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A SUPERCONDUCTING BEAM LINE†

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A complete superconducting beam line, including two bending magnets and eight quadrupoles, has been designed for use in a new experimental area at the ZGS. This beam line was expected to replace one of the conventional lines, provided it was competitive on a capital cost basis, and to provide a considerable practical experience with the many problems involved in the operation of a system of this type. It was intended to have the complete magnets constructed by industry and bids were received from eight vendors, showing their wide interest in the project, their high level of competence and the competitive range of their prices.

1. INTRODUCTION

A great deal of work on beam line magnets is being done throughout the world.(1) Some questions concerning superconducting beam lines, however, cannot be answered either by laboratory models or by 1 or 2 magnets in a line. The ideal situation is to construct an operational beam line where vital operational experience can be gained in the areas of system performance, reliability and experimenter convenience. At Argonne it was felt that industry was capable of supplying suitable magnets given proper specifications and we hoped these magnets would be competitive with conventional magnets and power supplies on a capital cost basis.

To this end designs and specifications were developed that would give prospective vendors the freedom to utilize their own production techniques. Vendors were chosen on the basis of competence as shown in past performances and technical knowhow primarily in the cryogenic field. Technical responsibility of the vendor was limited to the areas in which they were competent. Argonne was responsible for the choice of the superconductor, the field uniformity, conductor location descriptions, and values of magnetic forces. The vendor was responsible for conductor placement, support of forces, and cryogenic design.

The beam line chosen was to be installed in a new experimental area and consisted of 8 quadrupoles and 2 bending magnets. It was planned to build this superconducting beam line only if the price was competitive with a conventional beam line.

To further reduce capital costs an existing liquefier was to be incorporated in the beam line. The machine capacity was 100 liters per hour while beam line requirements were less than 50. The 50 liter per hour surplus could then be utilized for other experimental uses or as a reserve if a liquefier breakdown occurred.

Fixed price bids were received from eight vendors. The majority of these bids were in a price range that was competitive with conventional magnets. Vendors submitted complete proposals that described their solutions to the problems and showed a high level of competence and interest in this type of project. Unfortunately, the project had to be cancelled due to insufficient funds for any type of beam line.

2. PANOFSKY QUADRUPOLES

Among the many configurations which could have been considered for the superconducting quadrupoles, the Panofsky-type seemed ideally suited for the project and the choice needs to be explained in detail.

The first possible solution would have been (as was used for bending magnets) to use the warm iron of an existing quadrupole and to replace the conventional windings by superconducting coils. However, the limited space available for these coils and the particular shape and number of the housings in which they would have to be located made this solution very inconvenient and certainly more expensive. Furthermore, the field shape could be greatly disturbed due to the fact that the conductors would not completely fill the volume occupied by the conventional coils, because of the cryogenic environment, and a new pole profile would have to be found to correct this defect.

Another possible solution would have been to design an air core quadrupole following one of the

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many existing configurations in which the field gradient is shaped by means of appropriate current distributions. Such devices require more superconducting material than Panofsky quadrupoles, are more complicated to build, and do not easily comply with the necessary mechanical tolerances, all factors which add to the cost. Furthermore, the stray field problem has to be considered and the addition of an iron shield would further increase the structure complexity and the cost.

Panofsky quadrupoles, on the other hand, have not been very popular up to present and the few known examples have shown rather poor performances. One reason for this is that this type of quadrupole has only been considered in connection with conventional windings for which problems of high current density and of very large energizing power requirements impose severe limitations. Also, with conventional coils, the conductors are large and do not lend themselves easily to accurate positioning in the coils, an important factor with regard to the field quality. However, with superconducting windings, such limitations no longer exist and the advantages of Panofsky quadrupoles can be fully exploited. These advantages are: ideal quadrupolar field in a square or rectangular aperture, quasi independence of the gradient uniformity on the iron saturation up to a much higher field than with classical quadrupoles (allowing higher performances than the latter), small weight of iron and a large reduction in the outer dimensions compared to classical quadrupoles.

Consequently, Panofsky quadrupoles appear to provide an ideal intermediate solution between low field iron-pole and high field air-core quadrupoles.

The following characteristics were requested for the quadrupoles of the present beam line: field gradient 3900 G/in., clear bore diameter 8 in., length 3 ft, field gradient uniformity better than 0.1 per cent over 6 in. diameter and 0.3 per cent over 8 in. diameter, lateral width of the quadrupole including cryostat not to exceed 16 in. The complete characteristics are given in Table I and the general design is shown in Fig. 1. This design was the result of a series of technical choices and analyses which can be summarized briefly.

1. The iron had to be at liquid helium temperature since no separation is allowed between the windings and the iron walls for the integrity of the field configuration.

TABLE I

Panofsky quadrupole characteristics

Maximum current	500 A
Ampere turns	720 000
Maximum gradient	3920 G/in.
Distortion at 3 in. radius with a current of 500 A	± 40 G
Gradient at 440 A	3470 G/in.
Distortion at 3 in. radius with a current of 440 A	± 12 G
Clear bore diameter	8 in.
Bore temperature	80 °K
Length of magnetic iron	36 in.
Type of magnetic iron	9 % Ni steel
Radiation shield cooling	liquid nitrogen
Overall width	15⅜ in.
Overall length	44 in.
Overall height (not including current leads and fill line)	24 in.
Total weight	approx. 1200 lb
Vacuum	at least 10^{-5} torr (common with beam line)
Outer jacket material	aluminum or stainless steel
Number of turns of each coil	30 × 6 = 180 turns
Cross section of each coil	2.07 in. × 0.46 in.
Total number of turns	1440
Total length of conductor	11 000 ft
Self-inductance of the quadrupole	0.35 H
All the coils are in series electrically	

2. The necessity of keeping a minimum width for the magnet led to the choice of an unsymmetrical iron yoke and to the use of this iron yoke for the walls of the liquid helium vessel. For this last reason and in view of the magnetic forces on the iron, 9 per cent Ni-Steel was chosen over the usual low carbon steel which is too brittle at low temperature for a welded structure. The magnetic properties of 9 per cent Ni-Steel show a decrease of about 10 per cent of the *B* vs *H* curve compared to ordinary iron, but this curve can be expected to be enhanced by about the same order of magnitude when operating at 4.2 °K. However, the thickness of iron was increased in order to compensate for an eventual difference in the actual magnetic properties.

3. The main characteristics of the coils were easily determined, applying the Panofsky formulae(1) to the case of a square aperture

$$e = \frac{W}{2\left[\frac{4\pi}{10}\frac{j}{g} - 1\right]} \tag{1}$$

$$NI = 2Wej \tag{2}$$

where e is the thickness of the winding in cm, W the width of the winding square bore, j the average current density in A/cm^2, g the gradient in G/cm

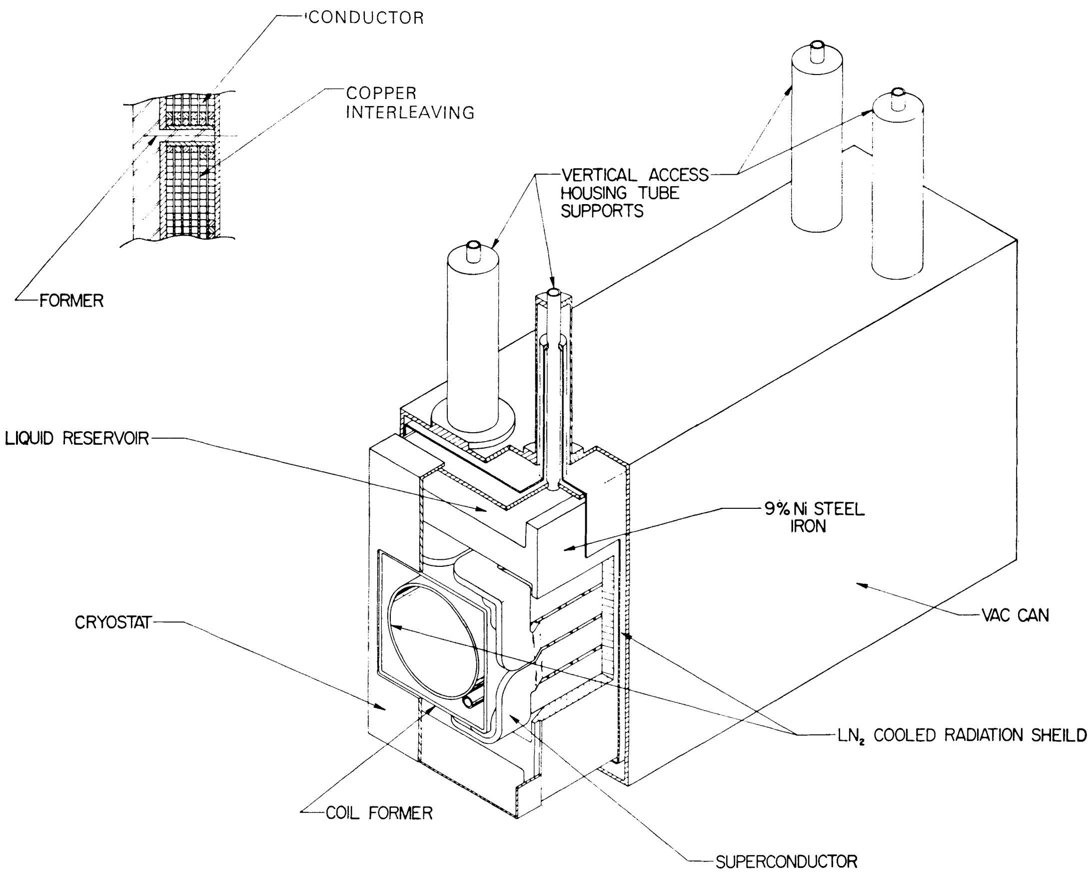

FIG. 1. Design drawing of Panofsky Quadrupole.

and *NI* the total number of ampere-turns. A current density of 15000 A/cm^2 was adopted as a reasonable figure in view of present experience. This value is not critical in the present case and led to a winding thickness of about 0.5 in. and to a total of 720000 ampere-turns for a gradient of 3920 G per inch.

4. Next the dimensions of the iron were determined with the aim of finding a minimum weight and a minimum lateral thickness compatible with the required field quality. This determination was based on the results of computer calculations using the TRIM(3) program. An example of these results is shown in Figs. 2 and 3, corresponding to two different currents in the conductor, respectively 500 A and 440 A, and to the case of an unsymmetrical iron yoke with a lateral thickness of 1 in. and a top and bottom thickness of 3 in. The curves shown in these figures correspond to the amplitude in gauss of the field deviation from the ideal linear variation law and provide a direct estimate of the global field perturbation throughout the useful bore, showing the effect of the iron asymmetry and of the iron finite permeability. In the final design the above thicknesses of iron have been taken as 1.5 in and 3 in.

5. The detailed specifications of the windings were then established by considering the various practical aspects of their fabrication and operation. For a rated current of 500 A, consistent with a low heat load requirement, a conductor of square cross-section 0.060 in. × 0.060 in. was adopted. A compact type of winding was chosen with on cooling channel for helium circulation through the coils. Cooling is achieved by heat conduction from turn to turn and from turn to copper interleavings laid between layers. The conductor was specified as a multifilament composite containing at least 60 filaments twisted at a minimum rate of 2 twists per inch. Ebanol insulation was requested

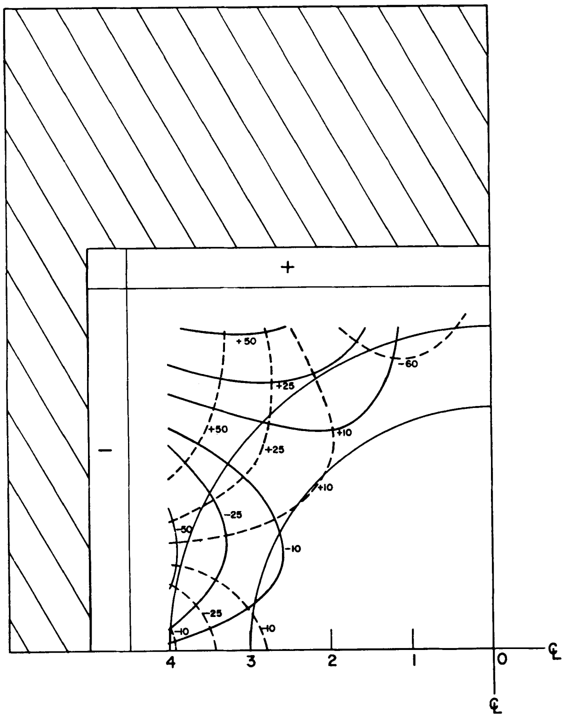

FIG. 2. Field error map from TRIM in a quadrant of Panofsky Quadrupole with unsymmetrical iron Ampere-turns 157 500 per coil—Field gradient 3470 G/in.—Maximum induction in iron 20 500 G. Solid curves: field horizontal component; Dotted curves: vertical component.

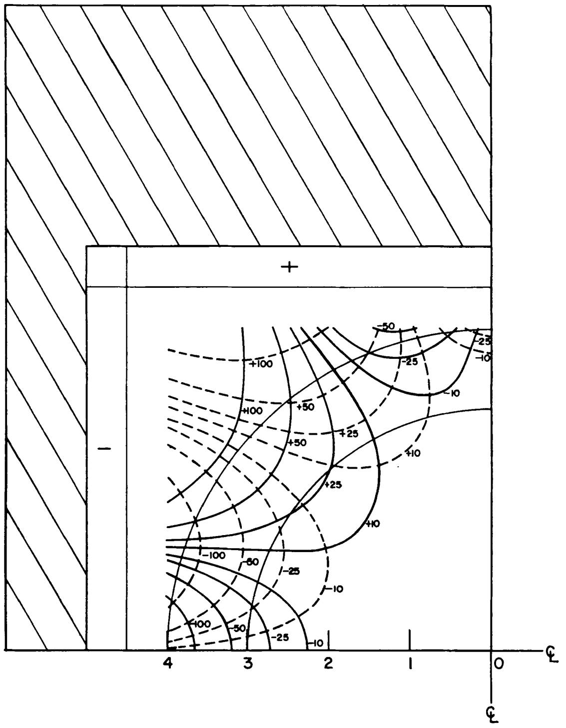

FIG. 3. Field error map from TRIM with 180000 ampere-turns per coil—Field gradient 3920 G/in.—Maximum induction in iron 22 200 G. Solid curves: field vertical component; Dotted curves: horizontal component.

on the conductor and no extra organic or plastic insulation was allowed inside the winding. Combination of this type of conductor with conduction cooling techniques ensures adequate stabilization of the superconducting winding. Each of the four coils of the quadrupole is subdivided into two sections in order to reduce the size of the end turns. The two sections overlap at the end as shown in Fig. 1. Each section is formed of two 3 ft long straight runs of rectangular cross sections at right angles to each other and of two end turns bent in the planes of the straight runs so as to leave the inside bore totally open without increasing the lateral dimensions of the magnet. The eight coils are assembled on a one-piece square former, which ensures accurate positioning, and are rigidly contained between this former and the walls of the iron box.

Detailed specifications were given to the vendor for the main technical features such as insulation, winding process, cooling, mechanical tolerances, power leads, etc.

6. One of the most important features is the definition of the mechanical tolerances of the winding in accordance with the required field gradient uniformity. For this a computer program, PANOF, was specially developed, based on the method of magnetic images. This method is very appropriate for the study of small perturbations and inhomogeneities which could not be easily simulated in the TRIM program, because of the finite size of the mesh used in the latter. Furthermore, PANOF requires much less computer time, since the field needs only to be calculated at a limited number of points. By means of this program a large number of cases have been investigated such as: size effect of the spacers between the adjacent sections of the winding, tolerances of positioning of each section and of the individual conductors inside the sections, effect of inhomogeneities in the packing factor of the coils, size effect of the separation between the coils and the iron. One of these cases is illustrated in Fig. 4 in a way similar to those of Figs. 2 and 3 previously described.

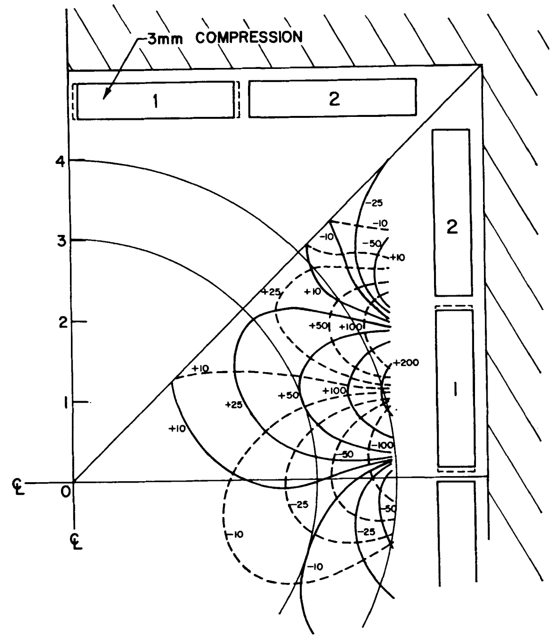

FIG. 4. Field error map from PANOF due to a symmetrical width compression of one of the sections keeping the same number of ampere-turns —Field gradient 3800 G/in. Solid curves: field vertical component; Dotted curves: horizontal component.

From the above, the final dimensions of the structure were decided and the tolerances were specified as follows: 0.002 in. on the conductor dimensions, 0.01 in. on the dimensions, symmetry and positioning of the former and of the iron, even distribution of the conductors in the cross-section of the coils within 0.02 in.

7. The force distribution in the windings was calculated by numerical integration using the field given by program PANOF. Each wall of the iron box is subjected to a resultant outward force of 20 tons, which is the difference between the outward force on the conductors and the inward force on the iron, respectively of 32 tons and 12 tons each. The attractive and compressive forces on the conductors remains in a very conservative range, with a maximum pressure of 300 psi.

3. BENDING MAGNETS

The design of the bending magnets was relatively simple since, for economic reasons, it was decided to use the warm iron of an existing conventional BM105 bending magnet and to replace the conventional windings by superconducting coils. In view of the much higher current density achievable in the superconducting winding, the space available inside the iron frame was large enough to house the superconducting coils with their complete mechanical and cryogenic structure.

The main points which had first to be investigated were the effect on the field uniformity of the reduced size of the coils, the magnetic forces on the straight runs of the coils and the mechanical tolerances of the winding. The first point was solved by use of program TRIM which showed that the field homogeneity was preserved in the same volume as for the conventional magnet and that the flux density did not increase in the iron. The force analysis gave the following results: the horizontal force on each straight run toward the iron is 30 tons per coil, i.e. 60 tons total. The attraction force between two adjacent straight runs is 5.5 tons and the total vertical force on the coils for a displacement from the medium plane is 50 tons per inch.

The tolerances on the conductor positioning were not found to be critical and the only specified tolerance concerned the vertical centering of the coils with respect to the iron median plane within 0.04 in., which is necessary for limiting both the asymmetry of the field and the vertical force.

The general configuration of the winding is shown in Fig. 5. The conductor is the same as for the quadrupoles and is rated at 500 A at 30 kG. The winding is made of two coils, each one being formed of two 6-ft long straight runs and two ends bent upwards and downwards respectively as shown on the figure. Each coil contains eight single pancakes with 31 turns per pancake. The coils are assembled on two T-shaped spines which ensure rigidity of the straight runs against lateral forces. A common helium vessel contains the above assembly. This vessel is separated at the ends into two branches following the upper and lower ends of the coils. Cooling of the winding is ensured by circulation of liquid helium around the coils and around each pancake, allowed by insulating spacers which separate these pancakes. This cooling mode was made possible by the available space and was found safer in view of the long length of the coils and of the fact that most of the helium is kept in the reservoirs at the ends of the magnet.

4. CRYOGENIC DESIGN

Our intention in the design of the super-

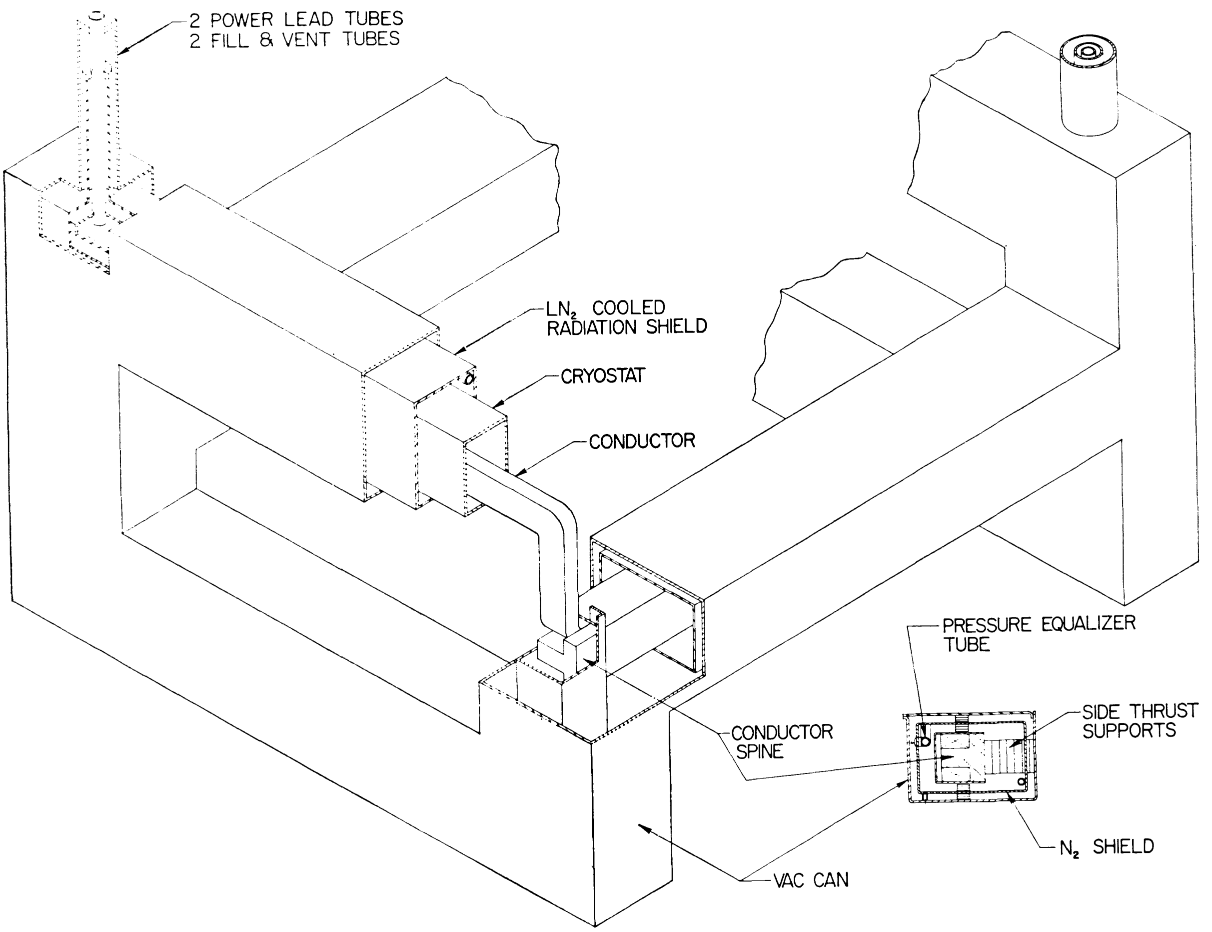

FIG. 5. Design drawing of modified BM105 bending magnet.

conducting beam line was to achieve a compact, sound cryogenic and mechanical design. This was accomplished by selection of certain parameters which we considered necessary for a good all-around design while keeping in mind that the units must incorporate low heat loss, minimum physical width dimension, adequate strength and economic construction.

Due to the large surface areas presented in both designs and the necessity of efficient space utilization, a 100 °K copper shield was chosen over superinsulation to reduce the radiant heat load. This complicated the design somewhat, but the LN_2 shield was preferred for overall reliability and rapid temperature equilibrium.

The permissible shield heat load was 100 W for the bending magnet and 20 W for the quadrupole. Shield cooling is by continuous N_2 flow through tubes on the shields of each magnet from a single source.

The quadrupole support system utilizes 4 vertical access housing tube supports; however, due to the conditions of possible frequent movement by unskilled personnel, bumpers are utilized to prevent destruction by acceleration loading. In the case of the bending magnet the side thrust of the conductor was so great that solid columns of glass-reinforced epoxy were utilized in addition to the vertical access housing tubes to act as side supports, which would transmit the 120,000 pounds of force to the magnet iron.

To prevent the use of costly flanges and sealing techniques, an all-welded construction was chosen. We have learned that although flanges, both warm and cold, are often convenient, they are more often costly due to continuing seal problems as well as being very expensive initially. Welded design requires very closely controlled winding, welding and leak testing along with pre-testing of conductors in cold condition, but all this is easily within the grasp of the cryogenic industry and further ensures a more carefully controlled construction technique.

The specifications were written so as to allow a flexible design in which the vendors could incorporate cost saving techniques so long as the heat leak-requirements of the specification and the tolerancing involved in the critical winding parameters mentioned previously were closely followed. Power lead design was the responsibility of the vendor which required a tested design of 1/2 W/lead prior to approval for use on the magnet. For the overall system design another stipulation was that there be utilization of 100 per cent of sensible heat of the gas and that the cooldown time do not exceed 24 hours. All this, it was hoped, would give a magnet with the field and heat loss requirements while utilizing the full design flexibility of each bidder.

Figures 1 and 5 show the basic design of the quadrupole and of the bending magnet with the important design features which were incorporated. The use of 4 access tubes allowed 2 for power leads, 1 for instrumentation (liquid level) and 1 for the cooldown system which each vendor was asked to devise.

System design was simplified by the utilization of the sensible heat of the return gas which eliminated the need for cold gas return lines and the subsequent heat losses involved. One large liquefier and dewar with a N_2-shielded transfer line would offer the greatest flexibility and lowest cost because, although it requires all magnets to be in one beam line, heat losses and maintenance problems would be less than for multiple liquefiers.

Transfer losses are kept at a minimum by use of a continuously cooled LN_2-shielded transfer line. The shielded line is constructed to have low cooldown mass and act as a trunk line with liquid He takeoff points at estimated intervals of 6–10 ft. Magnet tie-in is accomplished by use of low cooldown mass, unshielded vacuum jacketed U tubes which can be built easily up to 10 ft long to compensate for alignment problems involved in magnet positioning. The effect of the use of high loss tie-ins is offset by fill sequencing and large reservoirs on individual magnets. Each magnet is equipped with a liquid reservoir which holds liquid up to 12 hours without the necessity of refill. This allows shutdown of the liquefier for up to 12 hours without the beam line being affected and necessitates use of the transfer lines for only a short period of time every 12 hours. Each magnet is equipped with liquid-level sensors which will call for liquid for all magnets when only one is low. This makes the 'high loss' unit a controller, but prevents frequent line cooldown each time a magnet calls for liquid.

5. CONCLUSION

This beam line promised to be an important step in the investigation of the long run feasibility of the use of superconducting beam line magnets. The operational data gleaned over an extended period of time would have given both beam line users and operation groups data to compare the relative merits of conventional and superconducting beam lines.

ACKNOWLEDGEMENTS

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A version of Program TRIM has been adapted by R. Lari and J. Wilhelm and is operated at Argonne.

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