**A PROPOSAL FOR LAMINATED PIE MECHANICAL CONSTRUCTION OF A
TOROIDAL MAGNET FOR THE FAR DETECTOR FOR THE
MINOS EXPERIMENT***

Norman F. Hill

RECEIVED
AUG 12 1996
OSTI

In collaboration with

Thomas Fields, Victor Guarino, Emil Petereit⁽¹⁾, Paul Schoessow and Ken Thompson⁽²⁾

High Energy Physics Division
Argonne National Laboratory, Argonne, Illinois 60439

04 June 1996

Introduction

This proposal describes an alternative to the reference design for the construction of the toroidal magnet for the far detector for the MINOS experiment. There are many reasons why it is felt by the writer that this design is superior to the reference design. Most of the reasoning is based on previous experience with the construction of the present detector for Soudan II. In the construction of the present detector, it was necessary to handle very long structural steel elements. These were loaded in the mine shaft

* *Work supported in part by the U.S. Department of Energy, Division of High Energy Physics, Contract W-31-109-ENG-38.*

(1) *Technology Division.*

(2) *Accelerator Systems Division*

MASTER

HH

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

The submitted manuscript has been authored by a contractor of the U. S. Government under contract No. W-31-109-ENG-38. Accordingly, the U. S. Government retains a nonexclusive, royalty-free license to publish or reproduce the published form of this contribution, or allow others to do so, for U. S. Government purposes.

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

**Portions of this document may be illegible
in electronic image products. Images are
produced from the best available original
document.**

and lowered to the 23rd level of the mine. The amount of maneuvering required to load long pieces into the mine, and extract them at the bottom, is a formidable task when one considers that this must be done with long and not very rigid steel plates. In addition, the reference design calls for extensive final assembly welding in the mine, which will be a challenge from the ventilation standpoint. This design proposes to construct the steel planes from several steel sheets, and laminate them into the required thickness of four centimeters. The number of layers in the laminated stack is not crucial. However, the thinner the laminations, the less effort will be required to provide flat 8 meter diameter planes.

The 8 meter planes are constructed by cutting all of the steel plates to the same size, which is a pie shaped segment of either 30 or 22.5 degrees each. All of the plates in the construction are identical, which is conducive to rapid production and lower cost. All of the machining and hole drilling would be done in stacks. These stacks would be optimized for the machine by making them thick enough to use the maximum cutter diameter. These stacks would then be shipped to the mine, ideally in sizes that match the capacity of the hoist. It is hoped that the size of the stack, for both machining and for the hoist, would be the same. Since the holes in the sheets would be pre-drilled, these holes could be used to bolt the plates together into five ton pieces, which is the present hoist capacity. Once the plates are in the mine, they would be unbolted and separated into two stacks, one of drilled plates, and one of countersunk plates.

The advantages of the proposed laminated construction over the reference design are listed below.

1. The required flatness of the steel planes will be easier to achieve.
2. Except for final assembly, all fabrication is done above ground.
3. The required close magnetic contact between adjacent laminations, both in azimuth and in Z, will be easier to achieve.

4. The plates will be half the length of the reference design, and thus will be easier to handle.
5. The stacks of plates can be handled in five ton packets, which minimizes the number of hoist trips required. This is illustrated in Figs. 1 and 2.
6. No welding is required to assemble steel planes in the mine.
7. All steel pieces are identical with respect to size and hole positions. The only exceptions are the counter sinking of the holes in the outside plates.
8. Despite the larger number of radial gaps, better magnetic shunting across those gaps should yield less stringent joint tolerances, and smaller local field dips near the joints.
9. The four cm thick planes will be circular, not octagonal. This will avoid a large dependence of B upon azimuth, and will increase the usable fiducial mass.
10. All of the plates will fit in the existing cage, and no new equipment or special excavation is required.

Segmentation of the Planes

We have investigated a number of segmentation options. The current plan, which has been presented to the collaboration, calls for wedge shaped plates of 30° each and four laminated layers of 1 cm thickness. We will discuss this as Option 1. The other options are variations of this same arrangement. The options, as we see them, are listed below. At this moment there is no compelling reason to select any one option. It also should be pointed out that the number and thickness of the individual laminations is not critical to this design. There appears to be no reason, either magnetically or structurally, to set limits on the number of layers in the laminate structure. The primary reasons for selecting a particular thickness are the availability of raw steel plates, and the frequency

and amplitude of the out of flatness undulations, as received from the rolling mill. It has been observed from past experience that it is less difficult to achieve flatness in the individual steel sheets if they are thinner, and it is clear that the compression load to flatten thin sheets in assembly is less.

Option 1

In this arrangement each plate is $1/12$ th of 360° or 30° . The radii of the plates are 152.4 mm. at the inside radius and 4000 mm. at the outside radius. The arrangement of these plates to form a plane is shown in Fig. 3. There are four plates, each 1 cm thick, laminated to form a plane that is 4 cm thick. The weight of each plate in this arrangement is 717 lbs. In this configuration 48 plates form a plane.

Option 2

In this arrangement, the plates are $1/16$ th of 360° or 22.5° each. The radii are the same as in Option 1. The laminating arrangement is also the same as in Option 1. The weight of each plate in this configuration is 538 lbs. There are 64 plates in each plane.

Option 3

30 degree segments of $1/4$ " thickness. The weight is 455 lbs. per plate. A total of 72 plates form a plane.

Option 4

22.5° segments of $1/4$ " thickness. We will, for simplification of this proposal, use this option for all of the following description, keeping in mind that this is not meant to be a preferred option. The weight of each plate is 342 lbs. A total of 96 plates form a plane.

Fabrication of Pie Plates

Raw Steel Plates

Raw steel plates are available as coils from rolling mills in a number of widths. The ones that have been investigated are 70", 84", and 96". A layout of wedge plates for both the 30° and 22.5° options are shown in Figs. 4 and 5. For prototyping purposes, a low carbon 1006 steel is available in 70" widths. Since the production requirement is for such a large quantity of steel, the limitations that might be expected for small lots can for all intents and purposes be ignored; but it should be kept in mind that cost will increase if the chemical composition and size of the plates is far from standard. One would want to select the size based on mill width and then cut plates to minimize the waste. This may be another limitation on the width of the finished plates (30° versus 22.5°).

Plasma Cutting Wedges

Once the raw plates have been sheared to length, it is proposed that they be plasma cut to the shape shown in Figs. 6 and 7. In all cases it is proposed to plasma cut the wedge shapes from stacks of plates that optimize the precision of the edge. However, at the moment a stack of plates will be cut simultaneously. Due to the number of operations, the optimum height of the stack is not known, but three factors will affect this decision:

1. Plasma cutting
2. Machine capability
3. Loading of the mine hoist

By carefully evaluating all of these factors, some optimum stack height can be arrived at. It is intended that once the plasma cutting has been accomplished, the stacks of plates will be welded together. These welds are simple surface face welds, along the long edges of the plate stack. This concept of keeping the stacks intact through all of the operations, defeats some of the criticism of the number of pieces that must be handled during the operations.

Hole Drilling and Edge Machining Wedges

By making a careful evaluation of the machining operations, we have a scheme that will allow all of the machining operations to be performed without moving the plate stack. This is necessary because a large fraction of the cost for any option, is the cost of handling and maneuvering large plates.

A schematic representation of this machining setup is shown in Fig. 8. All of the operations for hole drilling and edge machining are performed in one position. The sequence of machining steps are listed below:

1. Place the welded bundle of plates on the fixture as represented in Fig. 6.
2. Drill all of the required holes in the bundle.
3. Place bolts in the holes.
4. Rotate the bundle to align one edge with the vertical.
5. Machine one edge, removing the previous weld.
6. Rotate to align the other edge with the vertical.
7. Machine opposite edge.

At this stage, a bundle of plates have all of the machining completed. It should be mentioned here that the precision of the edge machining is dependent on the requirements of the radial gap fit up. If the magnetic field calculations prove that larger gaps are acceptable, then a plasma cut edge may be sufficient and no edge machining may be necessary. At this point only one operation remains, that is to countersink the plates that will eventually be placed on the outside of the 4 cm planes. A stack of plates will be laid flat, and all of the holes in the top plate will be countersunk. As this operation is completed, the plate will be removed and the next plate will be countersunk. The plates with the countersinks will then be restacked and bolted together.

Handling Steel Plates

At all stages of fabrication, the plates will be either bolted or welded together in stacks. The stacks will remain together after all of the machining is complete. The stacks

will be very close to five tons each. This will allow the handling and shipping to be kept to a minimum piece count. One truck load would be four stacks, and loading into the cage at the mine would be done in these same five ton packages. The fixture, illustrated in Fig. 9, would be used for handling into the cage and for storage in the cavity. The use of these fixtures would reduce the amount of floor space required, since the storage foot print would be approximately 4 ft. $\times$ 6 ft. as opposed to the 8 ft. $\times$ 24 ft. required by the plates for the reference design. Handling fixtures will be designed so that the plate stacks are always handled from the small (inner radius) end. Lifting holes will be necessary for attaching a lifting device to this end of the stack.

Assembly of Steel Planes

Once the plates are in the mine, assembly will be accomplished by laying out the first layer of plates on the assembly fixture. A lifting fixture, that can extract the plates from the vertical storage/handling frame and rotate them to the horizontal, will be necessary. Each successive layer is placed on the previous layer, with the plates indexed 3° from the previous layer. When all layers have been placed in this manner, the bolts can be inserted. The assembly fixture is illustrated in Fig. 10. This fixture will accommodate the assembly of the layers of steel, and the insertion of the bolts. Once the plane is assembled, the fixture will be rolled out from under Bill Miller's multilevel structure, using a set of rails. Once clear of the structure, the fixture will be blocked on the rails and raised into the vertical position. A lifting fixture will be attached to the plane using existing bolt holes, and then the plane lifted, moved, and mounted to the detector support structure.

It should be made clear at this point, that this assembly scheme requires that the chamber planes must be installed on the steel after it has been mounted in its final vertical position. This requires that the chamber planes be assembled on a separate assembly frame that will be used to handle and mount the planes. Any other plan requires that the steel be assembled waiting for the chamber planes, for at least 4-5 days. It is assumed here that a steel plane can be assembled and erected in one two shift day.

In the reference design plan, floor space is required for five assembly stations and five support subframes for the steel. It seems more efficient to build subframes for the chambers, since they are much lighter and easier to handle. Also the structural steel, required to support the steel in a multilevel arrangement, is considerably more than that required to support the assembly of wire chamber planes.

Structural Analysis

Calculations, already done by both the Livermore Group and Argonne, have indicated that serious buckling problems are possible with the steel planes due to the large aspect ratio of size-to-thickness. If the reference design is used, and the planes are mounted on the floor, they must be stabilized with tie rods at the outside and at the center. It has even been suggested that some intermediate tie bolts may be required. These tiebolts, create serious interferences with the mounting and access to the wire planes. Many of the problems associated with buckling are ameliorated when the steel planes are supported at or near the top.

If one assumes that the planes will be supported from the top or near the top, the primary problem is reduced to one of maintaining the integrity of the plane. This becomes a simple problem of inserting enough bolts, pins, or rivets to preserve that integrity. One additional criteria is that it is assumed that all of the load is carried in friction. This is necessary since it is impossible to predict the number of bolts in contact with their respective holes.

Since the load is carried in friction, the purpose of the bolts is to create the normal force necessary to flatten the plates, and maintain the required friction between plates in the lamination. We have done two simple calculations to investigate the required number of bolts. First it has been suggested that high carbon (high strength) bolts may not be acceptable for magnetic reasons. Assuming that this is true, we used 1010 steel as the bolt material, and specified 1/2" bolts as a baseline. The following calculation identifies the number of these type bolts required. The proposed design of the bolts is shown in Fig. 11.

Nominal 1/2 " bolts machined from 1010 steel.

$$d = 1/2''$$

Area of Minor diameter

$$A_s = \frac{\pi d^2}{4} = .196 \text{ in}^2$$

Yield strength of 1010 steel

$$\sigma_y = 30 \times 10^3 \text{ psi} \Rightarrow 1010 \text{ bolts}$$

Stress @ 80% of yield

$$\sigma = (.8) \sigma_y = 24,000 \text{ psi}$$

$$\sigma = \frac{F}{A_s}$$

Maximum load on bolt

$$F = A_s \sigma = 4,712 \text{ lbs.}$$

From the *Handbook of Chemistry and Physics*

Coefficient of friction

$$\mu = .1 \text{ for dry metal on metal}$$

Friction Load each Bolt

$$v = \mu_F = (.1) (4,712 \text{ lbs.}) = 471.2 \text{ lbs.}$$

Total weight of steel plane

$$W_T = \text{Total weight} = 32 \times 10^3 \text{ lbs.}$$

$$n = \# \text{ bolts}$$

$$n = \frac{W_T}{v} = 67.9 \text{ bolts}$$

The number of bolts supporting the plane, in the worst case, is assumed to be 30. It is obvious from this calculation, that more bolts will be required than are available. This can be adjusted by increasing the number, or by increasing the size of the bolts. To set the scale we recalculated the same exercise using 1" high strength bolts. The following is the calculation for those bolts:

$$d = 1''$$

(Table 1-A, page 4-3, Manual of Steel Construction)

$$\text{A490 bolt} \rightarrow 42,400 \text{ lbs.} = F$$

$$\mu = .1$$

$$W_T = \text{Total weight} = 32,741 \text{ lbs.}$$

$$n = \# \text{ bolts}$$

$$v = \text{Friction load per bolt}$$

$$v = 4,240 \text{ lbs.}$$

$$n = \frac{W_T}{v} = \frac{32,741 \text{ lbs.}}{1,060 \text{ lbs.}} \quad \frac{W_T}{v} = \frac{32,741 \text{ lbs.}}{4,240 \text{ lbs.}}$$

$$n = 7.7 \sim 8 \text{ bolts}$$

This is obviously a much higher strength bolt than needed. Therefore, by optimizing the size of the bolt and varying the material, we will be able to select a bolt that will be satisfactory. For example, by using high strength bolts again, the same calculation indicates that the existing number of bolts is satisfactory.

$$d = 1/2''$$

$$\text{A490 bolt} \rightarrow F = 10,600 \text{ lbs.}$$

$$\mu = .1$$

$$v = \mu F = (.1) (10,600 \text{ lbs.})$$

$$v = 1,060 \text{ lbs.}$$

$$n = \frac{W_T}{v} = \frac{32,741 \text{ lbs.}}{1,060 \text{ lbs.}}$$

$n = 30.9 \text{ bolts}$

All of these calculations assume that there are no bending loads on the steel planes, and that they will be supported at or near the top of the plane. Once the support system has been selected, it will be necessary to do a thorough analysis of the entire system.

Prototype Construction

Argonne proposes to build one full size steel plane as a prototype for the mechanical construction of the laminated configuration. All of the concepts outlined in this proposal would be used. This prototype can be instrumented and powered to empirically test the magnetic fields, and the assembly and mounting of a plane of wire chambers.

During the assembly of this prototype plane, all of the ideas put forth here can be tested and modified as necessary. When these planes have been assembled and tested, a clear procedure can then be finalized with the knowledge gained in the exercise. Preliminary tooling would be used, where possible, to minimize the cost of this program. The steel width and carbon content might not be that which would be used in the final construction due to availability and cost.

Prototype Cost

Operation	Item	Material	Labor @ \$50/hr.	Multiplier	Total	Comment
Component Purchase						
	IF 1002 Steel	.2295/lb.		32,000 lbs.	\$7,344	
	1006 Steel	.2175/lb.		32,000 lbs.	\$6,960	
	1010 steel	.2175/lb.		32,000 lbs.	\$6,960	
	Bolts	\$28.20/set		480 sets	\$13,536	
	Structural steel support	\$.50/lb.	\$2.00/lb.	20,000 lbs.	\$50,000	
Total Purchase					\$70,496	
Fabrication						
	Plasma Cut Plates	0			\$10,320	
	Machine and Drill	0	368 hours		\$20,900	
	Countersink holes		345 hours		\$19,596	
Total Fabrication					\$50,816	
Assembly						
	Assemble Steel Plane		48 hours		\$2400	
Total Assembly					\$2,400	
Grand Total					\$123,712	

Production Cost Estimates

The following is a table of costs for the fabrication, and installation of the steel for the entire Far Detector Assembly.

Operation	Item	Material	Labor @ \$50/hr.	Multiplier	Total	Comment
Component Purchase						
	IF 1002 steel	\$.2095/lb.	0	20,000,000 lbs.	\$4,190,000	
	1006 steel	\$.1975/lb.		20,000,000 lbs.	\$3,950,000	
	1010 steel	\$.1975/lb.		20,000,000 lbs.	\$3,950,000	
	Bolts	\$.50/ea.			\$1,440,000	

Operation	Item	Material	Labor @ \$50/hr.	Multiplier	Total	Comment
Total Purchase					\$5,510,000	
Tooling						
	Bundle lifting Fixture	\$500	\$500	1 each	\$1000	
	Cage handling Fixture	\$500	\$10,000	6 each	\$63,000	
	Assembly Fixture	\$20,000	\$100,000	1 each	\$120,000	
	16 ton Plane Handling Fixture	\$500	\$2500	2 each	\$6,000	
	Machining Fixture	\$1,000	\$20,000	1 each	\$21,000	
Total Tooling		\$7,500	\$83,000		\$221,000	
Fabrication						
	Plasma Cutting		\$300	3,600 stacks	\$1,080,000	4" stacks/ 16 plates
	Weld Stacks		\$50	3,600 stacks	\$180,000	4" stacks/ 16 plates
	Ship to Mach.		\$200	3,600 stacks	\$720,000	4" stacks/ 16 plates
	Drill holes		\$575	3600 stacks	\$2,070,000	4" stacks/ 16 plates
	Bolt stack		\$100	3,600 stacks	\$360,000	4" stacks/ 16 plates
	Machine edges		\$250	3,600 stacks	\$900,000	4" stacks/ 16 plates
	Countersink. Holes		\$250	19,200 plates	\$4,800,000	
	Restack Countersink Plates		\$50	800 stacks	\$40,000	
	.Skid		\$50	3,600 stacks	\$120,000	4" stacks/ 16 plates
	Ship to Mine		\$300		\$720,000	4" stacks/ 16 plates
Total Fabrication			\$2125		\$10,990,000	
Load at Mine						
	Load on hoist and lower to 27		\$100	3600 stacks	\$240,000	
	Move to cavity		\$25	3600 stacks	\$60,000	
Total Hoist			\$125		\$300,000	

Operation	Item	Material	Labor @ \$50/hr.	Multiplier	Total	Comment
Assembly						
			3 man crew			
	Move and Position Plates Layer 1		\$390	600 planes	\$234,000	
	Move and Position Plates Layer 2		\$390	600 planes	\$234,000	
	Move and Position Plates Layer 3		\$390	600 planes	\$234,000	
	Move and Position Plates Layer 4		\$390	600 planes	\$234,000	
	Move and Position Plates Layer 5		\$390	600 planes	\$234,000	
	Move and Position Plates Layer 6		\$390	600 planes	\$234,000	
	Bolt Plane		\$600	600 planes	\$360,000	
	Drill Support		\$400	600 planes	\$240,000	
	Install Support		\$100	600 planes	\$60,000	
Total Assembly			\$3440	600 planes	\$2,064,000	
Install						
	Lift Plane		\$100	600 planes	\$60,000	
	Move		\$50	600 planes	\$30,000	
	Install		\$100	600 planes	\$60,000	
Total Install			\$250	600 planes	\$150,000	
Grand Total					\$13,650,000	

Shipping

Shipping of the steel would be dealt with in the same manner as all other handling requirements. The assumption is that bundles of steel, weighing approximately five tons would constitute a load. Four of the bundles would then provide the proper loading for over the road limits of 85,000 lbs. gross. This allows a payload of 40,000 lbs. Each load would then consist of 117 plates.

Figure 1

Figure 2

Figure 3. 30° segments, full plane array.

Figure 4. Cutting pattern for 30° plates.

Figure 5. Cutting pattern for 22.5° plates.

Figure 6. 1/16 (22.5°) plate stack.

1/16th STACK
MACHINING OF 24 PLATES IN ONE SET-UP

Figure 7. 1/12 (30°) plate stack.

1/12th STACK

MACHINING OF 20 PLATES IN ONE SET-UP

MACHINING FIXTURE

Figure 8. Machining fixture.

Figure 9. Plate stack handling fixture.

Figure 10. Steel plane assembly fixture.

Figure 11. Captive bolt for holding laminations.