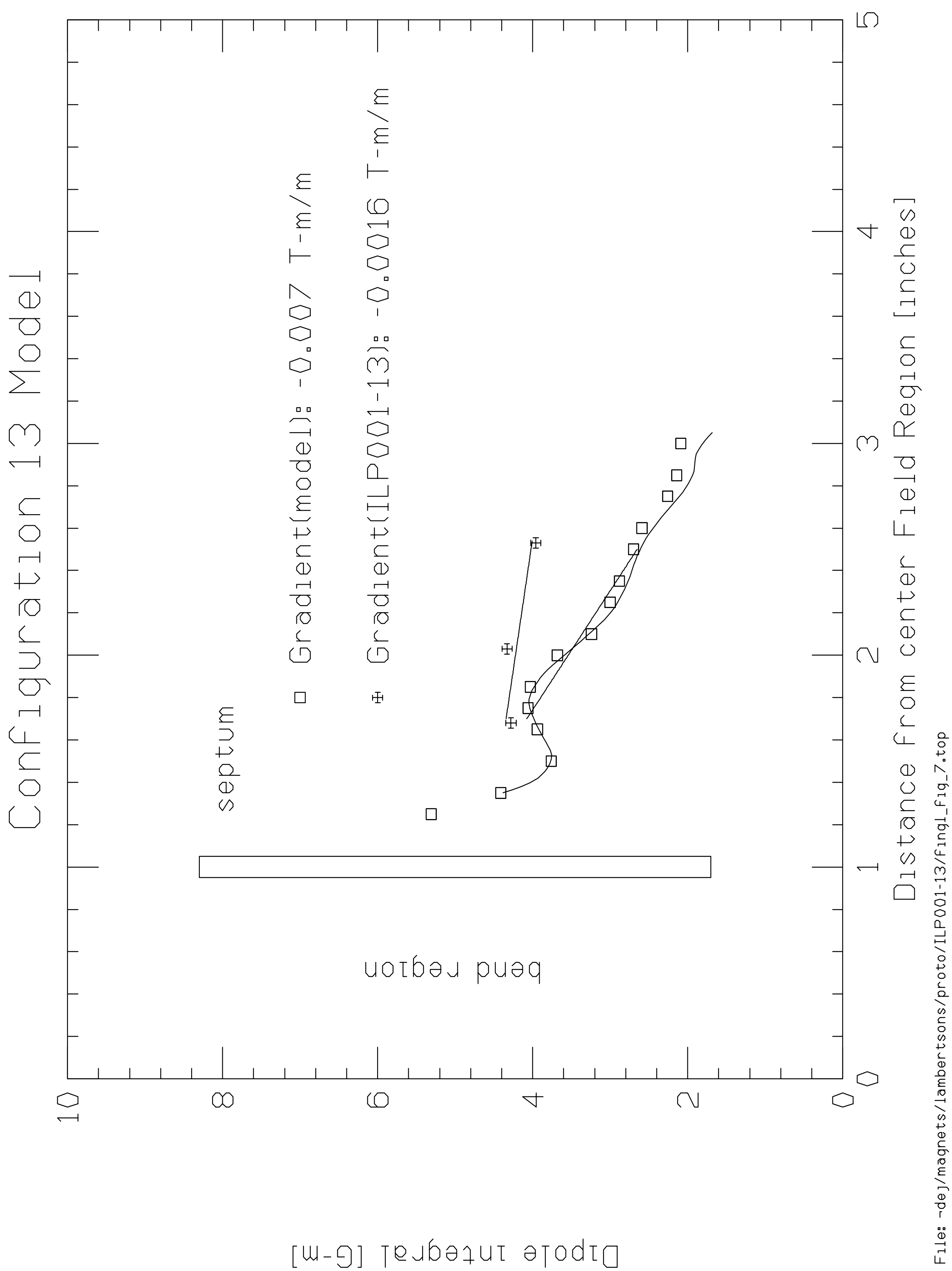

ILP001-13 Feild free integral (0 to -16inches)
Model bend field - 1T (3600A for ILP001-13)
ILP001-13 data @ Y = 2.53
ILP001-13 data @ Y = 2.03
ILP001-13 data @ Y = 1.68
Model @ Y = 1.65
Model @ Y = 2.03
Model @ Y = 2.53
current [Amps]
0
1000
2000
3000
4000
Integral Bdl [G-m]
0
1
2
3
4
5
6
File: ~dej/magnets/lambertsons/proto/ILP001-13/final_fig_5.top

Figure 2:



Configuration 13 Model
septum
bend region
Gradient(model): -0.007 T-m/m
Gradient(ILP001-13): -0.0016 T-m/m
Distance from center Field Region [inches]
Dipole integral [G-m]
File: ~dej/magnets/lambertsons/proto/ILP001-13/Fingl_Fig_7.top

Figure 3:

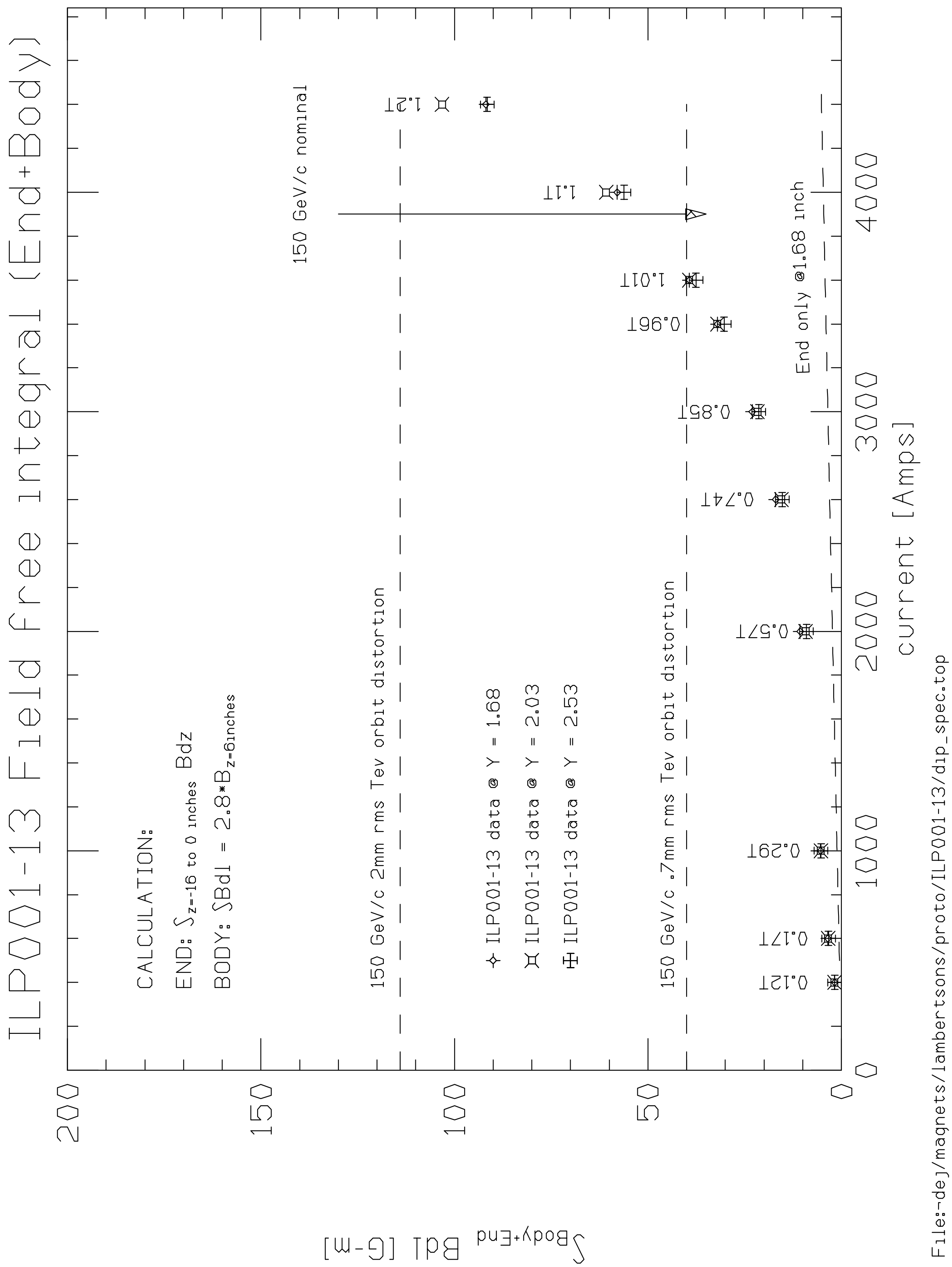

ILP001-13 Field free integral (End+Body)
CALCULATION:
END: ∫z=-16 to 0 inches Bdz
BODY: ∫Bdl = 2.8*Bz=6inches
150 GeV/c 2mm rms Tev orbit distortion
150 GeV/c .7mm rms Tev orbit distortion
150 GeV/c nominal
ILP001-13 data @ Y = 1.68
ILP001-13 data @ Y = 2.03
ILP001-13 data @ Y = 2.53
End only @1.68 inch
0.12T
0.17T
0.29T
0.57T
0.74T
0.85T
0.96T
1.01T
1.1T
1.2T
current [Amps]
∫Body+End Bdl [G-m]
0
1000
2000
3000
4000
50
100
150
200
File:~dej/magnets/lambertsons/proto/ILP001-13/dip_spec.top

Figure 4:

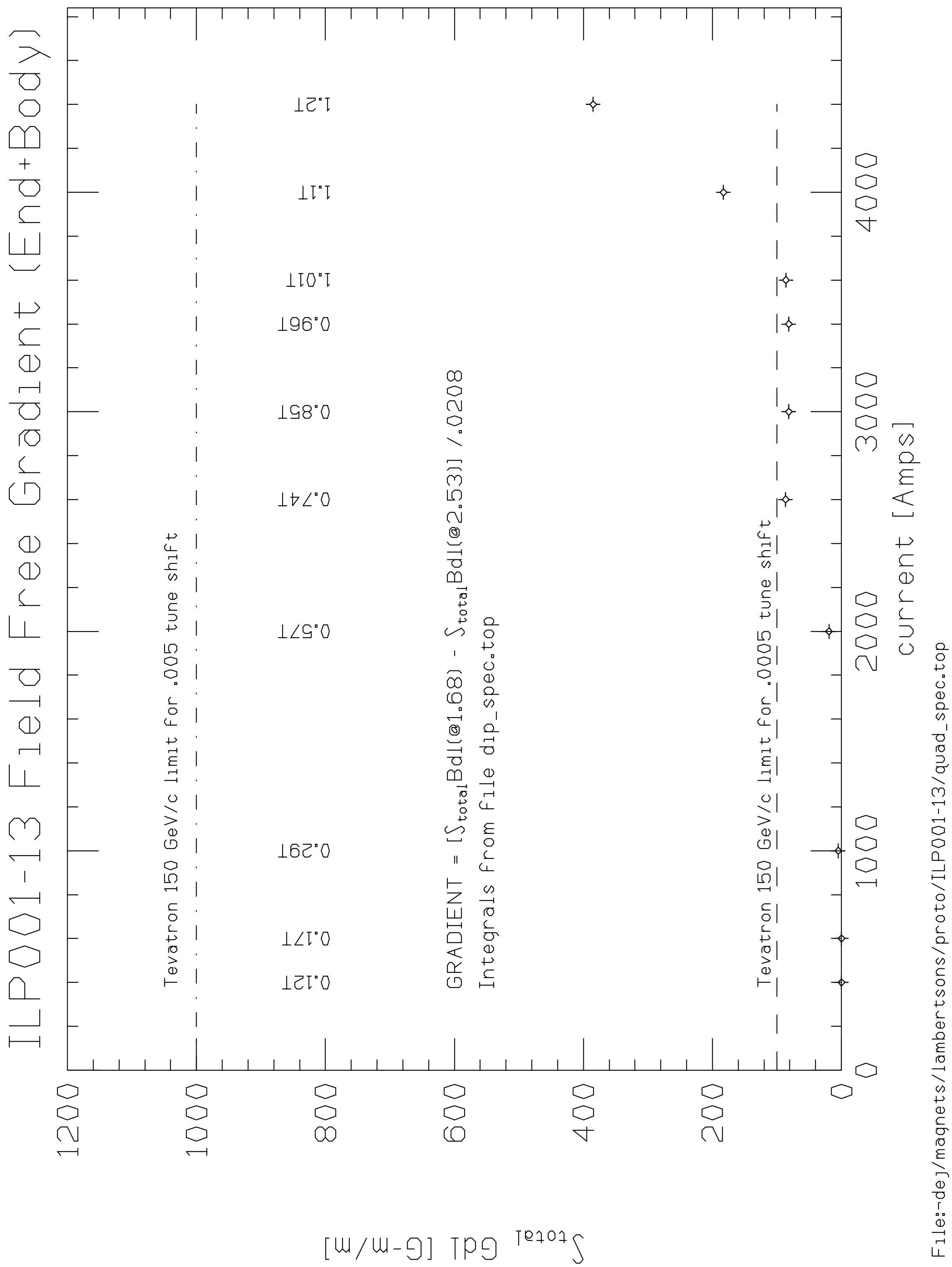

ILP001-13 Field Free Gradient (End+Body)
Tevatron 150 GeV/c limit for .005 tune shift
0.12T
0.17T
0.29T
0.57T
0.74T
0.85T
0.96T
1.01T
1.1T
1.2T
GRADIENT = [∫totalBdl(@1.68) - ∫totalBdl(@2.53)] /.0208
Integrals from file dip_spec.top
Tevatron 150 GeV/c limit for .0005 tune shift
1200
1000
800
600
400
200
0
1000
2000
3000
4000
current [Amps]
∫total Gdl [G-m/m]
File:~dej/magnets/lambertsons/proto/ILP001-13/quad_spec.top

Figure 5: