Chapter 4

Magnet steel and coils

4.1 Overview

This Chapter describes the design and fabrication of the massive steel plane structures of the MINOS near and far detectors. These toroidally magnetized, 1-inch thick steel planes are suspended vertically in large arrays. Each steel plane also provides mechanical support for a plane of scintillator detector modules. The 8-m wide steel planes of the far detector are assembled in the Soudan underground laboratory from 2-m wide plates. The smaller near detector steel planes are made from single steel plates and require no underground assembly work. This task also includes the design and construction of the multi-turn coils, the power supplies and cooling systems used to magnetize the planes, and the instrumentation used to measure the magnetic fields in the planes. The design addresses several important engineering issues, including the mechanical stability and flatness of hanging planes with very large width to thickness ratios, and the effect of the composite plane structure on magnetic field quality. A program is under way at Fermilab to check the design calculations by constructing a number of full-size prototype planes. The first of these planes has been hung and provides initial confirmation of these calculations. This prototype detector plane program includes scintillator and steel integration checks, verification of safe steel handling techniques, and training for the detector assembly crews. The magnet steel and coils task also provides the fixtures for handling steel planes and the near detector support structure.

4.1.1 The far detector

The MINOS far detector will be installed in a new underground laboratory in the Soudan mine. The 5.4 kt structure is assembled from 8-m wide, 1-inch thick octagonal steel planes. The 486 steel planes are arranged as two "supermodules" of 243 planes each, separated by 1.5-m long gaps to allow space for installation of the magnet coils. An 8-m wide octagonal plane of scintillator detector "modules" is attached to each steel plane before it is raised to a vertical orientation and installed in a supermodule. A supermodule contains 242 planes of scintillator detectors and 243 steel planes with a center-to-center spacing of 5.94 cm. Each plane is hung by two "ears," which are extensions of the octagonal plane structure, similar to the hanging files in a file drawer. The scintillator detector is described in Chapter 5 and the installation of the steel and scintillator planes is described in Chapter 7.

Figure 4.1 is a sketch of a hanging steel plane and the detector support structure. Each steel plane is constructed from eight 2-m wide, 0.5-inch thick plates of steel which are welded together in a cross lamination to form the full octagon. A hole at the center of each plane is provided for the magnet coil that carries 15,000 A-turns of current through the center of each supermodule to produce an average toroidal magnetic field of 1.5 T in the steel planes. The return leg of the coil is located in a shallow trench in the floor directly under the axis of the supermodule.

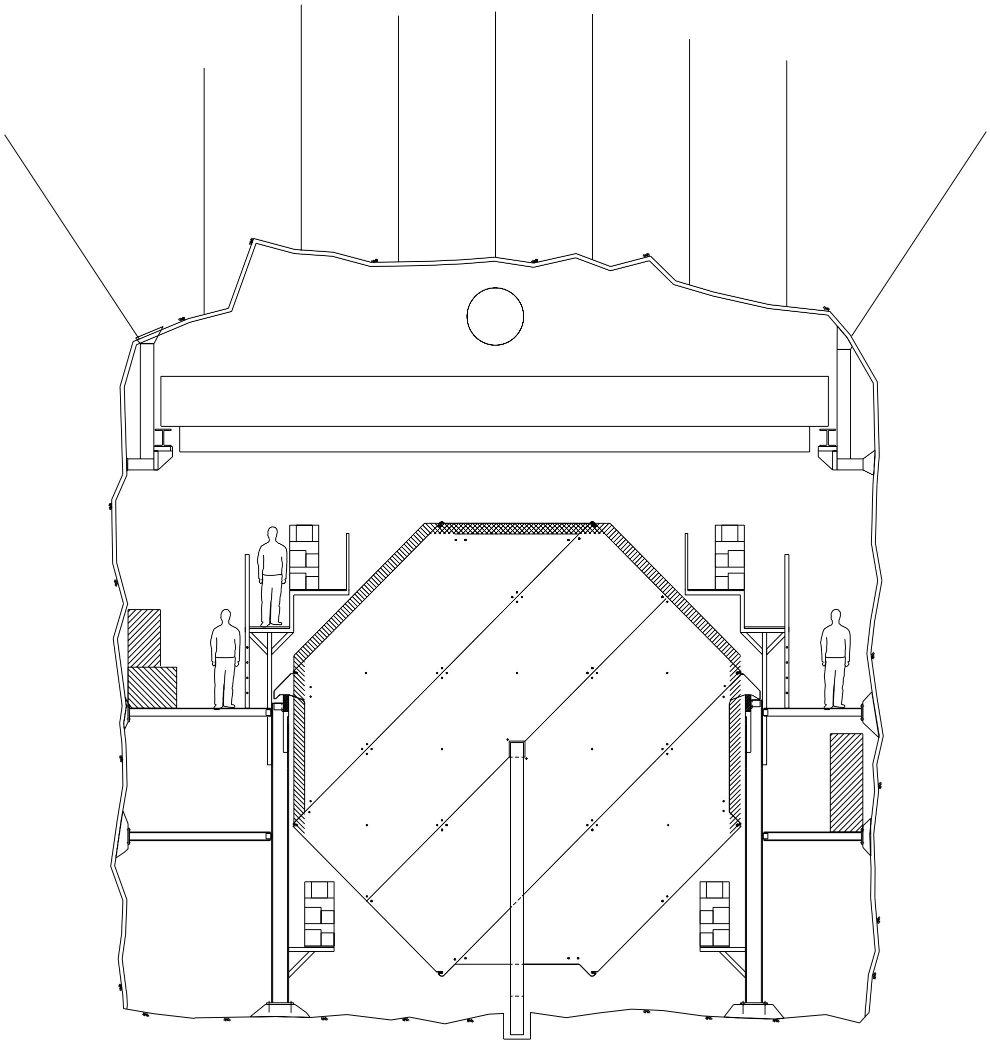

Figure 4.1: Sketch of an 8-m wide MINOS far detector steel plane hanging from the detector support rails. Four of the eight steel plates which make up the plane are visible; the other four plates are behind the first four and are oriented at 90° to them. Also shown are the detector support structure, the side walkways, the racks for photodetectors and electronics, the magnet coil and the overhead bridge crane.

The engineering and fabrication of the detector support structure is part of the MINOS cavern excavation and outfitting task and is described in the MINOS Far Detector Laboratory

Technical Design Report[1]. It is very similar to that for the near detector (described below).

4.1.2 The near detector

The 980 ton MINOS near detector will be installed in the new NuMI near hall at Fermilab[2]. The near detector is essentially a smaller version of one of the far detector supermodules. Because the neutrino beam at the near detector is only about 1 m in diameter, the detector plane geometry is designed to reduce the area (and cost) of the steel planes. A near detector plane and the detector's support structure are shown in Figure 4.2. The "squashed octagon" planes are small enough (6.2 m wide by 3.8 m high) that they can be manufactured as single, 1-inch thick units. They do not have to be assembled from 0.5-inch thick plates as in the far detector. The smaller beam area also allows most of the scintillator detector planes to be much smaller than those in the far detector. As shown in Figure 3.4 in Chapter 3, most of the first (upstream) 120 planes have scintillator modules covering only a 2.8 m $\times$ 2.8 m area. The last (downstream) 160 planes have full scintillator coverage only on every fourth steel plane; the remaining three out of four planes in this section do not have scintillator. The scintillator module design is described in Chapter 5 and the installation of the steel and scintillator planes is described in Chapter 8.

A hole is provided in each plate for the magnet coil, offset 0.56 m from the center of the plane. Because of the near detector's squashed-octagon geometry and the offset coil, the near detector coil must carry nearly three times as much current (40,000 A-turns) to achieve a magnetic field of about 1.5 T in the beam region. The return leg of the coil is located near the lower 45° edge of the plane.

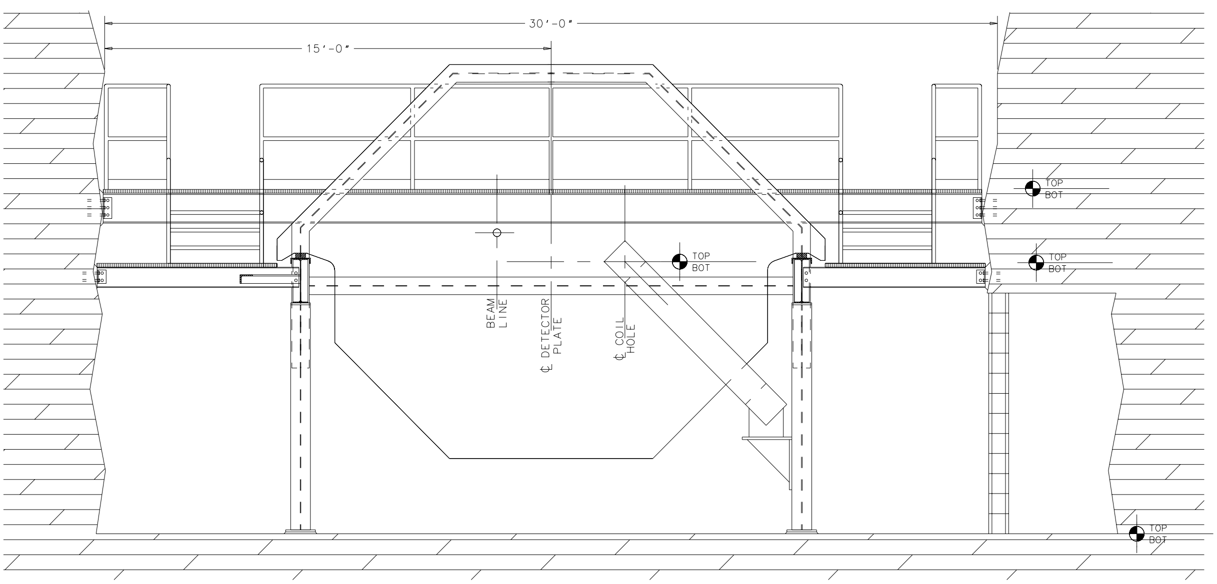

Figure 4.2: Sketch of a MINOS near detector steel plane hanging from the detector support rails. Also shown are the detector support structure, the side walkways, the magnet coil, the magnet support, and the bookend. (Dimensions shown are in feet and inches.)

A preliminary design of the near detector support structure has been completed by Facilities Engineering Services Section (FESS) at Fermilab. This structure conforms to Fermilab engineering standards and to the AISC code for structural steel fabrication[3]. The support includes "bookend" structures which constrain the first plane of each supermodule to be plumb in the vertical orientation and square to the support rails. Then bookends also provide a reference to ensure the flatness and stability of the sequentially installed planes for each supermodule.

4.1.3 The steel planes

4.1.3.1 Steel plate fabrication

Choosing the steel for MINOS planes required some compromises. The carbon content must be high enough to give high tensile strength, but low enough for good magnetic properties[4, 5]. We have chosen steel in the range specified by AISI 1006 low-carbon steel, with the properties summarized in Table 4.1. By requiring the carbon content to be between 0.04% and 0.06% (standard AISI 1006 steel can have carbon content between 0.04% and 0.08%), we can guarantee high magnetic permeability while still maintaining adequate tensile strength. The specification for MINOS steel[6] is the same as that used for the BaBar magnet steel[7].

Property	Specification
Tensile strength:	
Ultimate tensile strength	40,000 psi minimum
Yield strength	20,000 psi minimum
Elongation of 2 inches	22% minimum
Chemical composition (% by weight):	
Carbon	0.04% to 0.06%
Manganese	0.40% (max.)
Silicon	0.40% (max.)
Sulfur	0.01% (max.)
Phosphorous	0.07% (max.)
Nitrogen	0.008% (max.)
Aluminum	0.05% (max.)
Chromium	0.05% (max.)
Copper	0.06% (max.)
Nickel	0.06% (max.)
Molybdenum	0.01% (max.)
Vanadium	0.01% (max.)
Niobium	0.01% (max.)

Table 4.1: Mechanical and chemical specifications for MINOS steel plate material. The chemical composition specifications also include upper limits on the content of possible contaminants such as sulfur, phosphorous and nitrogen.

Dimension	Far detector	Near detector
Plate thickness	12.7	25.4
Thickness tolerance	$+0.8, -0.254$	$+1.8, -0.254$
Finished plate width	2000	3810
Finished width tolerance	± 0.76	± 0.76
Flatness over any 12 ft length	8.0	14.5
Max. number of waves	8 waves per 8 m	4 waves per 4 m

Table 4.2: Dimensional tolerances on steel plates for MINOS far and near detectors. All dimensions are in millimeters.

The specified steel is readily available at low cost from a wide variety of vendors, has a low carbon content for good magnetic properties, and is strong enough for MINOS planes. This steel has very good welding characteristics which is important for the assembly of the far detector planes; two layers of 0.5-inch thick plates are held together by 76 plug welds in each plane.

One of the most important properties is the flatness of the component steel plates. Steel producers and fabricators use an American Society of Testing and Materials (ASTM) Standard number A6, "Standard Specification for General Requirements for Rolled Steel Plates, Shapes, Sheet Piling, and Bars for Structural Use" for making steel plates. Table 4.2 gives the relevant flatness specifications for the MINOS far and near detector plates[8]. These specifications are about half of the ASTM standard values; several local steel vendors we have contacted claim to routinely produce steel plate which meets the flatness requirements in Table 4.2.

It is important to note that the flatness specifications are for single plates lying on a perfectly flat horizontal surface. The far detector planes are composite structures laminated from eight half-thickness plates, and will hang vertically; this may affect their flatness[9]. Prototype studies of full-size hanging steel planes, discussed in Section 4.4.5.1, will determine how the flatness of actual MINOS planes, hanging vertically, compares with the specifications listed in Table 4.2. Initial results from the first full-sized prototype plane show flatness deviations which are consistent with numerical models and within tolerances.

Steel plates must be cut to the proper shapes before they can be used. Many shops in the Midwest can handle plates of this size. The most inexpensive way to cut the plates to MINOS specifications[8] is to use a numerically controlled plasma torch. The plates for the MINOS single-plane test, described in Section 4.4.5.1, were fabricated in that manner. Measurements of the widths of gaps between edges of the plates in the assembled plane are very encouraging; less than 2 m out of the $\sim$40 m of gap length are more than 1 mm in width, and these gaps are all less than 3 mm wide. An alternative, more precise, way to cut the plates is by machining them. Several shops in the Midwest can machine plates of this size with the required accuracies. Based on these initial results, the baseline MINOS cost estimate[10] assumes cutting with a plasma torch, which is cheaper than machining. If more extensive experience from the four-plane prototype (Section 4.4.5.1) shows that plasma cutting does not provide an edge true enough to give gaps under 1 mm, then machining can

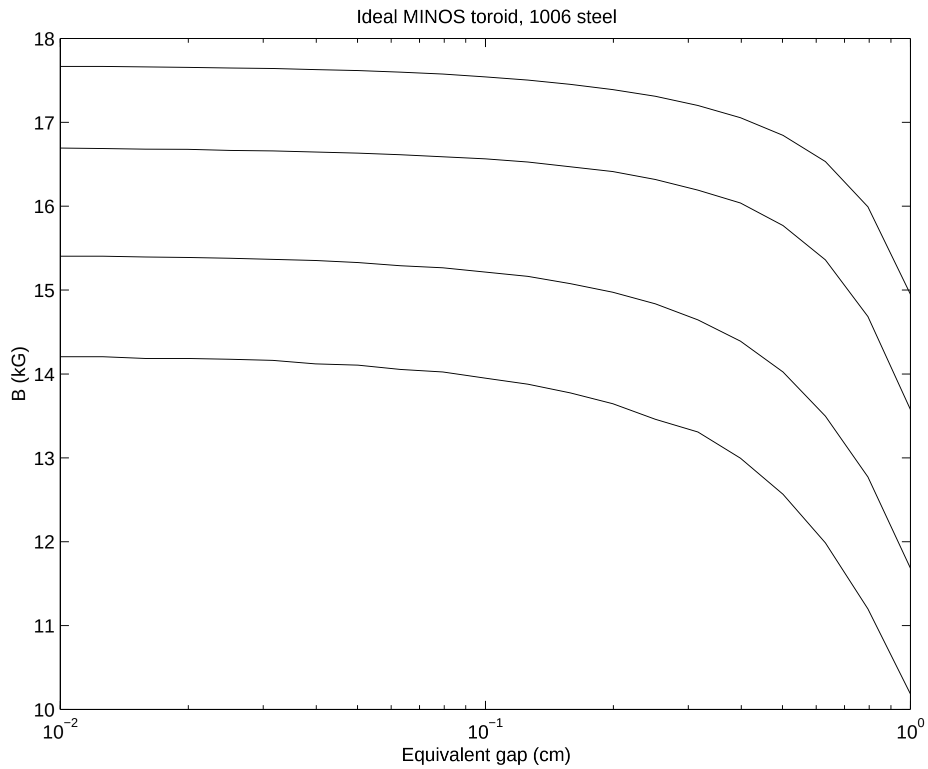

Figure 4.3: B-field *vs* the cumulative gap length at different radii for far detector octagons made from AISI 1006 steel. From top to bottom the curves show the results for R = 50, 100, 200 and 300 cm. For R = 200 cm, a 1 mm rms variation of a 5 mm effective gap results in a 0.1 T spread in the field distribution.

meet that gap requirement, albeit at higher cost.

Calculations show that an edge gap of less than 1 mm between individual plates does not degrade the magnetic field significantly[11]. A Monte Carlo simulation verified that the effect of 1 mm edge gaps on the magnetic field in a plate is small; for a muon passing within a few millimeters of a 1 mm gap, the field distortion contributes a potential directional uncertainty of about the same size as the multiple Coulomb scattering in the plate[12]. However, larger average gaps will require a higher coil current to achieve the average 1.5 T field level. Figure 4.3 shows the cumulative effect of all edge gaps on the average toroidal field at several radii. The field falls significantly for integrated gap widths larger than 5 mm[4].

4.1.3.2 Steel handling procedures

Procedures for handling steel plate sections and assembled MINOS planes are being developed as part of the magnet steel and coils task, and are a major focus of the prototype work described in Section 4.4.5. These optimized procedures will be used for the installation of the MINOS far and near detectors, described in Chapters 7 and 8. The large plates of steel must be handled carefully to avoid permanent deformation. Since standard handling at steel fabricators produces plates within the flatness specifications, similar procedures will be used at the experimental sites.

The far detector plates must fit into the hoist cage[1] at the Soudan site. This requires the 8-m octagons be formed from 2-m wide plates. A new cage has been designed specifically to carry MINOS plates from the surface to the underground laboratory, as described in Chapter 7. That Chapter also describes the monorail system which carries the plates from the shaft to the experimental cavern. Plates are packaged in sets of four (enough to build one of the two layers of a single octagonal plane), to match to the hoist's weight capacity. Additional holes are provided in the steel plates to aid in rigging the packages of plates onto and off of the shaft cage. The steel handling and assembly procedures are described in detail in Chapter 7.

A custom-sized 100-m deep drop shaft is provided near the entrance to the MINOS near detector hall[2]. This shaft allows the near detector planes to be delivered as one-piece plates that require no underground assembly. An overhead crane lowers near detector steel planes onto a cart which transports them down the access tunnel and into the hall. In the hall itself, an overhead crane lowers the planes onto a strongback for scintillator detector mounting. The steel-handling procedure for the near detector is described in more detail in Chapter 8.

4.1.3.3 Steel plane assembly and mounting

The procedures for assembling and mounting the far detector steel planes are being developed as part of the full-size plane prototype studies[13] described in Section 4.4.5. Detailed installation plans based on these procedures are described in Chapters 7 and 8; the current concepts for the plane assembly and mounting procedures are only summarized here.

The far detector planes are constructed using a strongback as the assembly fixture. The steel plates are laminated in a criss-cross pattern where the top plates are at 90° to the bottom plates and are welded together with a series of 1-inch diameter plug welds. The strongback provides a flat surface for plane construction. To minimize the gap between the layers, four movable hydraulic jacks ("the compression rig") force the plates together prior to welding. The strongback also has reference elements to ensure minimal gaps between adjacent plates. Near detector planes are single steel plates and require no welding.

After the plane is laminated, fixtures for mounting scintillator modules and fiber optics cabling are attached to the plane. This is described in detail in Chapters 7 and 8. After the scintillator modules are mounted and tested, restraint clips are installed to hold the plane to the strongback. The strongback is then used as the lifting fixture while the planes are lifted to vertical and transferred to the detector support structure.

4.1.4 Steel support structures

The MINOS steel support structures are critical interfaces to the detector planes. The closest equivalents to these supports in industrial construction are overhead bridge crane rails. The first and most important requirement is that the rails have sufficient bending strength to support the weight of the planes without sagging. Because the steel planes must be mounted sequentially, if there is not enough strength against bending between the vertical columns then the planes will tend to slip down the rails or will hang at an angle with respect to the vertical. The rail strength and column spacing have been chosen to prevent this problem. In addition, the support rails have a structural frame, or bookend, at the upstream end of each supermodule. The bookend is adjusted to be square to the direction of the rails and plumb with local gravity. The first plane of steel is bolted to the bookend to ensure that the starting plane is correctly mounted. Additional planes are constrained to be parallel to the first by the axial restraint system, described in Section 4.4.1.2.

The second important criterion for the support structure is that the two support rails must be properly aligned, similar to a pair of crane rails. A "guiding" ear on one side of each plane is closely matched in width to its rail ($-0.0/+0.10$ inch). The other ear has a flat surface which allows the second rail to wander by ± 1 inch from the guiding rail. The detector will follow the alignment of the first rail, which could cause problems in alignment of the axial restraints if the guiding rail is not sufficiently straight. The design of the detector support structure includes appropriate tolerances to prevent such problems.

The support structure must also support all of the ancillary equipment needed to operate the scintillator detector planes, as described in Chapters 5, 7 and 8. It is important that the weight of such equipment (e.g., the multiplexing boxes, photodetectors and electronics crates) be carried by the main detector support structure, and not by the steel's ears. Of course, all walkways and service platforms are also held up by the support structure.

The far detector support structure has been designed by CNA Engineering Consultants and is part of the Soudan cavern detector outfitting task[1]. The near detector support structure has been designed by Facilities Engineering Services Section (FESS) at Fermilab and is the responsibility of the magnet steel and coils task.

4.1.5 The magnet coils

The designs of the magnet coils for the MINOS near and far detectors are based on a Fermilab engineering study. The far detector uses a water cooled coil[14] with a total of 15,000 A-turns for each supermodule. The near detector coil (which is about the same length as a far detector supermodule) must carry a 40,000 A-turn current and requires substantially more cooling and a higher current power supply. These coils produce an average toroidal field (at a radius of 2 m) of 1.5 T in the far detector steel planes and a similar field at the position of the neutrino beam in the near detector. As shown in Figure 4.1, the far-detector return coil is routed vertically down from the coil holes on the ends of the detector and runs in a floor trench directly under the central coil. The near detector return coil is routed along the lower 45° face of the uninstrumented flux-return side of the steel plane, as shown in Figure 4.2. These locations minimize interference with photodetectors and electronics.

The far-detector coil-cooling water is provided by a local closed loop system; this is supplied by the MINOS far detector outfitting task[1]. The coil cooling system is connected to the cavern cooling system that carries the heat up the shaft to a heat exchanger on the surface, as described in Section 7.4.1.6. The low conductivity cooling water system for the near detector hall is provided as part of the NuMI project facility.

4.2 Requirements and performance criteria

4.2.1 Goals

The goals of the magnet steel and coils task are:

- To design and fabricate the multi-plane steel structures for both the far and the near detectors, including their assembly fixtures, while optimizing the flatness and magnetic properties of the steel planes.
- To prove the feasibility of the designs and procedures for the manufacture and safe erection of the planes into stable mechanical structures meeting required physical specifications.
- To design and provide the coils, power supplies, cooling and monitoring elements for exciting the magnets to the required field levels and thermal dissipations.
- To design and fabricate the near detector support structure.
- To build and test a succession of prototype structures for optimization of the magnet design details, to enable a demonstration of the integration with active detector elements and electronics into a working system prototype, and to train technical staff for their final manufacture and installation of the detector underground.

4.2.2 Performance criteria

The most critical performance criteria for the magnet steel and coils are:

- **Energy resolution.** The magnetic field in the steel planes must be known and stable to 5% so that the muon momentum resolution does not dominate the overall energy resolution. However, the relative near-far magnetic field calibration must be known to 2% to meet systematic error requirements; this can be achieved using events with stopping muon tracks. (Local mass variations in the steel plane structures must be known to about 10% for good calorimetry, but this should be very easy to achieve.)
- **Fiducial mass.** For the CC disappearance measurement the fiducial masses of the near and far detectors must be known to 1%. The mass of the far detector plates can easily be measured using a digital scale attached to a crane. The fiducial target region in the near detector is limited to a 25-cm radius circle near the center of the plane. The average thickness of the target region must be measured to 0.05 mm precision for the 40 planes of the near detector target.
- **Flatness.** Residual waviness or nonflatness of the steel planes must be within the 1.5 cm tolerance required by the scintillator planes, i.e., each 2.54 cm thick plane must be completely contained within a 4.04 cm thick planar volume to leave enough space for the scintillator planes when adjacent steel planes are pushed together. In particular, the steel planes must not change their flatness outside of this 1.5 cm tolerance during the raising and mounting operation. (The scintillator module mounting is flexible enough that the modules will not be damaged by plane movement within this volume.)

- **Radioactivity.** The steel planes must be free of contamination from radioactive material. Any such contamination should not significantly increase the singles counting rate from photodetector dark current and the room radioactivity counts in the exposed edges of scintillator planes. (Very small amounts of ^{60}Co are occasionally found in commercial steel.)
- **Costs and schedules.** The cost of fabricating, installing and operating the steel and coil system must be minimized in the context of the entire experiment. The present design has resulted from tradeoffs among many interrelated parameters, e.g., expensive plane flatness allows a given detector mass to be installed in a shorter cavern; expensive underground assembly space allows schedule goals to be met and makes more efficient use of manpower; coils with more conductor area cost more to fabricate but save cooling and operating costs.
- **Safety.** The steel planes must be kept stable and safe against structural failure due to mechanical stress at all stages of assembly, mounting and operation.

4.2.3 Tasks

The following tasks are included in the magnet steel and coils WBS element:

- **Steel plane fabrication tasks**

  1. **Steel plane components.** Design, procure and deliver to the Soudan mine and/or Fermilab, as appropriate for far/near detectors and prototypes. These include shaped octagon steel plate components, axial bolts, center bore pieces and ear spacer plates.

- **Near support structure task**

  2. **Near support structure.** Design and procure components for the near detector hanging-file support structures.

- **Steel handling fixture tasks**

  3. **Strongbacks.** Design and procure strongback components for the far and near detectors.
  4. **Near detector transport carts.** Design and procure components for the near detector materials transport carts.
  5. **Far detector compression devices.** Provide devices to mate with the far detector compression rig and force the far detector plates together prior to welding.
  6. **Welding.** Provide systems for automatic submerged arc welding of the far detector plane components into octagonal planes; provide criteria and protocols to ensure the quality of the resulting assemblies.

- **Magnet coil tasks**

7. **Magnet coil design.** Design and provide components for the magnet coils and their supports for both the far and near detectors; this includes design of procedures for the delivery of coil components into the detector caverns, for their assembly on site, for their insertion into the steel bore, and for their final interconnection.
8. **Field calibration and monitoring.** Design and provide fixtures and equipment to measure the magnetic fields within the near and far detectors, directly and by on-line measurement of the excitation current.
9. **Fabrication and installation.** Provide mechanical fixtures for manufacturing the coils on the Fermilab and Soudan sites, for handling their components and for installing them in the detector bores.
10. **Electrical systems.** Specify and procure the power supplies and control systems for the near and far detector magnet coils.
11. **Cooling systems.** Design and provide components for the magnet cooling systems; for the far detector magnets this includes connection to the Soudan cavern cooling system which is supplied as part of the far laboratory detector outfitting task; for the near detector this includes connection to a deionized water cooling system that is supplied as part of the NuMI project facility.

- **Full-scale prototyping tasks**

12. **One-plane prototypes.** Provide a proof of principle that far detector planes can be fabricated, assembled and hung safely. Perform initial measurements of mechanical and magnetic properties.
13. **Four-plane prototype.** Provide a prototype to check all aspects of the design, assembly and performance of the far detector steel and scintillator planes.
14. **Steel-handling prototype.** Provide a simulation of the Soudan hoist cage and shaft stations to demonstrate safe and efficient handling of the far detector plates at Soudan.
15. **Four-plane training prototype.** Construct a prototype of the final detector assembly in order to train the far detector assembly supervisors and crew bosses.
16. **Four-plane near-detector prototype.** Provide a four-plane prototype of the near detector to check the design of the near detector and to train the near detector assembly crews.

4.3 Interfaces with other MINOS systems

4.3.1 Scintillator detector planes

The steel planes interface with the scintillator detector planes by supplying the mechanical support for the detectors, as described in detail in Section 7.4.3.3. Chapter 7 also describes the scintillator plane "clear zone" for getting signal fibers out of the modules. The design of the steel has allowed for a clear zone (20 cm on the sides, 40 cm on the top and 25 cm on the bottom) around the perimeter of the octagons for signal fibers and for the other hardware which is permanently attached to the scintillator planes. The axial restraint bolts and the ears take up small areas inside the octagons which the scintillator planes must avoid. The scintillator planes must also avoid the axial restraint collars which surround the central coil holes. The design of scintillator modules which satisfy these constraints is described in Chapter 5.

4.3.2 Near and far detector installation

The magnet steel and coils task must be carefully coordinated with the near and far detector installation procedures. An important interface issue is the integration of the steel packaging and shipping with the rigging and storage facilities at the Soudan site. The existing infrastructure at the Fermilab site makes this integration relatively simple for the near detector but the more limited facilities at Soudan make the far detector situation somewhat more difficult.

The new cage for the Soudan-mine hoist has been specifically designed for underground delivery of 5.5-ton "bundles" of pre-sorted steel plates. The preparation of these bundles will be combined with weighing each plate and with quality control measurements. These operations will be performed after delivery of the steel plates to the surface building in Soudan. Storage for one month's worth of steel is provided in the surface building. Additional storage, if needed, will be provided by the steel fabricator.

The assembly of the magnet coils is an interface area where the optimum solutions for the near and far detectors are different. Since the fabrication of the near detector coils can take advantage of existing facilities at Fermilab, the relatively short access shaft has been designed to accommodate the underground delivery of prefabricated, full-length coil sections. The far detector coils, however, must be fabricated underground due to restrictions imposed by the existing shaft. In addition, the coil cooling system at Soudan must interface with a cavern cooling system which is considerably more complex (because of the much greater depth of the far detector cavern) than the corresponding system in the near hall.

To reduce excavation costs both detector halls have been designed to be as small as possible. Because a plane can only be moved with the aid of a strongback, the limited floor space effectively means that planes cannot be removed once they have been mounted on the detector support structure. Although the two most recently installed planes could, in principle, be removed for repairs, this would be time consuming and difficult. This constraint places a high premium on careful quality control during the final checkout of steel and detector planes prior to mounting.

4.3.3 Far detector cavern outfitting

The Far Detector Laboratory Technical Design Report[1] describes the outfitting of the far detector cavern at Soudan and the special equipment required for the installation and operation of MINOS detector systems. The operation of these systems is described in Chapter 7. The following systems are included in the "detector outfitting" task:

- The cavern cooling system and associated electrical systems.
- The MINOS detector electrical and fire suppression systems.
- The detector support structure, including electronics platforms.
- The 3-deck shaft cage for moving detector components underground.
- The underground monorail systems for moving heavy steel and scintillator components.
- The steel plate storage carts and 2-ton rolling gantry cranes.
- The mezzanine storage and testing area in the Soudan 2 cavern.
- The pedestals and compression rigs for steel plane assembly.

The far detector support structure is shown schematically in Figure 4.4. The steel and coil task includes detector plane prototyping and careful testing of the steel handling systems and procedures before underground detector installation begins.

4.3.4 Near detector hall

The near detector support structure has been designed by the Facilities Engineering Services Section at Fermilab in coordination with the design of the near detector hall by the NuMI civil construction task. In addition to supporting the detector planes, this structure also provides walkways which give access to the near detector instrumentation and to the DAQ room. The downstream access shaft and the downstream surface building have been designed to accommodate the installation of the near detector coil components[2].

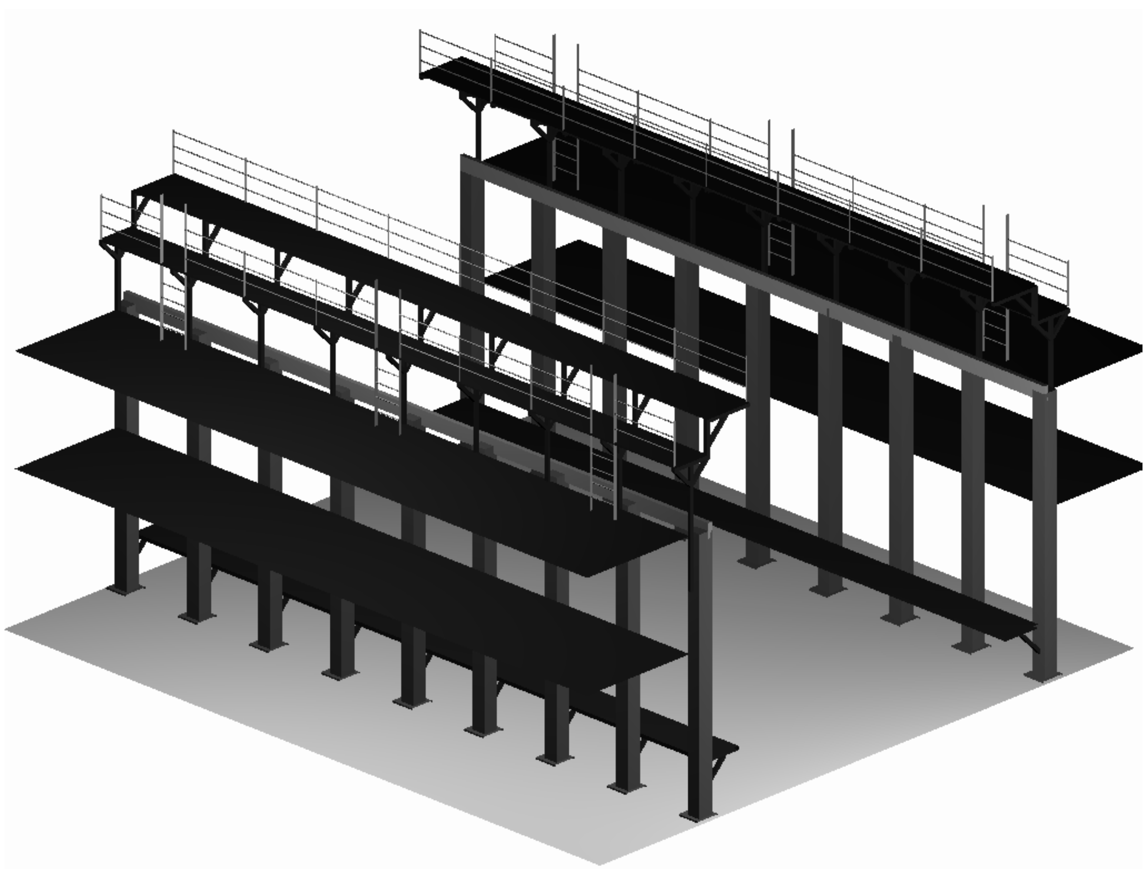

Figure 4.4: Sketch of the far detector steel support structure. The steel plane support rails are the horizontal members at the top of the vertical columns. The upper electronics platforms and personnel access ladders are located above the rails; the lower electronics platforms are cantilevered from the vertical columns.

4.4 Description of WBS elements

This Section describes the magnet steel and coil activities included in each WBS-2.1 Level 3 task. The associated EDIA activities are included in the individual tasks at Level 4, and in the detector plane prototype program within this task (Section 4.4.5).

4.4.1 Steel plane fabrication (WBS 2.1.1)

4.4.1.1 Steel planes

This WBS element includes the purchase of all of the steel plates for the two far detector supermodules and the near detector. The basic requirements on the mechanical and magnetic properties of MINOS steel have already been discussed in Section 4.1.3.1 above.

In order to widen the base of potential vendors, bids for the steel will be requested both from integrated producers (who supply and fabricate steel plate) and also from specialized suppliers (who either make plate or only process it)[15]. Bid requests will also include all axial restraint bolts, center bore pieces, and ear spacer plates. The far detector steel plates will be purchased in a few large orders, whose optimum size will depend on tradeoffs among a number of factors: the uniformity of steel composition and dimensions within large batches, the reduction in unit costs for large production orders (which may depend on individual vendor facilities), and the cost of storage at the vendor.

The magnetic specifications for MINOS steel plates are essentially identical to those used to purchase the plates for the BaBar magnet return yoke[7]. In addition to specifying carbon content between 0.04% and 0.06%, good magnetic properties also require that the plate be hot rolled, with cold processing kept to a minimum. U.S. steel producers generally will not accept direct specification of magnetic properties. The large BaBar steel order was produced in Japan, and consisted of three separate melts. Their measurements of sample magnetization curves indicate that magnetic uniformity of better than $\pm 10\%$ can be expected, which is adequate for MINOS provided that the plate-to-plate variations are measured and included in the experiment's database.

The operation of MINOS scintillator detectors is quite sensitive to any radioactive contamination of the steel planes, which could significantly increase the singles counting rates of the photodetectors. Steel producers use a ^{60}Co tracer in their ceramic furnace linings to indicate when the linings have become thin enough to require replacement. Thus, very low levels of ^{60}Co contamination are relatively common in steel samples. The MINOS specification of less than 0.15 gammas/kg/sec above 0.5 MeV is the same as that used for the steel plates of the Soudan 2 detector. The Soudan 2 experience with 1000 tons of steel calorimeter plates has shown that there is a very low likelihood of significant radioactive contamination (no steel was ever rejected for this reason), so this is not expected to be a serious problem for MINOS. However, it will be necessary to measure the radioactivity of each steel melt, and to have an agreement with the steel producer about how to proceed if a problem is detected.

The 8-m diameter far detector steel planes, shown in Figure 4.1, are assembled at the Soudan detector site from two layers of 2 m wide plates which are plug welded together to form a very strong, flat structure, as described in Section 4.4.2.3 below.

The much smaller near detector steel planes are fabricated from single plates by a com-

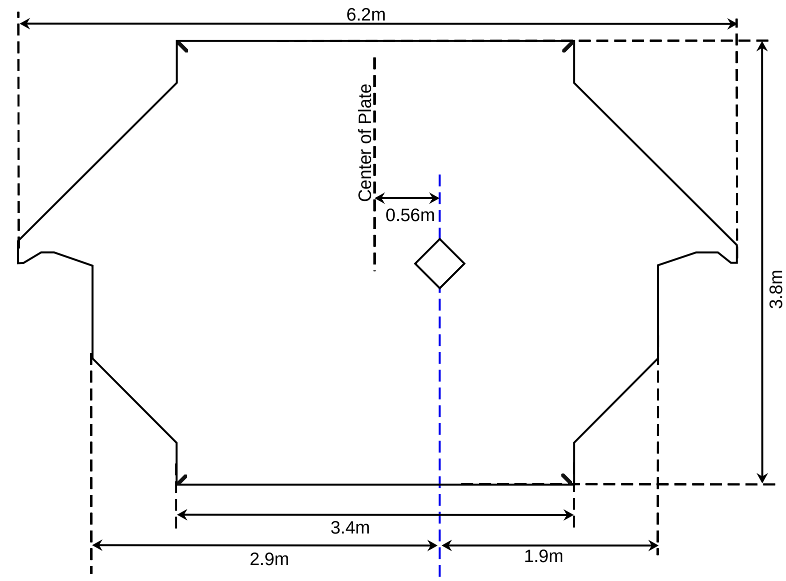

Figure 4.5: Drawing of a near detector steel plane. The beam is centered halfway between the central coil hole and the left vertical edge of the plane.

mercial manufacturer and require no underground assembly work except to attach the scintillator modules. Figure 4.5 shows a drawing of the "squashed octagon" shape of a near detector steel plane. The criterion for the shape of the steel was to provide an adequate magnetic field in the beam region with as little steel as possible for the magnetic flux return path. The planes are made from the same low carbon, hot rolled steel as the far detector. Reducing the amount of steel in the near detector reduces the cost of the steel by about 45% compared to a 6-m wide regular octagon with the same instrumented area. Each plane is made as a single 1-inch thick piece.

The flatness tolerance for the single-piece near detector steel planes may be somewhat harder to to achieve than for the laminated far detector planes. In order to meet the required tolerance of 1.5 cm the manufacturer must provide plate with a flatness of 50% of the allowance in the ASTM A6 standard. This is similar to flatness specifications which are routinely achieved by plate manufacturers. In contrast, in the far detector the laminating process can remove residual bowing in the plates.

It should be noted that the cost estimate does not include preservatives for the steel. Our design study shows this step to be unnecessary, so we have removed it to save the cost of paint and the labor to apply it.

4.4.1.2 Axial restraints

There are three kinds of axial restraints used to stabilize the detector planes, as mounted, for both near and far MINOS detectors. The first restraint consists of "axial bolts" at the eight corners of each octagon; these attach each plane to the previous one as it is installed. The planes are constructed with slots near each of the eight corners which are large enough to accommodate cutting tolerances. Axial bolts also attach the first plane to the bookend. This ensures that the array of planes starts out plumb and square, and remains so. The present design of the bolt is shown in Figure 4.6. The design is expected to evolve as experience is gained with the flatness achievable in actual welded and erected planes during prototype tests (see Section 4.5.2).

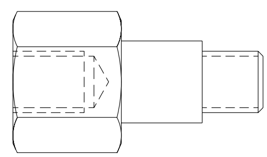

Figure 4.6: Sketch of an axial bolt which is used to restrain the eight corners of each MINOS steel plane. The 3-inch long bolt has threads on both ends to attach to the bolts for adjacent planes. The 1-inch long, 1-inch diameter center section fits into a hole in the steel plane.

The second axial restraint is the collar around the magnet coil hole in each plane. This restraint serves two functions. It sets the spacing in the center of the planes to give the correct gap between planes, and it provides a smooth bore through which the magnet coil can be inserted. The coil hole in each steel plane is deliberately made slightly larger than required for the coil and collar. The collar then allows the centers of the planes to be aligned laterally by taking up all of the tolerance differences caused by the oversize holes, imperfections in the plane assembly, and any misalignment of support rails. These axial restraints do not need to hold against large forces because the bookend is strong enough to stabilize the plates vertically through the axial bolts. Precautions will be taken to minimize the cumulative buildup of forces during the assembly of far detector supermodules and the near detector (see Section 4.5.2). Figure 4.7 is a sketch of the coil collar design. The dotted annulus in the face-on view indicates the allowance for adjusting the position of the collar relative to the 30-cm $\times$ 30-cm square hole in the steel plane. Each coil collar bolts to the previously installed collar, and has eight threaded holes to accept the bolts from the collar on the next plane to be installed.

The third axial restraint consists of spacers with the exact shape of the ears, which are welded to the ears. This restraint also serves to fill the gap between adjacent planes so that the ears cannot tip out of a vertical plane. The spacers also supply additional bearing area for the weight of the plane; however, our safety analysis does not make any allowance for this in order to be as conservative as possible.

4.4.1.3 Stability of hanging planes

The stability of the MINOS planes when they are hanging is a difficult engineering problem. Study of this problem was begun at Livermore and continued at Fermilab[16, 17]. All of the analysis has been done for one plane (the single plane test) hanging on the rails with no supports or other engineering aids. In the final detectors, the array of planes bolted to each other and to a bookend is more stable than a single plane. Engineering a stable single plane is an approach that produces a very conservative design for the full detector.

Analyses at both Livermore and Fermilab showed that the planes do not fail from over-stressing the ears. Static hanging planes with no tilt or out-of-plane forces produce stresses

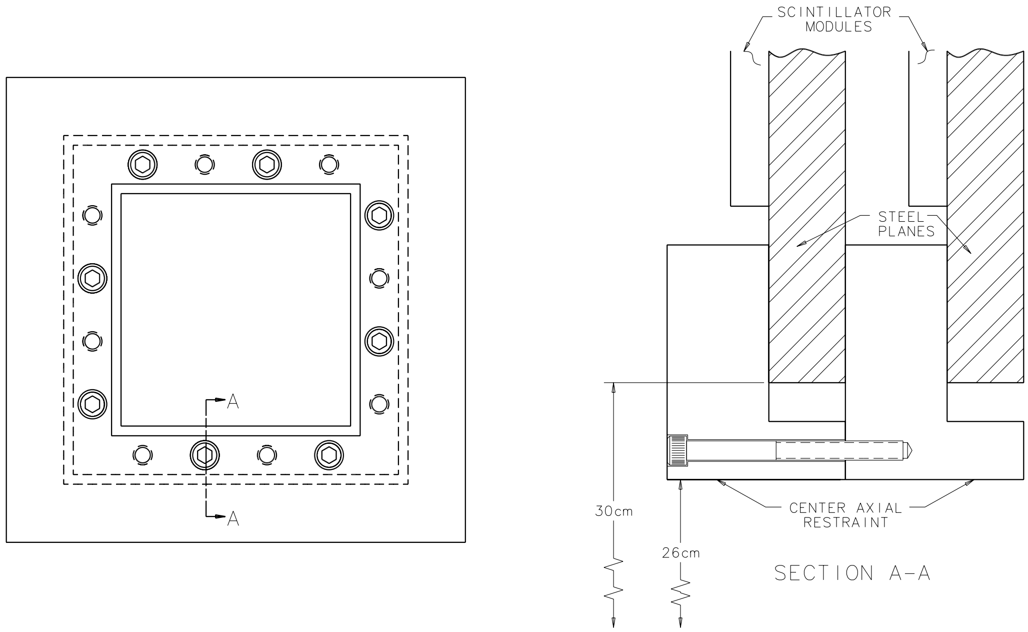

Figure 4.7: Two views of a steel plane coil collar. The face-on view (left) shows the bolt pattern and adjustment allowance (space between the dotted lines). The section view (right) shows how adjacent collars bolt together. The coil hole in the center of the collar is 26 cm × 26 cm.

in the ears of 4500 psi. This stress does not count the bearing area which the ear spacer plates would add. Clearly, this is well below the minimum yield stress of AISI 1006 steel which is 20,000 psi, giving a safety factor of 4.4. The finite element diagrams of the stress show that this is also very localized at the stress riser of the corners of the rails, and would gradually be reduced by local yielding of the metal. The bulk of the planes and much of the ears show stresses far less than even the 4500 psi. Solutions for this static case were obtained using Pro/Mechanica at Livermore and ANSYS at Fermilab; the results agreed within 10%.

Much of our engineering design work to date has focused on the possibility of failure by buckling. Buckling can take on many forms for hanging planes. The planes can fail if they are allowed to rest on the rails at some angle off the vertical. They can also fail by application of a force in the center of the plane which causes bending at the middle, thus pulling the ears off the rails. This bending has many modes, much like the modes a drumhead can take when oscillating. Most of the higher order modes do not appear to cause catastrophic failure but do distort the plane within its flatness allowance.

In order to understand better the buckling characteristics of a hanging plane, engineering analyses were performed at both Livermore and Fermilab. At Livermore, linear eigenvalue theory was used to determine the buckling safety factors for the plane with a variety of constraints and at small angles. Fermilab repeated these calculations to calibrate the models, and then analyzed the problem again. The results were in good agreement. The Fermilab solution showed that for a 0.75-inch thick plane the buckling safety factor is 1.68, and for the 1-inch thick plane the safety factor is 2.99.

Fermilab conducted analyses using nonlinear large deflections to study the post-buckling behavior of the steel plane. It was shown that, after the initial buckling, the plane warps and tilts to one side, but it is still stable; there is no instantaneous failure of the plane. The analysis showed that the warping and tilt increase as the load on a plane increases.

Preliminary test results using a scale model tend to confirm these conclusions:

1. The plane itself will not buckle if it is kept vertical.
2. The plane will be stable after buckling.

The test specimens were 1/10-scale planes with a thickness of 0.032 inch. Dimensional analysis shows that the scaled plane's buckling characteristics are very similar to those expected of the 1-inch thick full-sized plane. Since it is not possible to increase the density of the scaled plane, an additional load was applied by hanging a weight from the plane's center. The specimen began to buckle when an additional load of 4330 grams was added, more than the 3361-gram weight of the specimen itself.

From studies of the steel planes so far, we have shown that a hanging steel plane will not fail by buckling. If the plane is tilted, or if there is an excessive perpendicular load to cause the plane to buckle and tilt, the stress at the ears may exceed the yield stress of the material and the plane may fail by an ear tearing off. The conclusion of the analysis is clear: the system design must never allow the planes to sit on their support rails without axial restraints of some kind.

4.4.2 Steel handling fixtures (WBS 2.1.2)

4.4.2.1 Strongbacks

The design of the strongbacks is one of the most important tasks in the steel project. The strongback must be as light as possible, strong enough to keep the steel and detector planes flat during assembly and mounting, and must conform to both AISC steel construction code and to ANSI B30.20 "Below the Hook Lifting Devices." It must also hold the steel and detector plane assembly securely during the mounting procedure, without interfering with the plane of scintillator modules which completely covers the top surface of each steel plane. The design analysis was performed according to AISC requirements, including all of the bolted connections and all bending and torsion stresses in the members. ANSI B30.20 requires that any lifting fixture be designed with a minimum safety factor of at least three. The prototype far detector strongback shown in Figure 4.8 was designed at Livermore to these standards. The outer rim and cross members are made from 4-inch $\times$ 16-inch, rectangular cross-section, structural steel tubing. Two W16 $\times$ 40-lb wide-flange I-beams are used for the main lifting members. The prototype strongback was found to be flat to about 1 cm over the entire 50 m^2 work surface. This prototype strongback has been successfully used in the New Muon Lab at Fermilab to lift and mount the first prototype steel plane. All joints are bolted so that the strongback can be disassembled for moving down the Soudan mine shaft.

The near detector strongback is similar to, but significantly smaller than, the far detector strongback. It is essentially an assembly platform and lifting fixture for the steel and scintillator detector planes. A conceptual design has been completed at Fermilab. The steel planes for the near detector are manufactured as single pieces and do not require welding or a compression rig.

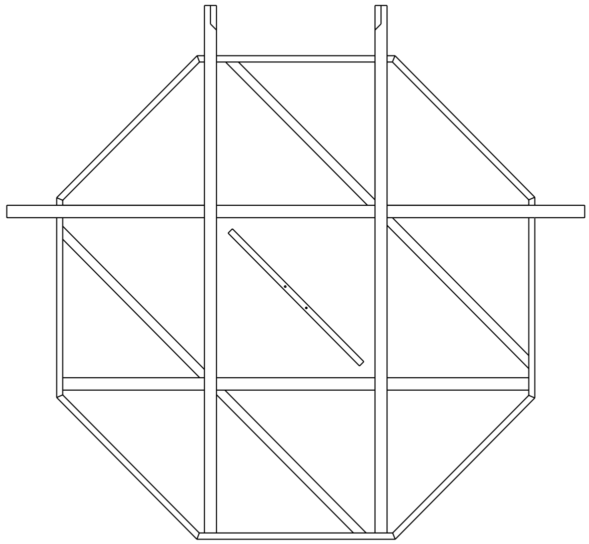

Figure 4.8: Sketch of a MINOS far detector strongback. The diagonal center piece supports the middle of the plane. Its ends are attached to the main structure (not shown in this drawing).

The carts for steel movement in the near detector hall are also included in the magnet steel and coils cost estimate. The near detector carts are similar to the far detector carts that have been designed as part of the Soudan site preparation task[1]. Each near detector cart carries only a single steel plate.

4.4.2.2 Far detector compression devices

The far detector compression rig is designed to force the individual plates together against the strongback during welding to remove any residual waviness; two compression rigs are required for far detector assembly. Calculations using plate theory indicate that a force of 5000 lbs is required to compress two typical plates together to within our specified flatness criteria. The compression rig has four compression devices, 5000-lb hydraulic jacks, that can be individually moved around the plates to supply a total of 20,000 lb of compressive force. The jacks are positioned to flatten the high spots around each weld location and then are reset after the weld is made. The tests described in the next Section have demonstrated the viability of this approach.

The far detector compression rig, shown in Figure 7.3 in Chapter 7, has been designed by CNA and will be constructed as part of the far detector hall detector outfitting task. The design uses a cantilevered jib structure which fits in the limited cavern space. The steel and coil task will provide the eight 5000-lb hydraulic jacks.

We have chosen a specific weld sequence pattern to minimize weld-induced stresses during the assembly of steel plates into octagonal planes. The pattern shown in Figure 4.9 starts the welding at the center of the plates and works to the outside. This pattern flattens the plate from the center and moves towards the edges. As welds are placed at larger radii they

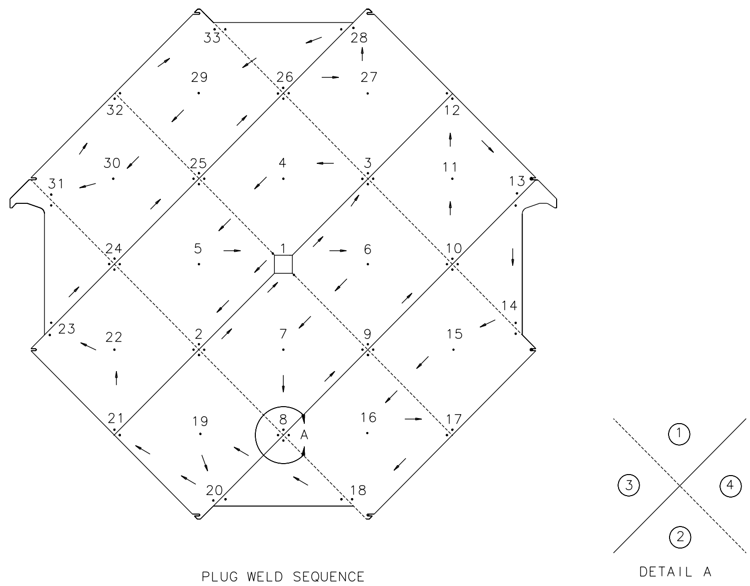

Figure 4.9: Sequence of plug welding operations to assemble an 8-m wide, 1-inch thick octagonal steel plane from eight 2-m wide, 0.5-inch thick plates.

support the flattened areas around the inner sections of the plane.

4.4.2.3 Far detector welding

The plates are welded together to form a plane by 72 one-inch diameter plug welds, as shown in Figure 4.9. Two additional welds are made at each ear to increase their strength. Several different welding processes have been evaluated, including Submerged Arc Welding (SAW), Flux Cored Arc Welding (FCAW), and Gas Metal Arc Welding (GMAW). We have chosen the SAW method for the final production process. Livermore built and tested a prototype SAW welding head using components from an existing welding turntable. For MINOS, SAW is a particularly attractive process because it produces the least arc flash and smoke, which is important for assembly in underground enclosures. The SAW process is simple because the only variable is the on-time of the arc. It can be made fully automatic so that uncertified welding technicians are able to operate the system and a professional welder is needed only to perform quality checks. Although the installation plan includes a certified welder who is always on duty, he or she is mainly occupied with tasks other than plug welding.

The Livermore MINOS group did a test with a pair of 1.2 m^2 plates to discover how the flatness of the plates changed during welding. These plates were measured for flatness before any welding and then again after welding. The gaps between the plates were measured at several times during a series of bolting and welding operations. To model the compression rig, the plates were bolted together with nine 1-inch bolts. The top plate had holes drilled in it to measure the gap between the two plates using a depth gauge. Figure 4.10 shows the plates with the features called out. Welds A, B, C, and D were done first. After the bolts were removed then weld E was done.

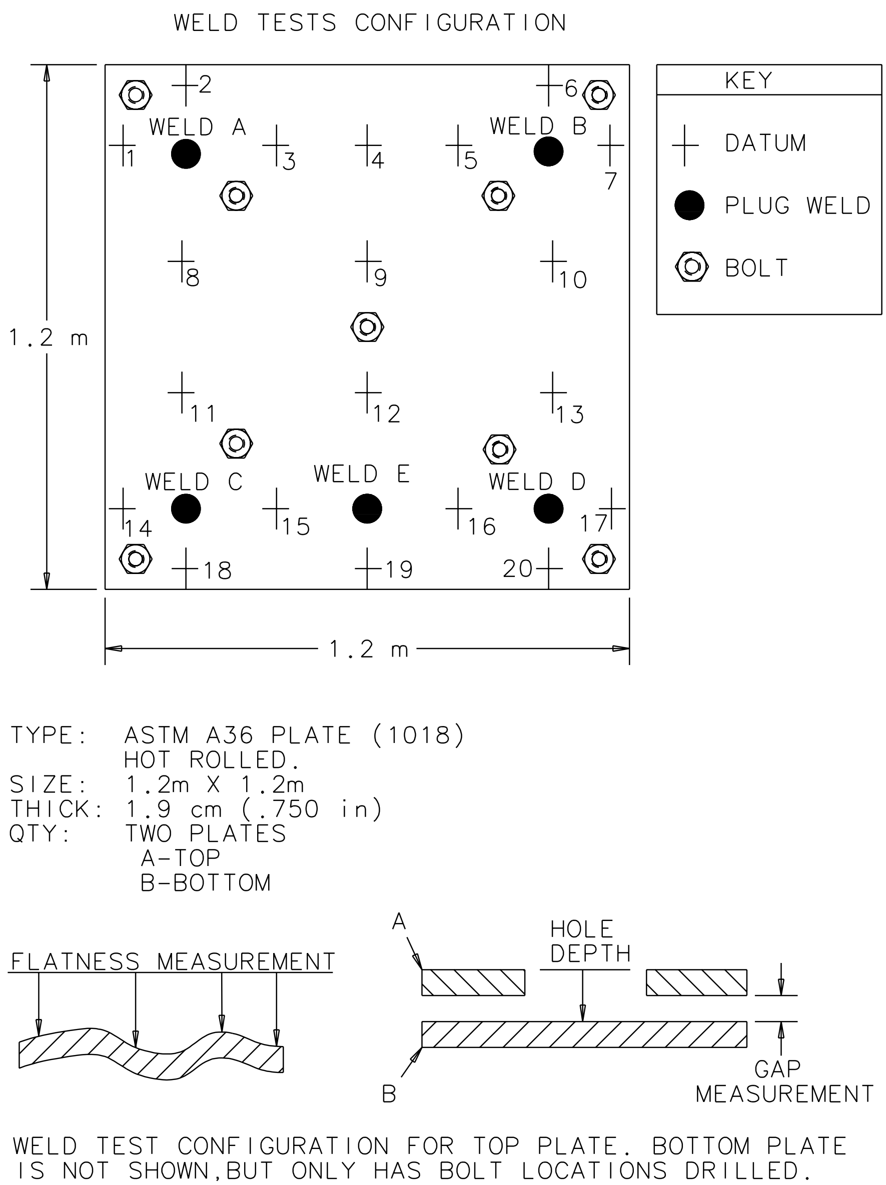

Figure 4.10: Sketch of the Livermore 1.2 m plate plug-welding test setup.

The plates were not pressed against a flat surface, but were only bolted to each other. The plate flatness was measured before and after welding using a Leitz Coordinate Measurement Machine. The finished welded assembly had a flatness around the average of the two individual plates. Although the flatness observed was acceptable, it could have been improved by pressing both plates against a flat platen such as a MINOS strongback.

A summary of the inter-layer gap measurements is shown in Table 4.3. Measurements were taken before the steel was bolted together, after it was bolted, after it was welded, after it was unbolted, and after it was welded at location E. No distortions were seen in the plates at any time during or after the welding.

Measurement	Before bolting	Bolted only	Bolted & welded	Welded only
Median	0.78	0.24	0.25	0.28
RMS	0.68	0.08	0.06	0.09
Max	2.31	0.46	0.41	0.48
Min	0.15	0.13	0.15	0.13

Table 4.3: Gap measurements (in mm) made during the Livermore test of changes in steel plate flatness caused by plug welding. The data represent the spaces between the two plate layers.

Tests of the plug welds were made at Livermore to measure the shear strength of the welds. The results showed that the welds are linear in shear for an applied force of 25,000 lbs. If we assume that all of the welds on a given plate participate uniformly in supporting the plate in shear, then the shear stress is less than 400 psi for any weld, giving a safety factor of around 60. Despite the uncertainty about the uniform loading of the welds, this is a very conservative safety factor. It will also be necessary to do coupon tests for every worker who will operate the welder during detector installation to ensure that the weld quality is adequate; this is much like the procedure used to certify a code welder.

4.4.2.4 Transfer from strongback to rails

The most important restriction in transferring a steel plane from the strongback to the rails is that the ears of the planes cannot support both the weight of the plane and the weight of the strongback. The present design uses a shelf on the bottom edge of the strongback to support the weight of the plane while it is raised to the vertical and carried to the support rails. A sketch of this design is shown in Figure 7.11 of Chapter 7. Clips on the top and at the center only restrain the plane on the strongback from tipping off; these clips support no weight. When the plane is positioned at the proper place on the rails, the clips are removed and the plane is lowered onto the rails. As the strongback is lowered, the plane ears pick up the plane weight and the strongback continues to drop away until it is completely free. The design requires that the "top" layer of each steel plane have edge notches at several locations so that clips can grip the edges of the "bottom" steel layer without touching the scintillator modules.

Included in the cost estimate is a "nudger" mechanism to slide a single plane along the rails for a short distance. This will be needed if the final version of the strongback clips requires some additional space between planes to disengage them. This is a design feature which the 4-plane prototype test is intended to address, as described in Section 4.4.5.2.

Another feature which needs to be verified during the single-plane test (Section 4.4.5.1) is that the design of the strongback permits the safe installation of the axial restraint bolts (see Section 4.4.1.2 below) immediately after a plane has been placed on the rails. As described in Section 4.4.1.3 below, the stability of the planes is such that no part of the assembly and hanging operation should allow a plane to hang alone on the rails without such restraints.

4.4.2.5 Safety

Safety considerations have been included as integral design requirements for all steel handling systems for both the near and far detectors. Safety issues for all NuMI-MINOS facilities are described in the NuMI Project Preliminary Safety Assessment Document[18].

4.4.3 Near detector support structure (WBS 2.1.3)

An initial design of the near detector support structure has been completed by Facilities Engineering Services Section (FESS) at Fermilab as shown in Figure 4.2. The design is in compliance with the Fermilab ES&H manual and the AISC Manual for Steel Construction[3]. As in the far detector structure design by CNA[1], the critical factors included in the design are the stiffness of the support beams, the alignment of the rails and the requirement that the structure support all ancillary equipment.

The support rails for the planes are similar to industrial crane rails; bending moments are supported by a deep I-beam, and lateral moments are supported by a channel welded to the top of the I-beam. The rail has a 4-inch wide bar on top of the channel for the plane ears to rest on. Lateral support for the structure is provided by beams running from the support columns to the walls of the cavern. The lateral supports also provide the frame for work platform decks and walkways at the elevation of the ears. Longitudinal stabilization is provided by cross braces that are built into the framing under the deck. With this placement, the braces allow access to the bottom of the detector and leave clear egress aisles under the decks on each side of the detector.

4.4.4 Magnet coils (WBS 2.1.4)

4.4.4.1 Design and properties of the coils

There are two identical coils for the far detector, one for each supermodule. The far detector coils provide a total of 15,000 A-turns of current in the 30-cm square central bore of the far detector planes[14]. These coils are designed so that their components can easily be moved down the existing hoist cage and so that they can be assembled underground without significant interruption of the assembly of subsequent detector planes. Due to the asymmetric shape of the near detector steel, the single near detector coil must carry nearly three times as much current as a far detector coil (40,000 A-turns). The different current requirements and the more convenient access at the Fermilab site have led to substantially different optimizations of the near and far detector coils.

Each far-detector coil is fabricated from 163 turns of 1/0 gauge stranded copper wire housed inside a 25-cm diameter, water-cooled, copper jacket. The outer jacket is cooled by water flowing through eight copper tubes. Seven additional tubes provide cooling near the center of the coil. A cross section of a far-detector coil is shown in Figure 4.11. Each of these coils carries a current of 92 A. In order to provide more working space under the detector, the return leg of each coil has been routed through a shallow trench in the floor of the cavern.

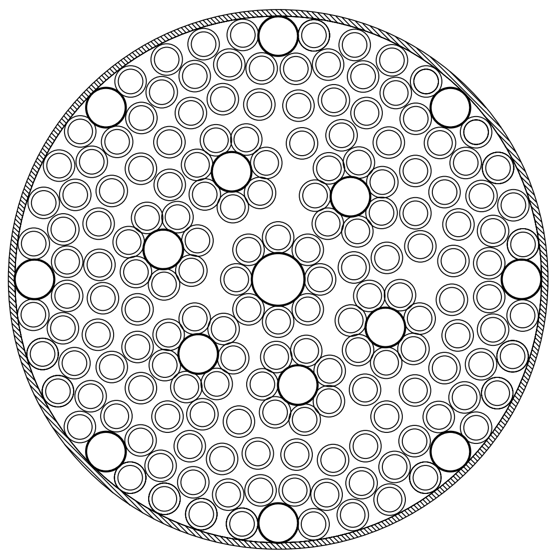

Figure 4.11: Sketch of a cross section of one of the far detector supermodule coils. The larger diameter circles represent the copper cooling tubes and the smaller circles are the 163 turns of 1/0 gauge stranded copper wire. The outline of each of these conductors is a to-scale representation of the insulator thickness. The outer circumference is a copper jacket directly cooled by eight cooling tubes.

Detailed calculations and simulations of the far detector magnetic field configuration have been performed by MINOS groups at Argonne, Fermilab and Livermore for hot-rolled AISI 1006 low carbon steel[5]. Figure 4.12 is a plot of lines of constant field in one of the steel octagons of the far detector. Small variations in these configurations are predicted in the end planes (due to the return leg of the coil). The small fringe fields from the steel and the coil can affect photodetectors and produce mechanical stresses that must be accommodated. Initial calculations indicate the fringe fields will be small in the region of the photodetectors.

The thermal properties of this coil design have been evaluated at Fermilab using ANSYS calculations[19]. The outer jacket of the coil will have a maximum increase in temperature of less than 2°C. To gain greater confidence in these FEA calculations, they have been tested in a 1-m long by 5-cm diameter coil. The measured temperature increase in the center of the model coil, as a function of current, agreed with model calculations to better than 5%.

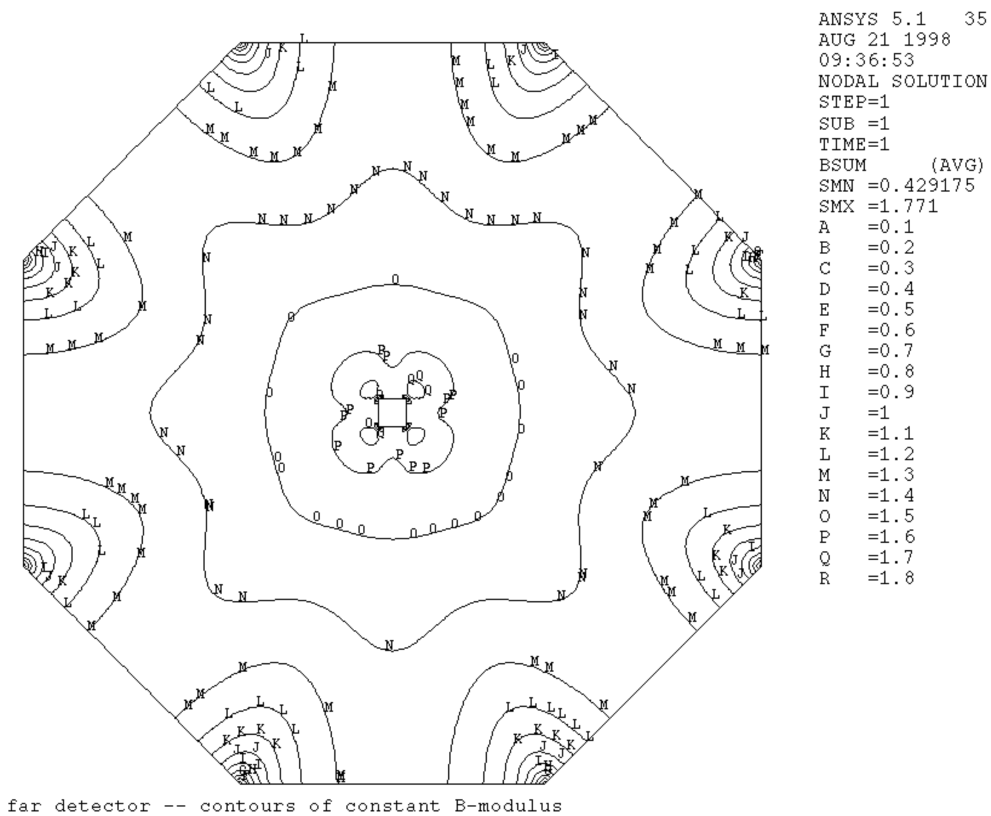

Figure 4.12: Contours of constant B-field magnitude in one of the far detector steel octagons for a 15,000 A-turn excitation. This two dimensional calculation was for a solid steel plane (with no gaps between plates) made of AISI 1006 steel, with a 0.3 m $\times$ 0.3 m square hole.

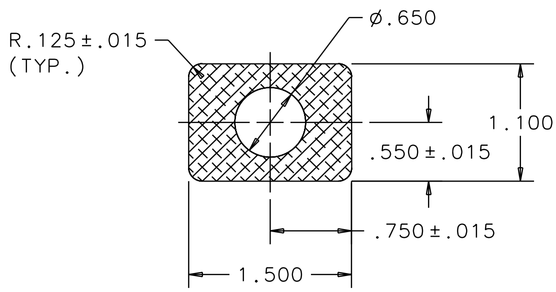

Figure 4.13: Sketch of cross section of one of the 48 conductors in the near detector coil. (All dimensions are in inches.) The conductor is cooled by flowing low conductivity water through the center channel of the conductor.

The relatively high current in the near detector coil requires significantly more cooling than is needed for the far detector coils. Each turn of the near coil is formed from 1.1-in$\times$1.5-in rectangular-cross section aluminum conductors[20] with a 0.65-inch diameter water-cooling channel through its center. The cross section of the one of these conductors is shown in Figure 4.13. The coil has 48 turns where the conductors are arranged in a 6 by 8 rectangular pattern. Each near-detector conductor carries 833 A for a total of 40,000 A-turns.

The near-detector coil produces a toroidal magnetic field averaging about 1.5 Tesla in the target region of the near detector. Figure 4.14 shows the magnetic field contours for a near detector plane. In the near detector there are no photodetectors or electronics on the flux return side of the steel plates so the relatively high magnetic fringe fields on that side do not affect detector operation.

4.4.4.2 Magnetic field calibration and monitoring

The magnetic field must be known accurately in this experiment to achieve the required precision on muon momentum measurements (5% absolute and 2% relative, near to far detector); MINOS energy resolution requirements are explained in Section 5.2. The detailed prediction of the field distribution through the detector relies upon precision simulations using the measured magnetic characteristics of the steel plates as input. Predictions will be verified in field calibration tests during the prototype plane assembly studies described in Section 4.4.5.

The nature of the steel plane fabrication increases the likelihood of errors in prediction of the magnetic field distribution: the large amount of steel required implies that many batches of steel will be needed, each of which can have a different chemistry and hence different permeabilities. The chemistry of individual steel melts will be carefully monitored and controlled and the permeability of plates will be measured after rolling. The plate-to-plate gaps within the composite far detector planes will affect the field, as described above in Section 4.1.3.1. Each assembled plane will have different gaps and thus different reluctances. In order to monitor these various effects each plane will have a pickup coil wound around the toroid to permit measurement of the integrated flux during excitation so that one can compare fields of different planes. Each coil power supply will have a current regulator and precision readout to continuously monitor its current. These systems are included in the cost estimate for the magnet steel and coils task.

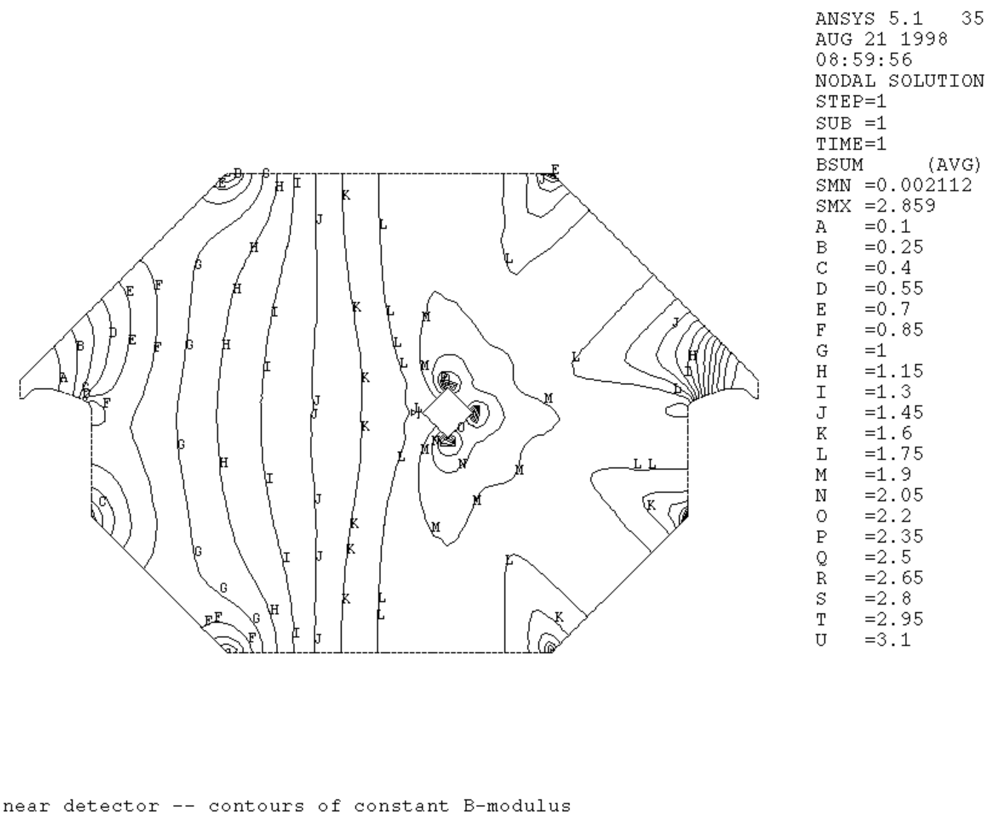

Figure 4.14: Contours of constant B-field magnitude in one of the near detector steel planes. This two dimensional calculation was for a solid plane made of AISI 1006 hot rolled steel with a 30 cm square coil hole and a current of 40,000 A-turns.

4.4.4.3 Far detector coil fabrication and installation

This process involves close coordination between the present task and the far detector installation tasks described in Chapter 7. The far detector coils have been designed to be assembled underground with minimal labor, fixturing and specialized tools. Coil assembly and installation will cause only a short pause (about two weeks) in the assembly of detector planes after a supermodule is completed. All coil components are packaged to fit easily into the Soudan mine hoist cage.

The components of the far detector coil, the conductor and cooling tubes are delivered to Soudan coiled on reels. The outer jacket is shipped in open sections small enough to fit into the hoist cage. After the last planes of a supermodule are installed, the coil cooling jacket is assembled. The sections are brazed together and the outer cooling tubes are soldered to the inside of the outer shell.

The cooling jacket is then inserted into the completed supermodule. The flexible 1/0 gauge copper wire is pulled through the jacket in single turn lengths and each conductor is labeled. Seven times during the winding of this coil, copper cooling tubes are unrolled and inserted into the coil. After the coil is wound electrical-distribution grade crimp connections are used to connect the separate turns of the coil. Finally, the cooling tubes are plumbed into the cavern cooling system.

One of the advantages of this design is that after the cooling jacket has been inserted into a supermodule, the coil installation and commissioning can proceed in parallel with the assembly of the next supermodule. Another advantage is that, if repairs are needed, faulty turns can be removed and replaced. Further description of the coil installation process is provided in Section 7.4.3.6 of the Far Detector Installation Chapter.

4.4.4.4 Near detector coil fabrication and installation

The design of the near coil takes advantage of the existing above-ground facilities at Fermilab. It is built in half-coil packs in a surface building and then moved to the cavern as two complete units. The drop-shaft into the NuMI near hall tunnel has been designed to allow a full 60-foot long coil segment to be lowered into the cavern.

The aluminum conductor is delivered to Fermilab on spools where it is uncoiled and wrapped with insulation. Lengths of conductor are then bent to an L-shape and bonded together to make one half of the coil pack – either the center bore or the return half. The return half is placed underneath the assembled near detector and the “L” end is lifted at a 45° angle. The center portion is then inserted through the supermodule bore using a special “spreader bar” lifting fixture to support the free end of the conductor assembly as it enters the bore. This fixture is provided by this task. Note that the center segment of the coil assembly weighs about 500 kg, is flexible, and could be easily damaged if overstressed. After the two sections of the coil are mounted in place, electrical and cooling water connections are made. Further description of the coil installation process is provided in Section 8.4 of the Near Detector Installation Chapter.

4.4.4.5 Coil cooling systems

The water cooling system must maintain the magnet coils at 25°C to ensure that scintillator systems are not prematurely aged. Since no current is carried in the cooling tubes in the far-detector coil, the cooling system can operate using ordinary water. This means that the cooling pipes can be directly plumbed into the cavern cooling system. This system transfers heat, via multiple pumping stations, to a surface cooling tower. The far-detector water cooling system will carry about 19 gpm/coil and is designed to carry off as much as 25 kW of heat per far detector supermodule.

The coil cooling system for the near detector will connect to a low-conductivity water (LCW) magnet cooling system provided by the NuMI project facility . The water cooling system will run at about 22 gpm and must carry off the 80 kW of heat generated by the coil.

Both the near and far coils will be instrumented with thermal sensors, electrical sensors, and interlocks to detect possible hot spots in the event of local mechanical or electrical failure.

4.4.4.6 Electrical system

Both the near and far MINOS coils are powered by standard switching supplies. The far detector has two PEI 20 kW Trim switching power supplies, one for each supermodule coil. The input power is 480 V, 3 phase, and the output is 92 A at 190 V. Total power dissipated in the two far detector coils is 37 kW. The high current near detector coil uses a standard Fermilab switching power supply to deliver 833 A at 96 V. All supplies are equipped with input and output filters to reduce electronic noise pickup. The near detector coil power dissipation is 80 kW. All power supplies have remote readout and remote control capabilities.

4.4.5 Detector plane prototypes (WBS 2.1.5)

4.4.5.1 Single plane prototype

A single plane prototype is currently hanging in the New Muon Lab at Fermilab. It consists of an 8-m octagon fabricated from eight steel plates, each 1 cm thick (rather than 1.27 cm thick as planned for the far detector). The main goal of the test is to provide a proof of principle that such planes can be fabricated commercially, assembled, and hung safely. The 2 cm thick prototype plane, which is thinner than the 1-inch thick planes of the baseline design, represents a "worst case" scenario for evaluating the mechanical stability of the detector planes during handling and after erection.

During assembly, measurements were made to judge the flatness of the planes and the gaps between plates. Stresses in the ears were measured as the plane was erected and are consistent with model calculations. The after erection flatness of the plate was also consistent with theoretical expectations. We plan to continue extensive study of the first one-plane prototype and, using the infrastructure in the New Muon Lab, to examine at least one more one-plane prototype. These studies will be designed to evaluate 1-inch thick planes, to study detector plane mounting techniques, to evaluate the effects of loads on the plane, and to perform initial measurements of magnetic fields.

The current infrastructure in the New Muon Lab will be augmented by a second plane-support structure. This new support will allow multiple planes to be raised and lowered, a feature that will allow different scintillator module mounting schemes to be prototyped and tested. The new support will also include a prototype of the final bookend structure.

4.4.5.2 Four plane prototypes

Three 4-plane prototypes will be constructed in the New Muon Lab at Fermilab. The initial 4-plane test will be used to check all aspects of the design, assembly, integration, and performance of the MINOS far detector system. The second prototype will be constructed somewhat later in order to train the far detector assembly supervisors and crew bosses. Finally, a 4-plane prototype of the near detector planes will be constructed to check the design of the near detector and to train the near detector assembly crews.

The first 4-plane prototype will execute the first complete integration of the entire far detector system. It will include four steel planes, three prototype scintillator planes with calibration and diagnostic readout systems, and a magnet coil carrying 15,000 A-turns. It will thus be possible to determine any mechanical interferences of the various components parts during assembly. Necessary design changes can be worked out early in the construction cycle. For the steel system, this will be the first opportunity to see if the design of the strongback will permit a simple and safe installation of the axial restraint bolts. A first fitting of the center-bore restraint system will also be possible. Procedures will be tested for all phases of the mechanical assembly of the final detector.

The initial 4-plane prototype test will be undertaken after extensive studies of the single plane prototype described above. The single-plane studies will be continued with the individual planes of the 4-plane prototype as they are constructed. All mechanical engineering and integration issues will have been resolved by the time the 4-plane device is finally constructed and tested. Integration of the steel planes with the scintillator detector planes and the magnet coil will be a particular focus of the later stages of this work.

After the initial prototype studies are completed, a second 4-plane prototype setup will be used to train the installation crews for the far detector, as described in Chapter 7. Afterwards, a single 4-plane prototype of the simpler near detector planes will be constructed in order to train the near detector installation crews. (Near detector installation is scheduled to begin about a year after the start of installation at Soudan.)

These studies will include detailed measurements of the magnetic properties of the detector. It will be possible to obtain observational data showing the effects of gaps between plane components on the field. Measurements will also determine the heating effects of the magnet coil on the scintillator planes. Fringe magnetic fields will be determined and compared with calculations and measurements of their forces on the planes and on the conductor. The effects of the fringe fields on the photodetectors will also be established.

Alignment procedures for the detector will also be finalized during these studies. These include the methods to determine the positions of the scintillator planes relative to the steel. The procedures and equipment used to measure the actual positions of the scintillator modules on the steel after mounting will be verified. The alignment of the planes on the rails will also be studied.

4.4.5.3 Far detector steel handling

A full-scale mock up of the Soudan shaft and hoist cage will be set up in the New Muon Lab at Fermilab. This structure will be used with the 4-plane prototype steel plates to study steel handling operations to ensure safe, efficient, underground handling of the far detector plates.

4.5 Future optimization and engineering

Many of the future optimization and engineering studies associated with the steel and coils task are summarized in Section 4.4.5. The present Section will concentrate on topics which were not previously discussed in detail.

4.5.1 Steel plane fabrication

Steel plane fabrication techniques for the far detector have been thoroughly studied at several MINOS institutions. The present baseline design was developed by the Livermore group. Their cost estimate includes a number of cost-saving techniques, for example, ordering special long sheets which, when cut in a certain pattern, minimize the amount of scrap. One of the largest remaining uncertainties concerns the gaps between plate edges after assembly. The first single-plane prototype test has already shown that plate to plate gaps are generally less than 1 mm; only about 2 m of the total 40 m length had gaps larger than 1 mm. (These were in the 2 to 3 mm range.) However, if further experiences show that the gaps can not be maintained within specifications, the plate machining option would be a viable alternative procedure for reducing the widths of gaps between steel plates, although it would increase the plate cost somewhat.

If plasma cutting continues to look feasible, the design of the far detector plates will be slightly modified. The central hole in the far detector plates will be changed from the current square hole to a 30-cm circular bore.

4.5.2 Steel handling and mounting fixtures

Testing of the prototype strongback with the 4-plane prototype (Section 4.4.5.2) will indicate what changes must be made before the production strongbacks for both the near and far detectors can be ordered. The present design is well engineered, meets the required flatness specifications, and has successfully hung a bare 8-m steel plate. Experience with fully instrumented planes may require that the plan and the design be changed. It is possible that the clips holding the plane onto the strongback may have to be moved in order to expedite their disengagement. These clips might also have to be moved to accommodate some detailed features on the scintillator planes or their mounting brackets which have yet to be specified. In addition, the detailed design of the strongback for the near detector planes, which have a different size and shape, still remains to be done.

A second important issue is the degree to which the actual planes, as fabricated and erected, contain residual variations in flatness which require variable lengths of axial bolts to serve as stability restraints at the octagon corners. It is an important safety consideration that mechanical stress energy not be accumulated during the sequential assembly of the multiple planes of the near detector and the far detector supermodules. Bolts of variable lengths, or additional shims or similar devices, may be required to achieve this during detector assembly.

The far detector compression rigs will certainly be able to perform as required. The first welding tests from the one plane prototype, however, indicate that much smaller forces may be sufficient to flatten the steel. In one alternative scheme, the compression could become an inert mass which is moved using the small gantry cranes at each workstation.

4.5.3 Magnet coil installation

A prototype of the far detector coil will be constructed to study the performance of the coil and cooling system and to optimize the installation procedure. Prototype coil studies performed as part of the prototype program described in the previous Section will use these techniques.

The near detector coil installation procedure involves the construction of two monolithic 48-turn L-shaped segments. A large fraction of the installation effort is devoted to connecting the conductor segments to each other, to the power supply and to cooling water system. Prototype studies will also be used to evaluate splicing techniques.

Chapter 4 References

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