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TITLE: COST REDUCTION POSSIBILITIES FOR A HEAVY-ION ACCELERATOR FOR INERTIAL CONFINEMENT FUSION

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COST REDUCTION POSSIBILITIES FOR A HEAVY-ION ACCELERATOR FOR INERTIAL CONFINEMENT FUSION

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Abstract

A design was produced for a single module in a cost-optimized accelerator appropriate for a commercial heavy-ion power plant. The goal of the study was to determine if the cost of the accelerator module could be reduced through design options, selection of materials, and manufacturing techniques. Independent cost estimates were obtained for the three main components of the module, and cost reductions of 20% from the cost calculated by the heavy-ion accelerator design/cost-minimization computer code LIACEP were identified.

Introduction

Conceptual designs of multiple-beam heavy-ion induction linear accelerators for use in ICF power plants have been done using the Lawrence Berkeley Laboratory computer code LIACEP[1]. The LIACEP code calculates the physics and mechanical parameters that produce a cost-optimized accelerator, given the desired output energy, ion energy, pulse repetition rate, etc. LIACEP is designed to be very general in order to be valid over a wide range of parameters. The goal of this study is to examine a representative accelerator module to determine if cost-reduction possibilities exist through the choice of design parameters, materials, and manufacturing techniques. A representative module near the middle of the accelerator was chosen. A conceptual design of the module was performed, and independent cost estimates of the main components were obtained. These independent cost estimates, using greater flexibility in the choice of manufacturing techniques and materials, were compared to the cost estimates generated in the LIACEP computer code to determine if cost reduction possibilities exist.

Module Design Details

The module selected for this study is at the 1 GV point of a 5-Hz, 4.25-MJ accelerator that uses 5-GeV, 200-amu ions with charge state +3. Sixteen beamlets are accelerated with 7×10^{-5} Coulombs per beamlet. The normalized emittance is 8.7×10^{-6} m-radians, the undepressed tune is 85°, and the depressed tune is 10.5°.

Figure 1 illustrates some of the features of this module, and Table 1 lists some of the engineering details. The module is enclosed in a corrugated steel can to hold the dielectric fluid that fills the space between the coils and around the central insulator. Support and spacing for the acceleration coils was provide by plastic (G-10) pieces placed under and around the coils.

The coils were assumed to have a volumetric packing fraction of 0.8. The central insulator contains metallic field-shaping rings. A cryogenic vacuum pump, to keep the pressure in the beam volume to 10^{-7} torr, is supplied every fourth module, with beam diagnostics filling the space in the other three modules normally occupied by the cryogenic pump. The superconducting quadrupole magnet assembly with 16 magnets is constructed as a unit and each magnet position will be adjustable in the accelerator. It was also assumed that the central insulator would be coated with a sealant to reduce the possibility of gas and dielectric fluid leaks into the vacuum region.

Module Cost Analysis

The LIACEP-generated costs for this module are presented in Table 2. Independent cost estimates were obtained for the three components indicated with a n asterisk in Table 2, (the induction coils, the central insulator, and the superconducting quadrupole magnets). These three items represent ~63% of the total estimated cost for the module. The independent cost analysis for these three items began with the actual costs of constructing similar existing items. These costs were then scaled to the physical size required for the module. It was assumed that this module would be used in a 10th-of-a-kind power plant being built near the year 2025. This assumption means that there is time for technology improvements to occur in the manufacturing of the components, and production runs of ~100 000 induction coils and superconducting magnets and production runs of ~10 000 central insulators are be assumed. Thus there will be cost savings due both to technical improvements in the manufacturing process and in the learning due to multiple unit construction[2]. The learning curve applied to the costs was assumed to have an exponent of 0.8.

The cost estimate for the amorphous iron acceleration coils was based on the costs of producing 110 Metglas™ coils for Sandia National Laboratory in Albuquerque. An additional assumption was that the cost of magnetically acceptable amorphous iron would be equal to the lowest cost available today, \$4/kg. At present, the lowest cost Metglas™ has unacceptable magnetic properties for this application. Learning was applied only to the labor portion of the cost, with the largest contribution coming from winding the coil. The cost estimate for the 13 coils is 109 k\$, which is substantially lower than the 229 k\$ estimate generated by LIACEP. Two assumptions are required to achieve this lower cost; further development of the amorphous iron material to improve the magnetic properties at the lowest cost currently available, and automation of the winding of the cores. The acceleration cores would be wound on preconstructed mandrels that would support the coils and provide the necessary electrical properties when they are in place in the accelerator. This would reduce the amount of bowing produced in the winding process and allow easier handling of the cores.

The insulator costs were based on insulators produced for Los Alamos National Laboratory for the injector assembly for a heavy-ion accelerator. The known costs were scaled to the physical size required for the module, taking into consideration additional complexities of producing large-scale components. Learning was then applied to the entire cost of the insulator because there appeared to be considerable opportunity for technological improvements in the method of constructing the insulator. The cost estimate obtained for the central insulator was 112 k$ compared to 160 k$ given in LIACEP.

Three methods were proposed to provide these cost reductions. The first was to construct the insulator out of ReX™ (Recrystalized Glass) using a spin casting process. This process has been used previously to produce inexpensive insulators containing metallic parts. The process has currently been abandoned. However, the process could easily be revived if it is found to be cost effective for this application in induction accelerators. A second method of producing the central insulator would be to use porcelain manufacturing techniques. Parts near the size of the proposed insulator are currently being produced, and processes to bond metal to the porcelain have been developed. The porcelain process has the advantage that only minimal development is required to produce the desired insulator. The third process identified to produce the insulator is the use of wound composites such as fiberglass or Kevlar™. Components of the size required are being produced today and the winding process lends itself readily to automation. The problem with using composites as a vacuum boundary is that they have unacceptably high outgassing properties. However, research is underway to develop coatings that would reduce the outgassing. These coatings may also provide protection against oil and gas leaks into the vacuum.

The costs for the superconducting magnets was based on the cost quotes for superconducting quadrupole magnets designed for the Relativistic Heavy-Ion Collider[3] accelerator at Brookhaven National Laboratory. A conservative scaling of the costs to the physical size required for the module was used and a learning curve was applied to the labor portion of the estimated costs of the magnets. The independent cost estimate for the magnets was 140 k$ compared to 131 k$ computed by LIACEP. These costs, obtained by taking into accournt the automation possible in the winding, testing, and construction of superconducting magnets if the production run of the magnets was on the order of 100 000 magnets, verify the costs used in LIACEP.

The effect of high-temperature (liquid nitrogen) superconducting magnets on the cost of the accelerator module was also examined. It is believed that while high-temperature superconducting magnets will have a significant effect on the efficiency and operating cost of the accelerator, they will have a minimal effect on the capital cost of the accelerator. Since the magnets are only used for focusing, the projected improved current and magnetic field capacity of the high-temperature superconductors will not change the basic design of the accelerator. The accelerator will still require the same number of modules, amorphous iron induction cores, etc. The only capital cost effect will be a small cost savings in the refrigerator costs (~0.5% of the total module cost), and the savings due to reduced material and labor cost for the high-temperature superconductors. The latter saving are speculative at this point because practical high-temperature superconductors have not bee produced.

Conclusions

The results of this study indicate that an approximately 20% reduction in the cost of a heavy-ion accelerator module from that estimated by the traditional design/cost computer code, LIACEP, appears possible. Detailed examination of other portions of the module could reveal other possible cost reductions, especially in the pulse electronics portion, which is presently being examined by LBL. These identified cost reductions indicate that the LIACEP costs estimates can be reduced, thus making the heavy-ion linear induction accelerator concept for ICF more attractive and worthy of further study.

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2. Krawiec, F., and Flaim, T., "Solar Cost Reduction Through Technical Improvements: The Concepts of Learning and Experience." Solar Energy Research Institute report SERI/RR-52-173D (February 1979).
3. Willen, E. H. "Magnets for RHIC," Brookhaven National Laboratory report, BNL 38966, Presented at ICFA Workshop on Superconducting Magnets and Cryogenics, Brookhaven National Laboratory, 12-16 May 1986.

Acknowledgments

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TABLE 1.

1-GV MODULE PARAMETERS

Number of beams	16
Core voltage	0.5 MV
Accelerating gradient	1.83 MV/m
Number of amorphous iron coils	13
Quadrupole field at bore	3.37 Tesla

TABLE 2.

LIACEP-CALCULATED COSTS

ITEM	COST (k$)
* Core	229
* Insulator cylinder	160
* Superconducting quadrupole magnets	131
Pulse electronics	123
Vacuum, support & alignment, computer, beam management and control	26
Magnet refrigerator, quadrupole structure, and magnet power supply	104
Conventional facilities	64
MODULE TOTAL COST	838

MODULE DESIGN DETAILS

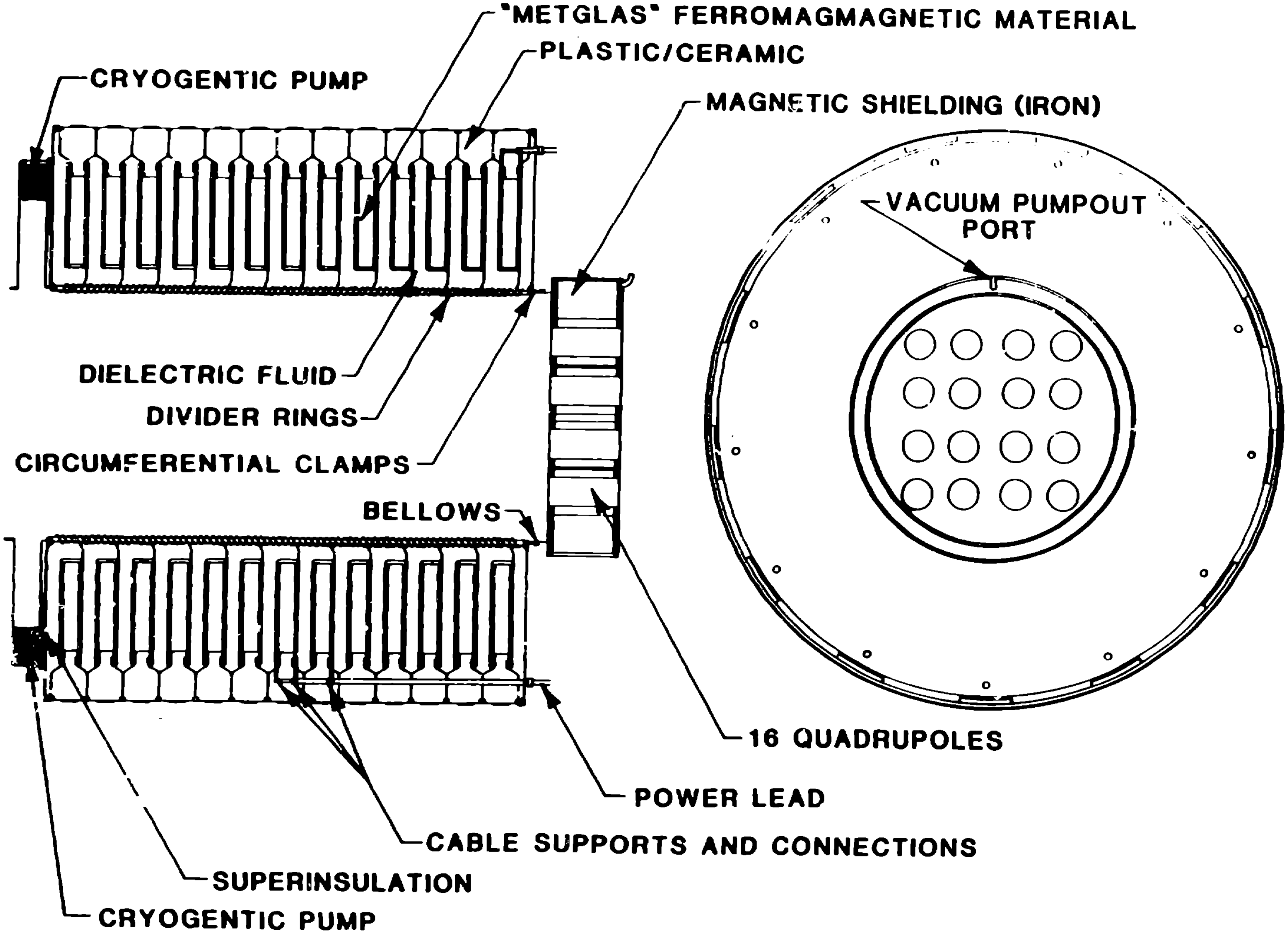

Figure 1. Drawing of the "Representative" Accelerator Module

COST REDUCTION ANALYSIS FOR AN ICF HEAVY-ION ACCELERATOR

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Viewgraph 2.

LIACEP provides basic design parameters for a heavy-ion accelerator. The purpose of doing a more detailed design is to provide information to costing and manufacturing engineers so they can identify areas where costs can be reduced. Additionally, the design will aid LBL in their continuing studies on heavy-ion accelerators. Cost reduction possibilities were examined by Los Alamos personnel and engineers from BDM Corp.

PROJECT OBJECTIVE

- Examine potential cost reductions for a heavy-ion accelerator module

Viewgraph 3.

The starting point for the study was a cost-optimized LIACEP design. The design called for a 16-beam, 5-GV accelerator. A representative module at 1 GV was selected for detailed study. The dimensions, materials, components, and costs for this module were obtained from the LIACEP output. A more detailed design was performed and iterated with LBL personnel. The agreed-upon design was examined by Los Alamos and BDM personnel to obtain costs for the major-cost components and suggestions for cost reduction strategies.

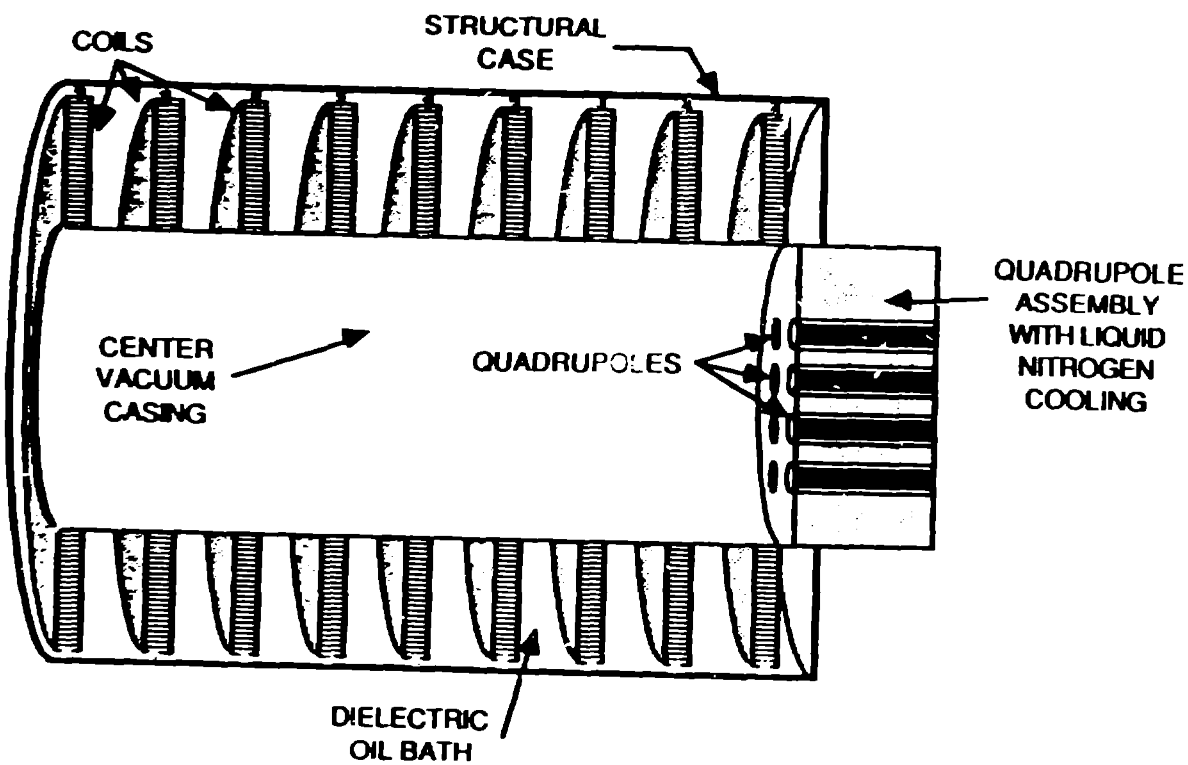
LIACEP WAS VERY USEFUL

- Produced a cost optimized design
- Generated dimensions, number of coils, magnetic field strength, etc.
- Produced a baseline cost estimate

Viewgraph 4.

The module geometry is shown, illustrating the major components.

MODULE GEOMETRY



Viewgraph 5.

LIACEP is an accelerator design code that produces a cost-optimized design for the accelerator. In a typical run, LIACEP will optimize costs by varying induction coil sizes, number of induction coils, quadrupole magnet lengths, etc., maintaining consistency with design principles for a specified heavy-ion accelerator. The output of the code includes the physical characteristics and a cost breakdown of the module.

Project Steps

1. Use LIACEP to generate base case accelerator parameters and cost
2. Select a "representative" accelerator module for the study
3. Produce a design
4. Obtain independent cost estimates for major items in the module
5. Examine manufacturing techniques to lower costs
6. Investigate optimum module assembly strategy

Viewgraph 6.

The representative module chosen was near the middle of the accelerator.

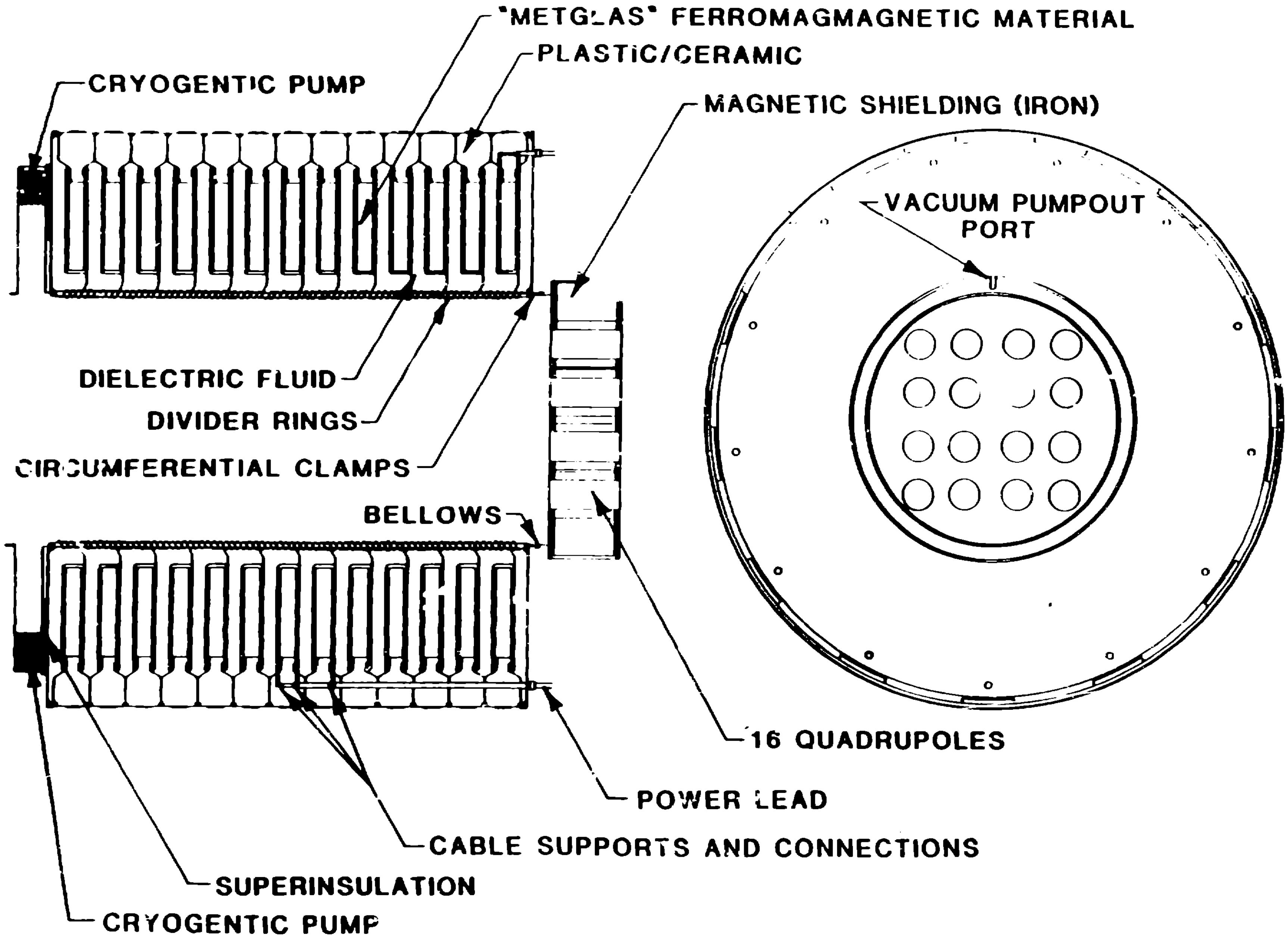
A REPRESENTATIVE MODULE WAS SELECTED

- Ion voltage at module is 1GV
- Core voltage is 0.5 mv
- Accelerating gradient is 1.83 mv/m
- 13 amorphous iron induction cores
- 16 beamlets and 16 superconducting quads
- Quadrupole field at bore is 3.37 Tesla
- Pulse repitition rate is 5 Hertz

Viewgraph 7.

This is a drawing of the design chosen after interactions with LBL and Los Alamos personnel.

MODULE DESIGN DETAILS



Viewgraph 8.

The design features were chosen to fulfill the technical requirements for the module and to provide a low-cost solution to some of the design problems.

DESIGN CHARACTERISTICS

- The module will be inclosed in a steel can and will be suppc y a precast concrete cradle.
- Plastic (G-10) supports will be located around the coil to support the coil and to provide coil spacing.
- The space around the cores will be filled with a dielectric fluid and/or glass beads
- The quadrupole assembly will be constructed as a unit. It will be sealed and tested before it is shipped to the construction site. Alignment of the assembly in the accelerator will be provided for.

Viewgraph 9.

As in all preliminary designs there are a number of unresolved issues. The Los Alamos design engineers felt that not enough space was provided to accommodate the superconducting magnets and their adjustment mechanism. No detailed design of the quadrupoles was done to confirm this. One big concern of LBL personnel was the choice of dielectric fluid to use in the spaces around the induction coils, and how can the fluid be prevented from leaking into the vacuum if a pinhole leak should develop. It was suggested that some sort of sealant could be put around the central insulator/vacuum boundary to insure that the dielectric fluid not leak into the vacuum. The amorphous iron coils will need an insulation between turns capable of withstanding the 50 volts difference while still providing a packing fraction of 0.8. Present coils with milar insulation have a packing fraction of ~0.6. A silicon dioxide coating on the amorphous iron was one suggestion. Also, because the amorphous iron coils in the accelerator are going to be different widths, trimming methods for amorphous iron are needed. At the present there is no equipment available that can produce the central insulator with the size, electrical, and outgassing properties necessary for this application. New production equipment or alternate production methods will be required to construct this insulator.

DESIGN ISSUES

- Space requirements for superconducting quads
- Dielectric fluid choice
- Possible sealant for insulator column to prevent leaks into vacuum
- Insulation for amorphous iron sheets to achieve 0.8 packing fraction
- Ways to trim amorphous iron
- Insulator manufacturing

Viewgraph 10

We assumed a costing basis appropriate for an electric power plant driver. Because we are dealing with a tenth-of-a-kind accelerator that has about 1 000 modules, each with 2-13 induction coils and quadrupole focussing for 16 beamlets, mass-production techniques will be used. This means that the production runs for coils and quadrupole magnets will be in the hundred thousands and the production runs for the insulator columns will be in the ten thousands. The assumption of construction during the year 2025 means that some technological improvements are possible, such as commercial high temperature superconducting magnets.

COSTING BASIS

- Costs appropiate for the year 2025
- Assume 10th-of-a-kind facility
- Assume design will incorporate duplicate modules

Viewgraph 11.

These costs were obtained from LIACEP. They are the price of the item FOB the factory. They do not include the overhead, management, engineering, and construction costs for the accelarator.

LIACEP CALCULATED COSTS

*Core	229 k$
* Insulator cylinder	160 k$
* Superconducting quads	131 k$
Pulse electronics	123 k$
Vacuum, support & alignment, computer, beam management and control	26 k$
Magnet refrigerator, quadrupole structure, magnet power supply	105 k$
Conventional facilities	64 k$
TOTAL	838 k$

Viewgraph 12.

The main cost reduction strategies identified for the coils are concerned with the continued development of the amorphous iron and automated winding procedures. Low-cost amorphous iron is now available, although its magnetic qualities are somewhat inferior to high-cost material. Future cost optimization studies could include the tradeoffs between lower cost materials and quality.

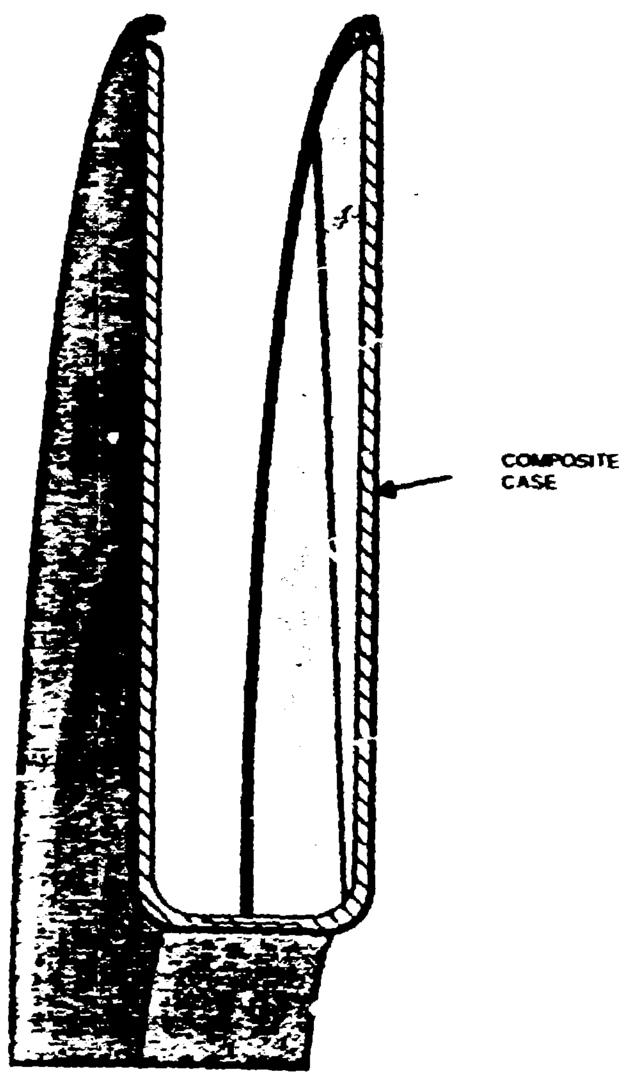
CORE COST REDUCTION STRATEGIES

- Continue development of amorphous irons and improvement of magnetic properties
- Automate winding machines and large scale production
- Preconstruct core structure and support
- Development of an intercoil insulator

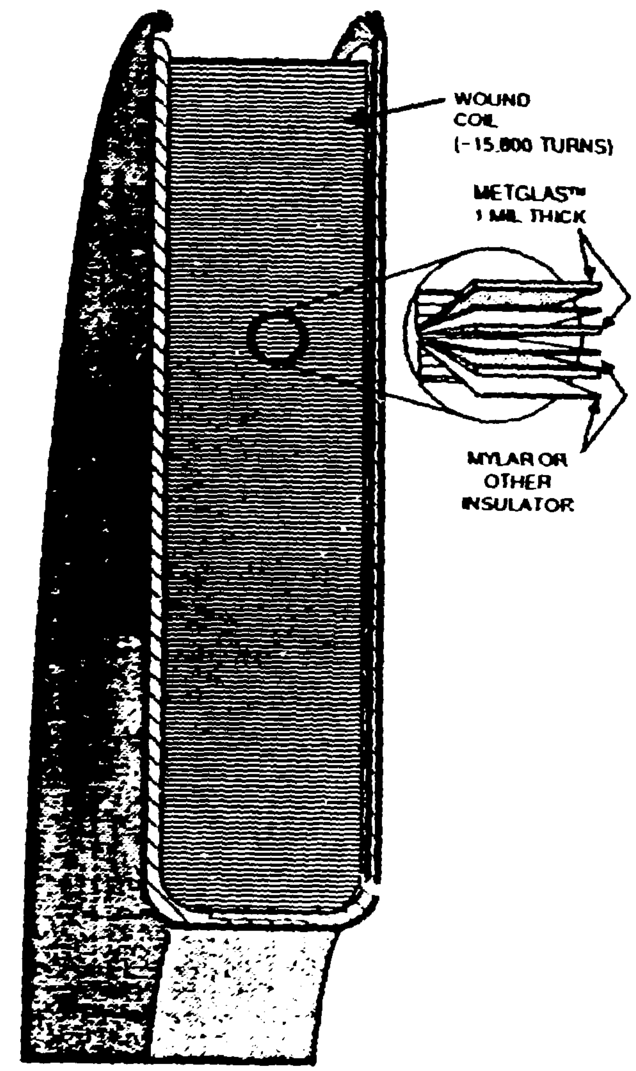
Viewgraph 13.

Diagram of a amorphous iron coil.

CORE DETAILS



COIL CORE STRUCTURAL

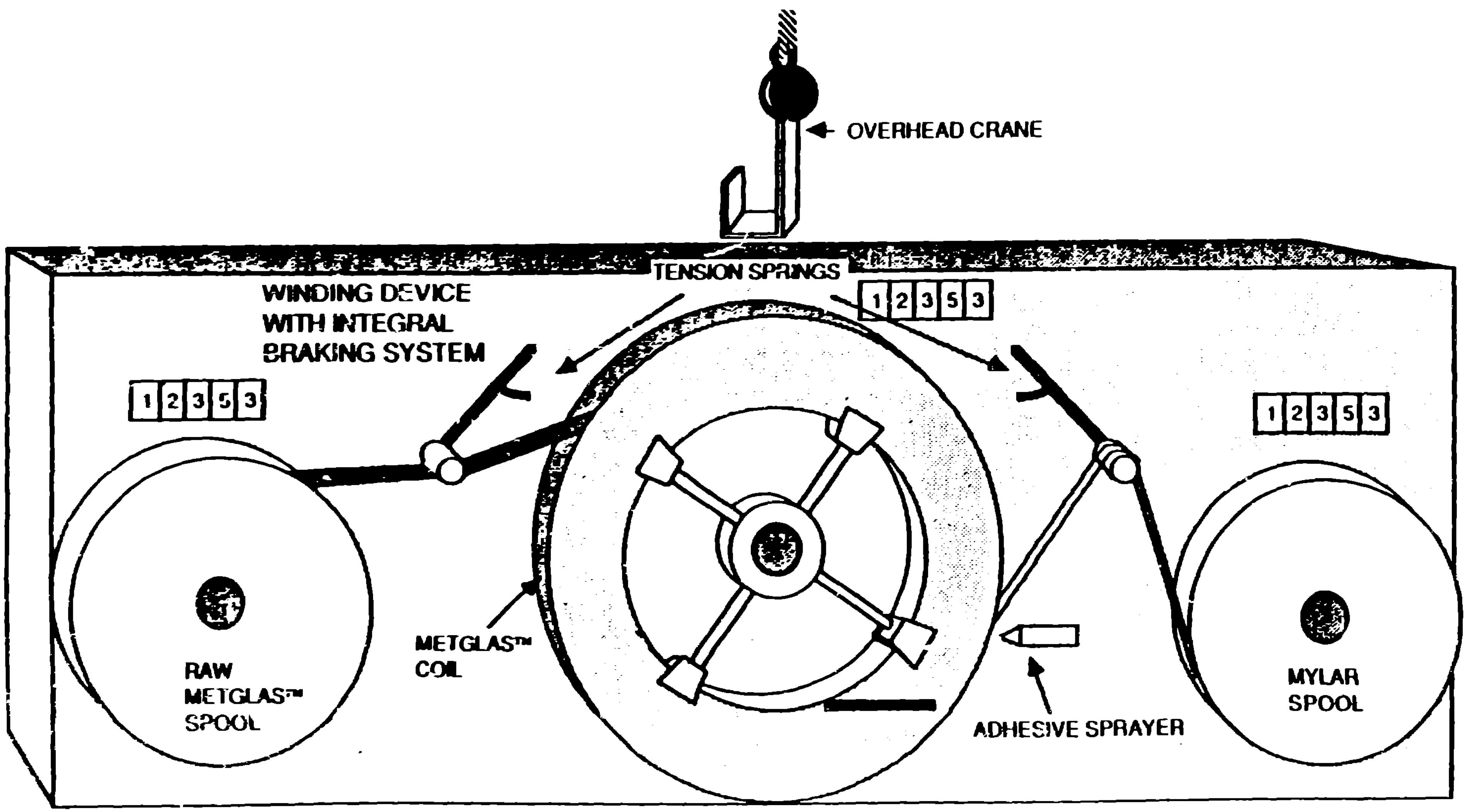


METGLAS™ WOUND COIL

Viewgraph 14.

Schematic of a amorphous iron coil winding machine.

AMORPHOUS IRON COIL WINDING MACHINE



Viewgraph 15.

The basis for the cost estimate for the induction coils was 110 Metglas™ coils that were purchased by Sandia Laboratories. The assumption was made that the amorphous iron cost in 2025would be equal to the lowest cost Metglas™ product now available. Unfortunately, this low-cost Metglas™ presently does not have the required magnetic properties. Learning was applied to the cost of winding the coils, with the assumption being that when 100 000 coils have been produced, automated winding machines will be in operation. Substantial cost reductions appear possible.

CORE COST ANALYSIS

ASSUMPTIONS

- Amorphous iron cost is \$4/kg
- Present day winding cost based on production run of 110 coils
- Learning applied to winding costs for 100 000 coils

COMPARISON

Cost of 13 coils ~ 109 k\$
LIACEP-calculated cost = 229 k\$

Viewgraph 16.

These three fabrication possibilities were suggested as a way to lower the cost of the insulator. The recrystallized glass (ReX) spin casting method was used in the past to make inexpensive insulators incorporating rings. However, this method is no longer being used in the construction of insulators. A technique to bond metal to the ceramic glass has been developed which would enhance the attractiveness of this fabrication method. Porcelain companies are already producing products near the size required for the insulator and can also bond metal to the porcelain. This process is more adaptable to volume production. Much work is going on at present in the development of filament-wound composites. If the development projects now underway to make an insulating and non-outgassing product are successful it may provide a low-cost alternative for production of the insulator.

INSULATOR MATERIAL FABRICATION OPTIONS

- Recrystalized glass spin casting
- Porcelain processing
- Filament wound composites

Viewgraph 17.

The cost basis for the insulator was a batch of 71-cm diameter insulators made for the heavy-ion accelerator injector. Scaling factors used were suggested by E. O. Ballard of Los Alamos. Since present day insulators of this size are custom made, it was assumed that with production of 10 000 units, automated production would be used, and also other options for constructing the insulator may be used. Learning was applied to the total cost of the insulator. The estimated cost of the insulator is substantially less than the cost as predicted by LIACEP.

INSULATOR COST ANALYSIS

ASSUMPTIONS

- Cost based on a batch of 30 insulators
- Fabrication cost scaled with area
- Field ring cost scaled with area
- Finishing costs independent of size
- Learning applied to the total cost

COMPARISON

Cost of the insulator ~ 112 k$
LIACEP-calculated cost = 160 k$

Viewgraph 18.

With the large number of magnets required for a heavy-ion accelerator (~10 000), automated magnet winding and structure fabrication are possible. This would reduce the labor costs normally associated with superconducting magnet production. It was suggested by BDM corp that powdered-metal technology would be the optimum method of fabricating the structure for the quadrupole assembly.

SUPERCONDUCTING MAGNET COST REDUCTION STRATEGIES

- Automated production possible with large production runs
- Powdered metal technology for qudrupole structure assembly manufacture

Viewgraph 19.

The basis for the costing of the superconducting quadrupole magnets was a detailed cost estimate for magnets being produced for the RHIC at Brookhaven National Laboratory. The scaling used for the proposed quadrupole magnets was conservative. Learning was only applied to the labor portion of producing the magnets and not to the materials. The cost estimate does not include the cost of constructing the whole quadrupole assembly. Depending on the difficulty of this operation, the cost of an assembled quadrupole magnet assembly could be higher.

SUPERCONDUCTING MAGNET COST ANALYSIS

ASSUMPTIONS

- Cost based on superconducting quads for RHIC (1987 costs)
- Material costs proportional to magnet length and field gradient
- Labor costs proportional to the square root of the magnet length and field gradient
- Learning applied to winding labor

COMPARISON

Cost of superconducting quadrupole magnets ~ 140 k$
LIACEP-calculated cost = 131 k$

Viewgraph 20.

There is much excitement about high-temperature superconducting materials. For this application, the new superconducting materials will not have much affect on the cost of the accelerator unless the magnets themselves are significantly cheaper. Refrigerator costs would be significantly lower, but are not a large cost item in the accelerator. Additionally, this accelerator would not benefit greatly from the higher field strength possibilities of the new magnets unless the magnet cost itself could be lowered. Just as many magnets would be required no matter what the field strength of the magnets. The eventual material and fabrication costs and the current carrying capacity of the new superconductors are unknown at this time, so the effect of this new development on heavy-ion accelerators is unknown. There does seem to be general agreement that magnets made from these new materials should be commonly available by 2025. This is a possible topic for further studies.

HIGH TEMPERATURE SUPERCONDUCTOR ARE NOT EXPECTED TO HAVE A LARGE CAPITAL COST IMPACT

- Material and winding costs dominate the magnet costs
- The use of liquid nitrogen as a coolant will primarily affect operating costs

Viewgraph 21.

Fabrication of the individual components should take place at a manufacturing site. The components would then be shipped to the plant for final assembly. This assembly method takes advantage of the savings from manufacturing the component in automated facilities. A completed module will be too large and delicate to ship long distance over existing transportation networks.

ASSEMBLY METHODS

- Individual large components -- coils, insulator, quadrupole assembly -- will be constructed in manufacturing facilities off site.
- The modules will then be assembled on site.
- Assembled modules will be transported to their location in the accelerator

Viewgraph 22.

We have accomplished three things in this study. First, we have constructed a conceptual design of an accelerator module. This design is a starting point for discussions on design problems and methods of possible cost savings. Second, the cost of three major components were calculated by extrapolating from existing components. These extrapolations indicate that the methods in LIACEP may overestimate costs and that cost reductions are possible. Third, we have suggested some automated manufacturing methods that may make possible these reduced costs.

OUR STUDY INDICATES MODULE COSTS ~20% LESS THAN LIACEP

- A conceptual design of an accelerator module has been completed.
- Some manufacturing methods that could produce these cost savings have been suggested.
- Independent cost estimates indicate that large scale manufacturing of components could result in costs lower than the estimates in LIACEP.

Viewgraph 23.

There are further cost tradeoffs to be studied in the accelerator design. These include maximizing the number of identical components in the accelerator consistent with an efficient accelerator design. Examining the tradeoffs inherent in setting tolerances and determining which tolerances may be increased without adversely affecting accelerator design is also important. In addition to these tradeoff studies, other portions of the accelerator could be examined for cost savings possibilities. Finally, more detailed study of the different manufacturing methods may be of use to further quantify cost reductions.

FURTHER STUDIES

- Similar activities can be done for other portions of the accelerator.
- More detailed studies of the manufacturing methods and costs are needed.
- Examinine the accelerator to determine optimum number of families of identical modules from a manufacturing and design viewpoint.
- Examine accelerator design with the intention of creating as much component commonality as possible.