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RESEARCH PROPOSAL

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State University of New York
Stony Brook, NY 11794

Principal Investigator: Michael D. Marx
Professor of Physics
Physics Department
SUNY at Stony Brook
Stony Brook, NY 11794-3800
SS# 106-26-2648
Telephone: 516-632-8102/8095

Collaborative Investigators: T. Fields
Argonne National Laboratory

L. Littenberg
Brookhaven National Laboratory

S. Gottesman
Grumman Corporation

R. Weinstein
University of Houston

R. McNeil
Louisiana State University

L. Rosenson
Massachusetts Institute of Technology

B. Pope
Michigan State University

University of Michigan
L.W. Jones

J. Luton
Oak Ridge National Laboratory

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Michael D. Marx
Principal Investigator

Peter Paul
Chairman, Dept. of Physics

Robert F. Schneider
Acting Vice Provost for Research
Research Foundation Endorsing Designee

PROPOSAL FOR DEVELOPMENT OF SUPERCONDUCTING AIR CORE TOROIDS AS A PRECISION MUON SPECTROMETER FOR SSC EXPERIMENTS

T. Fields
Argonne National Laboratory

A. Carroll, I.-H. Chiang, J.S. Frank, J. Haggerty,
L. Littenberg, W. Morse, R.C. Strand
Brookhaven National Laboratory

A. Favale, S. Gottesman, E. Schneid
Grumman Corporation

K. Lau, R. Weinstein
University of Houston

R. McNeil
Louisiana State University

J. Friedman, E. Hafen, P. Haridas, H.W. Kendall,
L. Osborne, I. Pless,L. Rosenson, R. Verdier
Massachusetts Institute of Technology

B. Pope
Michigan State University

L.W. Jones
University of Michigan

J.N. Luton
Oak Ridge National Laboratory

M. Marx*
State University of New York at Stony Brook

* Contact Person

ABSTRACT

We propose to develop a precision muon spectrometer system based on superconducting air core toroids for SSC detectors. This system offers the promise of momentum resolution capable of reconstructing Z°'s of 500 GeV P_T to their natural width, while dramatically reducing the weight of the detector by eliminating tens of thousands of tons of iron. We will develop detailed specification of momentum resolution required, as a function of polar angle, to study a variety of SSC physics processes. Several toroid designs with matched measurement systems will be studied in sufficient detail to choose an optimal system for an SSC experiment. The designs will make trade studies on performance, cost, schedule and construction issues. In addition, we will survey available technology for trajectory measurement, both inside and outside the field volume, and develop concepts for, and simulate the performance of, large scale tracking systems. We will also study backgrounds from hadron punchthrough and decay, using simulations and available data, to determine muon identification requirements, minimize absorber and hadron filters, and elucidate effects of muon radiation on pattern recognition. Finally we propose to develop ideas for fast muon triggers based on systems of Cerenkov or scintillation counters, and develop prototypes for precision streamer chamber tracking devices.

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1. PHYSICS

The primary motivation for constructing a 40 TeV hadron collider is to uncover the mechanism for symmetry breaking in the electroweak sector generates the mass of the W and Z^{o} (Ref. 1).

While the source of this breaking may be controversial, the mass scale below which it must manifest itself is not. All theories indicate that strong interactions of the longitudinal components of the vector bosons, i.e.

$$W^{+}_{L} W^{-}_{L} \rightarrow Z^{o}_{L} Z^{o}_{L}$$

must increase, violating unitarity in the 1-2 TeV range unless some mechanism suppresses it. This situation exactly parallels the previous need for the W and Z^{o}, which prevented the weak cross sections from violating unitarity around 300 GeV.

The simplest standard model predicts the existence of a physical Higgs singlet, H^{o}, whose width increases like M_H^3, and decays predominantly (for $M_H \gtrsim 2M_Z$) into vector boson pairs. Supersymmetric models, which have profound implications for unification of all forces, predict partners for the known objects and also new W′ and Z′ bosons at higher mass, all of which have well defined interactions and decay, but unknown mass. Many of the predicted particles produce W's and Z's in their decay chains, as well as decays characterized by the absence of leptons in the presence of jets and missing P_T.

In addition to the explanation of symmetry breaking, the SSC program will be concerned with searches for new heavy quarks (including top, if it has not been found at the TeVatron) and leptons. Again one finds in the signatures for these particles, vector bosons (i.e. $t \to Wb$), leptons, jets and missing P_T.

Thus one finds that the vector bosons, W and Z^o, and hence their decay products - e, μ, jets and ν, must be well measured and identified for a successful attack on SSC physics. For the broadest possible approach to these signatures, one should study decay modes to <u>both</u> electrons and muons as well as quarks (jets) to provide confirmation of new signals in several channels. Given the levels of predicted backgrounds, there will be a premium on good resolution which, for many studies, translates directly into enhanced signal-to-noise ratios. One should provide the maximal possible solid angle to increase statistics and should strive for maximal uniformity in detection techniques, in both rapidity and azimuth, to provide the best possible understanding of background.

It is crucial at the SSC to attempt to measure muons as accurately as one does electrons. For many processes, measuring both leptons gains a factor of <u>four</u> in statistics (i.e. $H \to ZZ$ or WW) if one can measure ee, $e\mu$ and $\mu\mu$ channels. In addition, one can investigate μe correlations as arise in heavy quark decays; and, since muon systematics and backgrounds are different from electrons, muons can provide confirmation of rare processes. In particular, muons can be found without the stringent isolation cuts often necessary for electron identification.

Most detectors can readily achieve these goals for electrons, jets and missing P_T, by using good calorimetry. In the following sections, we explore the need for enhancing muon performance and suggest that the use of superconducting air core toroids will provide the requisite resolution and acceptance for muons.

2. IMPORTANCE OF RESOLUTION AND ACCEPTANCE

Detecting the Higgs at the SSC will be a challenge. Above $M_H = 2M_Z$ the Higgs will appear as a resonance in the W or Z pair mass spectrum, with width increasing like M_H^3. As the value of M_H approaches 1 TeV, it appears as an enhancement in boson pair rate, rather than as a resonance. The backgrounds to the signal are primarily from QCD production of boson pairs and as the top mass increases lepton backgrounds become severe. The cleanest signatures are in

$$\begin{array}{lll} H^\circ \to Z^\circ & + & Z^\circ \\ \quad Z^\circ \to \ell^+ \ell^- & & Z^\circ \to \ell^+ \ell^- \end{array} \qquad (1)$$

and somewhat worse in

$$\begin{array}{lll} H \to Z^\circ & + & Z^\circ \\ \quad Z^\circ \to \ell^+ \ell^- & & Z^\circ \to \nu \bar{\nu} \text{ or } q\bar{q} \end{array} \qquad (2)$$

and

$$\begin{array}{lll} H \to W^\pm & + & W^\pm \\ \quad W^\pm \to q\bar{q} & & W^\pm \to \ell\pm \nu \end{array} \qquad (3)$$

Shown in Fig. 1 are the signal and $q\bar{q}$ background for $H \to ZZ$ for two top mass values (Ref. 2). Gluon production of Z pairs can substantially increase the background level above what is shown. In Fig. 2 (Ref. 3) are shown the lepton pair mass distributions from Z decay from a 400 GeV Higgs as a function of detector resolution. Figure 3 shows an example of the deterioration of the Z signal relative to the background from heavy top (Ref. 4) as detector resolution is degraded. One sees that the muon signal measured in air (3a) is comparable to that for electrons measured in a calorimeter (2a), but also notices the deterioration of the signal

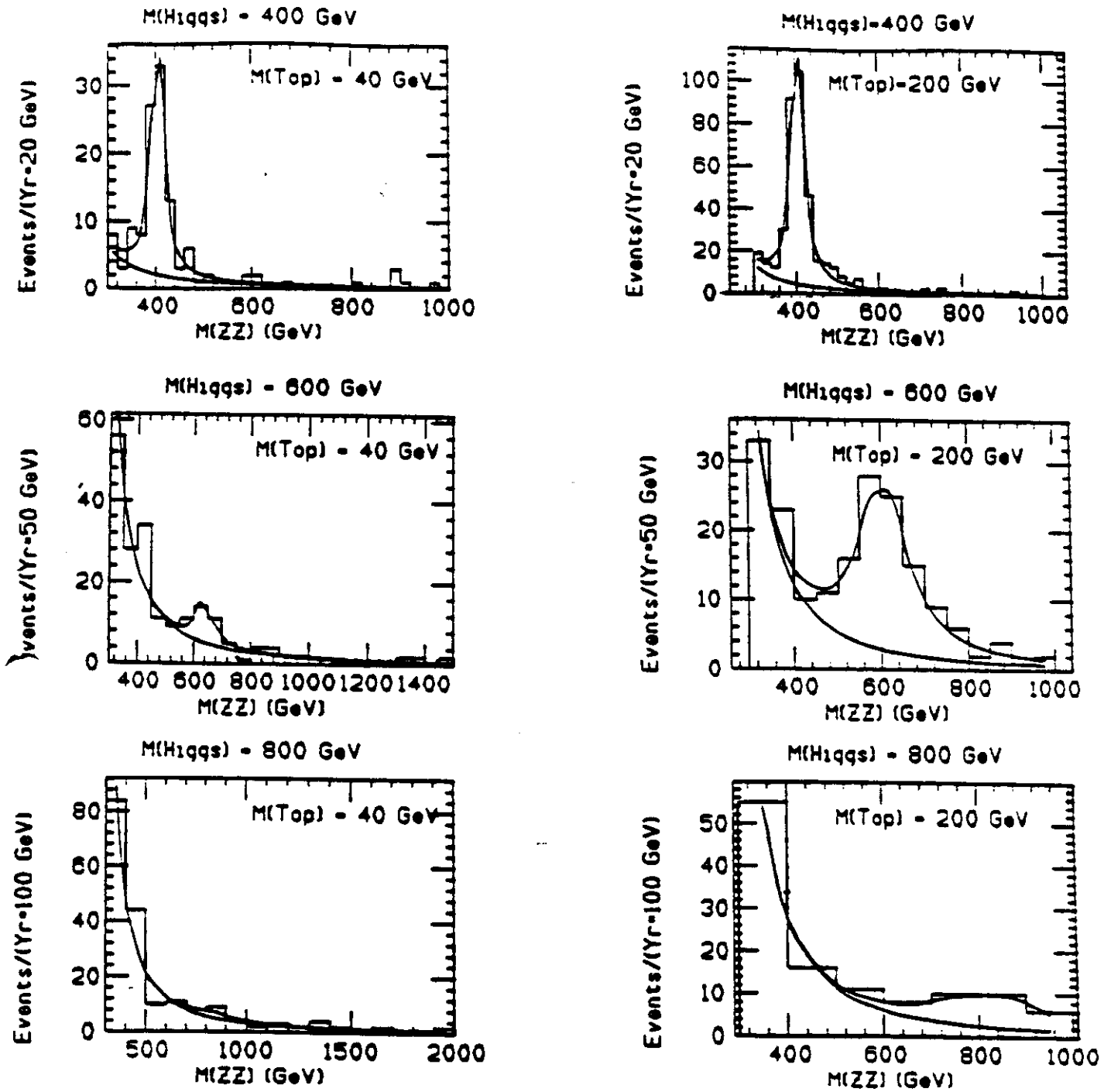


Figure 1

The ZZ invariant mass distribution arising from Higgs decay and from the background process $q\bar{q}\to ZZ$. The distribution is shown for Higgs masses of 400, 600, and 800 GeV and top masses of 40 and 200 GeV. If the background process $gg\to ZZ$ were to be included, the background would be increased by a factor which is about 1.7 (1.6) for M_{ZZ}=400(800)GeV (Ref. 2)

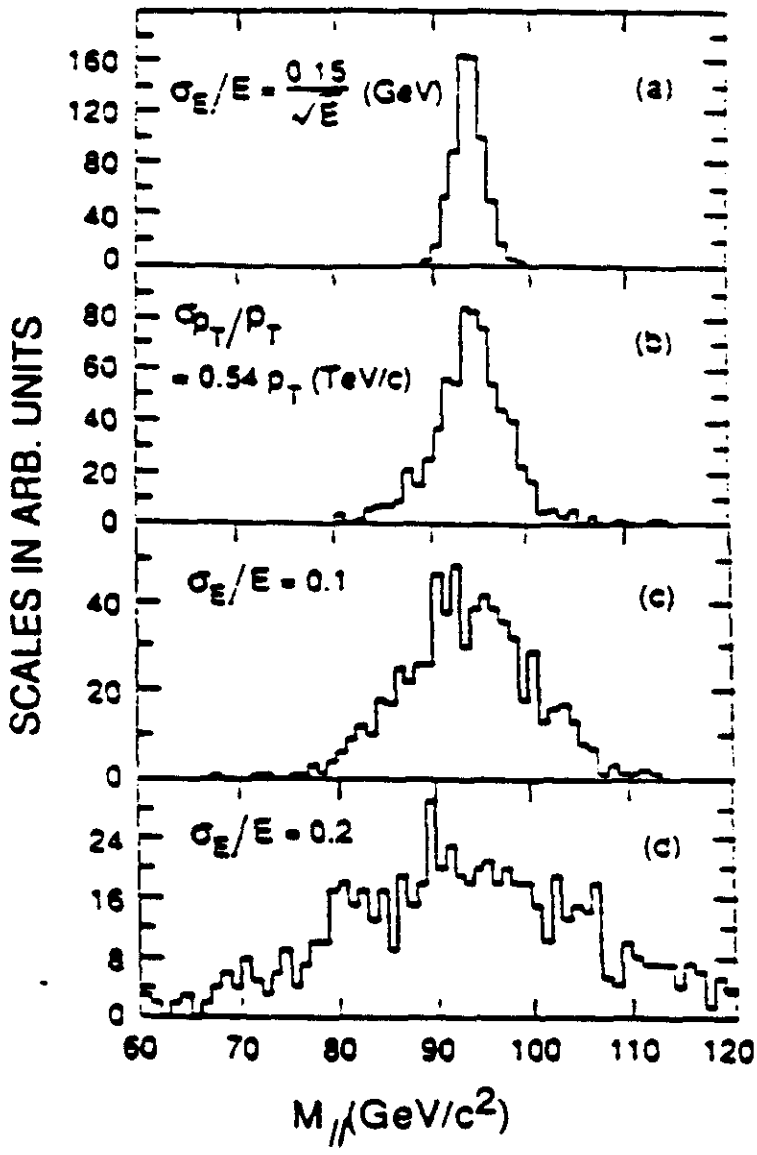


Figure 2

Di-lepton invariant mass distributions for various energy momentum resolutions for leptons from Higgs bosons of 400 GeV/c^2 mass decaying into $ZZ \to 4\ell^{\pm}$ (Ref. 3).

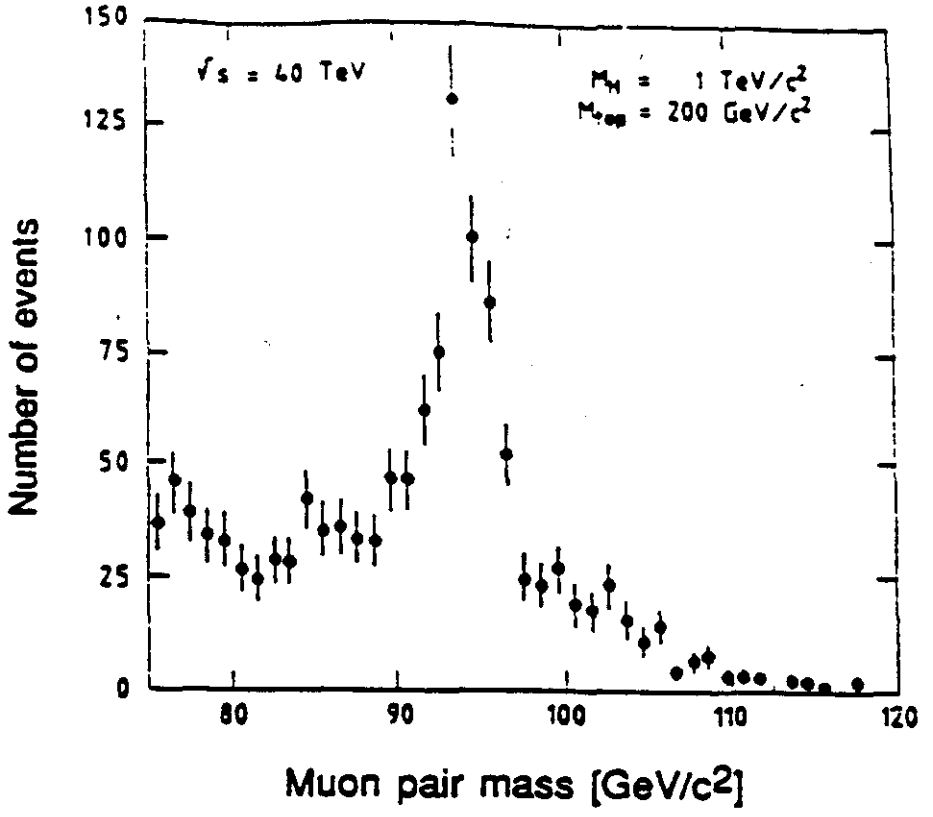


Figure 3a

The reconstructed invariant mass distributions of dimuons from Higgs→ZZ, with 1 TeV Higgs and 200 GeV top for the L3 + 1 detector. The Higgs signal is clearly visible above the heavy quark background.

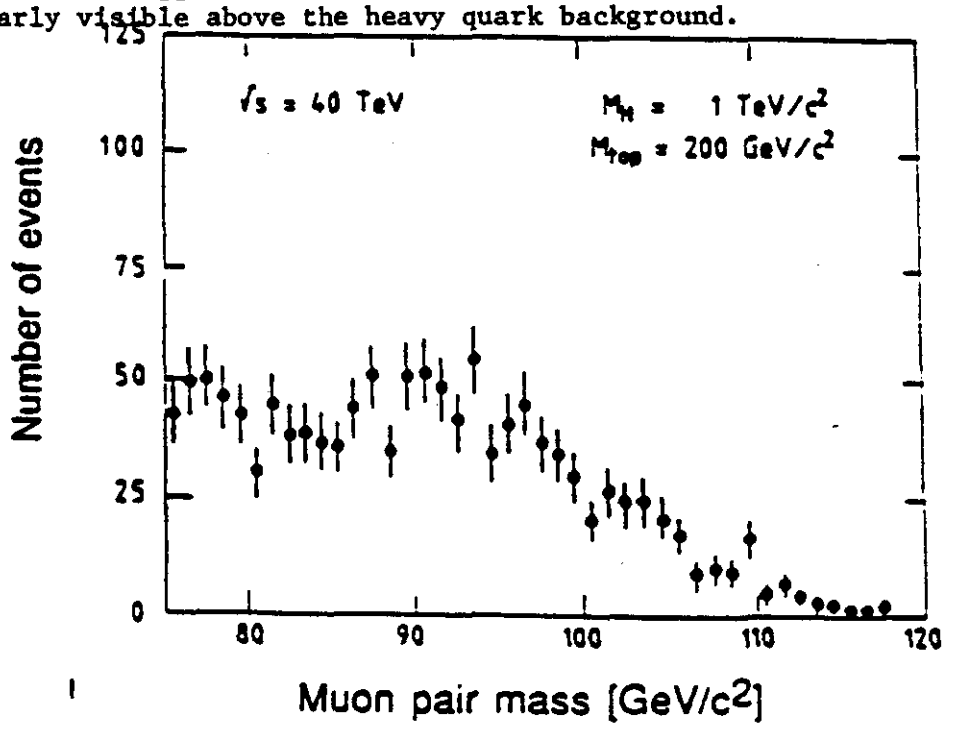


Figure 3b

The reconstructed invariant masses distributions of the same dimuons, as in Fig. 3a, but with the momentum resolution of an iron toroid $\Delta P_T/P_T = .09 + .11\ P_T(\mathrm{GeV/c})$ (Ref. 4).

(2c, d and 3b) that is due to the poor resolution of iron toroid measurement of the muon momentum. In Fig. 4 (Ref. 3) we see the degradation in signal to noise on the reconstructed Higgs mass from ZZ pairs. Measurements using calorimetry (b) or internal solenoids (c) are quite good, while the muon signal measured in iron (d,e) is suppressed by poor resolution. Thus, the mass reach for decays to muons measured in iron will be significantly lower than that attainable through electrons, and crucial comparisons of decay channels will be difficult to make. For the channels where only one Z° decay to leptons is detected, resolution translates directly into signal to noise levels, and the optimum is reached when the Z can be reconstructed with an error at the level of its natural width.

The impact of angular acceptance for the Higgs signals is shown in Figs. 5 and 6 (Ref. 5). Here the acceptances for two leptons (signalling reaction 2) or four leptons (reaction 1) are shown as a function of minimum angle of coverage. Solenoidal detectors have resolution functions which deteriorate in the forward region, resulting in signal losses of more than a factor or two.

Perhaps the best example of the need for both good acceptance and good resolution is available in the detection and identification of a new Z. Several Z´s arise naturally in superstring inspired supersymmetric models. For example, one appears as E(6) breaks to SO(10) and another arises as SO(10) reduces to SU(5). Rosner (Ref. 6) has shown that the distinguishing feature of the various possible physical manifestations of the Z is the lepton asymmetry, which is a strong function of the Z mass and is largest at high rapidity. The asymmetry as a function of rapidity, as shown in Figure 7, indicates the importance of measurements

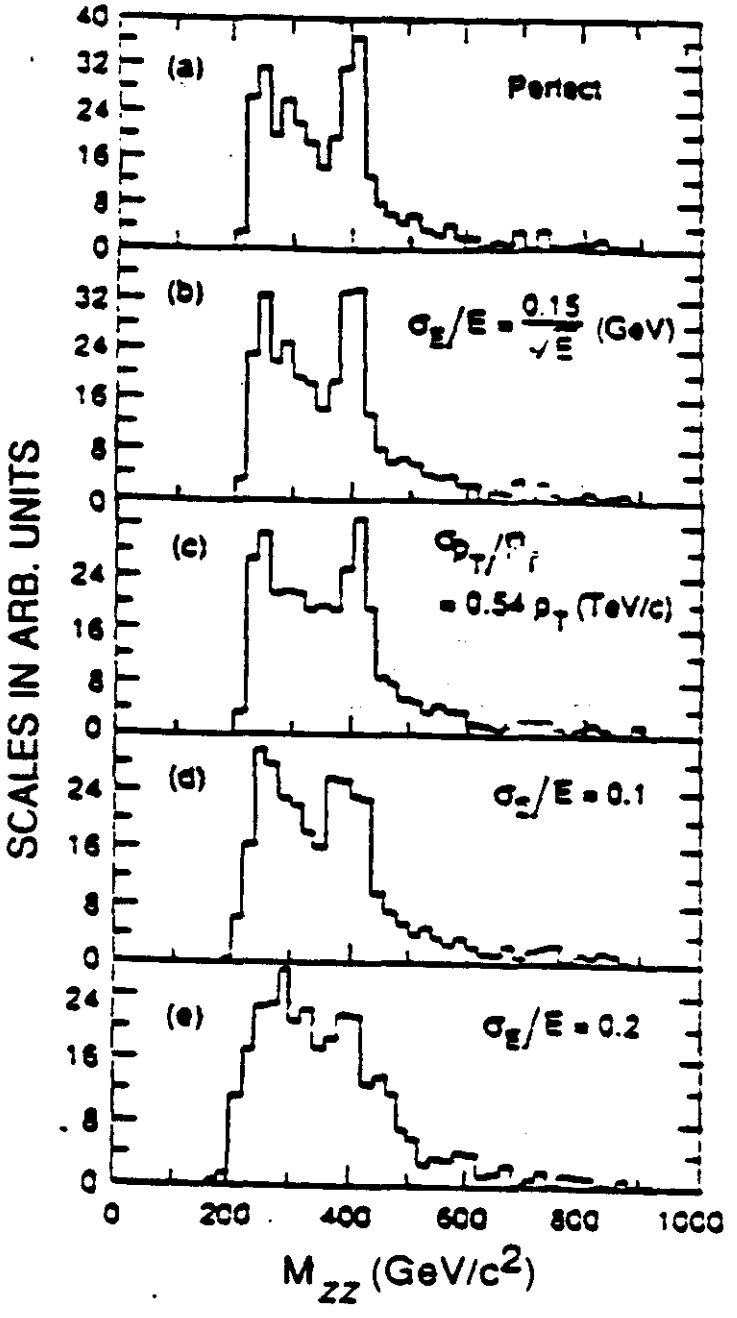


Figure 4

Z-pair mass distributions for various energy or momentum resolutions for $H \to ZZ \to 4l^{\pm}$ for M_H=400 GeV/c^2, along with the background from continuum ZZ production (Ref. 3)

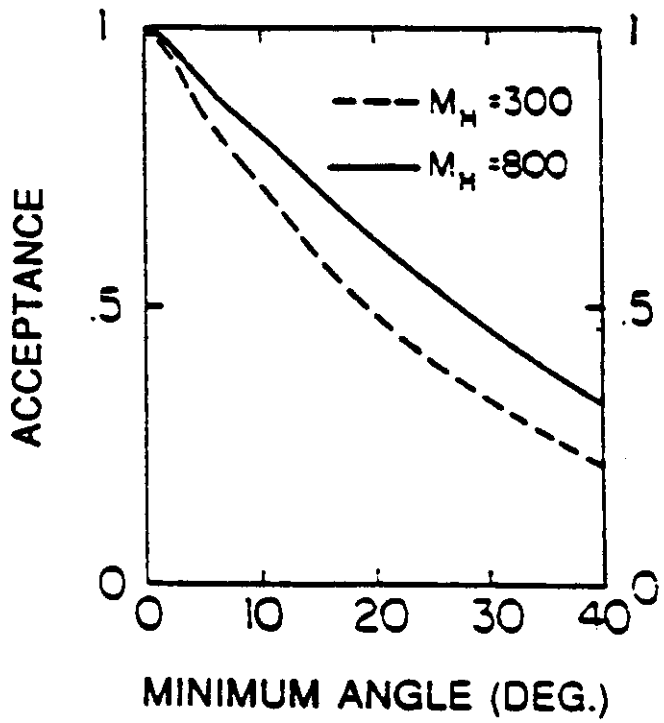


Figure 5

Two-lepton angular acceptance for $Z=\ell\ell$ from continuum $H^0 \rightarrow ZZ$ events with Higgs masses of 300 and 800 GeV (Ref. 5).

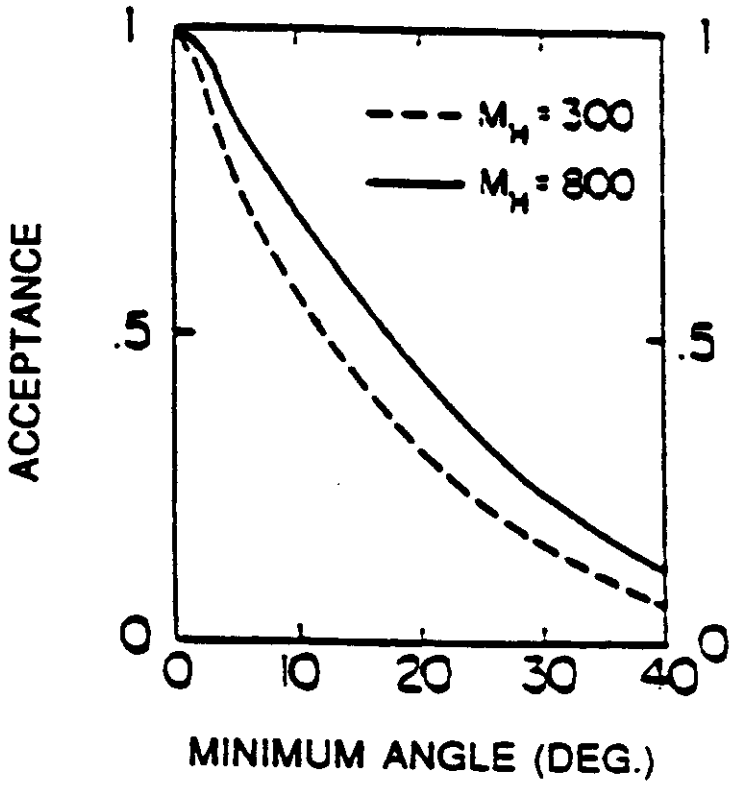


Figure 6

Four-lepton angular acceptance for $ZZ \to \ell\ell\ell\ell$ from $H^o \to ZZ$ events with Higgs masses of 300 and 800 GeV (Ref. 5).

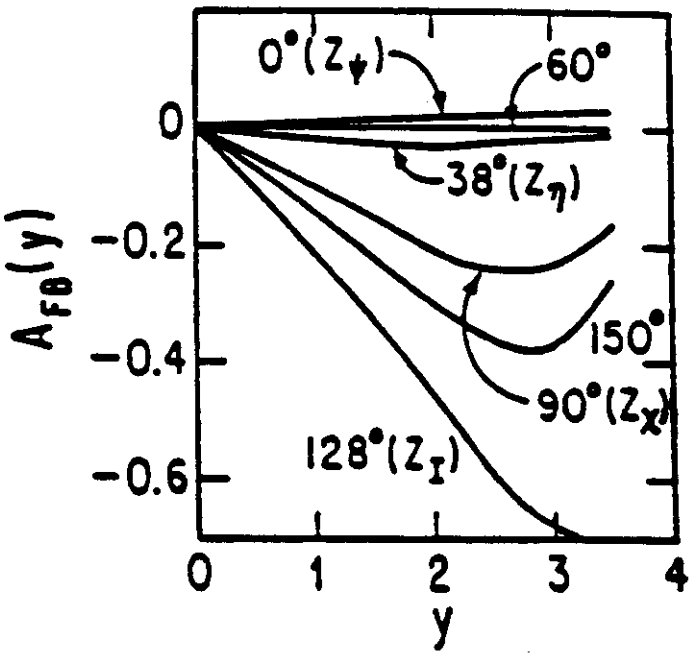


Figure 7

Forward-backward asymmetries in $pp \to Z'(\theta) + \ldots \to \ell^- \ell^+ + \ldots$ for $\sqrt{s}$=40 TeV, as function of rapidity. Here $M\{Z(\theta)\}$ = 1 TeV. θ is the model dependant mixing angle to be determined (Ref. 8).

at or beyond y = 2 (below 20°). Figure 8 shows the lepton acceptance from Z decay for various Z masses (Ref. 5). Adeva et al. (Ref. 7) have studied the impact that resolution has on the measurement of the asymmetry. Figure 9 shows the effect of measurement using iron toroids; Figure 10 shows the expected and "measured" asymmetry as a function of mass at large rapidity. Our conclusion is that solenoids cannot be used to measure asymmetries and iron toroids do not have sufficient resolution to distinguish between different hypotheses. The thrust of this proposal is a system of toroidal magnets which could supply the requisite acceptance and resolution.

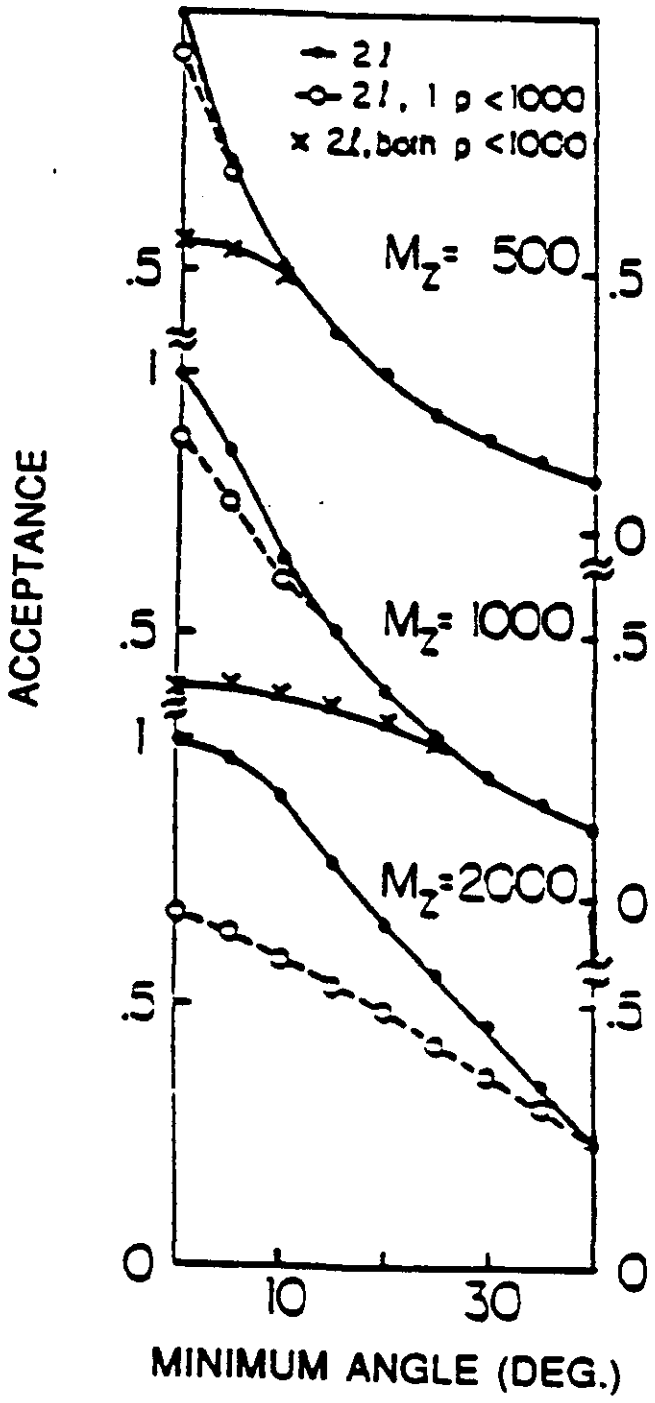


Figure 8

Two Lepton angular acceptance for $Z' \to \ell\ell$ for Z' masses of 500, 1000 and 2000 GeV. (Ref. 5).

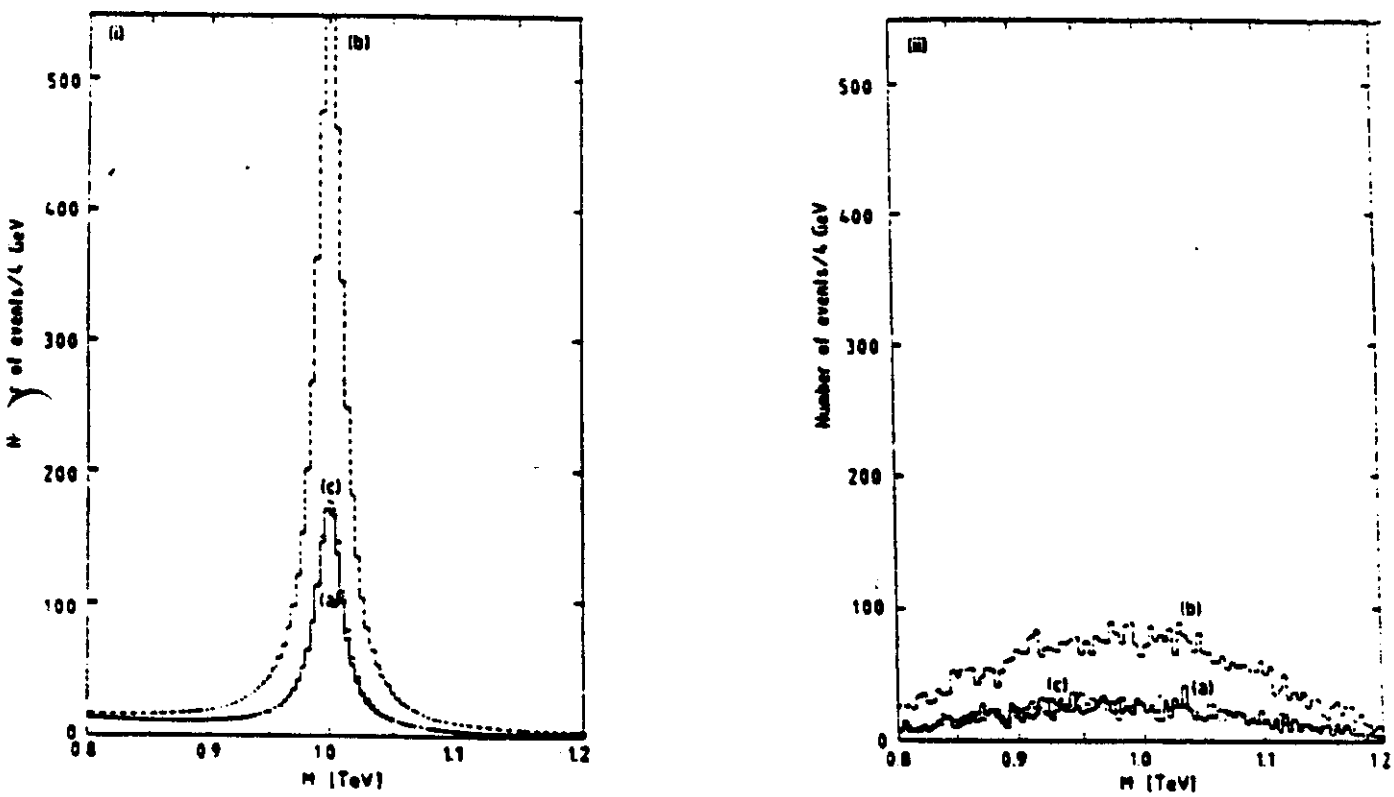
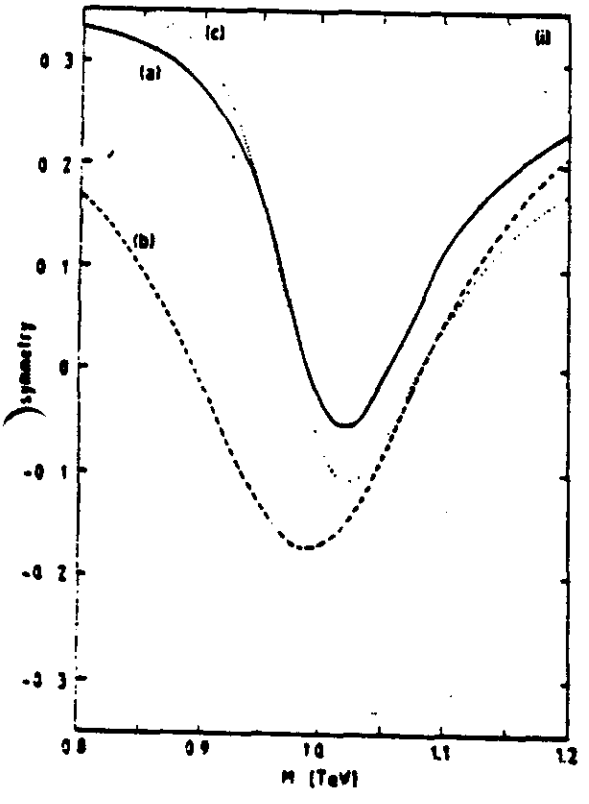


Figure 9

The differential cross-section $d\sigma/dm$ for $pp \to \ell^+\ell^-\chi$ (ℓ=e μ) as a function of the lepton invariant mass M around the Z′ width of 25 GeV. Solid, dashed and dotted lines denote various models. Case (i) corresponds to a perfect momentum resolution, case (ii) to a momentum resolution of 15 percent (Ref. 9).



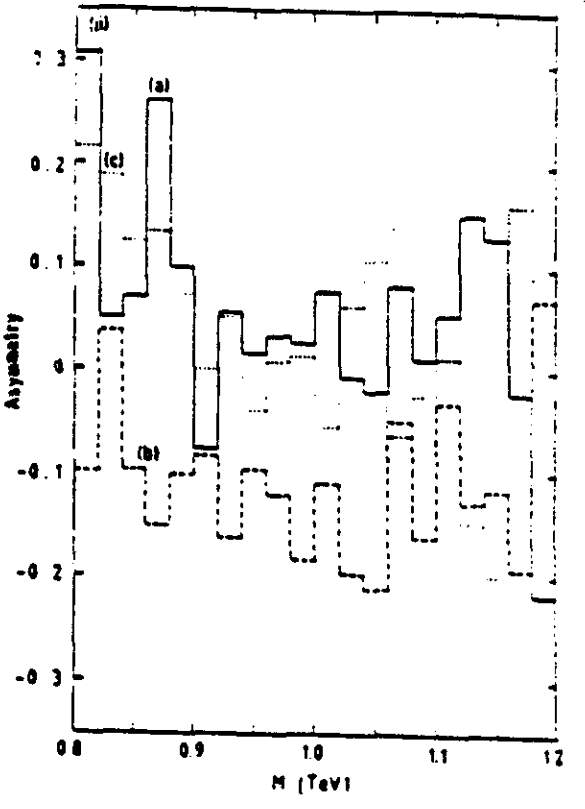


Figure 10

The same as in Fig. 9 but for the lepton asymmetry (Ref. 9).

3. SUPERCONDUCTING TOROIDS AS A MUON SPECTROMETER

In order to obtain the best possible precision in muon momentum measurements at the SSC one should measure the magnetic deflection in air rather than in iron where radiation effects become severe at SSC energies and one is limited in resolution by multiple Coulomb scattering. At the energies of interest, air measurements are limited only by available field length and the resolution and number of measurements.

A proposed solution for enhancing muon resolution and acceptance, is a spectrometer constructed from superconducting air core toroids. This provides the possibility of generating a purely azimuthal field always perpendicular to the trajectories, and by simple arrangement of the currents one can create a field integral which increases like $1/\sin\theta$, ensuring a P_T resolution independent of η. This is shown schematically in Fig. 11, which shows three configurations of current elements for toroids. The first shows a configuration with constant field integral; the second, one which would generate the optimal $1/\sin\theta$ dependence; and the third a version which was studied for feasibility.

The use of toroids with lumped coils in a hadron collider environment has been previously discussed (Ref. 8); but the geometry proposed here is one of distributed, rather than lumped, coils. The configuration envisioned is shown in Fig. 12. It consists of a central and two end toroids, each with 8 independent octagonal coils, with space available for tracking chambers in the field volume between inner and outer coils, and/or tracking detectors before and after the coils. The coils are independent and space can be provided between supports for

SSC - TOROIDAL DETECTOR

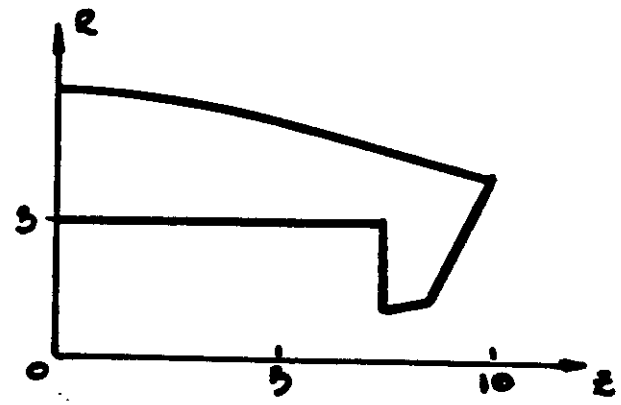
Field Requirements: Geometry

Calorimeter Cavity 3 m diameter x 15 m long

Field Volumes

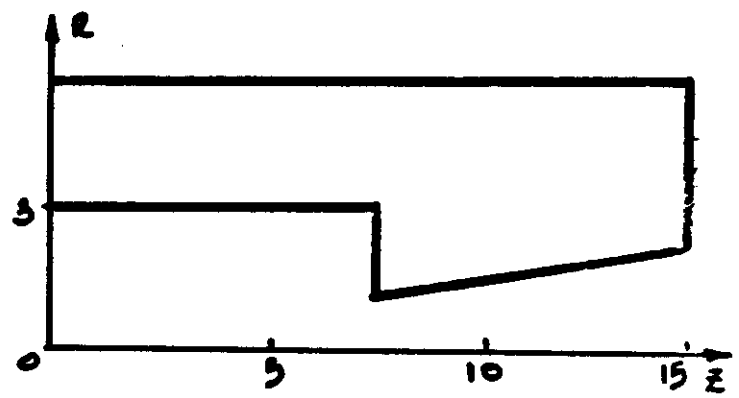
1

$$\int_{\ell} B\,d\ell = \overline{B}L = \text{constant} = 4\text{T-m}$$



2

$$\int_{\ell} B\sin\theta\, d\ell = \overline{B}L' = \text{constant} = 4\text{T-m}$$



3 For Design Study

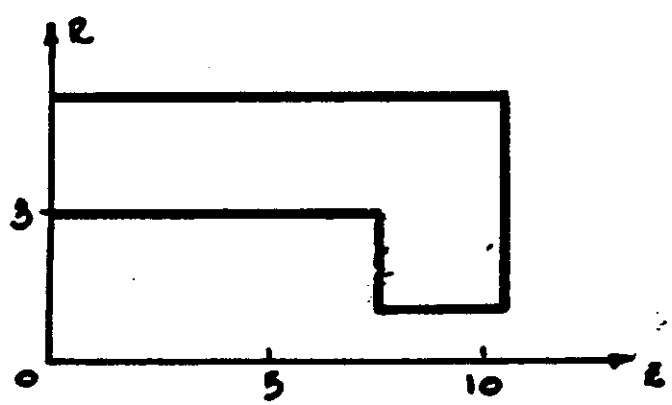


FIGURE 11

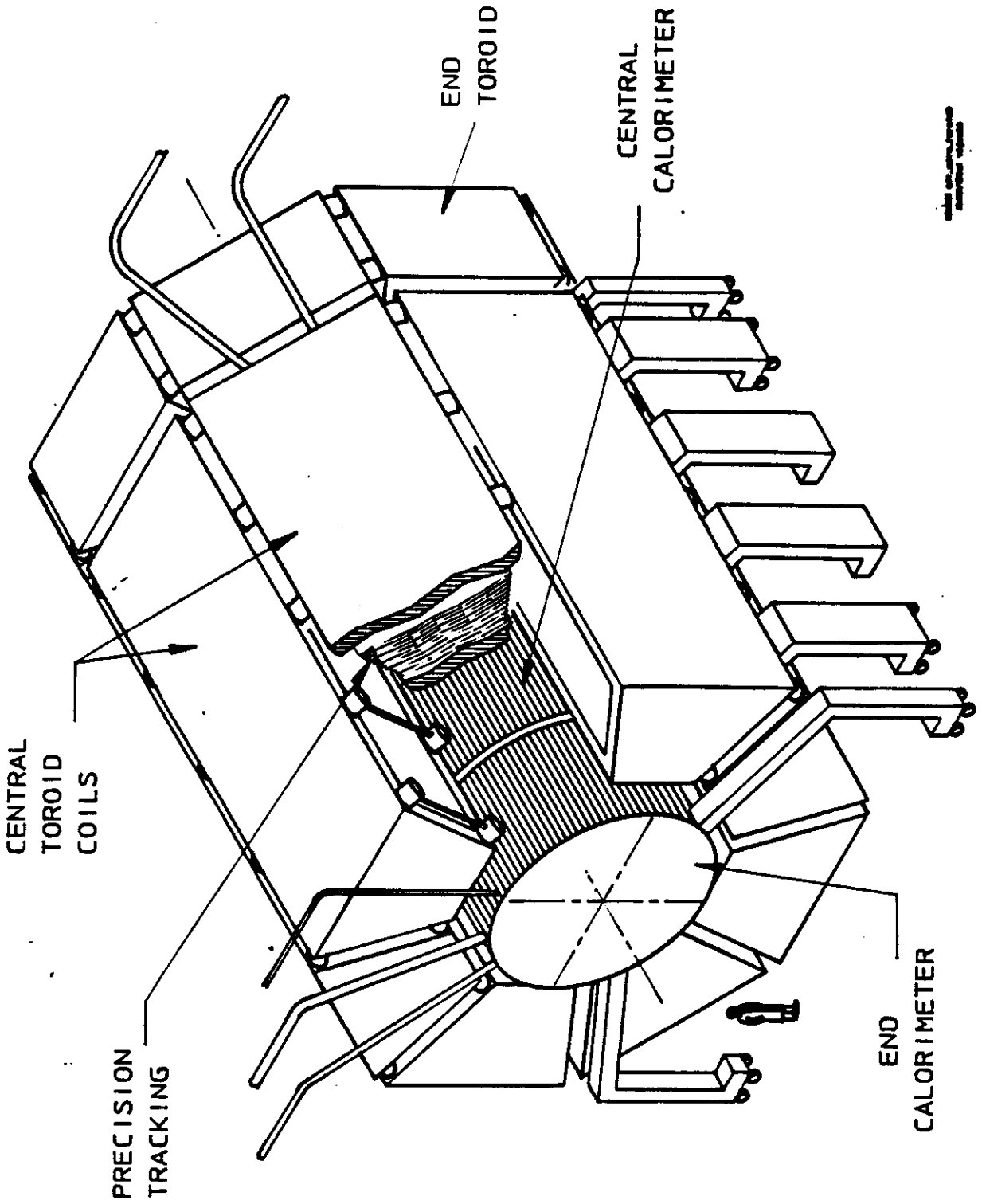

END
TOROID
CENTRAL
CALORIMETER
CENTRAL
TOROID
COILS
PRECISION
TRACKING
END
CALORIMETER

FIGURE 12

access, services and support for the internal detectors. The total weight of such a system of toroids is estimated at 2500 tons. This should be contrasted with the muon systems of other designs which require ten to twenty times this weight in iron.

In high energy physics applications, the proposed use of superconducting toroidal magnets is novel. The use of toroidal iron magnets in colliding beam detectors is common, and small, warm air core toroids have been used as spectrometers such as in the forward UA2 detectors. This is to be contrasted with the use of solenoids which appear in many e^+e^- detectors and are the basis for several of the designs considered for the SSC. There is some concern that the suggested designs for a large system of superconducting toroids might be impractical, and so the proposed effort is directed towards dispelling these concerns and providing a firm basis for the use of such magnets at the SSC.

Toroidal magnets are utilized frequently in the field of fusion energy for confinement of plasmas. In particular there has been a concerted international effort to develop the expertise for the construction of high field superconducting toroids. As an example, the Large Coil Task has recently completed its mission to study a superconducting toroidal system at O.R.N.L. and we quote from the executive summary of the final report: (Ref. 9).

"A multinational program of cooperative research, development, demonstrations and exchanges of information on superconducting magnets for fusion was initiated in 1977 under an IEA agreement. The first major step in the development of TF magnets was called the Large Coil Task.

Participants in the LCT were the U.S. D.O.E.,EURATOM,JAERI,and the Department Federal de l'Interieur of Switzerland.

"The goals of the LCT were to obtain experimental data, to demonstrate reliable operation of large superconducting coils, and to prove design principles and fabrication techniques being considered for the toroidal magnets of thermonuclear reactors. These goals were to be accomplished through coordinated but largely independent design development and construction of six test coils, followed by collaborative testing in a compact toroidal test array at fields of 8T and higher.

"....The last coil was completed in 1985 and the test assembly was completed in October of that year... Over the next 23 months the six coil array was cooled down and extensive testing was performed. Results were gratifying as tests achieved design-point performance and well beyond. (each coil reached a peak field of 9T.) Experiments elucidated coil behavior, delineated limits of operability, and demonstrated coil safety."

The characteristics of the six coils, highlighting the many distinctive features of the independent designs are reproduced in Table 1. The fusion energy field has confidence in the technology for these magnets. Designs exist now for future operating machines of sizes comparable to those suggested here for SSC detectors, and with peak fields (and thus forces) much higher than required for high energy applications. Thus the initial reaction of industrial and laboratory experts to the designs of a toroidal spectrometer for muons in the SSC environment has been very favorable (See Appendix 6.3).

Table 1
Distinctive features of the LCT test coils

Participant	United States	United States	United States	EURATOM	Japan	Switzerland
Direction	ORNL	ORNL	ORNL	KfK	JAERI	SIN
Coil	GD	GE/OR	WH	Siemens	Hitachi	BBC
Conductor	IGC/GD	IGC	Airco	Vacuumschmelze	Hitachi Cable Ltd.	SASM/BBC
Superconductor	NbTi	NbTi	Nb_3Sn	NbTi	NbTi	NbTi
Cooling mode[a]	PB	PB	FF	FF	PB	FF
Design current (A)	10,200	10,500	17,760	11,400	10,220	13,000
Current density, winding (MA/m^2)	27.4	24.7	20.1[c]	24.1	26.6	30.7
Current density, coil (MA/m^2)[b]	15.3	15.7	17.6	16.3	16.0	17.8
Design MA turns	6.40	6.53	7.53	6.70	6.73	5.95
Winding configuration	Edge wound, 14 layers	Flat wound, 6 double pancakes	In grooves in 24 plates	Flat wound, 7 double pancakes, impregnated	Edge wound, 20 double pancakes	Wound in 11 double pancakes, impregnated
Structure	Type 304L SS, welded case	Type 316LN SS, bolted and welded case	Al alloy 2219-T87, bolted plates	Type 316LN SS, bolted, sealed case	Type 304LN SS, bolted and welded case	Type 316L/316LN SS, bolted case

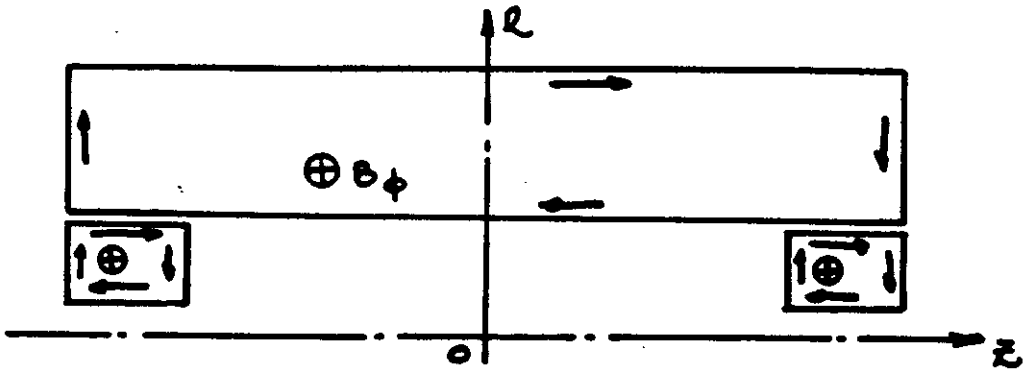
[a]PB: boiling at 0.1 MPa (4.2 K); FF: 1.2 MPa (3.8 K).
[b]Average over total cross section of winding and structure in nose region.
[c]Includes plate structure inside the outermost conductor boundary.

In order to establish the feasibility in a more rigorous examination, a study utilizing expertise from two fusion laboratories (P. Bonanos PPPL, J. Luton ORNL) was commissioned. Starting from an initial configuration shown at the bottom of Figure 11, with a field integral of 4.2 Tm at 90° and 20 Tm at 5° and requiring currents of 3×10^{7} A, their study included choice of magnet configuration, field shape, structural analysis and superconductor selection. A summary of their report is appended to this proposal (Appendix 6.1). The full report will be available before November. To simplify the initial work, a configuration of simple rectangular coils was taken. We examined two arrangements of central and end toroids and found that a version with shortcentral and large radius end toroids was more efficient in coverage although leading to larger magnetic forces (see Fig. 13). A simple structural arrangement of aluminum cylinders to support the coils was adequate with thicknesses of aluminum varying from 15 to 30 cm (see Fig. 14). In this regard it was found that even with the large bending power of the design the total material thickness was less than 30 radiation lengths with no optimization attempt made, and most of this was due to the stainless vacuum vessel walls and to the conductor. The selected superconductor utilizes a cable composed of SSC strands with an overwrap of additional copper strands; the cable is enclosed in a stainless steel conduit and cooled by single phase helium flowing in the interstices.

The conclusions of both experts, plus the reactions of outside reviewers, was that construction of such devices is clearly feasible (See Appendix 6.3). The performance requirements can be achieved using criteria more conservative than those used in the fusion program, and the design restraints are less severe. It was also suggested that considerable opportunities exist for enhancement of performance,

Coil Configurations Examined

1 Long Central Torus with Toroidal Plugs



2 Shorter Central Torus with Toroidal End Caps

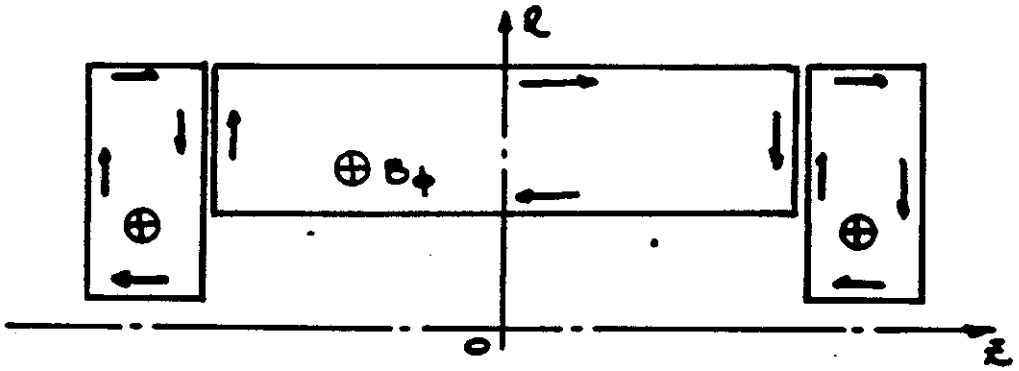
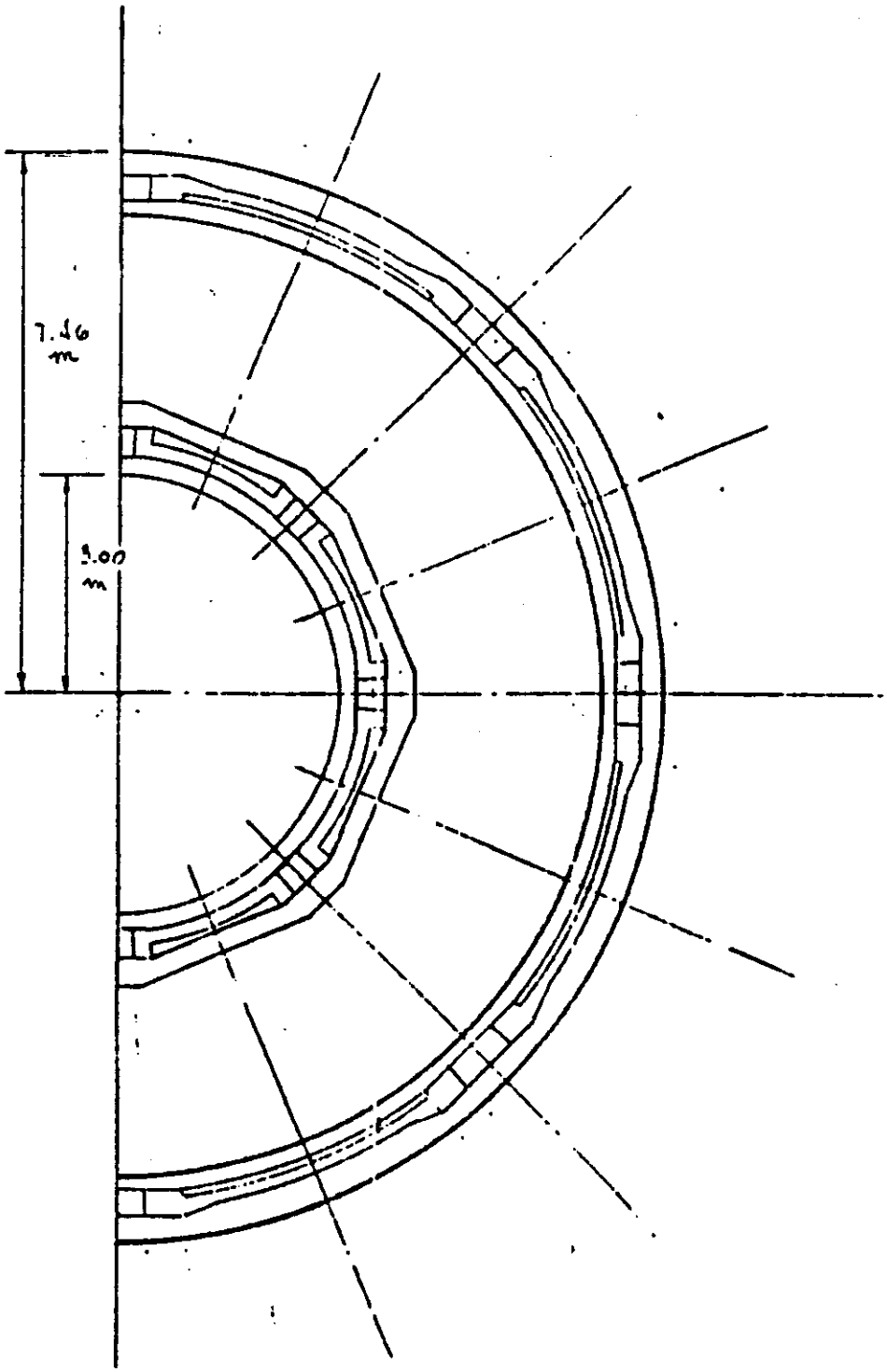


FIGURE 13



CENTRAL TORUS
CROSS SECTION

FIGURE 14

reduction of material thickness, and optimization of design. This optimization program is one of the major thrusts of this proposal.

4. PROPOSAL FOR DEVELOPMENT OF SUPERCONDUCTING TOROIDAL SPECTROMETER

The development of toroids for use at the SSC requires a multifaceted approach, which will include parallel development of several design configurations of the magnets themselves, as well as detailed investigations of technologies available for measuring the muon trajectories; calculations of muon backgrounds from hadron cascades, in order to determine whether the calorimeter and toroids need to be augmented with additional material to reduce backgrounds and improve muon identification; and finally, development of schemes to provide discriminatory and fast triggers for muons. We discuss below some of the major issues to be considered, and then present plans for execution of these studies.

There are two extremes of approach to the use of such toroids at the SSC. One is to achieve the highest possible resolution by measurement of the muon momenta in the field volume. This method requires multiple high precision measurements of points on the trajectory, and has been pioneered by the L3 group at CERN. In this approach one is limited only by the available BL^2 and the number and precision of measurements, and not by multiple scattering, which is negligible. One must design the toroids for insertion of the muon chambers into an atmospheric pressure volume, and provide access for servicing the chambers and associated electronics. In this case one must optimize the toroid design for maximal clear space and access, and the structural elements of the design are only optimized for cost and fabrication ease.

The other extreme is to measure only the entering and exiting directions of muons. In this case the measurements will be limited in precision by the multiple scattering in the toroid conductor,supports and vacuum shells. For the simple designs considered to date this results in a limiting precision of about 5%, which is significantly better than that available with iron toroid systems. It should be possible to reduce this limit, as this was not a specification of the initial model studied. (Appendix 6.1). To achieve better resolution with external measurements, optimization of the toroid requires maximal field integral, reduction of material and use of aluminum rather than steel wherever possible. No access requirements to the field volume permits elimination of two dewar shells and provides the possibility of support structure, which may reduce the overall materials requirements and possibly the cost.

Finally it may be necessary to have hybrid schemes, with most measurements done outside, but some identification or measurement of the trajectory required inside the field to aid particle identification and background suppression. Optimization of the chamber positions and resultant momentum resolution, will be a primary task of the tracking simulation studies.

In the optimization of the toroids, we will also consider the field shapes, as well as the leakage of the field outside the toroidal volume due to the fact that the conductors will not uniformly fill the surfaces. This has implications for detectors inside the toroids, for punchthrough in the inner muon chambers, as well as for forces between the the central and end toroids. We have already established that these stray fields can be reduced to a large extent by addition of extra conductors near the gaps between coils.

In the design optimization, we will consider separate issues for the central and end toroids. The end toroids have more universal utility, and may provide the means for solenoidal detectors to improve muon measurements in the forward regions. It is our intent to work with groups developing solenoidal based detectors, so that forward superconducting toroids could be integrated into their designs. The end toroids have inherently larger field variations, ranging from 6T at the inner radius to 1T at the outer radius, for the designs considered so far. Both the higher field and greater variation have implications for chambers operating in this field (ExB effects) and for the performance of the toroid itself. Because of the 1/R variation of the field, there is a premium on minimizing the distance from the interaction point to the toroid, (radially and along the beam) and thus also on the size of the central tracking and calorimetry volumes (See Appendix 6.4) The central toroid has a smaller field range, which simplifies chamber considerations and a lower absolute field, which provides a greater margin for optimization of conductor and structure.

A critical element in the designs will be the properties (electrical and mechanical) of the superconductor. Our initial designs will be based on the cable in conduit conductor mentioned above, but it is important to study this choice, make several samples and test their properties. While this program is costly, it has enormous cost and time leverage on the development of toroids, and has been stressed by many experts (see Appendix 6.3).

Although the requirements which the most important physics target processes impose on muon detector performance have been discussed in some

detail in the literature, in our judgment a reassessment of this subject is necessary. We would reexamine both the selection of the physics targets, and the demands that each process makes on the detector.

Tentatively, our approach is to require that the detector be adequate to detect and study certain important processes in the minimal Standard Model with maximal efficiency. These appear to be quite demanding, so that a detector suitable for them will be adequate to explore most of the proposed extensions to the Standard Model. The processes include high mass Higgs production and decay, the related high-mass IVB pair polarization, and single high P_T Z^o production. There is often more than one accessible signature for the relevant processes, and each must be examined for possible constraints on the detector.

Relevant detector performance parameters include geometrical aperture, momentum and angular resolution, transverse momentum threshold, and the maximum momentum of interest. Control of these parameters imposes requirements on the actual structure of the detector: the size, thickness, and current distribution of the toroids, and the nature and placement of the tracking and triggering devices. The requirements on each parameter must be examined at a number of different time-scales, ranging from the bunch crossing time to many months (the offline analysis scale). Thus, for example, at the first level trigger time it might only be necessary to determine momentum well enough to impose a P_T threshold of 20 GeV/c, whereas at higher level triggers successively better resolution is required.

It is also desirable to allow for possible future upgrades of the detector and of the SSC itself. Thus one would want to ensure that any

kinematically possible muon could eventually be studied and higher luminosity can be accommodated.

We will study the momentum resolution possible with various toroid configurations, by constructing a detailed simulation of muon transport through the material, field and track detectors, and iterate with the toroid designs to provide the optimal configuration of field and chamber placement. In parallel with this we will perform a comprehensive study of available technologies for muon tracking, as well as development of high resolution streamer chambers as tracking detectors.

Another objective of this proposal is to achieve a detailed understanding of the backgrounds to the muon system penetrating the calorimetry. We must determine the number and spectra of particles entering the muon chambers and toroids, as well as a study of showers accompanying muons produced by the radiation of muons in the calorimeter material. Since triggering is expected to be done outside the toroids, we will also have to transport the backgrounds through the field to determine possible candidate trigger particles and determine the requirements for the trigger in terms of position, angle and linkage to tracks before and inside the calorimeter.

A major topic of investigation for this proposal will be the development of the requirements of the trigger system itself. Because of the high luminosity, there will be a premium on development of a trigger that can minimize the time required. In addition a severe background for muons will be cosmic rays. The trigger should provide a cutoff at low momenta to bias against punchthrough, and directionality for higher level improvement of the threshold.

All of these issues are highly correlated, and the results of each study have impact on the toroid designs. These studies have to be done in parallel and be coordinated, so as to permit iterative optimization. This is illustrated in Figs. 15 and 16 which is an attempt to indicate the linkages between the tasks and show the flow of the entire development of the spectrometer. Shown are a flowchart of tasks (Fig. 15) and a timeline (Fig. 16).

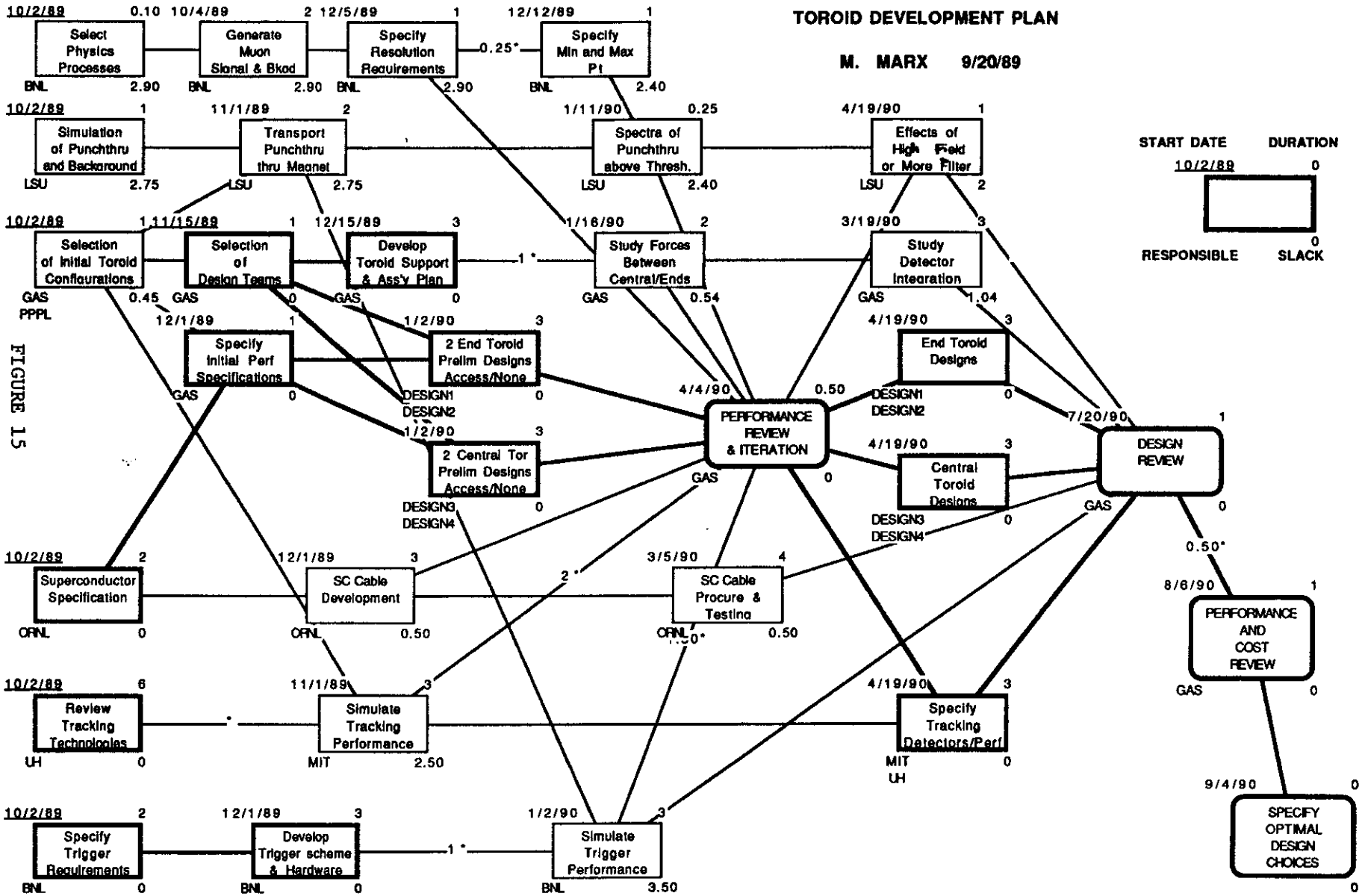

TOROID DEVELOPMENT PLAN
M. MARX 9/20/89
START DATE
DURATION
RESPONSIBLE
SLACK
Select Physics Processes
Generate Muon Signal & Bkgd
Specify Resolution Requirements
Specify Min and Max Pt
Simulation of Punchthru and Background
Transport Punchthru thru Magnet
Spectra of Punchthru above Thresh.
Effects of High Field or More Filter
Selection of Initial Toroid Configurations
Selection of Design Teams
Develop Toroid Support & Ass'y Plan
Study Forces Between Central/Ends
Study Detector Integration
Specify Initial Perf Specifications
2 End Toroid Prelim Designs Access/None
2 Central Tor Prelim Designs Access/None
End Toroid Designs
Central Toroid Designs
PERFORMANCE REVIEW & ITERATION
DESIGN REVIEW
PERFORMANCE AND COST REVIEW
SPECIFY OPTIMAL DESIGN CHOICES
Superconductor Specification
SC Cable Development
SC Cable Procure & Testing
Review Tracking Technologies
Simulate Tracking Performance
Specify Tracking Detectors/Perf
Specify Trigger Requirements
Develop Trigger scheme & Hardware
Simulate Trigger Performance

FIGURE 15

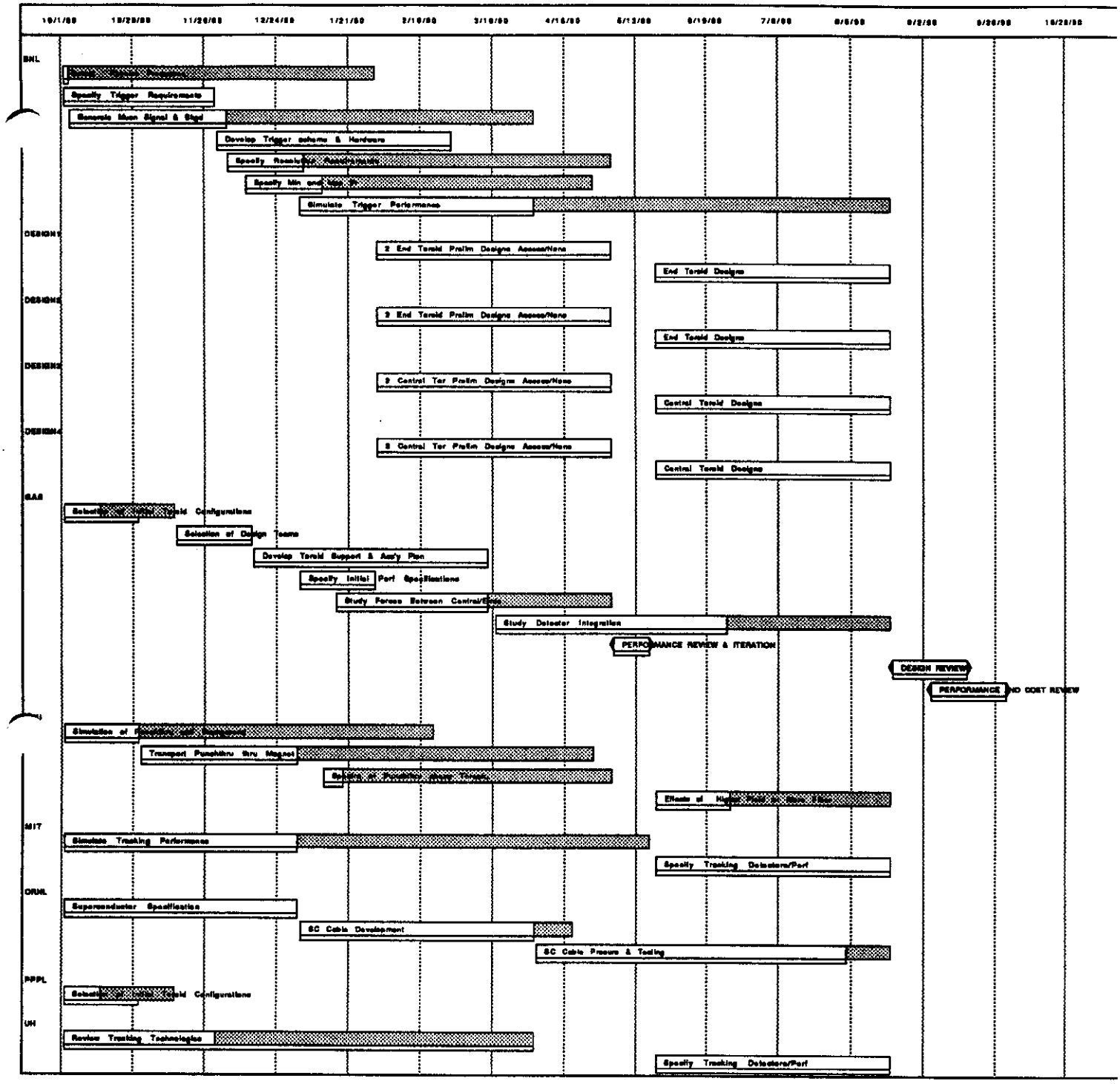

BNL
Specify Trigger Requirements
Develop Trigger scheme & Hardware
Simulate Trigger Performance
DESIGN1
2 End Toroid Prelim Designs Assess/Rank
End Toroid Designs
DESIGN2
2 End Toroid Prelim Designs Assess/Rank
End Toroid Designs
DESIGN3
2 Central Tor Prelim Designs Assess/Rank
Central Toroid Designs
DESIGN4
2 Central Tor Prelim Designs Assess/Rank
Central Toroid Designs
GAS
Selection of Design Teams
Develop Toroid Support & Assy Plan
Specify Initial Perf Specifications
Study Detector Integration
PERFORMANCE REVIEW & ITERATION
DESIGN REVIEW
PERFORMANCE
MIT
Simulate Tracking Performance
Specify Tracking Detectors/Perf
ORNL
Superconductor Specification
SC Cable Development
SC Cable Procure & Testing
PPPL
UH
Review Tracking Technologies
Specify Tracking Detectors/Perf

FIGURE 16

4.1 DEVELOPMENT OF TOROID DESIGNS

Our approach to the development of toroids for use at the SSC relies on the active participation of universities, national laboratories and industry in order to address the issues mentioned in the previous section. The scientific and engineering issues must be studied in parallel in order that meaningful tradeoffs between scientific and engineering requirements can be performed in a timely manner. The development flowchart (Fig. 15) identifies the major tasks to be performed and the institution that has the lead responsibility for the task. Completion of all tasks will result in several candidate designs for the central and end toroids, establish the expected scientific performance of these designs and generate reliable cost predictions for use in SSC detector systems.

The development flow chart details the critical tasks for the scientific issues which are the physics requirements (Brookhaven National Laboratory), calorimeter leakage or punchthrough (Louisiana State University), event triggering requirements (BNL) and muon tracking technology and requirements (M.I.T. and Houston). The toroid engineering design studies (Grumman) will utilize magnet manufacturing companies who will be assigned specific configuration options for investigation. Our intent is to investigate alternative configurations that show initial promise for SSC detector applications. Involvement of Grumman with a prime responsibility for system engineering early in this development program is considered an important factor in our plan to integrate the system and scientific issues in a timely manner. The engineering personnel to be utilized by Grumman have prior system engineering and

toroid design experience from DOE magnetic fusion programs such as the Princeton Plasma Physics Laboratory Tokamak Fusion Test Reactor.

Grumman is implementing an integrated design, modeling and analysis system will utilize the SDRC I-DEAS (Ref. 10) design packages. These design tools will allow us to construct three-dimensional models of the superconducting air core toroids to perform dimensional checks, mechanical analysis and assembly studies. Additional programs can be added to the system to assess toroid acceptance and resolution.

Grumman's experience in nuclear and radiation physics, the fusion program, accelerators and accelerator technology provide unique qualifications to be responsible for the development of super conducting air core toroids. A brief outline of these experiences is given in Appendix 6.2.

Prior to the start of this proposed development effort, we have formed working groups to establish initial parameters of the air core toroid concepts. Two configurations serve as a common starting point for this design effort. One is a central toroid and end cap toroid that utilizes external measurements of the muon to determine the momentum of the muon. This design may allow a simpler mechanical design but may limit momentum resolution. The alternative configuration will provide adequate internal volume and access for the measurement of the trajectory sagitta in the field volume. The studies comparing the engineering impact of various scientific parameters will form the basis of comparison of cost and schedule effects with predicted performance. Concepts for, and analysis of the support structure for the toroids and the massive generic calorimeters inside will be also be provided. Our flow chart

shows the coalescence of all the studies during an initial design and performance review and again at a later review marking the completion of the alternative configuration studies by the magnet manufacturers. Grumman will provide guidelines for these reviews and coordinate the technical exchange of information between the study institutions. Argonne National Laboratory will take the responsibility for ensuring that reviewers from other detector configurations and independent magnet shops attend these reviews and provide critical input.

During the preliminary design phase, we will establish the initial performance specifications that each magnet configuration must satisfy. These specifications will address the dimensional interfaces, the field integral requirements at all angles, the internal access requirements set by the tracking technology, and upper limits on the amount and location of scattering material, and any identified penetration through the toroid volume. Additional system studies relating to weight, magnetic forces, support structures, field assembly and transportability issues, cryogenics, materials and costs will be addressed by Grumman. The importance of addressing these issues at an early stage has been stressed by many of the industrial concerns with capability to fabricate the toroids (see Appendix 6.3). The completion of the preliminary design phase will establish the range of parameters for all key issues relating to use of toroids for the SSC.

The preliminary design review will address the adequacy of the alternative designs and, iterations of these designs will be identified based on overall system scientific, engineering, cost and schedule considerations. A second phase of the study will be to refine these designs so that an SSC configuration can be identified, the scientific

performance and benefit clearly determined and the cost and schedule issues well understood. After the performance and cost reviews and the selection of optimal design choices have been made, it should be possible to integrate such an optimal toroid design with other parts of an SSC detector, and to specify the toroid with sufficient detail to permit the procurement of a reference design adequate for fabrication.

4.2 SUPERCONDUCTOR DEVELOPMENT

Although preliminary coil design and analysis can proceed using the initial specifications for the superconducting cable, it is critical to actually develop the techniques for production of the cable, produce sample lengths, and test their electrical and mechanical properties. Until such data is actually available, conductor costs and coil winding times are difficult to predict, and thus can have major influence on the overall cost and time of magnet fabrication.

We propose to procure full-sized conductor cables of sufficient length for reliable testing. Heaters and instrumentation will be provided to study critical current, change of flow parameters with magnetic load, stability, quench pressure for intermediate-length normal zones, response to changing current, and effectiveness of the coolant connections, which depend upon flow transverse to the compacted cable. As flow path lengthens, toroid construction costs will go down and reliability up. We plan to do the tests, on samples 30-m long placed in a background field provided by an existing coil. The first sample will consist of SSC multi-filamentary NbTi strands surrounded by pure copper strands all spiral wrapped with metal foil and inserted in a metal sheath, preferably aluminum alloy. The second sample will use the same multifilamentary strands, but clad with aluminum stabilizer. No strands without NbTi are anticipated for this sample. Similar tests will also be done on two long samples of cable having only a few strands (3 to 7). Strands will be identical to those of the short samples, and the results of four tests will be compared. Suitable instrumentation appropriately located will be provided for determining voltage differences, current,

temperatures, pressures, flow, and strain. The data will be analyzed and compared with theory, a post-test inspection done on the samples, and a report prepared.

Facilities available at ORNL for carrying out the proposed work include two each 25-kA power supplies which can be paralleled to provide current for the short sample, a 30-A, 500-V heater power supply, an 8-T superconducting magnet with 15-in. clear cold bore, data acquisition system, and helium liquefier. The conductor development work would be carried out by the staff of the Magnetics & Superconductivity Section of the Fusion Energy Division of ORNL. They have extensive experience in resistive magnets; forced-flow, pool-boiling, and Nb_3Sn tape superconducting magnets; cryogenics; magnet fabrication, monitoring of industrial efforts; technology transfer; and foreign collaboration. As needed, they have access to the extensive shops and services of DOE's Y-12 Plant, the remainder of the ORNL scientific staff, and the engineering division which serves all three sites.

4.3 MUON TRACKING SIMULATIONS AND DETECTOR DEVELOPMENT

A. Simulation Studies and Technology Survey

In order to optimize the magnet and tracking chamber designs, the MIT group will carry out studies of reconstructed momentum resolution, fit bias and efficiency for large-statistics samples of signal and background muons generated by Monte Carlo techniques for a variety of realistic potential detector and toroid configurations.

The power and flexibility of our existing package of geometry, track propagation and fitting programs will allow us to simulate detector geometries at a level sufficiently detailed to make accurate assessments of detector capabilities. The detailed representation of the mechanical detector design from the toroid studies will permit interactive optimization of detector performance and cost. Comparative evaluation and optimization of detectors with respect to measurement of trajectories inside or outside the field volume and hybrid schemes, as well as comparison of performance with other candidate SSC detectors, can be performed. As the detector design evolves, the effects of changes in the physical detector configuration on the performance can be monitored.

A first version of a track fitting package for studying the performance of muon detectors for SSC using external air core toroid magnets is being tested. It implements a formalism that was initially developed and used in Monte Carlo studies and data analysis for the Fermilab neutrino program, and which was subsequently generalized for use with the SLD detector at SLC. The technique is designed to find unbiased,

robust, and statistically efficient estimators for the initial muon position and momentum most likely to have produced an observed set of hits in an array of planar detectors. We carry out a global fit (one that uses all data simultaneously) by propagating an unscattered track through the detector, using a direct stepwise integration of the equations of motion including energy loss and calculating the covariance matrix en route using local values of the radiation length. The calculation of the particle trajectory and the covariance matrix requires a detailed knowledge of the detector material layout, detector plane locations and orientations, magnetic field, radiation length, and accounting for radiation and dE/dx loss throughout the trajectory.

The primary goal of this study will be to determine the choice of detector arrays and magnetic field configurations that will best meet the physics goals of the muon detection system. To optimize the mass resolution, we must study the momentum resolution throughout the detector for a wide range of detector array deployments and magnetic field configurations. In particular, initial studies will include the numbers, locations and position resolutions of chamber arrays before, after, and within the magnetic field region; use of increased measuring moment arms with decreased field strength; and the effect of mechanical supports, coil materials and current distributions on attainable resolution.

In parallel with this simulation effort the Houston group will assemble a complete review of existing technologies available for muon tracking. We will compile parameters of these technologies as to performance (resolution and speed) and spatial requirements and consider the environment in which the chamber must operate (e.g. ExB effects and background). These data will then be included in our simulation studies

and as input to the toroid designs. We will then be in a position to determine which existing technologies are appropriate for further development or refinement for the SSC environment.

B. Development of Streamer Chamber Tracking Detectors

The requirements for momentum accuracy imposed by the physics objectives described earlier present severe problems for the operation, mechanical positioning and stability of the muon detectors. The problems inherent in achieving the required specifications are far from conventional and should be confronted and solved as soon as possible. We are proposing the development of streamer chambers operating in the drift mode as the position measuring devices for the high energy muons. A number of groups (Ref. 12, 13, 14) have studied such chambers and have found them to provide position measurement resolution of 100 to 200 μm, depending on the details of the system. We also have developed considerable experience in the implementation of drift tubes and muon detectors using a tube structure in Fermilab experiments E-594, E-665 and in the SLD and LVD projects. We envision using tubes of aluminum, possibly coated to increase the surface work function and/or resistivity. This is one of the many questions that must be investigated to optimize the performance of such systems. We propose an open tube geometry to allow easy placement of the wires.

We find this type of device particularly promising because it has the following merits:

1) the structure can be extruded and thus is relatively

inexpensive to produce

2) the mechanical structure is inherently stiff and provides stable support for the wires, a feature which is necessary for minimizing positioning error.
3) the device provides excellent pulse height and rise time, 60 mV in 20 nsec
4) the tubes act as cables giving no degradation in rise time over 6m.
5) staggered tubes from a common extrusion give a measure of the beam crossing time and resolve the left-right ambiguity
6) the drift times can be made short and thus minimize data pipeline problems.
7) the position measuring resolution is in the appropriate range. With some optimization and the use of multiple detector layers we believe the momentum measuring requirements can be achieved.

We have prototypes of these extrusions on hand which were made to examine the behavior of streamer chambers with a reliable cathode while building graphite covered plastic tubes. These turned out to be more stable than their plastic counter-parts. We have checked that the mechanical tolerances for these extrusions are in the 1 mil range.

The behavior of streamer tubes as drift chambers has been examined (Refs. 12 and 13) with plastic tubes where mechanical positioning of sufficient accuracy was not achievable. Even with such unstable materials they obtained resolutions in the 100-200 micron range. Ultimate resolutions with a significantly more rigid material, better mechanical

positioning of tubes and wire, "cooler" gases, and high energy beams (minimum scattering), are expected to be better.

To understand the characteristics of these devices and to attempt to optimize their performance we plan to study their mechanical properties, high voltage properties, spatial measurement accuracy, performance for various gas mixtures, and reliability and efficiency. We propose to build a nest of these extrusions of near realistic size and test all the above characteristics. In doing so we plan to develop the electronics which would assign time slots to a biplane traversal at the chamber output end and thus be available for triggering decisions. Even if the tube technology we propose to develop were to be surpassed by some other technique, this electronics development could still have a useful SSC application.

Whatever the means of muon detection, the required spatial measurement resolution is in the tens of microns range and so present problems in accurate placement, stability and measurement and monitoring of wire placement.

We plan to engage outside engineering help to make some preliminary studies on these mechanical problems. The aim would be to come up with solutions and examine their relative merits. We will examine some of the problems in small scale from the use of the nest with in-house engineering, that would also provide the liaison to the contract engineering.

4.4 PUNCHTHROUGH SIMULATION STUDIES

A crucial consideration in the optimization of the design of any muon spectrometer for SSC detectors is the level of backgrounds from hadron punchthrough and decay. These backgrounds not only affect the ability to observe signals from rare physics processes at SSC, but also the ability to form a low-rate trigger for muons. The punchthrough background is of particular importance to the development of a precision muon spectrometer system based on air core toroids where the insertion of extra filter material for punchthrough suppression sets the scale for the toroid system both in size and cost. An outstanding issue that must be understood before one could embark on the construction of muon spectrometer is the minimum hadron absorber thickness demanded by SSC physics. We will study the impact of the hadron punchthrough and muon radiation on the performance requirements especially with regard to occupancy and pattern recognition, for the design of the muon spectrometer including the toroid system, tracking and trigger system. We propose to study these issues at Louisiana State through simulation of the hadron punchthrough.

Past simulation studies (Ref. 14) have been concerned with determining the overall rate of punchthrough background. Perhaps as important a concern for an air core toroid muon spectrometer is the spectrum of particles exiting the hadron absorber. This has implications for both muon identification and triggering. To obtain such a spectrum requires detailed simulation of the passage of hadrons through the detector including all secondaries. This can be pursued with a combination of an

event generator (such as ISAJET), a detector simulation Monte Carlo such as GEANT, and a hadronic shower simulation such as GHEISHA.

A preliminary GEANT/GHEISHA simulation of the CCFR Neutrino Iron Calorimeter gives good agreement on pion punchthrough probability from 15-300 GeV (See Fig. 17). Fig. 18 shows the expected momentum spectrum of the leading charged particle reaching 12λ and 14λ when a 100 GeV pion is incident on the calorimeter. The punchthrough spectra are peaked at low momenta and this will be used with the incident spectrum to determine a minimum threshold for observing physics signals and for triggering.

The optimization of a detector design requires extensive simulation studies of the effects of detailed design choices such as hadron absorber thickness, toroid field strength, leakage field, chamber placement, and choice of trigger components in the detector. The amount of CPU and real time required would make these studies impractical using a simulation which follows all secondaries through the detector. Therefore a fast version of a punchthrough simulation must be developed which not only incorporates the interaction and decay probabilities, but has a hadron shower profile which can yield the multiplicity, energy distribution and lateral spread of the existing particles. We propose to develop such a fast Monte Carlo including punchthrough shower profiles.

A detector will be simulated with a tracking volume, calorimeter and possibly a hadron absorber. Where possible, the details of the detector will be generic for use in various SSC detector geometries. Spectra will be produced and parametrized for punchthrough at 1λ intervals from 8λ to about 25λ and over a wide range of incident hadron

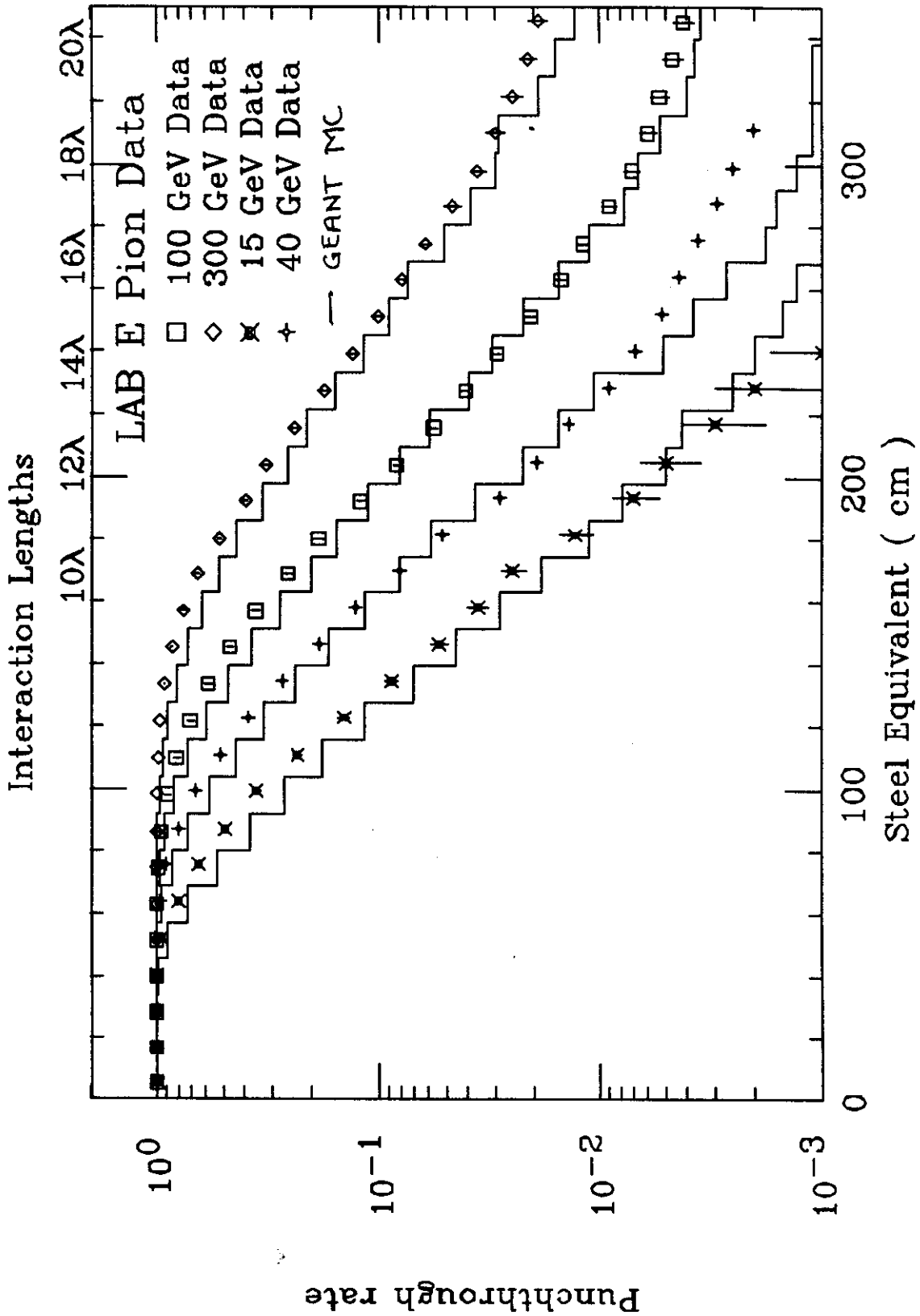
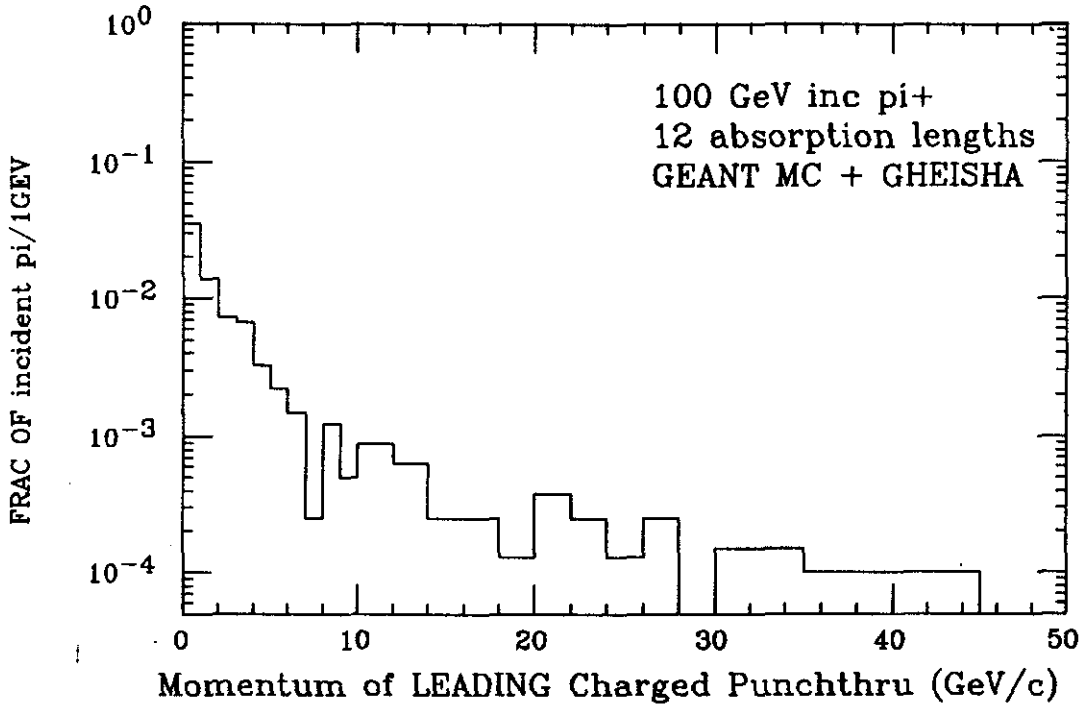

LAB E Pion Data
100 GeV Data
300 GeV Data
15 GeV Data
40 GeV Data
GEANT MC
Interaction Lengths
10λ
12λ
14λ
16λ
18λ
20λ
Steel Equivalent (cm)
0
100
200
300
Punchthrough rate
10^0
10^{-1}
10^{-2}
10^{-3}

FIGURE 17


100 GeV inc pi+
12 absorption lengths
GEANT MC + GHEISHA
FRAC OF incident pi/1GEV
Momentum of LEADING Charged Punchthru (GeV/c)

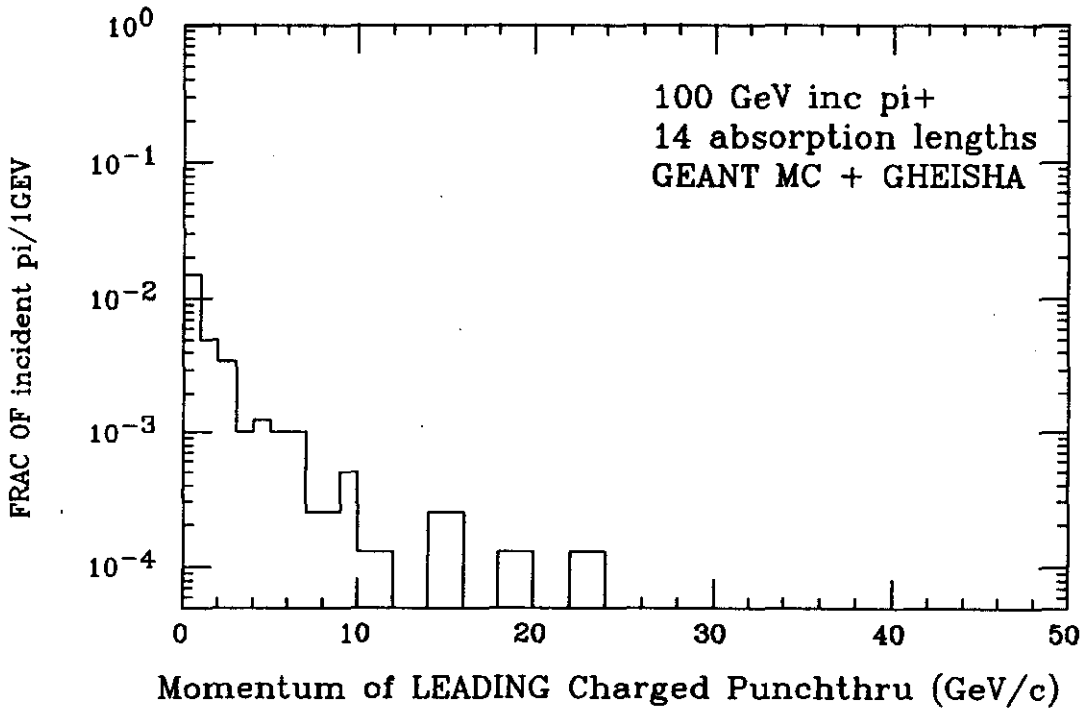

100 GeV inc pi+
14 absorption lengths
GEANT MC + GHEISHA
FRAC OF incident pi/1GEV
Momentum of LEADING Charged Punchthru (GeV/c)

FIGURE 18

momenta. It is proposed to use a minimum of two Vaxstation 3200's to perform the simulation and store the output spectra during which time a fast Monte Carlo simulation will be developed.

This work would take place at Louisiana State University. The fast Monte Carlo will then be used to investigate the impact of punchthrough backgrounds on the detailed design configuration of the toroidal muon spectrometer, using the same computer resources and requiring a year.

4.5 FAST MUON TRIGGERS

The requirements for a fast muon trigger are (1), a time resolution of better than 16 ns to tag the bunch crossing and (2), a rejection of better than 10^3 to reduce the input to the more sophisticated higher level triggers. The trigger must be efficient for the physics processes of interest. At Brookhaven, we will investigate a system which is insensitive to low P_T particles, and can generate a first level trigger decision in much less than 1 microsecond using fast coincidences and possibly look-up memories. Trigger calculations can be done locally and in parallel over the face of the detector, and the results combined later. Trigger information can be made available to the second level trigger system, which could be programmed to seek several potential muons, vary the minimum P_T, or use information from the calorimeter or inner tracking system to further reduce background in the higher level muon triggers.

The trigger will be developed to be efficient for several key physics processes and be efficient from threshold up to the highest accessible mass. We also want to collect a large sample of Z decays to $\mu^+\mu^-$, for calibration of the mass scale and resolution studies.

The technologies to be investigated are planes of scintillation counter hodoscopes, gas Cerenkov counters, lucite Cerenkov counters, and layers of straw tubes (in the region 2<eta<3). We will investigate the rejection of minimum bias events and cosmic rays and the acceptance for key processes. The simulation will include the effect of the interaction diamond, multiple scattering and radiation in the material before the

toroid as well as bending and scattering in the toroid itself. We will compare these technologies to the more standard approach of using PDT layers to form vectors, which requires long pipelines for storage due to the PDT drift times.

We will consider two planes of scintillation counters separated by approximately two meters after the toroidal magnet. Elements from the two layers will point back to the center of the interaction region in the bending plane. The width of the scintillation counters will be matched to the P_T cut we want to achieve in the first level trigger. We will study the optimal size for these counters to ensure sufficient flexibility in triggering, i.e. to allow for increase of the P_T threshold. The trigger will require a coincidence between an inner scintillation counter and the OR of the correct outer counter and its closest neighbors. This system is fast and efficient (large numbers of photoelectrons). Triggers from cosmic ray muons are reduced to acceptable levels since the coincidence system requires the muon to be consistent with coming from the interaction region.

Another type of triggering device we propose to study is a system of threshold gas Cerenkov counters. Current technology would probably allow counters of reasonable efficiency and muon threshold near 6 GeV/c to be deployed between the inner and outer muon chambers. These counters have a number of attractive features. They are very fast, are blind to neutrons and slow particles in general and give some measure of directionality. They may be used in combination with other technologies discussed herein. If further study supports their usefulness, modules will be made for the purpose of studying gas mixtures, light collection and segmentation.

Preliminary studies have indicated that muons from high P_T sources (Higgs, W, Z, Top, etc.) can be distinguished from the major real muon backgrounds from light quarks (b,c), by their angular divergence from a vector from the diamond center. For example, most top decay muons are within 40 mrad, including effects of the magnet, multiple scattering and the size of the diamond; while light quark muons are predominantly at larger angles. This is of course just a consequence of the relative P_T scales. A simple Fitch counter utilizing total internal reflection of Cerenkov light in a lucite sheet, may be able to provide this discrimination. Cerenkov light from relativistic particles normally incident on the counter will be totally internally reflected to photomultiplier tubes on both ends. Cerenkov light from particles incident at more than 6 degrees (100 mrad) to the normal will be totally internally reflected to only one photomultiplier tube with concurrent reduction of total light collected. The trigger would require a coincidence of both tubes and/or appropriate discriminator thresholds. This one counter could then provide fast information on both the position and direction of the particle and is not sensitive to low energy backgrounds. We are planning tests in the BNL test beam of UV transmitting lucite Cerenkov Counters. We will test long (about 8') counters with photomultiplier tubes on both ends, and will measure the amount of light as a function of incident angle with and without UV wavelength shifters and with quartz faced photomultiplier tubes.

The rates in the forward region ($2<eta<3$) are very high and may necessitate using straw tubes with short drift times (less than 50 nsec) to keep the occupancy to a reasonable level. Appropriate ORs of straw

tubes from different layers can then be put in coincidence to form the first level trigger.

5. BUDGETS AND MANPOWER

The major funding requests in this proposal are to support the engineering required to integrate the various designs with the physics requirements that are being developed, and to contract for at least four independent sample designs of the toroidal magnets. These designs would be based on initial specifications developed by Grumman to explore the range of options for toroidal spectrometers. Each sample design would be fully engineered and optimized within the specified constraints (e.g. maximal field, minimal materials, access requirements, etc.) such as to allow a reliable evaluation of performance, cost and time for fabrication and assembly. Grumman will have the responsibility of coordinating the designs, supplying common systems engineering support (cyrogenic and power issues, assembly issues, etc.) and considering integration of toroidal systems with supports of internal calorimeteric devices.

Funding is also requested to begin development of superconducting cable, which is a key input to the designs as well as for reliable operation of the spectrometers. This work will be carried out by Oak Ridge in conjunction with industry.

Funds are also required to support the detector development aspect of the spectrometer, from physics studies, tracking and punchthrough simulations, and development of hardware for a fast muon trigger and muon tracking detectors.

We also need funds to support travel to meetings with collaborators and magnet fabricators, and also to support independent consultants at reviews.

We list below the funding requests for this year giving first a summary, and then a breakdown by category, manpower and costs.

BUDGET SUMMARY

A.	TOROID DEVELOPMENT	1,620,000
B.	SUPERCONDUCTOR DEVELOPMENT	457,000
C.	TRACKING SIMULATION AND DETECTOR DEVELOPMENT	445,000
D.	PUNCHTHROUGH SIMULATION	66,450
E.	FAST MUON TRIGGER	160,000
F.	MISCELLANEOUS	165,000
	TOTAL	2,913,450

A. TOROID DEVELOPMENT

Personnel:

Argonne National Laboratory
T. Fields

Grumman Corporation
A. Favale, S. Gottesmann, J. Pusateri, E. Schneid

Brookhaven National Laboratory
A. Carroll

Michigan State University
B. Pope

University of Michigan
L.W. Jones

State University of New York At Stony Brook
M. Marx

Tasks

Toroid Specification and Integration:

-Prepare the initial specifications for the alternative magnet design studies.

-Provide technical oversight of up to four companies that will perform magnet design studies.

-Perform system level studies of the support structures, assembly procedures, cryogenics, material selection, power, schedule, and cost.

-Evaluate magnet design results provided by magnet contractors.

-Provide engineering/scientific liaison for the team.

-Establish design criteria for the selection of optimal designs for the SSC detectors.

-Evaluate interface requirements with other SSC detector components.

-Investigate integration approach at the SSC.

Sample Toroid Design Studies

BUDGET

Toroid Specification and Integration (26 man months @ 16,154 per man month)	420,000
Four Sample Toroid Design Studies: 18 man months per study @ 16,667 / man month (300,000 per study) Four Studies: @ 300,000	1,200,000
TOTAL	1,620,000

B. SUPERCONDUCTOR DEVELOPMENT

Personnel

Brookhaven National Laboratory
A. Carroll

Grumman Corporation
J. Pusateri

Oak Ridge National Laboratory
J. Luton

Michigan State University
B. Pope

Tasks

Sample Superconductor Development and Procurement:

-Determine four sample configurations.

-Procure sample conductors, with and without Al cladding,

-Procure tooling for bending sheathed conductor.

Superconductor Test:

-Design experiments.

-Install instrumentation.

-Prepare test facility.

-Assemble and install test rig.

-Shake down facility and run tests on four samples.

-Evaluate data, compare with theory, post mortem exam, prepare report.

The total level of effort estimated 102 man weeks.

BUDGET

Sample Conductor Development and Procurement (Materials and labor)	100,000
Superconductor Test (Materials and labor)	357,000
TOTAL	457,000

C. TRACKING SIMULATION AND DETECTOR DEVELOPMENT

Personnel

University of Houston
- K. Lau
- R. Weinstein

Massachusetts Institute of Technology
- J. Friedman
- E. Hafen
- P. Haridas
- H.W. Kendall
- L. Osborne
- I. Pless
- L. Rosenson
- R. Verdier

BUDGET	
Mechanical Engineer (1/2 time)	80,000
Electrical Engineer (1/2 time)	80,000
Mechanical Technician (1/2 time)	40,000
Electrical Technician	80,000
Programmer	25,000
Construction:	
Engineering consulting and design (outside)	50,000
Hardware	20,000
Shop & Drafting	30,000
Materials and Services	40,000
TOTAL	445,000

D. PUNCHTHROUGH SIMULATION

Personnel

Louisiana State University
- R. McNeil

BUDGET	
VAX Station 3200	15,000
VAS Station 3100	10,000
8 mm Tape Drive	5,000
Programmer (including benefits)	36,450
TOTAL	66,450

E. FAST MUON TRIGGER

Personnel

Brookhaven National Laboratory
- I.-H. Chiang
- J. Haggerty
- L. Littenberg
- W. Morse

BUDGET

VAX Station 3200	15,000
8 mm Tape Drive	5,000
Photomultipliers	10,000
Lucite Cerenkov Counters	10,000
Scintillation Counters	5,000
Gas Cerenkov Counters	10,000
Gas Systems & Controls	5,000
Electronics and DAQ	40,000
2 Technicians	60,000
TOTAL	160,000

F. MISCELLANEOUS

Travel (average of $5,000 per collaborator)	130,000
Outside Consultants (for reviews)	35,000
TOTAL	165,000

Appendix 6.1

SUMMARY OF STUDY OF FEASIBILITY OF SUPERCONDUCTING AIR CORE TOROIDS FOR SSC DETECTORS

J.N. Luton

The feasibility study described herein was carried out at the Oak Ridge National Laboratory (ORNL) and Princeton Plasma Physics Laboratory (PPPL). These institutions were selected because of their experience and expertise obtained through years of work with magnetic superconducting magnets, toroids, and with the Large Coil Task project. (This project involved the development of superconducting toroidal field magnets for fusion power (See Ref. 9). In several ways the requirements for fusion toroids are more severe than those for detector toroids. However, because of the sizes required for detector toroids, and the relative unfamiliarity of the detector and fusion communities with one another's problems and constraints, it was felt that a study to uncover any pitfalls was desirable.

The initial idealized geometry was composed of eight coils whose cross section in the plane of the conductor was half of a thick-walled hollow rectangle and whose magnetic axes were straight, wedged together to form a toroid whose major axis was that of the beam (See Fig. A1). The field-free internal volume had an inner radius of 3 m along the central 15 m length, and 1.25 m at each end. Each end was 3 m deep. The outer radius was 6 m along the entire 21 m length of the major axis.

The specified current was 3×10^7 Amp-turns, giving fields of 6, 2, and 1 T at the mentioned radii, and an integral Bdl of 4Tm along a 90° ray (i.e., in the torus equatorial plane). For practical reasons, the

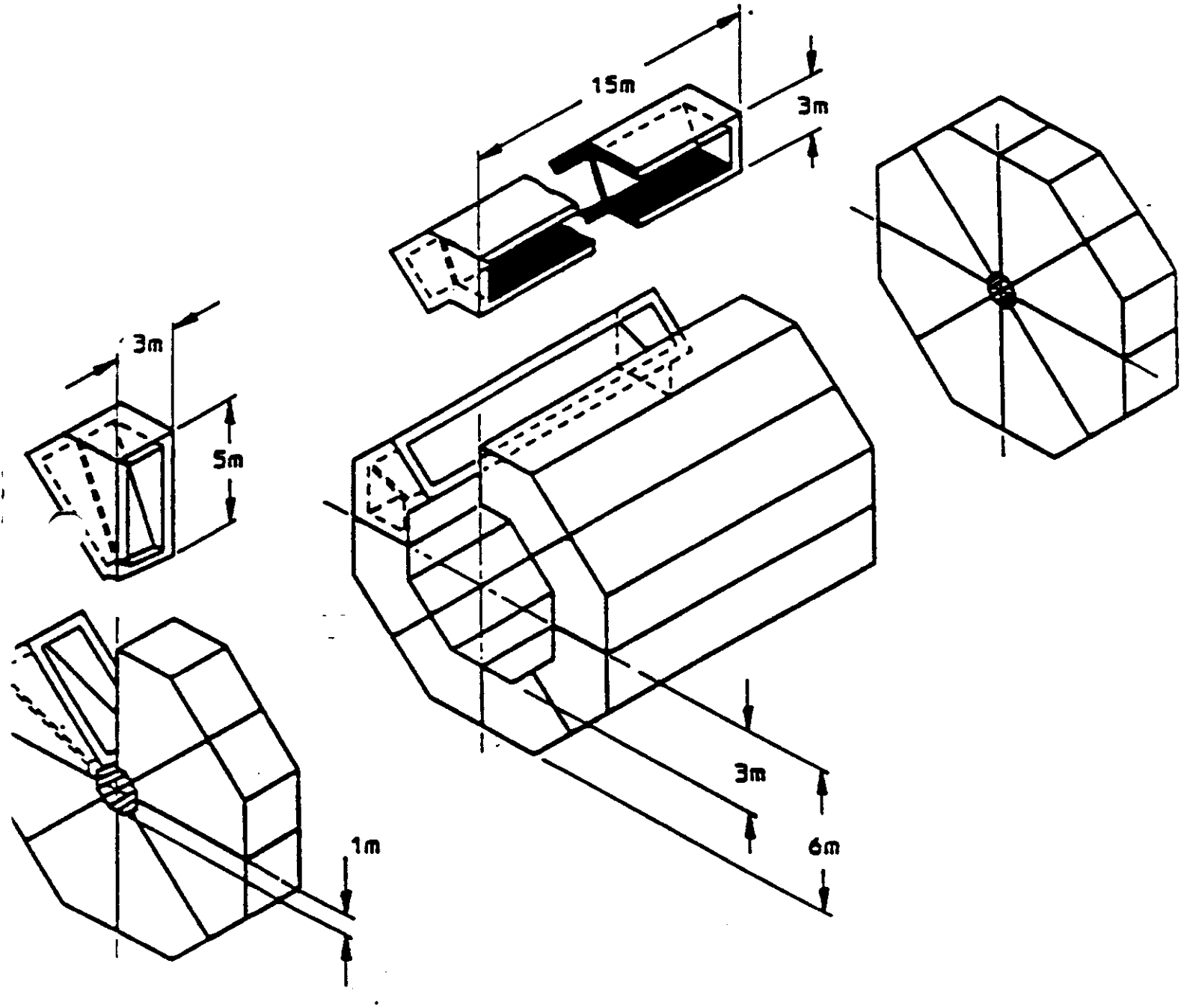


FIGURE A1

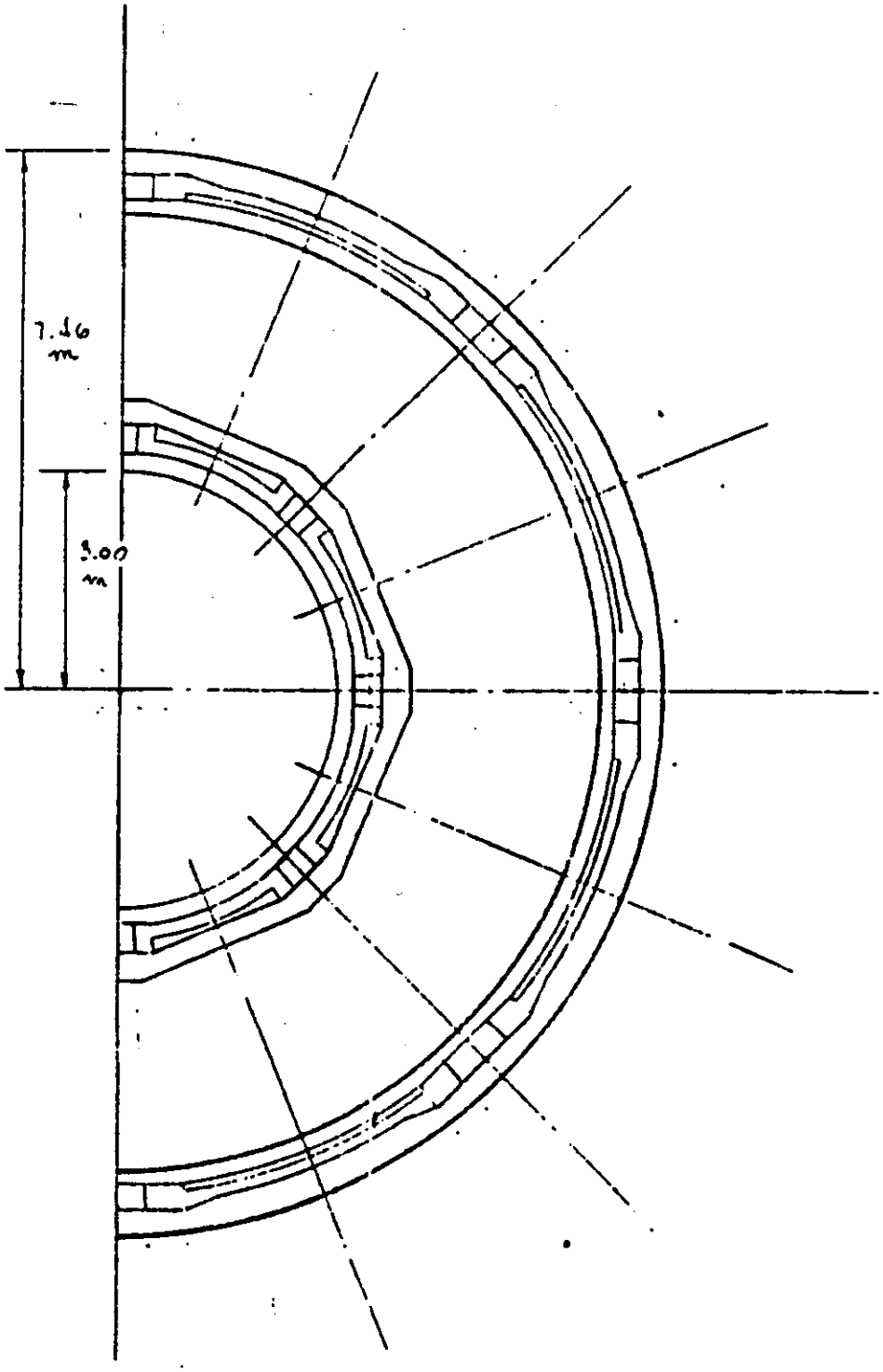
toroid was divided into a central toroid and two end toroids. In addition, flat octant coils were deformed into segments of a circular arch, and access gaps were added between octants.

The long horizontal runs of this winding pack did not seem appropriate for a conductor cooled by the production and free convection of bubbles in a liquid helium bath ("pool-boiling"). Therefore, a forced-flow conductor was chosen instead. To reduce costs and to have a larger cooling area, a cable-in-conduit type of forced-flow conductor was chosen, based on the conductor successfully used in the Westinghouse/Airco LCT coil. Furthermore, the fully developed and economical NbTi SSC dipole strands can be utilized. In order to provide additional copper and the possibility of helium entrances which could be easily and reliably made, additional strands of pure copper would be cabled around the SSC cable. The cable in any such conductor has little strength against transverse magnetic loads, and these magnetic loads must be carried and transmitted by the sheath. The sheath is also the helium containment member, and must restrain the pressure produced during quench by resistive heating of the conductor. The sheath stresses were examined briefly and are high. Careful consideration of these stresses must be given during design of the magnet, and experimental development work is needed to better quantify the quench pressure per unit length and the maximum allowed spacing of helium connection (present data on quench pressure vary by more than an order of magnitude). The material selected for the primary structure was aluminum because of its low cost and ease of machining; its greater required thickness compared to stainless would give better resistance to bending and buckling, and allow lower bolt loads at the structural joints between octants. Its relatively low electrical resistivity would allow it to be effective in abruptly

reducing the conductor current on activation of the dump breaker. The particular alloy selected was 2219-T87, because of its selection for the Westinghouse LCT coil and its good service there. The winding was assumed embedded in notches in the structure, which was otherwise a single thick-walled shell (See Fig. A2). A flexible finite element model was made which uses the magnetic loads generated at each element, and the resulting calculations showed that the stresses were quite low except in the corners, which had been assumed sharp. (See Figs. A3 and Table A1 and A2). A more detailed design using flange/web or honeycomb members should give considerable savings in weight and probably in cost. Nevertheless, it was encouraging that a solid structure appears feasible even for toroids with planar ends and no internal bracing.

The use of an aluminum structure raised the possibility of deliberately designing the toroids to be radiation "thin". This requires the substitution of aluminum alloy for the structural steel of the vacuum vessel walls and of the conductor sheath, and substitution of pure aluminum for some of the copper of the conductor cable. This latter could be accomplished by extrusion cladding of the multifilamentary strands with aluminum. Such strands have already been made experimentally in the U.S. under a SBIR, but further development is needed to demonstrate that a cable-in-conduit conductor from such strands can be produced and operated successfully. In the case of the thin toroids, the requirements on the in-field tracking would be much less, and it is expected that there would be room for internal structure. If so, the weight and cost would be reduced further.

The internal magnetic fields and stray fields were calculated and were satisfactory, although they like, the structure stresses, become



CENTRAL TORUS
CROSS SECTION

FIGURE A2

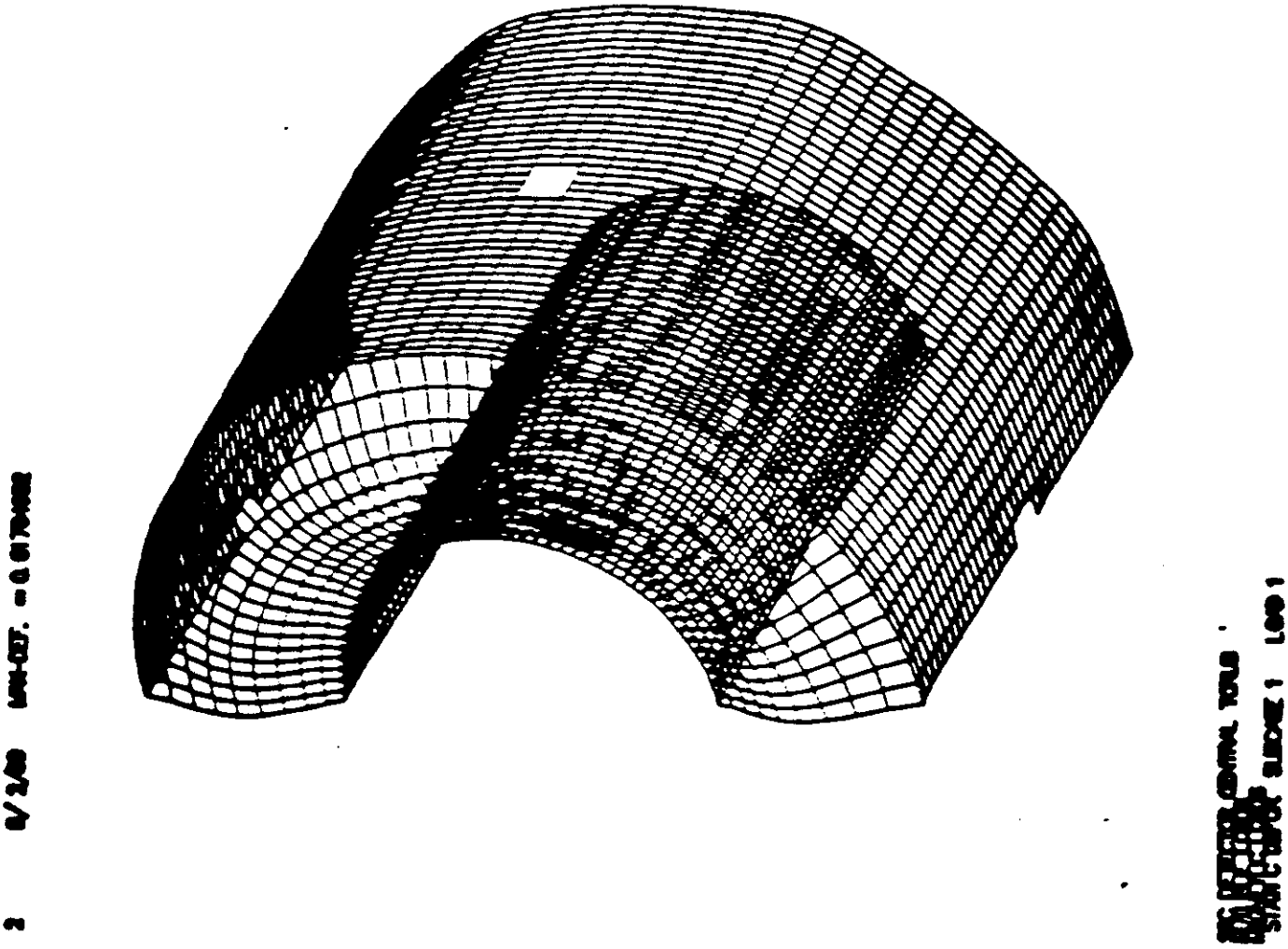
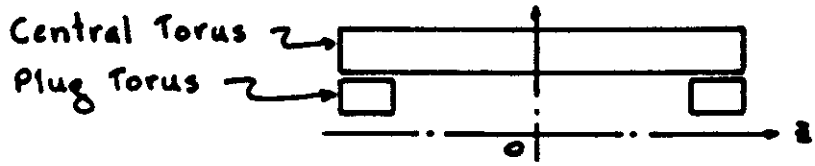


FIGURE A3

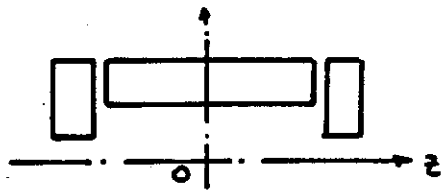
SUMMARY CHARACTERISTICS (1)



		CENTRAL		FORWARD	
DEWAR INNER RADIUS	m	3.00		0.78	
DEWAR OUTER RADIUS	m	7.46		2.90	
NOMINAL LENGTH	m	21.00		3.00	
HALF GAP ANGLE	deg	3.42		3.0	
COIL ARC FRACTION		0.68		0.69	
CYLINDER THICKNESSES	m	0.20	0.15	0.20	0.15
DEPTH AT JOINTS	m	0.40	0.30	0.30	0.30
END FACE THICKNESS	m	0.15		0.15	
HOOP STRESS Z=0	ksi	-3.0	2.0	-8.2	5.2
BENDING STRESS Z=0	ksi	-5.4	6.1	8.9	9.4
MAX BENDING STRESS : CORNER	ksi	25.2		38.1	
RAD. DISP. BTWEEN COILS	mm	-0.86	-0.54	-0.92	+0.70
RAD. DISP. OCTANT CTR	mm	-1.1	-3.1	-0.95	+1.33
MAX. DISP. - END FACE	mm	17.0		5.0	
COIL INDUCTANCE - SHELL	H	1.61		0.23	
STORED ENERGY	GJ	1.29		0.18	
TOTAL SEPARATING FORCE	mt	7586		7491	
CENTERING FORCE / OCTANT	mt	4021		1554	

TABLE A1

SUMMARY CHARACTERISTICS (2)



		CENTRAL	FORWARD
NOMINAL LENGTH	m	15.0	3.0
HOOP STRESS z=0	ksi	≈ (1)	-8.4
BENDING STRESS z=0	ksi		10.3
MAX. BENDING : CORNER	ksi		98.7
RAD. DISP. BTWEEN COILS	mm		-1.11 -3.0
RAD. DISP. OCTANT CENTER	mm		-1.17 -.78
MAX. DISP. END FACE	mm		
CYLINDER THICKNESS	m	0.20 0.15	0.20 0.15
DEPTH AT JOINTS	m	0.40 0.30	0.30 0.30
END FACE THICKNESS	m	0.15	0.30
COIL INDUCTANCE - SHELL	H	1.15	0.59
TOTAL SEPARATING FORCE	mt	7586	19510
CENTERING FORCE / OCTANT	mt	2872	2665

Al: 2219 - T87 @ 20°K	Long.	Tranv.
Min. Y.S. (ksi)	65.8	64.7
Min. UTS (ksi)	90.5	94.1
Avg. E (10^6 psi)	11.2	10.6
e (%)	13.4	11.4

TABLE A2

more favorable as the gap between winding octants is reduced (See Fig. A3). Current-carrying joints in the conductor can be resistance-welded butt joints as was done in the Westinghouse LCT coil except that their location on the conductor need not be predetermined. A stability margin of 150 mj per cubic centimeter of strands is achievable and sufficient. Protection of a quenching toroid against overheating is feasible even with all octants electrically in series, an advantage for the avoidance of unbalanced fault loads. A winding configuration was formed which allows, with certain restrictions, the winding at the larger-radius leg to occupy less space radially than at the smaller radius leg, thus utilizing the available space more efficiently.

Individual components (octants) are within the size and weight of components of other detectors, and shipping and on-site assembly are considered feasible. It is feasible to have the end toroids either as "caps" or "plugs". The magnetic forces between a central toroid and an end plug toroid were estimated and are smaller than the gravity loads; thus, separate mounting for easier access is feasible. The end plug has some advantages in size and smaller ratio of outer to inner radii compared to that of the end cap, but the end cap is preferred because it provides greater usable field volume.

The design and fabrication must of course be carefully done, and some development work is called for, but no insurmountable difficulties were found. The authors concluded that the use of such air-cored toroids for SSC detectors is feasible.

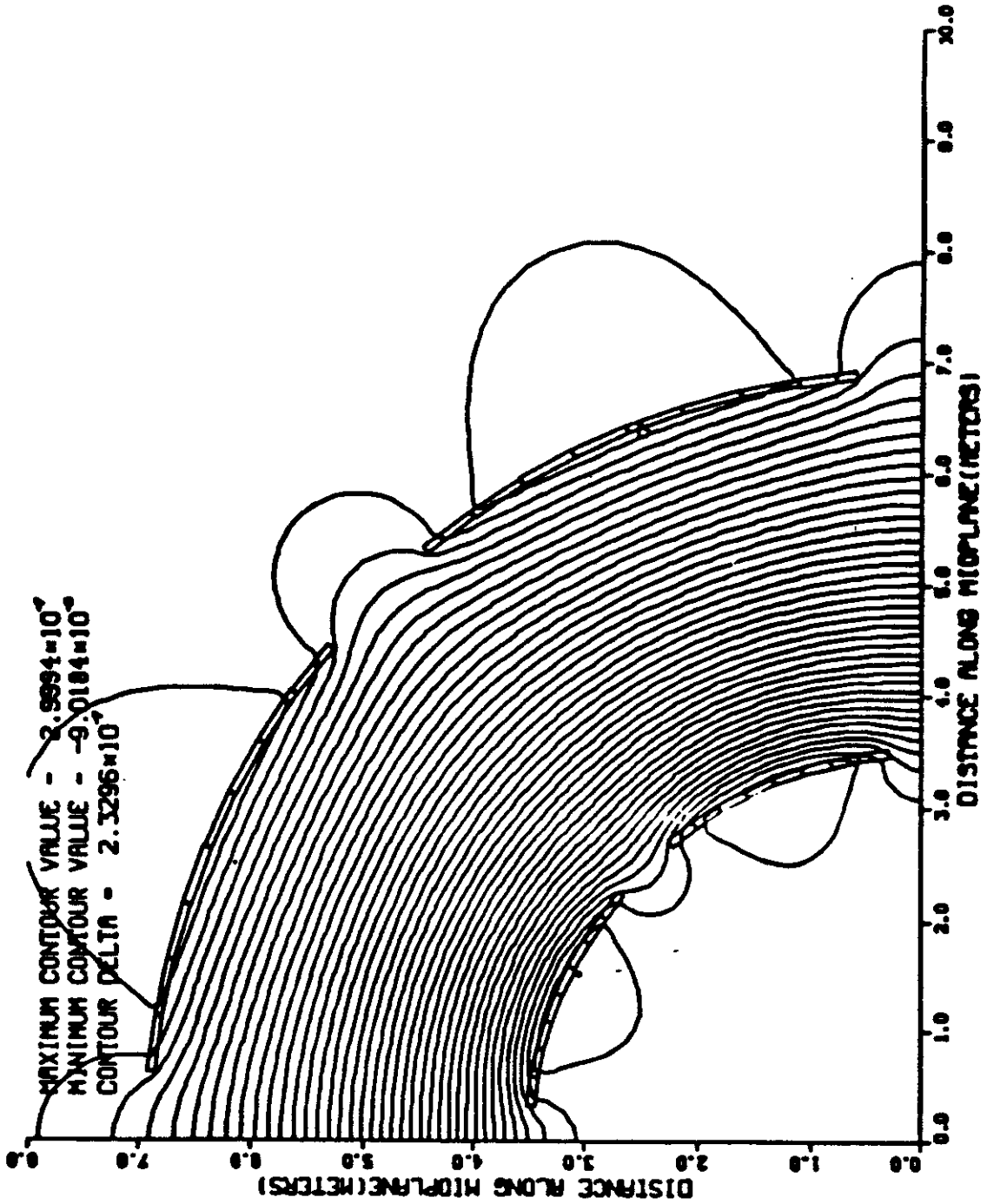

MAXIMUM CONTOUR VALUE - 2.9994×10
MINIMUM CONTOUR VALUE - -9.0184×10
CONTOUR DELTA - 2.3296×10
DISTANCE ALONG MIDPLANE(METERS)
DISTANCE ALONG MIDPLANE(METERS)
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
9.0
10.0

FIGURE A3

Appendix 6.2

GRUMMAN QUALIFICATIONS

NUCLEAR AND RADIATION PHYSICS

This work is mainly conducted by the Corporate Research Center of the Grumman Corporation. The Research Center has been involved in nuclear program for over 32 years. This work covers such topics as:

- Nuclear reaction and radiation transport code development
- Nuclear Activation of materials
- Use of nuclear reactions for microprobing material surfaces
- Radiation effects on electronics
- High Energy Gamma Ray Astronomy
- Development of wire chambers for high energy physics experiments in space and for X-ray crystal spectrometers
- Design, development, fabrication, test and operation of gamma ray and neutron detectors for military intelligence and neutral particle beam programs
- Design, development, fabrication of low power, hybrid nuclear electronics

Grumman's nuclear laboratory is equipped with a 4 MV Van de Graff, a 14 MeV neutron generator and a large complement of electronic equipment for nuclear counting. Grumman physicists have participated with national laboratory and university scientists conducting experiments on accelerators such as SLAC, CERN and the AGS at BNL.

The Fusion Program

Since 1975 Grumman has been a major player in the U.S. Fusion Program. We have work with every major laboratory in the free world and with most of the key universities. For example, Princeton Plasma Physics Laboratory, Oak Ridge National Laboratory, Lawrence Livermore National Laboratory, Lawrence Berkeley Laboratory, Los Alamos National Laboratory, Culham Laboratory, Cadarache Laboratory, JAERI Laboratory, University of Nagoya, M.I.T., UCLA and the University of Wisconsin. Our work covers both physics and engineering. Grumman has been responsible for the design of the toroidal magnets for the TFTR at Princeton and for all the reactor designs developed at the Fusion Engineering Design Center. In addition, Grumman was retained by the French government to supervise the assembly of the only superconducting toroidal magnet device in the free world i.e. the TORE SUPRA tokamak in Cadarache France. We are presently working with Princeton on the design for the next U.S. tokamak, the Compact Ignition Tokamak.

Accelerators and Accelerator Technology

Grumman is involved in the development, design, fabrication test and operation of LINACS and synchrotrons. Below is a listing of the accelerator programs Grumman has been involved with:

- Beamline design and procurement for BNL lethality test facility and beam neutralization and sensing facility.

- Design, fabrication and test of the RFQ for LANL's BEAR (Beam Abroad Rocket) program. This RFQ is the first space qualified accelerator.

- Design and fabrication of the ramped gradient drift tube LINAC for LANL's ATS facility.

- Industrial Partner with LNAL on their $400M Ground Test Accelerator. Grumman has 31 physicists, engineers and technicians at LANL.

- Industrial Partner with BNL on their Superconducting X-ray Lithography Synchrotron. Grumman has 11 physicists and engineers at BNL.

- Grumman is the prime contractor for the U.S. Army Strategic Defense Command's Continuous Wave Deuterium Demonstrator. This is a CW, cryogenic very bright deuterium accelerator.

- Grumman is under contract from Argonne National Laboratory to design a high current superconducting LINAC.

- Under its own funds, Grumman is developing automatic control systems for ion sources, both Penning and volume sources. In addition, we have a CW, RF development program for RF drive loops, seals and cavities.

Appendix 6.3

RESPONSES FROM MAGNET FABRICATORS

Attached are several responses to an initial query as to the feasibility of construction of a system of superconducting air core toroids. Also attached is the response of Westinghouse after participating in a review of the Luton-Bonanos feasibility study (Appendix 6.1) held in Dallas on August 17.

1.	Westinghouse	09/25/89
2.	Oxford	09/13/89
3.	Ansaldo	05/29/89
4.	General Atomics	06/08/89

Westinghouse
Electric Corporation

Power Generation
Business Unit

Power Generation
Operations Division

The Quadrangle
4400 Alafaya Trail
Orlando Florida 32826-2399

September 25, 1989

Dr. Michael Marx
High Energy Group
State University of N.Y. at Stony Brook
Stony Brook, NY 11794-3800

Subject: SSC Detector Toroidal Coils

Dear Dr. Marx:

We have reviewed the materials you supplied at your August 7, 1989 meeting and I have also discussed this information with Dr. Luton of the Oak Ridge National Laboratory.

Based on the information we have to date, we estimate the cost of the subject coils to be $125/135 M with a delivery schedule of 5/6 years after the start of the development effort.

A more definitive cost and schedule can be established as the coil design progresses. In particular, however, the following items should be addressed early in the program to minimize their impact.

(1) CONDUCTOR

Although the coil design and analysis can proceed using preliminary conductor characteristics, a point will come when the conductor must be developed, lengths manufactured and tested and the results made available to the designers. This should be done early in the program since conductor costs and winding times are largely unsubstantiated until data is available.

(2) MATERIALS

Final selection of materials could impact cost and schedule. Materials cost are straight forward, but we have found in the past that changes in fabrication requirements can have a greater impact.

Oxford Instruments Limited
NMR Division

Osney Mead
Oxford OX2 0DX
England

Telephone (0865) 241456
Telex 837332
Fax (0865) 240780

Dr M Marx
High Energy Group - Department of Physics
State University of New York
Stony Brook
NY 11794-3800
USA

JSHR/BAE

13 September 1989

Dear Dr Marx

EMPACT MAGNET

Unfortunately I was unable to contact you while you were in Madrid recently (8-13 September): the Spanish telephone system seems to have defeated me! Nevertheless the information sent on to me by my colleague Peter Penfold of OINA was very useful and some comments are well justified.

We recognise the approach being followed by Jim Luton and Peter Bonanos as we have been keeping in touch with the excellent work done by Oak Ridge and the various collaborative groups working on the LCP project. In general we approve of this type of conductor - variously referred to as cable-in-conduit or internally cooled cable superconductor (ICCS) - for those applications on a large scale where conductor movement and other generally unknown effects require the conductor to be capable of withstanding significant transient disturbances. The now somewhat old fashioned approach of a fully cryostable conductor can often lead to electrical and mechanical problems in the long term. This is a very generalised statement but in the main we would go along with the conductor philosophy. Precise parameters for the design and its method of manufacture obviously need a great deal of care and iteration to reach a preferred rating. At this stage I would suggest the overall current density of around 4 kA/cm^2 is higher than we would have expected for a magnet system of this size.

My own involvement in ICCS dates from around 1978 when I was working on the design of large superconducting generators and we were taken by the advantages of this conductor after initial talks with Mitch Hoenig of M.I.T. As a result we made a trial coil mainly to confirm computer predictions of the pressure produced in the conductor following a quench - not a trivial problem! This work was done in collaboration with Martin Wilson and Colin Walters at the Rutherford Appleton Laboratory. Martin Wilson is now in a senior position at Oxford Instruments managing our large project on the manufacture of a superconducting synchrotron for X-ray lithography. The results of this work on the ICCS conductor were published at the 1982 Applied Superconducting Conference and a copy of the paper is enclosed for your interest.

We already have some questions and would be grateful if you could consider these.

Registered Office
Osney Mead
Oxford OX2 0DX

Registered in England
Number 704320

A member of
The Oxford Instruments Group plc

We understand the detectors are to be located within the (between the large radius axial current path and the smal current path) and one advantage of using 8 octants for each allows the detectors to be inserted into place before themselves assembled together. Our question is whether yo these detectors without dissembling one or more of the probably means breaking vacuum and cryogenic connections.

On the conductor design, you have chosen a target stabil mJ/cm^3. Is this unit volume that of the winding package helium and insulation) or of the copper and copper/Nb- mention the conductor is based on the LCP Westinghouse de course niobium-tin. In EMPACT, you intend using t construction but using a niobium-titanium alloy.

We look forward to your comments and trust we will be discuss the project as the design proceeds and you are placing feasibility studies and design contracts.

In the meantime, I hope your investigations go well in th project.

Yours sincerely

J S H ROSS
MANAGER
SPECIAL PROJECTS GROUP

Enc. Published Paper on ICCS conductor

cc. Mr Peter Penfold (OINA)
Mike Bland

ns. rif. PMA/COMM/SCI/257/as

vs. rif.

SUPERCONDUCTING SUPER COLLIDER
Central Design Group
c/o Lawrence Berkeley Laboratory
Mail Stop 90/4040
Berkeley, California 94720

Att. Prof. Michael Marx

Genova, 29/5/89

Dear Prof. Marx,

we have received your letter dated May 11th, 1989 and take the chance to send you our first comments on your toroids:

- We are certainly interested to design, manufacture and test all the coils as well as the mechanical parts.

- In spite of the magnitude, on the manufacturing point of view, your toroids look feasible.

- As far as transportability is concerned, please note that our factory is placed very close to the port of Genova therefore until the port of Houston or New Orleans we do not see problems of transportation. From the US ports to Waxahachie we have no idea of the kind of roads available, but we are sure you can evaluate better then us.

- The delivery time of those coils would be typically about four or five years, depending if you include model, prototypes, samples, tests, etc.

- We are not able in this moment to evaluate the costs of those toroids because we need to do some predesign and some consideration.

ANSALDO ABB COMPONENTI s.r.l.
Direzione Generale, Via N. Lorenzi 8, 16152 Genova Italia
Tel. (010) 6551, Fax 010 6556209, Telex 270006 ANSCOC I, Telegr. ANSCOMP GE, C.P. 4657
Codice Fiscale, Partita IVA n. 03079140103, CCIAA N. 315609 Genova, Iscriz. Tribunale di Genova n. 51478
Sede Legale a Genova, Capitale L. 210.000.000.000

GENERAL ATOMICS

June 8, 1989

Michael Marx
SSC Central Design Group
c/o Lawrence Berkeley Laboratory
Mail Stop 90/4040
Berkeley, CA 94720

Dear Mr. Marx,

I have examined your requirements for the superconducting coils for the EMPACT detector of the SSC. Since your program is in the conceptual stage, it is difficult to give precise answers but here are my initial thoughts:

•General Atomics would be very interested in participating in the design and construction of these superconducting toroids. The GA Magnet Engineering Group was organized 13 years ago and has successfully designed, developed, and tested a wide variety of normal and superconducting magnets for research, defense, and commercial applications.

•The construction of the toroids will be challenging, but should present no insurmountable problems. Coils of similar size and field strength have been built by various groups around the world. Custom winding machines will have to be built to handle the large size and weight of the coils.

•Transportation of the toroids to Texas will be a major challenge. The end toroids, at about 44 tons per coil, can be transported by truck. They are similar in size and weight to the "T2" coils of the MFTF-B system. These coils were 3m x 3m x 3m in size and weighed 50 tons each. They were shipped by truck from San Diego to Livermore.

My calculations give the weight of the central toroids at about 100 tons each. Due to the weight and size of these coils, I believe they will have to manufactured at the Texas site.

10955 JOHN JAY HOPKINS DRIVE, SAN DIEGO, CA 92121-1194 P.O. BOX 85608, SAN DIEGO, CA 92138-5608 (619) 455-3000

•The program to build the superconducting magnets for the MFTF-B system was approximately the same size as that required for EMPACT. The preliminary design, detail design, construction, and installation phases for the MFTF-B system required about 4 years.

•The material cost will be the primary cost component. I have estimated the cost of the superconducting wire by assuming a current density of 5 kA/cm^2 and a cost of $6.50 /kA m. Using these parameters, I obtain a cost of superconducting wire of $900K per central toroid and $400K per end toroid. This gives a total superconductor cost of $13.6M.

The other major material cost will be the structural material. I have assumed 1 inch thick 304 stainless steel which costs $2 /lb. Using these parameters, I obtain a stainless steel cost of $310K for the central toroids and $100K for the end toroids. This gives a total stainless steel cost of $4.1M.

Using the above costs as a basis, and including other material costs and other tasks such as design, analysis, construction, transportation, and installation, I estimate the total cost at approximately $30M.

I hope that my opinions and cost estimates are of value to you. I can be reached at (619) 455-4252 if you have further questions.

Sincerely,

Chuck Gibson
Senior Engineer
Magnet Engineering Group

cc: J. Cruetz
E. Johnson

Appendix 6.4
TOROIDAL PARAMETERS AND PERFORMANCE

Fig. D1 shows an idealized distribution of current elements defining a toroidal system with definition of physical parameters. Note that central and end systems can be arbitrarily separated by introducing additional opposing current legs without changing field distributions.

The purely azimuthal magnetic field is given by

$$B(\text{Tesla}) = 2 \times 10^{-7} \; (NI(\text{Amps})/R(\text{meter}))$$

Thus the product B R is a constant for the system. As an example, for the toroids discussed NI = 3×10^7 Amps and BR = 6 Tesla-meters.

Of interest for this system is the variation of the field integral. This is tabulated below

	$\int Bdl$	$L \int Bdl$
90°	$BR \ln(R_o/R_i)$	$BR\,(R_o - R_i) \ln(R_o/R_i)$
Central	$(BR/\sin\theta) \ln(R_o/R_i)$	$(BR\,(R_o-R_i)/\sin\theta) \ln(R_o/R_i)$
Ends	$(BR/\sin\theta) \ln(Z_o/Z_i)$	$(BR\,(Z_o-Z_i)/\sin\theta\cos\theta) \ln(Z_o/Z_i)$

The stored energy for the central toroid is given by

$$U\ (\text{GigaJoules}) = 2.5\ L(BR)^2 \ln(R_o/R_i)$$

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