EMPACT

ELECTRONS MUONS PARTONS WITH AIR CORE TOROIDS

An Expression of Interest
for an Experiment
to be Performed
at the
Superconducting Super Collider

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ABSTRACT

The EMPACT experiment utilizes a broad approach to maximize its discovery potential for new phenomena accessible at the SSC. The high resolution detector has a balanced emphasis on, and large acceptance for, electrons, muons, jets, and noninteracting particles, and is capable of utilizing the ultimate luminosity of the SSC. The detector emphasizes excellent calorimetry augmented by TRD tracking, and employs an innovative system of superconducting air core toroids for muon measurements. Significant engineering effort has established the feasibility of a baseline detector concept and has addressed the related issues of support facilities, assembly, and detector integration. The design has been tested against the challenges of predicted phenomena, with the expectation that this will optimize the capacity for observing the unexpected. EMPACT's international collaboration has unprecedented support from major aerospace industries who are providing tools and expertise for project design and integration, which will assure that a detector optimized for performance and cost will be available for the first collisions at the new laboratory.

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1 OVERVIEW

1 - OVERVIEW

The Superconducting Super Collider (SSC) offers a unique opportunity for discovery of new physics and in particular for understanding the origin of mass. Many ideas relating to the question of mass have been suggested, including the standard Higgs boson and various extensions, supersymmetry, technicolor, or $t\bar{t}$ bound states as replacements for elementary Higgs bosons, composite models for quarks and leptons, and strong WW interactions. While none of these ideas is compelling, it is clear that any new physics will likely involve large masses and small cross sections and will have signatures involving the quanta of the standard model: electrons, muons, jets, photons, $W^\pm$, Z^0 , and neutrinos or other noninteracting particles. Since many of the signatures for new physics will involve combinations of these quanta, a balanced detector with good resolution and large acceptance for all of them will likely yield the best results.

We propose to build a detector, EMPACT (Electrons, Muons, Partons with Air Core Toroids) [1], that will provide the broadest approach to and maximal discovery reach for SSC phenomena. The current EMPACT design shown on the facing page has an inner region in which tracking and transition radiation detectors determine the event topology and help to identify electrons, muons, and other high momentum particles. This is surrounded by high quality electromagnetic and hadronic calorimetry, providing measurements of electrons and jets. The calorimetry is highly hermetic to give a good measurement of missing p_T . Outside the calorimeter are large air core toroids, which, with associated tracking, provide measurements of muon momenta with precision comparable to the calorimeter measurements of electron and jet energies over a similar solid angle.

Since many of the cross sections for new physics at the SSC are extremely small, there is a

substantial advantage in utilizing the ultimate luminosity of the SSC – estimated to be in excess of $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$. The EMPACT design, with its reliance on calorimetry and with its well shielded muon system, lends itself to high luminosity operation, and all design choices for detector elements will be reviewed in terms of their applications for high rates and radiation levels.

Many details of the design remain open, but we have invested enough engineering effort to convince ourselves that the general scheme is practical and that it will be able to provide the kind of well-balanced performance that we believe offers the best chance of discovering new physics at the SSC. This engineering has benefited greatly from a very productive partnership with high technology aerospace companies. They have provided intellectual, technological, and financial support for this proposal. We have pioneered the application of advanced engineering tools to the assessment of physics performance, allowing rapid evaluation, iteration, and optimization of design parameters. Our industrial collaborators provide the degree of professional planning and management demanded by a project of this scale.

1.1 PHYSICS MOTIVATIONS

The primary motivation for the construction of a 40 TeV hadron collider is to explore electroweak symmetry breaking – the origin of the masses of the gauge bosons and the quarks and leptons [2]. While the source of this symmetry breaking is unknown, the mass scale at which it must manifest itself is not. All theories indicate that strong interactions of the longitudinal components of the vector bosons, e.g., $W_L^+ W_L^- \rightarrow Z_L^0 Z_L^0$, must increase, violating unitarity in the 1 - 2 TeV range unless some mechanism suppresses them. The standard model is finite and renormalizable, due to the existence of a scalar Higgs singlet. Supersymmetric models, which have profound implications for the unification of all

forces, predict a host of new particles with well defined interactions and decays but undetermined masses. Technicolor and other dynamical symmetry breaking mechanisms replace the elementary Higgs mechanisms with composite particles. Many of these predicted new particles produce W's and Z's in their decay chains. Signatures for the production and decay of supersymmetric particles include events with like sign leptons or events with jets and missing p_T and no leptons. If the standard Higgs, supersymmetry, or technicolor models are not correct, there are still other possibilities for the source of symmetry breaking. Two extremes are the emergence of strong interactions between the bosons that will entail studies of boson pairs with masses in the 1–2 TeV range [3] and the possibility of a heavy top (around 200 GeV) condensate playing the role of the Higgs [4].

The cleanest method for discovering the standard Higgs boson above the Z^0Z^0 threshold is through the decay of the Higgs to two Z^0 's that subsequently decay to either electrons or muons. Figure 1-1 shows the contours in energy and luminosity for

Fig. 1-1 Luminosity Required to Produce in 1 Year 20 Standard-Model Higgs Bosons that Decay to 4 Charged Leptons (e, μ) as a Function of CM Energy (Mass of t Quark = 85 GeV)

producing 20 events with electrons and muons in the final state. Realistic detector and running efficiencies suggest that discovery in this channel for Higgs masses above 600 GeV will require the measurement of both electron and muon decays,

and most likely higher luminosity. Figure 1-2 shows the reconstructed 400 GeV Higgs signal with background as a function of detector resolution [5].

Fig. 1-2 400 GeV Higgs Signal on ZZ Continuum Background for Various Resolutions & Technologies. EMPACT resolution for muons is equivalent to EM calorimetry in (b).

The premium of good resolution and, again, the advantage of having equivalent resolution for electrons and muons are apparent.

As the Higgs mass increases and the cross section decreases, there emerges a need for searches in more complex decay channels. These include decays to Z^0Z^0 , where one Z^0 is detected through the leptonic decay, and the other is detected by its decay to either jets or neutrinos. The decays to WW are also available, but the double leptonic decay is un-

reconstructible, and the single leptonic decay, with the other W decaying to two jets, is subject to large background from the decay of heavy top and from QCD interactions producing a W and two jets. It is unclear if this signal can be seen, but good jet measurements will certainly be required.

For Higgs masses below the $Z^0 Z^0$ threshold [6] and above about 800 GeV, different approaches are needed. Below $Z^0 Z^0$ threshold, ZZ^* (virtual Z) production can be studied through similar channels as real $Z^0 Z^0$. Associated production of Higgs and W can be studied through the bb decay, requiring a good b tag and vertex detector. For some regions, $H \rightarrow \gamma\gamma$ is the only viable channel. This will likely require a dedicated detector because the methods known to achieve $\Delta E/E < 1/2\%$ at 100 GeV are likely to affect the hadronic resolution to the point that the missing E_T resolution is jeopardized. This is inconsistent with the broad goals of EMPACT. For a very heavy Higgs, elucidation of symmetry breaking will come through studies of $W_L W_L$ final states. Extraction of the signal may require a measurement of event multiplicities [7] that is particularly suited to the capabilities of a nonmagnetic detector.

The electroweak gauge group may be larger than in the standard model. In the search for new extended gauge groups, a key signal would be the detection of a heavy Z' boson. Figure 1-3 shows contours in energy and luminosity for producing 100 Z' events for various Z' masses. While resolution is not likely to affect the discovery of such an object because of the expected absence of background, an understanding of the character of the new object will come through measurements of its decay asymmetry. This requires a detector with good resolution and acceptance for muons in the forward region.

In addition to the exploration of the symmetry breaking sector, the SSC will provide the opportunity to search for evidence of new families of quarks and leptons. The SSC will be an ideal instrument for studying the top quark, whether or not it is discovered at the Tevatron. The top must be well under-

Fig. 1-3 Luminosity Required to Produce in 1 Year 100 Z' Bosons, with Standard-Model Couplings, as a Function of CM Energy

stood, because it is a background to Higgs studies as well as a possible source of symmetry breaking if its mass arises through dynamical means. In addition, it is still possible, for example, to contemplate the existence of a fourth generation whose leptons (charged and neutral) are sufficiently heavy to not affect the width measurements of the Z^0 .

With the energies available at the SSC, it will be possible to extend the Rutherford scattering exploration for substructure to the quarks themselves. Through studies of very high p_T jets, it will be possible to detect compositeness at the scale of tens of TeV or, equivalently, objects 10^{-5} of the size of the proton.

Finally, we note that the discovery limits of the SSC are determined by the energy and the luminosity of the machine. These are illustrated vividly by Fig. 1-1 and 1-3, which give discovery contours for Higgs and new Z' s. Designing a detector that can accommodate luminosities significantly above the design luminosity of $10^{33} \text{ cm}^{-2} \text{ s}^{-1}$ will greatly extend the usefulness and power of the detector for discovery of higher mass phenomena.

1.2 DETECTOR PHILOSOPHY

The common thread that links these physics objectives is the clear importance of studying the

intermediate bosons – the $W^\pm$, Z^0 and the photon – through their decay products, namely the electrons, muons, jets, and neutrinos, which also constitute the fundamental probes of high energy collisions. A detector that is capable of providing an optimized and balanced emphasis on all these accessible probes will provide the broadest possible attack on these critical issues. Perhaps even more significantly if these goals are accomplished, one will have a detector that can discover new and unexpected phenomena that historically have revealed themselves through the leptons as pointlike probes of the interactions. The EMPACT philosophy is to test the design of the detector against the challenges of predicted phenomena, believing that this also optimizes the capacity for observing the unexpected.

In order to cope with the challenges of the SSC, the EMPACT design seeks to optimize the detector by using uniform technology over the full solid angle, with excellent resolution for electrons, muons, jets, and neutrinos, while maintaining the capability to run at very high luminosity. Uniform technology is beneficial, because each detector boundary or change in technology necessitates some loss of signal and the possibility of background simulating rare processes. This is particularly true for key processes such as the Higgs decays to four lepton final states, where even small inefficiencies can combine to give poor acceptance. Combining signals from differing technologies or from systems with different detector response is difficult at best, as experience has repeatedly shown. Uniform technology also provides the key advantage to trigger on all the fundamental probes – electrons and photons, muons, jets, and neutrinos – in a uniform way over the full solid angle as discussed in Section 5.

Large acceptance in solid angle, especially in rapidity, is required for most predicted physics at the standard luminosity. For masses of new objects below 1 TeV, the decay products are distributed over ± 2.5 units of rapidity, and exploration of associated backgrounds suggests detector sensitivity to ± 3 units. This is especially true for measurements of forward-backward asymmetries for the study of high mass objects.

Good resolution is a requisite in many cases for optimizing signal to background. The exact specification is important to quantify, since good resolution is expensive. For electrons and jets, the resolution limits are naturally set by the systematic effects in a calorimeter. For muons, resolution comparable to that of electrons is desirable. To quantify this, muons and electrons from Z^0 decays of a heavy Higgs ($M_H = 800$ GeV) will both be measured with sufficient resolution to reconstruct the parent Z^0 at its intrinsic width. While the resolution for leptons is not critical for four lepton decays that are fully constrained, it may be a significant aid in signal to background in those channels where only one Z^0 can be identified. This is especially true at high luminosity where the ability to reject backgrounds may deteriorate due to loss of information from tracking or calorimetry [8]. For a heavy new Z' , good momentum resolution is not important for discovery but is required to study the decay asymmetry that characterizes the new particle. For the hadron calorimetry, we require resolution and segmentation that will not limit the reconstruction of hadronic W and Z decays.

Finally, a detector capable of utilizing as much of the ultimate luminosity of the SSC as possible will provide maximum discovery potential. To run at high luminosity, it will be necessary to modify the triggers and plan new strategies for handling pileup in the detector. It is our goal in the design of this detector to study the widest possible range of new phenomena accessible at the SSC. We will begin our studies at the standard energy and luminosity and, as the SSC luminosity improves and lower mass and transverse momentum phenomena are studied, we will provide a detector capable of utilizing luminosities of an order of magnitude higher. The SSC will have decades of useful life, and this detector will evolve and adapt with the machine to new physics for improved performance.

1.3 DETECTOR CONCEPTUAL DESIGN

We have begun the conceptual design of EMPACT based on the general principles stated above. The crucial element in this detector is the calorimeter that provides precision measurements of elec-

trons, photons, jets, and missing transverse momenta. The calorimeter, augmented by a tracking system, also provides particle identification. The absence of a central magnetic field allows for better hermeticity and simplified tracking functions at all luminosities, and optimization of the calorimetry is best accomplished in the absence of a field. A detector designed without the constraints of a central field offers advantages in acceptance, uniformity, and rate capability at the design luminosity and beyond for the high mass phenomena for which the SSC is being built. At higher luminosities, where low p_T tracks from multiple interactions create problems by looping in a magnetic field, EMPACT, with its reliance on calorimetry over magnetic tracking, will suffer minimal degradation of performance. In order to achieve resolution for muons equivalent to electrons over the full solid angle, we

are proposing to build a spectrometer based on a large system of superconducting toroidal magnets that surround the calorimetry.

The feasibility of the EMPACT concept has been established by the development of a baseline detector. An elevation view of the detector is shown in Fig. 1-4, and a quadrant of the detector showing key dimensions and weights is shown in Fig. 1-5. The design incorporates a tracking system based on azimuthal straw tubes operated as a transition radiation detector as discussed in Section 2. Pixel detectors for tagging b decays are being explored. The tracking system occupies a volume 1 m in radius and 5 m in length. Surrounding the tracker is a volume for calorimetry, 3.5 m in radius and 17 m in length as discussed in Section 3. We are currently evaluating two technologies: (1) liquid argon (LAr) with uranium plates as in Fig. 1-4 and (2) scintillat-

Fig. 1-4 Elevation View of EMPACT Detector

Fig. 1-5 Quadrant of the EMPACT Detector Showing Key Dimensions (cm) and Weights

ing fibers embedded in lead (SPACAL) as in Fig. 1-5. The SPACAL would be augmented with either a silicon based electromagnetic section or silicon pre-converter. Beyond the calorimetry are measuring stations for muon trajectories, sufficient to give an entrance point in the central region and an initial direction in the forward region. The toroidal magnetic system is divided into central and end regions, and provides adequate bending with minimal multiple scattering – typically much less than five radiation lengths in each magnet. Outside the magnets are two further measuring stations that provide the exiting direction for the muons. The muon system is described in Section 4, while the triggering, data acquisition, and computing are in Section

5. The performance specifications for the baseline detector are given in Table 1-1. In Section 6, simulation studies to evaluate the physics potential of EMPACT are discussed.

At this stage of the project, the baseline has evolved from various concepts and arrangements of its detector subsystems and from consideration of a feasible approach to detector support and assembly. The relatively light weight of the detector permits a novel support scheme that suspends the entire detector from overhead frames, as shown in the illustrations on the front and back covers. This novel scheme intrudes minimally in the positioning of detector elements and services, allowing almost

Table 1-1 EMPACT Baseline Specification

TRD/TRACKING			
Coverage*	 $\eta < 3$		
Rejection.....	3×10^{-3}	for	$P_{\pi} < 50 \text{ GeV}/c$
Efficiency.....	90%	for	$P_e > 1 \text{ GeV}/c$
			$P_{\mu} > 100 \text{ GeV}/c$
			$P_{\pi} > 150 \text{ GeV}/c$
Channels.....	384 000		
CALORIMETRY (LAr Option)			
Coverage.....	$\eta < 3$	EM and HAD	
	$3 < \eta < 5.5$	HAD only	
Depth.....	11 λ Active	12 λ Total	$\eta = 0$
	14 λ Active	15 λ Total	$\eta = 3$
	12 λ Active		$3 < \eta < 5.5$
Segmentation..	0.02 EM	0.04 HAD	$\eta < 3.0$
($\Delta\eta = \Delta\phi$)		0.2 HAD	$3 < \eta < 5.5$
Channels.....	156 000 Barrel		
	117 200 Ends		
	2 000 Forward		
Energy			
Resolution...	0.15/($\sqrt{E(\text{GeV})}$) + 0.01	EM	
($\Delta E/E$)	0.5/($\sqrt{E(\text{GeV})}$) + 0.02	HAD	
MUON SYSTEM			
B max.....	1.5T Central	4.5T Ends	
Field Integral..	3.6Tm	$\eta = 0$	
	18.6Tm	$\eta = 2.5$	
Stored Energy.	1GJ per toroid		
Coverage.....	$\eta < 2.5$		
Spatial			
Resolution ..	200 μm		
Max Drift	1 cm		
Planes.....	32 Bend	16 Non Bend	
Channels.....	500 000		
Resolution.....	3% 100 GeV; 5% 500 GeV	$\eta = 0$	
($\Delta P/P$)	1% 100 GeV; 2% 500 GeV	$\eta = 2.5$	
* η is written for absolute η everywhere in this proposal			
MP90-3180-016			

complete muon coverage, discussed further in Sections 4 and 7. The assembly studies have generated a baseline facility plan that suggests that major fabrication and subassembly work be completed at surface facilities. Lowering essentially completed subassemblies into the interaction hall will minimize time, effort, and space underground. This is shown schematically in Fig. 1-6, and discussed further in Section 7.

The baseline detector is being used for evaluating and iterating the detector design. For each detector element, we use the baseline to develop engineering models using state-of-the-art CAD/CAE design tools available to us through our industrial partners [9]. These models provide a stringent test of the viability of the geometry, of the various proposed technologies, and of their integration into the full system. The models also provide a firm basis for the cost and schedule estimates, discussed in Section 8, that will provide data needed for a full cost/benefit optimization of the detector and for the identification of critical path R&D. We can test the physics performance of the detector by ray tracing through the models. The engineering models have good fidelity and include all the necessary intrusions of reality—services, supports, access, etc.—to begin the process of systems integration into a complete and buildable detector. In parallel with the engineering

Fig. 1-6 Cutaway View of The EMPACT Detector In Its Underground Hall with View of Surface Facility

of the baseline detector, we are developing more quantitative specifications for all the elements of the detector. By studying several key physics processes, we will extract the requirements on speed, segmentation, depth, and other critical parameters of the detector. This design already indicates realization of the goal of equal resolution for electrons and muons, as shown in Fig. 1-7, for a simulation of EMPACT performance reconstructing Z^0 decays to electrons or muons from a Higgs of 800 GeV.

Fig. 1-7 Reconstruction of Z^0 's from 800 GeV Higgs Decays to Electrons (A) and Muons (B)

Using simulations of various elements of the detector to evaluate the performance of the baseline design, we have already identified areas of possible improvement. We plan to complete the evaluation

of the baseline design from the physics and engineering aspects, and then to do complete iterations of all the parameters simultaneously. For example, we may expect to modify the volumes for tracking, calorimetry, and muon tracking while optimizing the field strengths of the magnets.

The remainder of this document provides specification and performance evaluations for the EMPACT baseline, details of integration and assembly considerations, cost, schedules, and information on management. The critical design choices and R&D are identified with estimates for funds required to complete these tasks in a timely fashion.

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2

TRACKING

2 - TRACKING

2.1 INTRODUCTION

The straight line trajectories of charged particles in the field free central region of EMPACT will allow a simple, robust solution to the challenge of tracking in this high rate environment. Charged particle tracking in the central region of EMPACT has several purposes:

- Observation of the event topology and multiplicity
- Assignment of tracks to vertices for events with several interactions
- Electron and photon identification
- Identification of tracks with high Lorentz factors (γ) by the detection of transition radiation
- Observation of secondary vertices displaced from the beamline in the vertex detector options.

To meet these goals, the inner tracking system in EMPACT is conceived as an assembly of detectors with complementary functions. A layered structure of straw proportional detectors with interleaved polyethylene foam slabs provides r - z tracking and serves as a transition radiation detector (TRD). Preceding and following this system are detectors for measuring the azimuthal positions of tracks. Gas pad chambers, which would provide good resolution in r - ϕ and adequate resolution in r - z, are a possible technology for this purpose. An attractive option under consideration is the inclu-

sion of a vertex detector consisting of either silicon pixel detectors or silicon drift detectors. These detectors would provide superior three dimensional tracking performance and would allow the reconstruction of secondary vertices. The various components of the inner tracking are discussed in more detail below.

2.2 THE TRD/TRACKER

One of EMPACT's principal goals is the efficient detection of electrons. The calorimetric identification of electrons does not by itself supply sufficient background rejection. High p_T photons and photons from π^0 decays outnumber prompt electrons by several orders of magnitude. Accidental overlaps of low momentum charged particles with electromagnetic calorimeter hits provide a copious source of false electron candidates. Performance requirements depend on the physics process; reducing overlaps by $10^2 - 10^3$ is desirable for improvement of the signal to background ratio for rare processes [1]. In EMPACT, a TRD provides powerful overlap rejection and electron identification capability. Measurement of TR is complementary and supplemental to calorimetric measurements. The practical theory of TR is well understood; reliable calculations can be made for the performance of a system design. Experimentally, performance of a TRD is simply related to the thickness (in e.g. cm) of the detector package [1].

In the present approach, the two functions of charged particle tracking and TR detection are combined in an integrated system. Proportional straw chambers filled with a xenon enriched gas detect TR x rays and the ionization of passing charged particles. The radiator materials interleaved with the straws provide mechanical support and rigidity for the straws. Particles with high Lorentz factors are tagged by counting the number of high energy hits in the many independent gas samples along their trajectory. This approach has the advantages of very high rate capability, modular construction, and robust performance.

2.2.1 Baseline Design

There are several options in the development of the radiators and the detectors. The baseline design used to evaluate both technical issues and performance is shown in Fig. 2-1. Work so far has pointed out several areas where this design can be improved, but for the present the design parameters have been held fixed so that system performance can be evaluated in a stable context.

The full detector is constructed from a number of independent modules. The octagonal structure is mechanically simple and has a small variation in the angles at which tracks traverse the straws. An attractive alternative is the pinwheel design shown in Fig. 2-2. Positive features of this design are that the radial intermodule gaps are eliminated and all straws are accessible from the outer circumference, where electronics and cooling could be located. Disadvantages of this design include increased occupancy for the inner straws and large variation in track obliquity to the straws. Extensive modeling and engineering studies will be required to evaluate the relative merits of these alternatives.

In both these concepts, the straws are oriented azimuthally, perpendicular to the beam and to the radial direction. This configuration has major advantages over axial straws:

- The straws are shorter, and hence the occupancy is low
- Straws at a fixed distance from the beamline subtend a fixed interval of rapidity and so have an occupancy independent of their z position along the beamline
- The azimuthal straw array gives excellent pointing to the beamline for track association with the correct primary vertex
- Reduction in layer-to-layer occupancy correlations - if two particles from different interactions (separated by more than a few millimeters at the beamline) hit the same straw in one layer, then due to the divergence of their trajectories they will hit different straws in subsequent layers
- In the octagon design, the average response from straws in different parts of the detector varies only at the 10% level, due to the $\leq 22.5^\circ$ variation of azimuthal angle within an octant; there is no polar angle dependence and no transition from central axial elements to transverse end elements.

Typical parameters of such a system can be determined based on the design shown in Fig. 2-1. The detector is composed of octagonal modules; each octant contains roughly 10 000 straws and weighs less than 50 kg. Electronics and gas routing are accommodated in the azimuthal gaps between octants. The gaps are projective, 2 cm wide at 35 cm radius. Including the effects of end connections, the acceptance in azimuth is approximately 90%.

The proportional straws are 4 mm in diameter. They are made with a double wrap of aluminized mylar and polycarbonate, with a total thickness of 25 microns [2]. The anode wire is 50 microns in diameter. In a gas mixture of 50% xenon and 50% CO₂ the maximum drift time would be approximately 40 ns. Addition of CF₄ would further reduce the drift time [3]. In the central region there are 24 double layers of straws, distributed from 35 – 77 cm

Fig. 2-1 Baseline Design for TRD/Tracker with Pad Chambers and Vertex Detector Options. (A) 3D model (B) Section views showing straw and radiator orientations and octant layout. Above the Beam is the Liquid Argon (LAR) Option; Below the Beam is SPACAL Option.

Fig. 2-2 Pin Wheel Concept for TRD/Tracker

from the beamline. The radiators form planes parallel to the beamline and lie between pairs of straw planes. Below 30° , the straw structure is similar, but the radiator planes are rotated to be perpendicular to the beam line. A total of 384 000 straws cover the range $\eta < 2.7$ in the SPACAL design and $\eta < 3$ in the liquid argon design (see Fig. 2-1).

The radiators are 1 cm thick slabs of 6% density polyethylene foam. This material is available in very uniform cell sizes and wall thicknesses. The radiators will likely be laminated with aluminized mylar to control xenon diffusion into the foam [4]. The transition radiation yield from polyethylene foams has been measured [3] to be approximately 80% of the yield from uniform polyethylene foils. The bulk material is cross linked by (typically) 4 Mrad exposure to gamma radiation. It is claimed by a manufacturer that the foam is dimensionally stable and experiences no changes in its material properties under further irradiation [5]. Tests of the effects of both gamma and neutron irradiation are in progress, in collaboration with the manufacturer.

Detailed calculations and Monte Carlo simulation of the performance of the TRD have been made [6]. The x ray spectrum from such a structure peaks at about 6 keV, with a steep fall off at lower energies due to absorption in the radiator. The median x ray energy is about 10 keV, and there is a small tail past 30 keV. The typical minimum ionizing energy deposition in the gas of one straw is approximately 1 keV, with a width to the distribution of order 1 keV and a tail of 3–5% beyond 5 keV. These parameters are quite well matched to x ray detection in xenon and to straightforward discrimination between the majority of the TR x ray interactions and charged particle traversals. With 1 cm thick foam radiators the x ray yield by electrons ranges from 0.6 – 1 per radiator depending on the angle of incidence. X rays are detected 60% of the time in the straws immediately following the radiator, and 20% of the time in subsequent straw layers. With this yield in 24 radiators, calculation shows that electrons with energy more than 1 GeV have 8 or more straws with pulse heights above the x ray threshold at least 90% of the time.

The thickness through a sector center is 6–8% of a radiation length, including the radiators, straws, gas, and wires. This material is uniformly distributed and highly instrumented. Multiple scattering is of no practical concern; photon conversions can be recognized with high efficiency, as discussed in Subsection 2.2.4.

Assuming 1.4 interactions per crossing and 8 charged particles per unit of rapidity, the mean number of charged particles from beam-beam interactions per straw per crossing is 0.016 for the straws at a radius of 35 cm and 0.007 for straws at 77 cm radius. The shaped pulses have a duration of 10–20 ns; with the maximum drift time of 30–40 ns, this implies a single tube occupancy of up to 4 beam crossings for a single traversal. The occupancy due

to event associated particles is 0.06 for the inner straws and 0.03 for the straws at the outer radius.

There are ≈ 70 ion pairs on average for each particle traversal of a straw. With gas gain of 1×10^4 , the dc currents are 0.05 - 0.1 μA . These currents give integrated charge doses on the wires of ≤ 0.04 Coulomb/cm per 10^7 seconds of running at design luminosity. This dose is fairly low compared to the typical levels of 0.1 - 1.0 C/cm at which wire chambers begin to suffer. Prospects for a long lifetime for these chambers are encouraging; detailed tests are being prepared. Standing currents lead to power deposition in the gas at the milliwatt level. This heat must be managed to prevent excessive gain variation. Preliminary calculations show thermal conduction through the straws and radiators is adequate at design luminosity [7]. Operation at higher luminosity is addressed in Subsection 2.4.

2.2.2 Electronics

Due to the large number of channels and the high channel density, VLSI circuits will be developed to meet the electronics requirements of the TRD/Tracker. In one concept, the signal processing for each channel proceeds through a preamp and shaper to digitization in two bits; this feeds a digital pipeline which feeds trigger processors and readout modules. The preamp and shaper most likely will be located at the straw end. The digitizing circuit, pipeline, and processors may be located there or may be either at the periphery of the TRD/Tracker, just inside the calorimeter, or outside the calorimeter. The choice of options will involve many issues, including the capability to develop circuits that will survive the radiation environment inside the calorimeter and the manageability of such a large cable plant in the case of external processors. For the present modeling purposes, the preamp and shaper have been taken to be at the straw end, and trigger and readout modules at the radial periphery of the

device inside the calorimeter.

The straw signal is digitized at three or four thresholds chosen to optimize both the tracking and the TRD performance. The first threshold level is set close to the noise level to give high efficiency for tracking charged particles. The second threshold level is located above the typical signal from a single particle and below the typical signal from two particles. This would have $\approx 50\%$ efficiency for minimum ionizing particles and $\approx 90\%$ efficiency for conversions. The third threshold level, at about 4.5 keV, has high efficiency for TR x ray. A fourth threshold at approximately 30 keV could be applied to veto hits with larger energy. Only a small fraction of TR x ray have energies above 30 keV, and they are not as useful due to the high fluorescence yield from the K shell of xenon. Rejection of high energy hits might reduce backgrounds from neutron interactions, ionization from slow charged particles, or energetic delta rays.

2.2.3 Trigger Participation

The pipelines feed data to trigger processors that extract a fast response trigger several μs after the crossing of interest. The trigger processor could use fast memory modules or massively parallel simple processors to implement rudimentary pattern recognition on the threshold data as described above. It is anticipated that trigger primitives would be candidate high Lorentz factor tracks associated with projective roads from the interaction region. Association with calorimeter response is done at Level 2, and could be done in a coarse way at Level 1 if needed. Detailed architectural studies and simulation are required.

2.2.4 Pattern Recognition Capabilities

Monte Carlo studies have been conducted for the baseline straw design shown in Fig. 2-1. Events were thrown using ISAJET; particles were then

propagated through a model of the detector, and energy depositions in the straws were accumulated. Photon conversions in the detector were included; transition radiation and dE/dx variations were modeled carefully. Random noise and event pile up were also included. Figure 2-3 shows an event display for the central modules; included are 15 minimum bias events overlaid on a "golden" event – a 500 GeV Higgs particle decaying to $Z^0 Z^0$ with each Z^0 subsequently decaying to $e^+ e^-$. Two octants of the central detector are viewed from the side, so that the straws are viewed end on. There are three symbols for hits to the straws, with larger symbols corresponding to higher energy thresholds. On the left side of the figure, straws above each of the three thresholds are displayed; on the right side, only straws above the third threshold are displayed. The same event is shown in the color illustration at the beginning of Section 2, where blue, green, and red symbols denote successively higher thresholds. The

pattern recognition capability of the detector is evident: photon conversions are easily recognized and the multiplicity associated with each vertex can be determined.

The straws provide $r - z$ tracking for charged particles. Tracks fit to hits in the straw array extrapolate out to the calorimeter or back to the beam line with a precision of less than a millimeter. This resolution along the beam line is sufficient to associate tracks with the correct vertex in crossings with multiple events, except for the rare vertices that are closer together than a few millimeters. The resolution in $r - z$ at the calorimeter face is well matched to the millimeter-scale localization of electromagnetic showers in the calorimeter.

Photons provide the most frequent electromagnetic trigger for the calorimeter due to the large number of π^0 decays and the predominance of high

Fig. 2-3 TRD/Tracker Simulation for 500 GeV Higgs Decay to Electrons and 15 Minimum Bias Events; (A) All hits, (B) Hits over TR Threshold

p_T photons over prompt electrons. Photons are recognized in the following ways in the TRD/Tracker:

- Unconverted photons have calorimetric energy with no associated track
- Conversions before the TRD have twice the usual number of x ray per radiator along the track and twice minimum ionization in the remainder of the elements
- Conversions in the TRD have noise levels in the straws before the conversion and double ionization and x ray levels after the conversion.

These signatures can be combined to give a very powerful rejection for photons. The pad chamber or vertex detector gives additional points on a charged particle track to provide further rejection of photon/charged particle overlap background.

2.2.5 Hadron Rejection and Electron Efficiency

Hadrons can fake an electron signal in the TRD/Tracker if:

- They are low velocity and hence heavily ionizing
- They have high momentum and generate significant amounts of transition radiation
- The fluctuations in dE/dx , possibly combined with energy depositions from overlaps with other charged particles, give a number of high threshold hits that satisfy the electron identification criteria.

A simple set of criteria can be established that lead to high electron efficiency and good hadron rejection for Lorentz factors below 1000 or so. The scheme is to exploit the large number of independent samples of the energy deposition by the charged particle in the straws. Electrons will have energy depositions characteristic of the minimum ionizing distribution except in the 20 to 30% of the straws in which TR x ray interacted. Simple cuts on the number of straws along the particle trajectory that exceed threshold 3, and on the number of straws that exceed the lowest but not the second threshold, are very effective in rejecting heavily ionizing low energy hadrons and minimum ionizing hadrons

plus overlaps, while high electron efficiency is maintained [3].

The performance of the TRD/Tracker in identifying electrons can be expressed using the rejection power R_p , defined as the ratio of the hadron efficiency for satisfying electron selection cuts divided by the electron efficiency for satisfying those same cuts; the cuts are set such that the electron efficiency has some constant high value of $\approx 90\%$.

The rejection power R_p is plotted in Fig. 2-4 for isolated tracks in the straw detector. The study was done by throwing additional tracks at random on top of Higgs events such as that shown in Fig. 2-3. The TRD/Tracker was then queried to see if the track satisfied the selection criteria that gave 90% effi-

Fig. 2-4 Rejection Power vs Lorentz Factor

ciency for electrons [6]. The rejection power is plotted against the Lorentz factor of the added track; the scale in terms of the corresponding pion energy is given at the top of the figure. Most false electrons arising from overlaps of charged particles and electromagnetic showers involve hadrons with mom-

enta in the 1 GeV region. Figure 2-4 shows that the TRD/Tracker rejects these tracks at the level of a few times 10^{-3} . This is the design goal for background rejection and efficient selection of rare events with high transverse momentum electrons.

Some of the physics to be studied at the SSC may require electron identification in or near jets. The electron identification power of the TRD/Tracker in jet events was studied by using ISAJET to throw jets with 500 GeV p_T into the central TRD/Tracker. Electron tracks were then superimposed on the event. Figure 2-5a plots the identification efficiency for these electrons versus the opening angle α between the electron and the axis of the jet. The electron efficiency remains high even close to the core of the jet. It is also important to know how many fake electrons will arise in jet events. The charged hadrons of the ISAJET event were interrogated to see if they met electron selection criteria. In Fig. 2-5b, the number of fake electrons, i.e., hadrons satisfying the electron identification criteria, is plotted vs α . The plot thus uses ISAJET to provide an estimate of the particle density and momentum spectrum near the jet. It is seen from this figure that the TRD/Tracker has high efficiency for electrons and good rejection of hadrons even close to the jet axis. It is also apparent that there may be a role for the TRD/Tracker in helping to define more precisely the location of the core of high energy jets.

2.2.6 Tagging of Particles with Large Lorentz Factors

With the aid of the TRD it is possible to identify not only electrons but also other charged particles with $\gamma \geq 10^3$. This is possible even inside jets, since the typical pion momentum is a few GeV. Of particular interest is muon tagging by the TRD, which would facilitate linkage to tracks from the muon spectrometer and aid in triggering on events with heavy objects (e.g., Z' or Higgs) with high momentum muons in the final state. Figure 2-4

Fig. 2-5 (A) Electron Efficiency vs Angle from 500 GeV Jet Axis (B) Number of Fake Electrons/Event vs Angle From 500 GeV Jet Axis

shows that muons above 100 GeV or pions above 150 GeV can be tagged. The TRD/Tracker does not distinguish such particles from electron candidates; that is the job of the calorimeter. This figure high-

lights the capability of the TRD/Tracker to select high Lorentz factor particles out of the sea of low momentum particles.

2.3 AZIMUTHAL TRACKING

The goals of azimuthal tracking are to provide additional tracking information for pattern recognition and for track/calorimeter matchup. Two dimensional readout would provide redundancy to the TRD/Tracker measurements in $r - z$. Good resolution would be useful for determining the multiplicity of charged particles associated with a primary vertex, which is expected to be a significant aid in selecting W decays to jets from the QCD backgrounds [8]. High resolution would be useful for finding secondary vertices. The ability to tag heavy quark decays in proton - proton collisions at the SSC may well be a crucial feature in the search for the Higgs and, if found, understanding its properties. A study in D0 has shown that within a radius R of 0.4 in $\phi - \eta$ space of a jet axis, most of the tracks are high momentum and a high resolution detector could be quite effective in tagging secondary vertices [9]. Several technologies that are candidates for measurement of the $r - \phi$ position of tracks are discussed below.

2.3.1 Gas Pixel Detectors

One possibility is the use of interpolating readout gas "pad" chambers [10]. Resistive interpolation between amplifier taps spaced along an azimuthal cathode strip will give $r - \phi$ resolution of 150 microns. These chambers have already demonstrated superior performance in heavy ion collisions with particle densities similar to what is expected at the SSC [11]. Using the known beam position, a single layer of chambers at a radius of 33 cm for the central region and with pad sizes of $(\Delta \phi \approx 2.8^\circ) \times (\Delta \eta \approx 0.015)$ could provide better than millimeter precision for the azimuthal track position extrapolated to the calorimeter. Several layers of pads might be desirable to assist pattern recognition. For the for-

ward systems, pad chambers would be mounted on the faces of the modules. The total thickness of the pad chamber is < 0.01 radiation length. There are $\approx 50\,000$ pad channels per layer at 33 cm radius. Occupancy per channel (including multiple events and track obliquity) would be at the percent level. This approach to azimuthal tracking provides a minimal capability; the resolution is not adequate for secondary vertex reconstruction, and performance within jets needs further study.

2.3.2 Silicon Pixel Detectors

A silicon pixel vertex detector would provide robust tracking capable of very high precision in a very high multiplicity environment. These devices are being developed under the SSC subsystem program, and study of optimal parameters of the vertex detector is in progress [12]. The following model presents an idea of how the concept would be carried out [13]. The detector would have three cylindrical tracking layers at 5, 10, and 15 cm radius about the beam. The inner layer would be about 30 cm long. Chips would be overlapped to insure 100% tracking efficiency. With a pixel size of $50\,\mu\text{m}$ on a side, charge sharing gives an average position resolution of $5\,\mu\text{m}$ both transverse and along the beam axis. Three layers of detectors provide redundant tracking. The third layer also provides additional information for the identification of electron pairs by dE/dx .

In a pixel chip, the average signal is 24 000 electrons per minimum ionization, while the typical noise is 200 electrons. Hence it is easy to distinguish closely spaced tracks produced by Dalitz decays or external photon conversion. For example, should a photon convert in the first layer of the vertex detector, the second and third layers will record the double charge. Having two layers to observe this charge reduces false pair identifications due to delta rays. Should a photon convert in the second layer, then the first layer would register no track and the

third a doubling of charge. A conversion in the third layer would leave no hits in the first and second layers.

When reconstructing secondary vertices it is important to exclude low momentum particles. These particles may have a large impact parameter at the beam line due to scattering in the beam pipe or in the detectors. This can generate false secondary vertices or worsen the resolution of true secondary vertices. The pixel detector will be of sufficient accuracy that it offers an innovative approach to this problem. If the middle layer of devices is thick enough, particles of low momentum will scatter sufficiently in the middle layer of the detector so that the trajectory hits in the three layers will not form a straight line consistent with the resolution of the devices. For example, if the middle layer is 0.03 radiation lengths and the hit in the third layer is required to lie within 45 μm of the extrapolation of the hits in the first two layers, then 90% of the particles with momentum above 10 GeV are kept and less than 7% of particles below 1 GeV are kept. Detailed studies of this technique will be required to determine the performance in and near jets. Since fake electrons are frequently due to low momentum particles overlapping an energetic photon, this technique may augment the TRD in reducing the background. The impact of this material on the performance of the TRD/Tracker and calorimeter systems will also require careful assessment.

2.3.3 Silicon Drift Detectors

Another very attractive technology for a vertex detector for EMPACT is the silicon drift detector (SDD) [14,15]. SDD's may be ideal detector elements for charged particle tracking close to the interaction region for the following reasons:

- Unambiguous position resolution of $\approx 4 \mu\text{m}$ in two perpendicular directions
- Assignment of hits from different bunch crossings with a timing accuracy of $\leq 1 \text{ ns}$, accomplished by placing two SDD's parallel to each

other at a small separation and causing electrons to drift in opposite directions

- A pipeline for storing the signals is inherent in the structure of the SDD.

A vertex detector of SDD's would provide secondary vertex reconstruction as discussed above. A geometry consisting of rings of detectors covering $\eta \leq 3$ has been designed for an SSC subsystem proposal [16] and could be adapted to the EMPACT geometry. These detectors have been produced and tested several times; the most ambitious application is currently being deployed in the NA45 experiment at CERN. Recently a JFET preamplifier has been realized on the same high resistivity silicon as the detector; this allows a good matching to the very small capacitance of the anodes of the SDD. A rigorous R&D program is in progress and it will be important to keep some attention on these devices.

2.4 OPERATION AT HIGH LUMINOSITY

Running at high luminosity ($\approx 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$) will focus on the high p_T physics of high mass systems with the goal of extending the physics reach to the mass range above one TeV and to cross sections lower than accessible at design luminosity. This will naturally follow an extended period of operation at lower luminosities, during which time the physics of lower and medium masses will be studied in detail. The performance requirements for high luminosity operation should then reflect the changes in the physics goals. High luminosity operations will require excellent calorimetry and efficient lepton identification. It is likely that multiplicities, vertex association and secondary vertex reconstruction will play little role in the high luminosity physics.

There are serious efforts in progress to develop radiation hard silicon detectors [12,13]. A practical response to the difficulty of operating silicon devices in such a high rate and high radiation environment could well be to remove them during high

luminosity operations. For high luminosity running, it is anticipated that the TRD/Tracker could be operated at a reduced gas gain, effectively blinding the detector to the flood of minimum ionizing particles while maintaining good efficiency for the detection of electrons and of high momentum muons and hadrons. Reduction of the gain would keep chamber currents and heat dissipation in the gas at acceptable levels and offers prospects for good detector lifetime at very high event rates. Validation of this technique will require careful studies of drift velocities and signal shapes at reduced fields. Monte Carlo studies will also be required to determine the impact on pattern recognition and tracking performance.

2.5 PRINCIPAL DEVELOPMENT EFFORTS

The technical developments needed to realize the TRD/Tracker and the vertex detector technologies are challenging. Principal areas where R&D will be needed are described below.

2.5.1 Simulations & Design Studies

The work so far has pointed out several possible improvements in the present design of the TRD/Tracker. Single layers of straws, rather than double layers, will be easier to assemble. The present 48 layers could be reduced to 32, and the amount of radiator increased. These changes could reduce the channel count and also improve system performance, especially for operation with reduced gain during high luminosity running. Performance in the forward modules needs to be examined in greater detail. The effects of gain variations must be incorporated in the studies. So far, there has been no simulation of the performance of the combined vertex detector and TRD/Tracker. Extensive design, engineering studies, physics simulation, and especially, pattern recognition requirements, are needed for development of the vertex detector parameters and for understanding of the combined systems. It will also be vital to determine the maximum luminosity at which these detectors can run. These and

many more issues must be addressed by calculations and by detailed simulations in order to arrive at an optimized design.

2.5.2 Electronics Development

Both vertex detector technologies are the subjects of active research under the SSC subsystem program. Prototypes and small scale experimental tests are in progress and much will be learned in the near term about the possibilities of using these devices at the SSC. The radiation tolerance of these devices will be of crucial importance in the assessment of their suitability for EMPACT, particularly considering the emphasis on operating at high luminosity.

For the TRD/Tracker, the readout electronics, its interface to trigger processors, and the trigger and readout processors represent key developments that will determine the performance of the detector system. State-of-the-art performance will be necessary in the following areas:

- Front end sensitivity, speed, and noise
- Data storage (analog or digital) during trigger decision
- Channel density
- Power dissipation
- An architecture allowing high speed data processing and communication with the trigger processor for particle identification purposes (electrons or high p_T particles, background rejection).

The performance of the TRD/Tracker concept can only be correctly evaluated if systems tests are carried out with realistic electronics. The development of this capability is a high priority.

2.5.3 Mechanical Developments

Structural supports and stability studies for the vertex detector must be an engineering priority. The high resolution of these devices places extraordinary demands on the mechanical system: both the

positional stability and the positioning systematics should be controlled at the μm level. Power dissipation and the cable plant are also serious concerns.

The mechanics of the TRD/Tracker system will also pose some interesting challenges. The modules themselves are quite light – less than 50 kg for each octant. Gaps between the modules must be minimized. Management of the gas supply and heat flow through the system requires careful engineering; cooling the electronics will impose further constraints. The goal here is to furnish the necessary utilities within a minimal intermodule gap.

One area in need of active study is the possibility of constructing the proportional chambers in a more traditional planar geometry, with the wires in grooves that could be milled or molded into the foam. While a number of technical problems would need to be solved, the manufacturability of the detector would be greatly enhanced by such an approach.

2.5.4 Cost/Benefit Analysis

Optimization of EMPACT will entail rigorous examination of the relative contributions from each part of the detector to the physics capability of the total. As an example, trade studies on electron identification and backgrounds will be made by studying signal and background with and without information from the vertex detector, TRD, and calorimeter. Segmentation of the calorimeter can be balanced with performance from the tracking systems. Next year it is anticipated that justification of the cost and specifications of all detector elements should be in hand.

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3

CALORIMETRY

3 – CALORIMETRY

3.1 PHYSICS REQUIREMENTS

Calorimetry plays a central role in EMPACT physics by providing energy measurements of electrons, photons, jets, and non-interacting particles such as neutrinos and photinos by missing p_T . Calorimetry is also relied upon as a particle filter, to aid in particle identification, and to measure muon energy loss.

The requirements are discussed briefly below. Given its importance to overall detector performance, lepton identification is considered as a separate topic. In later sections, candidate calorimeter technologies are presented that, with adequate R&D and engineering design, could meet these requirements.

- **Survivability** – The detector system, including the forward calorimeter, must operate reliably and with little degradation of performance for periods of years at luminosities up to $10^{34} \text{ cm}^{-2}\text{s}^{-1}$. This requires surviving radiation levels to hundreds of Mrads in the region near $\eta = 5.5$.
- **Dynamic Range** – At the low end, dynamic range is determined by the need to measure muons (i.e., a minimum ionizing particle) traversing a calorimeter cell. At the high end, it is set by the decay products of a very heavy Z' and very high p_T jets in the forward direction. It is anticipated that a dynamic range of at least 10^5 is required.
- **Energy Resolution** – The EM energy resolution at high energies is limited by the constant term. This will not limit the discovery potential of the detector system for a new heavy Z' . The energy resolution is important in determining the position of EM showers, as showers spread over more than one cell. Therefore, better EM energy resolution allows a better measurement of the energy in the tail of the shower and hence better position resolution. Hadronic energy resolution must be sufficient to allow good determination of the p_T spectrum of jets in order to test compositeness. Hadronic energy resolution also contributes to the reconstructed width of $Z^0 \rightarrow \text{jets}$.
- **Time Resolution** – Time resolution must be good enough to (1) correlate energy in a given cell with a minimum ionizing particle in a given crossing, and (2) associate jets with $E_T > 20 \text{ GeV}$ with the correct crossing.
- **Segmentation** – EM transverse segmentation is, as discussed below in the section on lepton identification, set by the need to cleanly identify electrons. Hadron calorimeter transverse segmentation must be such as to not degrade the resolution for $Z^0 \rightarrow \text{jets}$. Depth segmentation is not necessarily required to measure the energy lost by muons, since for isolated muons the entire energy deposited is used to correct the momentum measurement for precision muon physics such as $Z^0 \rightarrow \mu\mu$. However, such a correction requires fine sampling $\approx 2X_0$ (radiation lengths).
- **Total Depth** – Total depth must be sufficient to reduce the first level trigger rate for muons to a reasonable level, and to minimize punchthrough contributions to missing p_T as a background to SUSY searches.
- **Noise** – Noise in each calorimeter cell must be low enough to allow identification of a minimum ionizing particle, and low enough in a jet tower to permit the imposition of an electron isolation cut.
- **Hermeticity** – The calorimeter must be hermetic enough to do missing E_T physics as compared to the irreducible neutrino background limit.
- **Rapidity Range** – The physics requirements for coverage beyond $\eta = 3$ are given below. These requirements can be satisfied by calorimetry alone, without resort to forward tracking, muon measurement (the contribution of background muons to apparent missing p_T cannot be

greater than that due to background neutrinos), or electron measurement:

- By extending the measurement of E_T to $\eta = 5.5$, the apparent missing p_T due to energy escaping at small angles can be reduced to the level of the missing p_T from background neutrinos for missing $p_T > 100$ GeV [1-3]. A reasonable threshold for using missing p_T as a signature for interesting physics is 100 GeV, as the data rate due to the neutrino background is reduced to ≈ 1 Hz. The background rate increases very rapidly as the acceptance is reduced from $\eta_{\max} = 5.5$.
- In Higgs production via W-Z fusion, the Higgs is produced with limited p_T [4], and hence the recoil quark jets tend to be forward. Identification of these jets with $3 < \eta < 5$ could be a very helpful additional signature for Higgs production, especially for the more difficult Higgs decay modes (e.g., $H \rightarrow l^+ l^- \nu \bar{\nu}$). For the same reason, forward jets may be an important additional signature for identifying W-Z scattering in the strong-coupling case.

3.1.1 Lepton Identification

Although the interaction between a number of different detector subsystems determines the ultimate lepton identification performance of EMPACT, the calorimeter clearly plays a central role. The process of designing the EMPACT detector system will involve tradeoffs between the TRD/Tracker system, the EM calorimetry or preconverter, and the hadronic calorimetry in order to obtain the optimum e/π and e/γ separation at high luminosity and in the environment near jet cores. It is appropriate, then, to discuss here general requirements for lepton identification, with particular emphasis on their implications for calorimetry.

Good Electron vs Pion (e/π) Shower Discrimination – Clearly, fine transverse segmentation is important for good e/π separation. Sufficient depth segmentation may, in fact, be provided by a preconverter alone. Studies are underway to determine the combination of transverse and longitudinal segmentation for each technology under consid-

eration by EMPACT, that will provide the optimum e/π separation.

Reduced Hadron Photon Overlap – This overlap can be detected by very good position resolution. This is required in EMPACT since there is no magnetic field to eliminate low momentum particles from consideration. The tracker straws will give good position in the θ direction, but must be supplemented by azimuthal measurements. Such measurements could come from gas pad or pixel detectors as discussed in Section 2. The calorimeter needs to have similar resolution in θ and ϕ (≈ 1 mm) and can achieve it with either a preconverter or fine segmentation. This position precision becomes more difficult as the luminosity increases, since the pileup is more likely to affect the shower energy deposited in towers neighboring the shower.

Good Dalitz Pair & γ Conversion Rejection Efficiency These can be rejected by the TR patterns and the minimum ionization in the tracker and silicon devices.

Minimum Dead Material before the EM Calorimeter or Preconverter – A $2.5 X_0$ Pb preconverter, for example, is only 3% of an interaction length. Adding 5% X_0 of plastic before the preconverter nearly doubles the thickness in interaction lengths, resulting in a factor of two degradation in e/π rejection. This implies that care must be taken in the design and routing of readout cables from the tracking system.

Minimum Cracks in the EM Calorimeter – Care must also be taken during design to minimize or eliminate cracks, as they not only degrade efficiency for detection of multi-electron events, but can, for example, cause a Z^0 to mimic a W or a W to mimic a Z^0 decay to neutrinos if an electron is lost. In this manner, WZ^0 events are promoted to WW or Z^0Z^0 events, and the ability to study $W_L W_L$ scattering is impaired. The design methodology described in Subsection 3.3 allows careful, quantitative focus on the elimination of cracks in the detector system.

3.2 ALTERNATIVE TECHNOLOGIES

Three options for calorimetry in EMPACT are

being actively considered: (1) liquid argon, (2) scintillating fiber/lead (SPACAL) with a silicon preconverter, and (3) SPACAL with a full silicon EM section. In addition, technologies such as liquid scintillator and high pressure gas are under consideration for use in the forward ($\eta > 3$) region. The choice will be made on the basis of performance relative to the physics requirements of EMPACT, engineering feasibility, and cost (see Section 8). The general considerations that make each technology attractive, as well as the issues that must be resolved to meet EMPACT physics requirements, are discussed below.

3.2.1 Liquid Argon

The LAr approach to calorimetry has a long history, starting with the pioneering work of Willis and Radeka [5]. A number of LAr detectors have been built and successfully operated (Mark II, ISR806, E706, and HELIOS) and some very large collider based systems are presently under construction (SLD, D0, and H1). These systems constitute an invaluable experience base directly relevant to the task of developing a LAr system for EMPACT.

LAr is attractive for use in EMPACT for a variety of reasons: (1) radiation resistance, (2) the ease of transverse and longitudinal segmentation into arbitrary shapes and sizes, (3) linearity over full dynamic range, (4) good e/π response and energy resolution, and (5) large electron yield per GeV deposited and unit gain, leading to stable response and accurate triggering. Although many perceive liquid argon as slow, the peak of the current occurs at the crossing time and falls linearly. Since the number of electrons/GeV is large, the pulse can be shaped to reduce pileup and noise.

A successful EMPACT LAr design requires that a number of issues be addressed. Some of these items (listed below) are being studied under the SSC subsystem R&D program [6], but most can only be fully resolved in the context of a specific detector system like EMPACT.

Absorber Material – The choice of absorbers

such as lead, tungsten, and uranium has implications for response (e.g., compensation), as well as engineering feasibility and overall cost. The fabrication and beam test of a 1 m² lead/LAr stack to study e/π at 50, 100 and 150 ns shaping time is proceeding [6].

Hermeticity & Signal Handling – Modules and vessels must be developed that result in a minimum of cracks and dead material, and at the same time allow low inductance connections to be made between electrode and preamp.

Preamp Cooling & Radiation Resistance The preamps must be placed close to the electrodes to minimize inductance and to improve signal to noise. A means must be found to remove the heat that they generate, and their radiation resistance must be carefully studied, particularly for operation at luminosities in excess of $10^{33} \text{ cm}^{-2}\text{s}^{-1}$.

Table 3-1 Liquid Argon Calorimeter Measurement Errors

LUMINOSITY	10^{33}				10^{34}	
	0.04		0.32		0.04	0.32
$\Delta\eta, \Delta\phi$	σ_A (GeV)	$A \cdot \sigma_t$ (GeV·ns)	σ_A (GeV)	$A \cdot \sigma_t$ (GeV·ns)	σ_A (GeV)	σ_A (GeV)
EM	0.075	5	0.9	46	0.15	1.3
HADRONIC	0.13	14	1.6	139	0.27	3.2
σ_A IS THE ERROR ON THE ENERGY MEASUREMENT						
$A \cdot \sigma_t$ IS THE PRODUCT OF THE ENERGY & ERROR ON THE TIME MEASUREMENT						
MP90-3180-003						

Noise & Speed Performance – The noise performance of the calorimeter must be quantified. For example, Table 3-1 lists noise values calculated for a LAr calorimeter with EM cells of 0.04×0.04 and “jet” towers of 0.32×0.32 [7]. A drift time of 400 ns and a peaking time of 96 ns are assumed. Using these values, a 20 GeV jet has a time error of 7 ns at a luminosity of $10^{33} \text{ cm}^{-2}\text{s}^{-1}$. The drift time could, if required, be improved by the addition of methane, and the shaping time improved via electronics. Note that, since the table lists the total of thermal and pileup noise, the total noise values scale by less than the expected $\sqrt{L}$.

3.2.2 Scintillating Fiber/Lead (SPACAL) with Si Preconverter

EMPACT is also considering a calorimeter based on scintillating optical fibers embedded in lead absorber [8]. The fibers are directed radially outwards from the interaction point, grouped and attached to photodetectors mounted at the outside of the calorimeter in an almost magnetic field-free region. The SPACAL technique has a number of attractive characteristics:

- Fast response, with 3 ns risetime and charge integration time of less than 80 ns
- Good compensation, leading to a linear response and Gaussian lineshape (for electromagnetic showers and jets), and to excellent energy resolution with 1mm fibers for electromagnetic showers (measured to be $13\% / \sqrt{E} + 1.5\%$) and hadronic showers, as well as jets (expected to be $30\% / \sqrt{E}$)
- Very good hermeticity, if the use of a calcium-lead alloy will allow for self supporting towers without extensive support structure
- Uniformity of response as function of impact point and incident direction, even for very fine transverse segmentation
- Low noise and high photostatistics leading to a clear separation of a muon signal from the pedestal
- Good electron/hadron discrimination by transverse shower development cuts. In order to further improve electron/hadron separation, a thin lead/steel preconverter with a silicon readout can be employed inside the SPACAL calorimeter.

Much R&D and development work on this novel technology has been accomplished over the last three years by the SPACAL collaboration [8]. Prototype modules of a variety of sizes and shapes have been constructed and tested, including a 35 cm diameter by 2 m (10λ) deep stack of 20 towers, large enough to contain about 85% of hadronic shower energy. A full scale prototype tower (5.5 λ diameter and 10λ deep) is presently under construction, with beam tests scheduled for June 1990.

A successful EMPACT SPACAL design requires that a number of issues be addressed. Some of these items (listed below) are being studied under the SSC subsystem R&D program [9], but must be explored with the EMPACT constraints.

Module Survivability & Fiber Radiation Resistance – The most radiation resistant fiber available today is Kyowa's SCSN81 with additional 3HF wavelength shifter. Owing to its recovery from radiation damage, it is able to withstand 10 Mrad. This significant improvement over the 0.1 Mrad limit of scintillating material just two years ago is due to intensive R&D, and there is reasonable expectation of further improvements in the future. One could also, in principle, design and construct the calorimeter section beyond $\eta = 3$ in such a way that it can be regularly replaced.

Electron/Pion Separation – A thin and finely segmented preconverter just inside the calorimeter must be carefully designed, developed, and tested. Beam tests have shown that use of a preconverter with SPACAL yields a pion rejection factor of 6000 with 98% efficiency for electrons at 80 GeV. Monte Carlo studies have shown that with 1 cm square segmentation, the accidental overlap between a single charged pion and a photon is reduced to a negligible level. To maintain hermeticity, the energy deposited in the preconverter should be detected by means of a finely segmented layer of silicon.

Calibration – Schemes must be developed to accurately and easily calibrate the system. Radioactive sources inserted in fiber passages in the lead are one possibility under consideration.

3.2.3 Scintillating Fiber/Lead (SPACAL) with Si EM

Another attractive option for EMPACT is a hybrid system with a Si EM section and a SPACAL hadron calorimeter. Calorimeters involving square meters of silicon are presently in use in a number of experiments (UA2, NA35, DELPHI and SLD), and

a system with 50 m² (ZEUS) is under construction. There are a number of advantages of using silicon as the sampling medium for the EMPACT EM calorimeter. These include the compact nature of such a calorimeter, room temperature operation, non-saturating readout, absolute gain of the sampling medium, and the ease of gain adjustment and monitoring. Two particular advantages are worth additional comments.

Ease of Transverse & Longitudinal Segmentation into Arbitrary Sizes & Shapes – This helps allow identification of electrons near jets. A standard technique for tagging heavy quark jets is the identification of leptons with substantial transverse momentum to the jet axis. Such leptons are often marginally isolated from the surrounding jet activity. It can be argued that electromagnetic calorimeter segmentations as fine as 0.02×0.02 in η and ϕ are needed to do a good job of such tagging of electrons.

Fast Charge Collection – The overlap of multiple interactions would be held to a minimum with an EM calorimeter which employs silicon. Proper design of the front end electronics must accommodate the large capacitance of the silicon detector itself.

As with the other candidate technologies, a successful EMPACT Si and SPACAL hybrid design requires that a number of issues be addressed. Some of these items (listed below) are being studied under the SSC subsystem R&D program [10], but again most can only be fully resolved in the context of the specific detector system.

Cost – The perception and experience of silicon as an expensive sampling medium is based on small and more sophisticated applications than is required for good calorimetry. Based on the evolution of costs, it is likely that the cost of silicon diodes will be in the range of \$2 per square centimeter for an SSC experiment.

Compensation – The e/π response of a hybrid

system involving Si and SPACAL must be measured in beam tests.

Survivability & Radiation Resistance – Susceptibility to radiation damage is particularly problematic for hadronic calorimetry, although it certainly is not absent in the electromagnetic calorimeter. Silicon damage coefficients for electromagnetic energy deposition (from electrons or photons) are orders of magnitude lower than for neutrons. The neutron fluence in the EM section can be reduced significantly by adding thin (2 mm) sheets of polyethylene in each sampling gap and 2 cm between the EM and HAD sections [11].

3.2.4 Forward Calorimetry Technologies

The choice of forward calorimeter technology will be driven by the rate and the harsh radiation environment at $3 < \eta < 5.5$. For example, at $\eta = 5.5$ and $z = 15$ m, the expected dose at EM shower maximum is 200 Mrad in one SSC year [12]. The desire for uniform technology over all pseudorapidity drives one to consider both liquid argon and SPACAL in this region, requiring a careful implementation of readout electronics in the former case, and a very radiation resistant fiber in the latter. Other alternatives under consideration include a SPACAL-like design [13] in which scintillating fibers are replaced by tubes containing liquid scintillator that could be flowed or flushed at regular intervals. The attractive possibility of high pressure gas calorimetry is also being considered [14].

3.3 PROGRESS ON CALORIMETRY DESIGNS

3.3.1 Methodology

To arrive at the optimum calorimeter configuration for EMPACT, "baseline" calorimeter designs have been started that allow tradeoff studies to be conducted that consider (1) overall physics performance, (2) engineering feasibility, and (3) cost. These studies are being performed by an interdisciplinary team that has at its disposal state-of-the-art integrated design, modeling, analysis, and simula-

tion tools [15,16]. The tools allow the team to construct detailed 3D models that can be analyzed and optimized using structural, thermal, and magnetic codes. The physics simulation tools are then employed on the optimized 3D model geometries, allowing realistic calculation of performance parameters such as calorimeter depth, amount of inactive material, and energy resolution. Rather detailed baseline designs [17-19] have already been developed. Engineering tradeoff studies will continue in conjunction with ongoing technology R&D, prototype beam studies, and simulation to will permit timely and realistic convergence on the optimum calorimeter for EMPACT. Baseline designs and some major engineering issues presently under consideration are highlighted below.

3.3.2 Overall Constraints

The EMPACT baseline detector design constrains the calorimeter to a volume with an inner radius of 1 m, an outer radius of 3.50 m, and a total length of 14 m. No supports for the calorimeter may

penetrate the toroid magnets, and the endcap/barrel configuration should not inhibit reasonable access to the central tracker. Adequate passage must also be provided for tracker signal cables and utilities. A quarter section of the calorimeters for the liquid argon option is shown in Fig. 3-1. The constraints of the toroids and muon chambers can be seen.

3.3.3 Liquid Argon Calorimeter

Recent generic R&D studies [15,16] indicate that a liquid argon calorimeter system with excellent hermeticity for SSC physics can be engineered. The baseline design is shown in Fig. 3-2 and the upper half of the front illustration. Barrel and endcap vessel lengths and shapes have been optimized to maximize calorimeter depth for $\eta < 3$, while allowing ample space for cold-to-warm signal cable feedthroughs, utilities, and a realistic barrel support mechanism. Individual calorimeter modules are self-supporting, with aluminum strongbacks as primary structural members. The modules rest on tracks built into the argon vessels. Modules

Fig. 3-1 Quarter Section of Baseline Volume for Calorimetry Showing Liquid Argon Option. Dimensions in cm.

(A)

(C)

(B)

P90-3180-566

Fig. 3-2 (A) Overall 3D Model of the EMPACT Baseline Liquid Argon Calorimeter, (B) Detail of Barrel/Endcap Intersection, Including View of the Barrel Support Mechanism, (C) End View of Endcap and Barrel Calorimeters, Showing Signal Cable Feedthroughs and Calorimeter Support Mechanisms

are generally less than 10 metric tons each, and they do not contribute to the structural integrity of the vessels. The endcap calorimeter modules for $\eta \geq 1.5$ are, as seen in Fig. 3-2, assembled as disc-like monoliths in order to avoid azimuthal cracks. Uranium plates of 3 mm and argon gaps of 2 mm are assumed throughout.

The barrel (1710 metric tons) and endcap (560 metric tons each) calorimeters are supported by an aluminum tube that transfers loads to the toroid support structure. This tube also houses, and permits easy access to, the first layer of muon chambers. The barrel itself is supported by use of a simple strap-like support mechanism that attaches to the aluminum support tube; the endcaps rest on the tube via D0-like cold-to-warm supports.

The baseline design assumes three longitudinal EM segments and four longitudinal hadronic segments in the readout, with the latter fully interleaved for redundancy. Total channel count is then $\approx 156\,000$ in the barrel, and 58 600 in each endcap, assuming transverse segmentation of 0.025×0.025 for EM, and 0.05×0.05 for hadronic calorimetry. The 0.025 segmentation leads to pads smaller than 2 cm for $\eta > 2.35$, so it is coarsened to 0.05 beyond that point. This channel count assumes 0.025 segmentation for all three longitudinal segments in the EM. If, as in the D0 calorimeter, study shows that fine segmentation is only needed at shower maximum (the middle layer) the channel count could be reduced by 76 000 channels.

3.3.3.1 Physics Performance – The baseline liquid argon calorimeter design has an active depth of 11λ from $\eta = 0$ through 2, and grows smoothly to 14λ at $\eta = 3$. The aluminum vessels before the EM calorimetry total, on average, less than one X_0 , with a maximum of $3 X_0$ at the barrel corner region. The vessel wall thicknesses of this design, optimized via stress calculations such as shown in Fig. 3-3a, are such that cable placement within the calorimeter, and not the vessel walls at the barrel/endcap intersection region, is the dominant factor in determining the hermeticity.

Fig. 3-3 (A) Stress Analysis and Deflection (Greatly Exaggerated) Results for the Barrel Argon Vessel Under Combined Pressure, Thermal, and Gravity Load Conditions, and (B) Fractional Energy Resolution of the Liquid Argon Calorimeter for 100 GeV Transverse Energy Hadrons and Electrons

One quantitative measure of the hermeticity, the fractional energy resolution calculated using the method described in Ref. 15, is given in Fig. 3-3b.

A measure of hermeticity that can be directly compared to the ability of the calorimeter to measure missing E_T to the limit set by the real neutrino background is given in Fig. 3-4. The missing E_T spectrum shown in Fig. 3-4a was calculated using ISAJET to generate two jet events with a special modification to enhance events with large missing energy. Each track was then traced through a

calorimeter whose energy resolution was determined from the 3D engineering model of the baseline design for $\eta < 3$ (for $3 < \eta < 5.5$, no dead material was assumed), using the method described in Ref. 15. Shown for comparison in Fig. 3-4a is the spectrum if neutrinos could be measured. Fig. 3-4b shows the ratio of the missing E_T spectrum described above to that which would be obtained for a calorimeter with no dead material anywhere. This calculation, though it does not yet include the effects of shower fluctuations, is an encouraging indication that one can design a calorimeter to meet the requirements.

Fig. 3-4 (A) Missing E_T Distribution for LAr. Solid Data Resolution Plus Neutrinos; Dashed Data Resolution only. (B) Ratio of Missing E_T Cross Sections for Ideal Detector to LAC Design vs Missing E_T .

3.3.3.2 Issues Under Consideration – Summarized below is the status of a number of important engineering design issues. More detail can be found in Ref. 17.

- The vessel walls in the region around $\eta = 3$ are non-projective and have been designed to be as thin as possible. Further optimization will occur as the forward calorimetry design evolves.
- The design of calorimeter modules is presently focused on developing concepts that offer crack-less EM and hadronic geometries. Paths for internal signal cable routing from modules to the cold-to-warm feedthroughs that offer the smallest impact on the hermeticity are also being investigated.
- Preliminary tests have been made at Martin Marietta of preamp cooling in liquid argon in order to develop and calibrate thermal models that will be used in detailed vessel and cryogenic design. This modeling and test capability will also be of use in cold-to-warm feedthrough design.
- Preliminary designs for utilities and cryogenic services have been made, and the resultant requirements are incorporated in the EMPACT Resource Requirements Document [20]. Such designs will mature as the calorimeter design evolves and the tradeoff studies between detector subsystems are performed.
- Rather detailed assembly scenarios for the barrel and endcap calorimeters can be found in Ref. 17, along with concepts for the necessary support and handling equipment. Studies ex-

aming the tradeoffs between complexity and cost of handling equipment as a function of assembly above ground or in the hall are underway.

3.3.4 Scintillating Fiber/Lead (SPACAL) Calorimeter with Si Preconverter

A baseline scintillating fiber/lead calorimeter design has been developed for EMPACT. It consists of structurally independent 100 to 150 metric ton "super-rings" [19] of glued fiber/lead modules assembled into a barrel (1200 metric tons) and endcap (650 metric tons) configuration. Figure 3-5 shows the overall assembled system inside an aluminum support tube, and an individual super-

ring. Also represented in Fig. 3-5 is a 2.5 cm thick silicon-lead-steel preconverter array mounted on thin steel support tubes and discs inside the barrel and endcaps. This assembly is also shown at the front of this section.

The super-rings are attached to and supported by an aluminum tube that, as in the liquid argon case, carries calorimeter loads to the toroid support structure and contains the inner layer of muon chambers. Super-rings are assembled from individual modules built of 2 mm fibers and lead sheets with attached light pipes, phototubes, and aluminum end fittings as shown in Fig. 3-5. These individual modules, each with a mass of approx 65

Fig. 3-5 Baseline SPACAL Design Showing Assembly (Top) and Elements Building Up Super-Ring from Right to Left (Bottom)

Fig. 3-6 (A) Stress Analysis and Deflection (Greatly Exaggerated) Calculation Results for an Individual Lead/Fiber "Super-Ring" (Stress Levels in the Lead/Fiber Material are Never Greater than 350 psi.) and (B) Fractional Energy Resolution of the SPACAL for 100 GeV Transverse Energy Hadrons and Electrons

kg, are glued into approx 7 layers of 250 modules each to form a basic super-ring. Initial calculations (Fig. 3-6a) of the structural integrity of the EMPACT super-rings indicate that they have negligible deflection, and can be made self-supporting.

At the barrel/endcap interface, light from the truncated modules in the barrel is brought to phototubes located in the obvious notch in the outer barrel radius via clear fiber optics. Signal cables from the preconverter are brought out through a 5 cm gap between the barrel and endcaps.

The baseline design assumes 0.025×0.025 transverse segmentation and one longitudinal segment for a total phototube (channel) count in the fiber/lead calorimeter of approximately 60 000. The silicon preconverter baseline has a cell size of about 1 cm^2 , giving a total of 416 000 diodes. The plan is to reduce the data from each diode to a single bit.

3.3.4.1 Physics Performance – The total active depth of calorimetry is 11λ at $\eta = 0$ through 2, growing then to 14λ at $\eta = 3$. There is essentially no dead material before the start of the SPACAL. The hermeticity of the baseline SPACAL calorimeter is excellent, as represented by the energy resolution plot shown in Fig. 3-6b.

3.3.4.2 Issues Under Consideration – Summarized below is the status of a number of important engineering design issues. More detail can be found in Ref. 18.

- Martin Marietta manufacturing engineers have developed a preliminary baseline for mass manufacture of scintillating fiber/lead modules. Further developments will include investigation of automated manufacturing techniques and the important process of developing a method for accelerated testing of the lead glue fiber composite. The 2 mm fibers of this design allow a substantial cost savings, but the use of thicker fibers requires studies on energy resolution and the effect of muon channeling.

- Initial analyses indicate that the lead/fiber super rings are structurally stable. Further studies, and ultimately tests, must be made to understand the effect of creep in lead over the course of 5 to 10 years.
- Scintillator radiation resistance is perhaps the most critical issue for SPACAL calorimetry. Study of the overall survivability, both in terms of radiation and chemical effects, of modules built with scintillating fibers will be undertaken.
- A preconverter is important to the performance of a SPACAL calorimeter, so the process of designing this system has begun.
- The initial design assumes photomultiplier bases dissipating on the order of 0.5 W each. Even at this level, studies must be undertaken to optimize methods of cooling the system.
- Rather detailed assembly scenarios for the individual modules, the super-rings and the overall system have been developed [18], along with concepts for the necessary support and handling equipment. As in the liquid argon case, a variety of tradeoff studies involving assembly and handling are underway.
- The effect on the physics analysis of non-projective towers must be studied. Beam tests expected in June 1990 should show the extent of late developing showers and the consequence for triggering can be evaluated.

3.3.5 Silicon EM & SPACAL Hadron Calorimeter

A combination of hadron scintillating fiber/lead calorimetry with a $25 X_0$ silicon calorimeter that uses tungsten absorber is an option for EMPACT. The baseline design [19] for the silicon EM, shown in Fig. 3-7a along with the scintillating fiber/lead hadron calorimeter, is a modular barrel (65 metric tons) and endcap (14 metric tons each) configuration supported by very thin steel shells with non-projective inter-module steel structural members. Individual silicon/tungsten modules rest inside a steel ring (or disk, in the endcap case) assembly as shown in Fig. 3-7b. The barrel calorimeter, for example, has an inner steel shell 4 mm thick, and non-projective steel structures between

Fig. 3-7 (A) 3D Model of the EMPACT Baseline Silicon/Tungsten EM Calorimeter Mounted within the SPACAL Hadron Calorimeter. (B) Detail View of the Silicon EM Modules and Steel Support Structure

modules that are 2 mm thick. The whole assembly is connected to a 12 mm thick aluminum shell that is supported by aluminum straps that extend to the main central toroid structure. This structure is quite adequate to support the silicon/tungsten modules, as shown by the stress analysis shown in Fig. 3-8. It should be noted that a slight reduction in length of the baseline tracking system shown in Fig. 2-1 would be required with this calorimeter option.

The baseline design assumes sampling every radiation length; one cell is 5.5 mm thick with 2 mm reserved for readout. The system will require

Fig. 3-8 Stress Analysis and Deflection (Greatly Exaggerated) Results for the Steel and Aluminum Support Structure under Gravity Load Conditions

approximately 1150 m² of silicon, with 830 m² in the barrel and 160 m² in each endcap. With 4 cm² diodes, the system contains almost 3 million 4 cm² diodes, whose signals are summed into a total of 360 000 channels. Preamps will generate a total of 30 kW (10 mW per preamp). Leakage current power is small compared to that due to the preamps. The distribution of power and cooling requirements for this power needs study.

3.3.5.1 Physics Performance – The total active depth of calorimetry is $\approx 11 \lambda$ from $\eta = 0$ to 2, growing then to 14λ at $\eta = 3$, similar to the “pure” SPACAL case described earlier. There is never more than $0.75 X_0$ of material before the EM calorimeter. The hermeticity of the baseline SPACAL calorimeter is quite good. The silicon EM signal cables that pass between the barrel and endcaps are the dominant effect on the resolution in the region around $\eta = 1.5$.

3.3.5.2 Issues Under Consideration – Below is the status of a number of important engineering design issues specific to the development of silicon EM calorimetry that are presently under investigation. More detail can be found in Ref. 19.

- The details of module construction, including plate orientation, assembly, and manufacturing are under examination. The development of crackless assembly of modules or low Z (e.g., carbon composite) support structure is also under consideration.
- The issues of cooling and power dissipation in the silicon EM due to preamps and leakage current are currently being investigated.
- A thorough program to demonstrate the survivability of silicon calorimeter modules in the radiation environment is planned. The question of diode preamp integration is also being pursued.

3.3.6 Forward Calorimetry

The EMPACT baseline design, Fig. 3-1 includes a forward calorimeter of uranium liquid argon or SPACAL technology with a total active depth of 12λ and a coverage of $3 < \eta < 5.5$. The forward calorimeter is located between $15 < z < 17$ m, reflecting constraints due to the collider quadrupoles and the forward muon toroids. The inner and outer radii of the forward calorimeter are set by the need to extend beyond its fiducial limits by 1λ at $\eta = 3$ and 0.5λ at $\eta = 5.5$. Thus a forward calorimeter is approximately 2.5 m in length, 7 cm in inner radius, 1.6 m in outer radius and has a mass of 300 metric tons.

The baseline forward calorimeter has a tower-like readout structure, with transverse segmentation of $\Delta\eta \times \Delta\phi = 0.2 \times 0.2$ and one longitudinal segment, with ≈ 500 channels. Some technologies, such as liquid argon, would benefit from longitudinal segmentation to preserve timing precision, so the number of channels might be several times the number quoted above. The transverse size of a tower is 2.5 cm at $\eta = 5.5$, but studies [21] indicate that this can be increased by a factor of two inside of $\eta = 4.5$ without affecting E_t resolution.

Issues under consideration are:

- The impact of the endcap and forward calorimeter designs, including cryostats and support structure, on the ability to accurately measure E_T , is presently being examined, recognizing that at small angles the dominant error is angular
- A thorough examination of the survivability of candidate calorimeter technologies in the radiation environment found in the forward region is also planned.

3.4 ELECTRONICS CHAIN

3.4.1 Front End Electronics

As an example of issues relevant to the development of front end calorimeter electronics, a baseline electronics chain for liquid argon calorimetry is discussed. The front end of this chain, shown in Fig. 3-9a, employs JFET preamps that, as pointed out by Radeka and Rescia [22], must be located very close

to the electrodes in order to allow fast charge transfer. A ferrite transformer in the circuit allows for proper capacitive matching to the electrode, reduces required power by a factor of two and protects the preamp against discharges.

Preamps capable of reliable operation in liquid argon can be manufactured, as evidenced by the fact that only one of 576 preamps in the HELIOS (NA34) liquid argon calorimeter has failed during three years of operation and five cooldown cycles. Tests of such preamps in radiation environments similar to that anticipated at SSC have shown no deterioration in performance [23]. Work is ongoing in collaboration with Interfet Inc. to develop a monolithic JFET preamp specifically for an SSC liquid argon calorimeter.

3.4.2 Technology Independent Electronics

Beyond the front end, the electronics are very similar for all techniques, as shown in Fig. 3-9b. This block shows the analog memory and trigger sums electronics. These circuits hold all the calo-

Fig. 3-9 LAr Calorimeter Front End Electronics Block Diagram

rimeter signals for the Level 1 trigger for $1\mu\text{s}$. The dynamic range required for the EM sections is 10^5 (18 bits) to be able to record minimum ionizing particles (25 MeV) and electrons from a Z' (2.5 TeV). At present, the minimum power solution seems to suggest the use of CMOS analog memory (as opposed to digitizing the signals before the Level 1 trigger). Such analog memory requires detailed development, but it is likely that such devices will not be able to accommodate the entire dynamic range. Fig. 3-9b shows a solution with two parallel devices (each with 11 bit range), one with a $\times 1$ and the other a $\times 64$ bipolar shaping amplifier. All technologies will benefit by the use of such bipolar shaping to reduce the pileup noise - although the choice of shaping time may be technology dependent. The Level 1 trigger itself will be made from the output of other fast shaping amplifiers shown with a gain of five. This gain was chosen since the trigger would never need to be sensitive to signals near minimum ionizing and can be allowed to saturate at the high end. Then signals would be summed in towers - for example 0.1×0.1 for EM sums and 0.2×0.2 for hadronic sums. Appropriate triggers will be formed for electrons (EM with little hadronic energy behind), jets and missing p_T . The Level 1 electron trigger is expected to provide a pointer to the TRD/Tracker for a Level 2 trigger. This would allow the data from the TRD in the region of a large EM energy deposit to be processed in $\approx 10\mu\text{s}$. A box on the right of Fig. 3-9b hints at the buffering of event data that must occur after the Level 1 trigger and the eventual readout.

3.5 OPERATION AT HIGH LUMINOSITY

The purpose of running at high luminosity is to focus on very high mass or p_T and in this case the thresholds of the calorimeter triggers can be raised. The pileup noise only increases as $\sqrt{L}$ and when combined in quadrature with the electronic noise, as shown for the liquid argon case, would not limit the physics performance. The chief concern for high luminosity is the radiation resistance of all the components. The material in the calorimeter absorber to a large extent determines the radiation levels both inside the calorimeter and in the tracking

volume. This will affect electronics as well as any material - tracker straws, cables, etc., within these volumes. The R&D during the next year must resolve these issues.

3.6 PRINCIPAL DEVELOPMENT ISSUES

During 1991 and 1992, EMPACT must accomplish two things:

- Perform the R&D and prototype tests necessary to arrive at the optimum detector configuration to satisfy EMPACT physics goals
- Complete enough of the engineering design of the overall detector configuration to realistically establish the engineering feasibility and cost of the system.

In this section, critical R&D and engineering design issues are identified. These must be resolved in order to make the choices between calorimeter technologies that must be made if the optimum system is to be specified in a timely fashion. The costs of and plans for these activities are presented in Section 8.

EMPACT-specific prototypes for each technology under serious consideration must be developed if a realistic and honest estimation of physics performance, engineering feasibility, and cost is desired. Given the cost of a detector system such as EMPACT, and the fact that the choices made in 1991-1992 will have consequences 10 to 15 years later, it is imperative that adequate investment in system-specific prototypes be made before technology decisions are taken. Detailed simulation of each of the technologies is also needed to evaluate the physics potential of the design.

- Liquid Argon:
 - Physics Performance R&D
 - o Absorber material selection
 - o Construction and test of a full-containment EM and hadronic prototype
 - Engineering R&D
 - o Module survivability
 - o Preamplifier cooling
- Scintillating Fiber/Lead:
 - Physics Performance R&D

- o Construction and test of a projective full-containment prototype
- Engineering R&D
 - o Long-term survivability of modules in a radiation environment
 - o Analysis and test of the long term structural stability of lead/fiber structures
 - o Development of cost-effective mass manufacturing techniques
 - o Development of adequate calibration techniques
 - o Design and test of a preconverter system
 - o Material compatibility (glue/fiber/lead)
- Silicon EM & Scintillating Fiber Combination:
 - Physics Performance R&D
 - o Construction and test of a full-containment prototype
 - o Compensation in a silicon/scintillating fiber hybrid
 - Engineering R&D
 - o Long-term survivability of modules in a radiation environment
- Forward Calorimetry:
 - Physics Performance R&D
 - o Prototype studies, including front end electronics, for liquid argon, liquid scintillator, and high-pressure gas
 - Engineering R&D
 - o Long-term survivability of modules in a radiation environment.

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4

MUON SYSTEM

4 - MUON SYSTEM

4.1 MUON SYSTEM DESIGN SPECIFICATION

Muon systems for collider experiments determine to a large extent the scale - in size, weight, and often cost - of the entire experiment. Therefore, the specifications for such a system must be rigorously justified. The rationale for the measurement of muons rests with the increased statistics for exploring decays of heavy particles into both muons and electrons (e.g., a factor of four for Higgs to $Z^0 Z^0$ compared to electron measurement alone); the difference in systematics and backgrounds for electrons and muons that can provide confirmation of marginal signals; the requirement to measure muons in the forward direction, permitting determination of decay asymmetries for new heavy objects; and the ability to identify and measure muons closely accompanied by other particles.

The function of the EMPACT muon system is to trigger on and then precisely measure the momenta of muons in single and multiple muon events. The goal for the muon system is to measure muons over the full acceptance with resolution similar to that for measuring electrons with calorimetry. In order to make this quantitative, the goal is to reconstruct Z^0 's decaying from heavy objects, to the level of the intrinsic Z^0 width. The muon system should also have sufficient acceptance and resolution to measure the asymmetry of a new Z' . The trigger system must recognize muons above a minimum p_T , rejecting calorimeter punchthrough particles and muons from the decay of light quarks, and be flexible enough to increase the threshold as the luminosity increases. The limitations on the measurement system, for EMPACT as for all SSC muon systems, is determined by the capability of the first chambers after the calorimeter to withstand the rates and find

muon tracks in the presence of real and fake muon backgrounds, exacerbated by the burden of accompanying showers.

A muon spectrometer based on a system of superconducting air core toroids provides a unique opportunity for accomplishing these goals at the SSC. The toroidal field is efficient because it is always perpendicular to the particle trajectories, and the closed field obviates the need for massive quantities of iron for flux return. In addition, the particular realization of the toroidal field presented here allows the possibility of tuning the resolution attainable with the system by separate adjustments of the currents and hence the field in the central and end regions, as well as independent adjustment of the field lengths.

Although large superconducting air core toroidal magnets have not previously been used in high energy physics experiments, they have been successfully developed and applied in the plasma confinement fusion research program. The approach here is to adapt this proven technology for the EMPACT experiment. The feasibility of using large superconducting air core toroids for this experiment has been verified in an earlier study commissioned by the SSCL [1]. The conclusion of that report was although the sizes of the EMPACT magnets are larger than any previously built, the technology required to construct such a system is well within state-of-the-art, and therefore the EMPACT toroids can be constructed with a conservative design.

Initially two different magnet configurations were investigated. The first type provided access to the interior magnetic field volume so that muon detectors could be positioned within the magnetic field to

measure the trajectory's sagitta with minimal multiple scattering. However, this design was rejected after considering the consequences of requiring penetrations through the cold support structure and designing detectors to operate with high precision in a magnetic field. The second configuration considered has no access to the interior and all muon trajectory measurements are made outside the toroid in a nonmagnetic environment. This approach has led to the simplified toroid and detector design which is being proposed. Preliminary design studies indicate that toroids of sufficient bending power can be built with relatively little material to scatter muons.

The present system has three point measurements (point-line) in the central region, and four point measurements (line-line or angle-angle) in the end region where the momenta are higher. Each "point" consists of multiple measurements, typically 8 or 16 on each bend plane and approximately half as many for each non-bend coordinate. For the purposes of resolution studies, a single point precision of 0.2 mm, which is available in many current technologies, has been assumed. For the conceptual design, the focus has been on detectors built from limited streamer tubes, although other technologies including plastic tubes with strip readout, and high pressure, high resolution drift tubes are also being considered.

4.2 SUPERCONDUCTING AIR CORE TOROIDAL MAGNETS

4.2.1 Toroid Specification

A specific system of toroidal magnets has been considered as the basis both for a proof-of-principle and for an investigation of detail design alternatives. In this system, the magnetic field volume will serve as a refractive medium alone, as there are no position measurements in the field region. In order to optimize momentum resolution, the design maximizes bending power while minimizing material

thickness (radiation lengths) during the refractive process. Although considerable mechanical analysis effort is required to establish engineering feasibility and to optimize parameters, initial results indicate that this technique is both promising and effective [2].

The configuration chosen for study is shown in Fig. 4-1. Rectangular cross section toroids with peak surface magnetic fields of 1.5 T and 4.5 T have been considered for the central and end toroids, respectively. The preferred superconductor is NbTi in a stabilized, forced-cooling system with an aluminum alloy conduit. Most of the stabilizer is aluminum.

The magnetic field strength within the coil decreases inversely with radius and is well confined. It is purely azimuthal and homogeneous since the superconducting coils are closely spaced and uniformly wound. A bending length ($\int B dl$) of approximately 3.6 T m can be obtained at $\theta = 90^\circ$. This will increase with η , due at first to increased path length in the central toroid, and then to increased magnetic field in the end toroid, reaching a value of 18.6 T m at $\theta = 9.6^\circ$. The stored energy in each of the three magnets (one central and two end toroids) will be approximately 1 GJ.

The structural goal is to achieve a design that does not exceed more than a few radiation lengths in the combined dewar, support structure, and superconductor thicknesses for both the central and end toroids. This would imply thicknesses in the range of 20 to 30 cm of aluminum equivalent and would result in a muon momentum resolution of better than 3% at low momentum over almost the full rapidity range. A region of potentially poorer resolution corresponds to the overlap region between the magnets where a muon must traverse the material thicknesses of both the central and end magnets. This region also corresponds to a reduced bending length. The outer radius of the end toroid has been

Fig. 4-1 Layout of EMPACT Muon System Showing Key Dimensions (cm) of Toroids and Muon Detectors

set larger than that of the central toroid in order to partially offset this effect. The precise optimization of the geometry of this interface awaits detailed study of the physics processes and of the detector construction, assembly, and servicing.

4.2.2 Superconductor Specification

A promising design for a cable-in-conduit conductor (CICC) [3] for the air core superconducting toroids was carried out with the aim of reducing the radiation length compared to earlier designs. The cross section is shown in Fig. 4-2. Aluminum alloy was substituted for the usual stainless sheath to enclose the conductor, and pure aluminum was used for the major portion of the stabilizer copper that is found on conventional CICC conductors. The sheath would be continuously formed about the wrapped cable, obviating the need for a full length seam weld. The individual NbTi/Cu multifilamentary strands would be clad with stabilizing aluminum before cabling, sheath-

Fig. 4-2 Cross Section of Cable-In-Conduit Conductor

ing, and compaction to approximately 30% void. Although the conductor concept appears reasonable, it is an extension of the CICC art that remains to be demonstrated. Among other things considered were low temperature resistance of the stabilizer, stability margin, maximum quench pressure, sheath strength and loads, stored energy, dump voltage, conductor current density, helium path length, and conductor mass. All were found to be acceptable. If conductor development by producing and testing samples is successfully completed, the conductor and torus into which it is wound should be economical and perform satisfactorily.

It should be emphasized that further research and development on such a superconducting cable is crucial to the definition of the toroidal magnet design envisioned for the EMPACT proposal. At present two companies capable of producing such conductors have expressed an interest in participating in this development.

4.2.3 Conceptual Design Analysis of Toroids

A conceptual design of air core toroidal magnets that are radiation thin and permit high resolution measurement of muon momenta has been carried out [2]. A primary design issue has been the

Fig. 4-3 5 Degree Cross Section (All Dimensions in cm)

structural stability under both operating and fault conditions rather than stress analysis alone. The structure must support the magnetic pressure $B^2/2\mu_0$ directed everywhere outward from the magnetic field volume. Since the field-radius product $B \times r$ is constant for a toroid, there exists a net centering pressure on the cylindrical portions of the coil, i.e., a force directed radially inward. The annular end faces of each coil are subjected to equal and opposite axial forces $\pm F_z$. The axial force is independent of the coil shape between the inner and outer radii. The centering force is shape-dependent. Forces scale as B^2 . Stresses are constant for constant aspect ratio. By detailed mechanical analysis, it was found that keeping the structural spans at 5° azimuthally reduced the average amount of material and therefore the radiation lengths and multiple scattering effects compared to larger spans. The structural material is aluminum alloy 2219-T87, a well documented material for use at low temperatures, with a radiation length of 7.95 cm.

The approach that is suggested is to use bi-axially tensioned membranes (i.e., plates) placed in azimuthal planes that tie together the inner and outer cylinders and also connect the end faces to each other. The result is a tensioned vane that directly reacts the axial forces and supports, in part, the inner cylinder of the coil by using the radially outward pressure on the outer cylinder of the coil. This arrangement also improves the stability of the structure by controlling cylinder distortions and raising the buckling mode number. The chosen subdivision of 72 sectors, each with a 5° included angle, is selected to permit thin annular disks with reasonable deflections. Figure 4-3 shows the details of the 5° magnet segment.

This geometry has been evaluated over the angular range from the minimum detection angle of 9.02° ($\eta = 2.54$) to 90° . The ratio of rms multiple scattering angle to magnetic bend angle, a figure of merit for the design, is shown in Fig. 4-4. This does not include the scattering effects of supports, cables,

Fig. 4-4 Ratio of RMS Multiple Scattering Angle to Magnetic Bend Angle for Toroids versus Polar Angle

electronics or the utilities required for the magnet itself that will reduce transparency over localized areas. The region of poorer resolution, $30^\circ < \theta < 45^\circ$, corresponds to the overlap between magnets where a ray must traverse the material of both coils.

Muon trajectories through the vanes will suffer increased multiple scattering (about a factor of 4 or 5) compared to neighboring trajectories and hence will have worse momentum resolution. Careful design of assembly joints may limit the degraded fraction of azimuth to less than approximately 5%.

Additional effort to achieve a more optimal configuration is planned. A more complete description of the design of toroids is available in Ref. 2.

4.2.4 System Considerations

A considerable effort has been expended on assembly and systems considerations in order to confront and evaluate the problems inherent in realizing a toroidal magnet based detector as the design evolves. An ongoing engineering group has been set up to consider the size, weight, and transportability of the major toroid elements, as well as

the integration of muon detectors, calorimeter, supports, and systems.

A key feature in the implementation of the design is the high multiplicity of identical coil elements. The basic subdivision of 5° sectors is shown in cross section and perspective in Fig. 4-3 and 4-5. These coils will be fabricated in industry, and the requirement of 72 identical central coils and 144 end coils provides savings, reliability, and spares, and a high degree of optimization in fabrication techniques. The coils will be fabricated and completely tested before shipment to the site where the central coils will be assembled into 45° units for underground assembly. The end toroids can be completely assembled above ground and installed as a unit.

The central toroid dewar is designed to provide support for the calorimetry system and for support and alignment of the inner muon chambers (Fig. 4-6). It is designed to permit access and replacement of the muon chambers located between the dewar and calorimeter walls without removing the calorimeter. The toroid dewar inner wall is a double wall cylinder assembly; the outer wall is the vacuum boundary for the toroid, and the inner wall is the support tube for the calorimeter modules. The walls are joined together by eight longitudinal ribs that also support the muon chambers. A preliminary finite element analysis of the dewar/calorimeter support structure has been done (Fig. 4-7). This analysis prefers 12 ribs instead of 8, permitting thinner walls, but increasing the muon channel count. The end dewar walls are not only vacuum en-

Fig. 4-5 Central Toroid 5 Degree Coil Assembly

Fig. 4-6 Central Toroid Assembly

closures but also provide support for calorimeter cabling and vacuum plenums for calorimeter pumping.

The central components are independently supported on fixed overhead frames giving minimal interference with the coverage of the muon chambers, and the central toroid structure/conductor assembly is supported by room temperature tie rods (Fig. 4-8). The outer central muon detectors are supported from intermediate fixed frames. The end toroid structure, dewar, and muon chambers are similarly supported, except the support frames are mounted on rollers that permit lateral movement of the total assembly for installation, maintenance, and repair of otherwise inaccessible systems (Fig. 4-9). This support system is illustrated in the surface model shown on the front cover and in more detail at the front of this section.

4.3 MUON DETECTORS

4.3.1 Detector Specifications

In the current design, muon momenta will be measured with detectors before and after the bending field of the toroidal magnets. The requirements for these detectors are:

- Spatial measurement better than 200 μm , with an effective resolution of better than 50 μm due

VON MISES

(A) 8 RIBS

(B) 12 RIBS

Fig. 4-7 Stress Plots for Central Toroid Dewar for (A) 8 Ribs and (B) 12 Ribs

Fig. 4-8 Section Through Central Toroid Showing Overhead Support Frame and Muon Detector Packages

Fig. 4-9 View of End Toroid Showing Movable Overhead Support Frame

to the use of multiple wire measurements. This precision with the proposed field strength sets the momentum resolution

- Prompt output (< 150 ns) for use in the Level 1 trigger
- Timing identification to assign muons to their proper bunch crossing
- Absolute or monitored positioning of the detector elements to $25 \mu\text{m}$
- Low cost

- Compactness, a special constraint that applies to the layer between the central calorimeter at a radius of 3.5 m and central toroid at a radius of 4.0 m
- Minimal dead regions, though some will be unavoidable due to electronics cabling and detector end effects. This implies a maximum compaction for the resident electronics.

4.3.2 Conceptual Detector Design

There are a number of technologies available to meet the specifications. One option is to use multi-channel aluminum extrusion tubes operating in the streamer mode. Another option is to use plastic extrusion tubes with a strip readout system that offers the advantage of easier alignment than a wire readout system, but more complex electronics.

The final selection of a muon detector must await R&D. The present baseline is the multi-channel aluminum tube, wire readout system (Fig. 4-10). The merits of this option are:

Fig. 4-10 Corner of Muon Detector Package Showing Offset Double Layers of Tubes

- Aluminum extrusions are easily mass produced and relatively cheap. Some finish machining may be needed to obtain the desired placement accuracy both within the tube and in stacking
- The streamer chamber pulses are fast, typically

60 mV in 10 ns, thus minimizing amplification electronics

- The tubes themselves act as cables giving speed-of-light pulse transmission. Measurements show little time degradation in rise time
- Staggering adjacent layers by half a tube width provides a method of assigning the absolute time of traversal and therefore assignment to the proper bunch crossing
- Punchthrough rates, even at a luminosity of $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$, will not damage the tubes.

Single element resolution of 100 – 150 μm has been obtained, in one case [4] by multiple scattering and diffusion and in another case [5] by mechanical alignment. Work has begun on a program of building and testing prototype chambers. This will lead

to tests for ultimate resolution with a UV laser and to gas studies to optimize performance. The effects of delta rays and electron pairs on resolution will also be investigated.

4.3.3 Mechanical Support & Alignment

The proposed arrangement of muon detectors is shown in Fig. 4-11 in cross section and Fig. 4-12 in perspective from the 3D model. Since the overall weight of the detector is sufficiently low to permit tension members to support the detector from above, there is minimal interference of support structure with coverage. The inner central chambers are supported in a single package between the double wall toroid dewar/calorimeter support. In the forward regions, two layers of inner chambers provide a 1 m lever arm and are supported as a single package from the end toroids. The outer two layers are also

Fig. 4-11 Layout of Muon Detectors

Fig. 4-12 3D Model of Muon Detectors

constructed as packages with rigid trusses separating them. The packages will be subdivided only for convenience and ease of handling. The axial central chambers are divided into barrel and end regions to permit passage of services, but are staggered to provide complete coverage.

The accuracy of the muon momentum measurement is dependent on knowing the relative positions of the muon detector elements. All the detector modules will be supported from frame structures that are external to the central and end toroids, except for the stations between the central calorimeter and central toroid, that will be positioned in the calorimeter support cylinder.

Each detector module will have several reference surfaces that will relate the location of external reference marks to the internal detector planes. The goal is to determine the location of each reference surface to within $25\text{ }\mu\text{m}$. For this conceptual design, the following assumptions are made:

- The two outermost modules are accessible
- Detector modules located between the calorimeter and toroid are obscured by the toroid and are not accessible
- A minimum number of lines-of-sight through the toroid can be made available.

The concept being developed is an electro-optical system that would provide continuous monitoring of detector module positions. This

alignment technique calls for the construction of an alignment fixture that would be located above ground near the construction site. A full set of detector modules (three or four) would be placed into the fixture, and initial positions set and recorded for reestablishment in the final positions underground.

To minimize the number of lines-of-sight through the toroid, the outer modules are first aligned to each other, and then the inner modules are aligned to the two outer ones. Combinations of light sources, reflectors, and detectors will provide an overdetermined set of measurements which will provide accurate ($< 25\text{ }\mu\text{m}$) determinations of the deviations of the chambers in all six degrees of freedom [6].

The development program calls for a two year engineering effort to test and verify these concepts by building a prototype system capable of aligning one inner detector module and two outer detector modules. The degree of temperature stabilization required to achieve this precision over a large system must be established.

4.4 MUON PERFORMANCE

In this subsection the performance of a spectrometer based on superconducting air core toroids with detectors before and after the field volume is examined. This performance analysis is preliminary, but indicates the feasibility of triggering on, identifying, and measuring with high precision, muons from processes of interest at the SSC. While the approach of measuring muons with air core toroids is novel, the problem of selecting and measuring muons has many features in common with more traditional approaches. In particular, the toroids provide a similar filtering capability to meters of magnetized iron, so that triggering on muons after the magnet is reasonably clean. In all systems contemplated for the SSC, the limiting elements will be the chambers located directly behind the calorimetry and before the magnets. The rates in these chambers due to punchthrough, as well as prompt and decay muons, provide a severe challenge for pattern recognition. EMPACT has sev-

eral advantages over other designs because its compact tracking volume limits π and K decays, and the space allowed for calorimetry provides 12 to 15 absorption lengths of material before the first muon chamber. This is illustrated in Fig. 4-13,

Fig. 4-13 Total Absorber Material in Front of First Muon Chamber as a Function of η

which shows this material as a function of η using the ray tracing capability of the 3D engineering modeling system of Martin Marietta. (See Subsection 3.3.)

4.4.1 Punchthrough Simulation

The background from hadron punchthrough is of particular importance for the EMPACT detector where the thickness of the calorimeter and the hadron filter sets the scale for the toroid system both in size and cost. Issues that must be understood before embarking on the construction of a muon spectrometer include the minimum hadron absorber thickness demanded by SSC physics needs and the impact of the hadron punchthrough on the performance requirements for the design of the muon spectrometer, including the toroid system, muon measuring system, and trigger system. Work is in progress to study these issues through simulation of the hadron punchthrough.

Punchthrough from incident pions is studied using a GEANT3 plus GHEISHA Monte Carlo

simulation. Figure 4-14 compares CCFR [7] data and the GEANT simulation for the punchthrough

Fig. 4-14 Comparison of Data and Monte Carlo (Histogram) for Punchthrough Rate vs Depth in Steel

probability as a function of the thickness of an iron calorimeter of average density 4.2 g/cm^3 . In the range of momenta and absorber thickness, the agreement between data and simulation is good. Figure 4-15 shows the momentum spectrum $1/N_{\text{inc}} dN/dZ$

Fig. 4-15 Momentum Spectra of Exiting Particles for Different Incident π Momenta Compared to Monte Carlo

where $Z = P_{\text{out}}/P_{\text{inc}}$ and P_{out} is the exiting particle momentum measured by the E379 experiment [8] corrected for the energy losses a muon would have in a calorimeter of thickness 18.5λ . The curve is the result from a GEANT simulation and is in good agreement with the data. The spectrum is sharply peaked at low punchthrough momentum.

Punchthrough shower profiles were compiled using a GEANT simulation with π^+ of incident momenta from 20 GeV/c to 3 TeV/c on an iron block. Secondary particles were followed for momenta down to 1 MeV/c for electrons and 10 MeV/c for hadrons, and the position, momentum, and type of charged particles surviving after 10λ , 12λ , 14λ , and 30λ were recorded. The spectrum of the leading charged particle that exits the absorber after 14λ is shown in Fig. 4-16. As expected, this spectrum is peaked at low momentum. The non-leading particles are even more sharply peaked at low momentum. Figure 4-17 shows the multiplicity distribution of charged particles exiting the 14λ absorber from incident pions. It was found from the GEANT simulation that the charged punchthrough particle multiplicity increases with the incident pion momentum. This multiplicity must

Fig. 4-16 Momentum of Leading Charged Punchthrough from π^+ Incident on 14λ of Absorber

Fig. 4-17 Charged Multiplicity of Punchthrough After 14λ for Various Energy π^+

be taken into account when determining the backgrounds to prompt muons and in determining the cell size requirements for the muon system.

The punchthrough particle positions and directions are also recorded. It was found that the distribution of the punchthrough particles did not strongly depend on the incident pion momentum or absorber thickness. The direction of each outgoing punchthrough particle was used to project back to the front plane of the calorimeter. The distance between this projected position and the incident pion is shown in Fig. 4-18. For example, a 10 GeV/c muon would project back on average to within 2 cm

Fig. 4-18 Distance between Projection of Exiting Direction and Incident π^+ Position

of the original muon track, making it possible to further suppress the punchthrough background by linking the track in the muon tracking region to the track in the inner tracking volume.

The punchthrough probability, multiplicity, and position (relative to the parent) were parameterized and then used in an ISAJET analysis routine to determine preliminary background rates for the EMPACT detector with a calorimeter thickness as proposed. This is used to obtain the results presented in the following subsections. Work will continue on the GEANT simulation to refine these parameterizations and model a realistic calorimeter, instead of the block of iron used in the present study.

4.4.2 First Level Muon Trigger

The rate for the first level muon trigger must be kept below 10^4 Hz. The magnetic properties of air core toroids result in a simple triggering scheme, since the magnetic bend is almost independent of polar angle for constant p_T . Since hadrons are filtered by the calorimeter and low p_T muons are swept away by the toroid, the trigger will simply require tracks after the toroid to point back to the interaction region. The accuracy of the pointing can be used to vary the threshold of the trigger. As the luminosity increases, the threshold can be raised.

To simulate the first level trigger, events were generated using ISAJET. Muon sources included prompt muons from heavy quark decay that penetrate the calorimeter, π 's and K's that decay before reaching the calorimeter, and punchthrough using the parameterization discussed in Subsection 4.4.1. Particles that spray off the calorimeter edges or quadrupoles were not included. This contribution could be substantial in the forward direction and needs further study.

The differential cross sections for particles that penetrate the EMPACT calorimeter to the first layer of the muon chambers is shown in Fig. 4-19. The

Fig. 4-19 $d\sigma/dp_T$ for "Muons"

probabilities of an event producing a muon from π or K decay, hadron punchthrough, and a prompt muon that penetrates the calorimeter are 3.6%, 0.10%, and 0.12%, respectively. If only muons with p_T above 8 GeV/c are considered, prompt muons from b and c decay dominate the rate. A cut at a p_T of 4 GeV/c, as measured in the toroidal spectrometer system, will produce a total rate less than 10^4 Hz for a luminosity of $10^{33} \text{ cm}^{-2} \text{ sec}^{-1}$. A cut at a p_T of 12 GeV/c reduces the rate by a further factor of 10.

The trigger design considered for EMPACT makes use of measurements after the toroid. Two types of elements are involved in the first level trigger: a fast element, able to tag the muon to a single crossing, and a spatially accurate element, to permit clean momentum cuts. For the muon baseline design shown in Fig. 4-1, the detectors are assumed to be aluminum drift cells, operated in streamer mode, with a maximum drift of 2 cm. The outer two layers of chambers are separated by 3.5 m in the

central regions and also 3.5 m in the ends. These chambers then provide both spatial information for the trigger and the time tag. The trigger for EMPACT is a logical OR of individual drift cells that form a hodoscope. Hodoscope elements subtend a constant angle in the bend plane of 7.5 mr in the central region and 5 mr in the end region, corresponding to elements about 7 cm wide. A hit in the second layer of hodoscopes gives a valid trigger if it is within two elements of the projection from the center of the interaction region to a hit in the first hodoscope layer.

The results of applying this trigger scheme to a simulation of muons that includes multiple scattering in the calorimeter is shown in Fig. 4-20. This trigger accepts only 5×10^{-5} of the background spectrum while accepting 79% of muons from W decay and over 99% of muons coming from decay of a $1 \text{ TeV}/c^2 \text{ W}'$. This trigger is completely adequate to get a trigger rate less than 10^4 Hz . Restricting the projected track to pass within one element of the hit cell would give the rejection rate necessary to run at higher luminosity.

In the forward region of the muon detector there will be higher rates due both to muons and spray

Fig. 4-20 Efficiency vs p_T (GeV/c) for Central Toroid. D is the Allowed Distance in Elements from the Projected Position in the Second Hodoscope.

from the edges of the calorimeter and quadrupoles. One possibility being considered is the use of acrylic Cerenkov counters for the region covering $1.5 < \eta < 2.5$. This will provide fast timing to assign triggers to the correct crossing and reject low energy particles passing through the muon detectors. For EMPACT, this would require 3200 counters with two photomultiplier tubes for each counter. Acrylic Cerenkov counters will be tested in the BNL test beam this year.

4.4.3 Muon Identification

The identification of muons will require all parts of the detector, but it will be based largely on the information in the muon subsystem. The muon momentum will be measured by deflection in the air core toroid. The calorimeter will provide the energy loss for isolated muons and may help flag muons that are in jets. The central tracking system will identify the event vertex and tag high momentum muons ($\gamma > 1000$) in the TRD.

The background to the muon measurement in the muon detectors will come from other particles penetrating the calorimeter. ISAJET studies were made of all muons from top quark jets at greater than $10 \text{ GeV}/c$ (Fig. 4-21) and $1 \text{ TeV}/c$ (Fig. 4-22). The p_T spectrum of prompt muons, muons from π and K decay, and hadronic punchthrough is shown

Fig. 4-21 Differential Cross Section for Products from Top Jets with $p_T > 10 \text{ GeV}/c$

Fig. 4-22 Differential Cross Section for Products from Top Jets with $p_T > 1 \text{ TeV/c}$

in those figures, and it is clear that assigning p_T cuts as a function of the jet energy will select the prompt muons from the background. In addition, a very effective cut against punchthrough is to require a vector from the vertex to the measured muon position after the calorimeter to line up with the measured muon direction within multiple scattering errors, as described in Subsection 4.4.1.

For isolated tracks, the muon momentum measurement will be as described in Subsection 4.4.4. Hits from hadron punchthrough into the first measuring station of the muon system will degrade the muon measurement if they cannot be isolated from the correct hits. It is anticipated that by using drift cells of 2 cm or less, the hits will be separated into different cells and the momentum measurement will remain as specified. This is an important study to be pursued.

High energy muons lose much less energy in the calorimeter than high energy hadrons (see Fig. 4-23). However, for very high energy muons the energy loss from radiation is greater than the energy loss from ionization. Failure to correct for the radiative loss will seriously impair muon momentum measurement. The energy from stray hadrons should be distinguished from radiated energy from

Fig. 4-23 $p/(p + E_{\text{CAL}})$ for Isolated 800 GeV π^+ and μ^+

the muon. Depth segmentation in the calorimeter may offer a means to discriminate between these two energy depositions.

The TRD can provide additional information for the muon measurement. It will tag by transition radiation (see Fig. 2-4) muons with momentum greater than 100 GeV/c. The TRD angular resolution is about 1 mr and the first muon drift station also has an angular resolution of about 1 mr. The contribution from multiple scattering in the calorimeter for a muon with energy E is $(0.3 \text{ mr}) (TeV/E)$. Clearly EMPACT will be able to match high-momentum tracks in the muon system with tracks that radiate in the TRD.

The central tracking should also be able to tag the production vertex of the muon. There will be some softer muons that were not part of the trigger, but that are still of interest in the event. These muons must be distinguished from muons not belonging to the interaction of interest. The TRD tracking system can achieve a resolution along z of better than a millimeter, reducing the background by almost two orders of magnitude. The addition of the pixel vertex detector would clearly improve this and would also tag muons from heavy quark decays.

4.4.4 Momentum Resolution & Track Reconstruction Quality

The EMPACT muon track reconstruction quality has been studied for the conceptual magnet

model that is discussed in Subsection 4.2.3. The study was based on the assumption of groupings of multilayer devices, such as drift or streamer tubes. The groupings are represented as providing two "superlayers" of detectors to determine the trajectory before and after the magnet. The number of layers in these superlayers was varied to find the optimal distribution to minimize the momentum resolution. A crude representation of the material at smaller radii than the muon system was made by assuming the presence of a spherical "calorimeter" with a thickness equal to 450 radiation lengths. This material has very little influence on the momentum resolution but strongly affects the precision of the other track parameters.

A program was developed that incorporated the mechanical details of the proposed superconducting magnet and took into account multiple Coulomb scattering and measurement errors. The program is flexible with regard to input parameters and is well suited to optimization studies. The output of the program is the correlated error matrix for the χ^2 estimates of the five parameters that describe a particle track ($P, \theta, \phi, X_0, Y_0$) giving momentum, directions and intercepts. For simplicity, particles were assumed to lose no energy by ionization or radiative processes, and multiple scattering was taken to be Gaussian. The full details of this program are found in Ref. 9.

The results from this program were found to be in excellent agreement with the output of a well tested fitting and tracking program that had been developed earlier for the SLD detector [10]. Figures 4-24, 4-25, and 4-26 show the resolution of track parameters as a function of muon momentum and polar angle for toroidal magnets with $B_0 = 4.5$ T and $B_1 = 1.5$ T. B_0 (B_1) is the maximum field at the minimum radius of the end (central) toroid.

A series of studies were made of the performance characteristics of magnet/detector systems to give an indication of the range of magnet perform-

Fig. 4-24 Momentum Resolution as a Function of θ for the Baseline Design

Fig. 4-25 Resolution on Vertex Position for Baseline Design

Fig. 4-26 ϕ Resolution for Baseline Design

ance. The momentum resolution for a change in B_1 to 2.25 T is shown in Fig. 4-27 (compare to Fig. 4-24). The changes in the complicated structure that appears in the region $31^\circ - 45^\circ$, as one varies B_1 , arise from the interplay of the change in bending power due to variation of the magnetic field and the associated change in the multiple scattering in the superconductor in the coils and support structure. Another important factor in this region is the gap between the end and central toroid support structures that is required for access and mechanical support of other parts of the detector system such as the calorimeter and tracking system. All these aspects are under study and will be optimized in the final detector proposal.

Fig. 4-27 Momentum Resolution for Muons with Central Toroid Field at 2.25 T

To study the effects of these changes, a sample of 800 GeV Higgs decays into two Z^0 's decaying into muons was produced using ISAJET. The track parameters were modified by the previously described program, then analyzed. The Higgs particles were given the expected width, but the Z^0 's were generated with zero natural width to isolate the effect of the track fitting on the reconstruction process. The samples were selected to include only events for which all four muons fell within the acceptance of the model detector. This resulted in an efficiency of 77%. In Fig. 4-28, the effect on the

Fig. 4-28 Z^0 Mass Resolution $H \rightarrow Z^0 + Z^0 \rightarrow \mu^+ \mu^- \mu^+ \mu^-$
 $M_{Higgs} = 800 \text{ GeV}$

mass resolution for variations of both the end and central toroid field strengths is shown. The effect of a vertex constraint is displayed for comparison. Such studies will be used in conjunction with the detailed designs for the magnets to obtain parametric information on cost and schedule for various performance characteristics. These studies of physics and fabrication data, in conjunction with efforts on detector integration (Section 7), will give an excellent opportunity to design for cost and performance.

In summary, it seems possible to design a detection system, based on a superconducting toroidal magnet, that has excellent acceptance over a large range of rapidity and with resolution properties for muons equivalent to the calorimetric resolution available for electrons.

4.5 OPERATION AT HIGH LUMINOSITY

The muon system residing after 12 – 15 absorption lengths of calorimeter is likely to be the system least sensitive to major increases in luminosity. In order to maintain reasonable trigger levels, the minimum p_T threshold will be raised above 12 GeV/c to provide a Level 1 rate less than 10^4 Hz at a luminosity of $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$. The absolute rate of punchthrough particles peaks strongly at high η . The issues here are both the lifetimes for the inner chambers, and the ability to find tracks in these

chambers, and the ability to find tracks in these chambers given a trigger and track segment in the outer chambers. The chambers beyond the magnet, protected by 18 Tm of field integral providing 6 GeV/c of transverse kick, will not limit system performance. The simplest strategy will be to limit the η coverage to avoid the areas of highest punch-through, which are also subject to spray from the edges of the calorimetry. Since high luminosity running will be directed at higher mass objects, whose decay products are more central, this reduction of coverage will not limit most search capability. All of these issues merit careful analysis as the detector design develops.

4.6 PRINCIPAL DEVELOPMENT ISSUES

The critical issues for development of the EMPACT muon system are:

Toroidal Magnet

- Detailed designs by vendors capable of fabrication resulting in cost/schedule parameterization for radii, length and field [11]
- Superconductor development, including manufacture and test of samples leading to design input data for current capacity and winding times
- System issues including supports and services.

Detector Support

- Preliminary designs of supports for outer chambers, including analysis of rigidity, stability and temperature stabilization
- Development of optical alignment tools and analysis, including fabrication of model test system.

Detector Development

- Pattern recognition analysis including full treatment of punchthrough and radiation backgrounds to determine requirements on number

and readout of bend and non-bend coordinate detectors

- Simulation of performance for muon resolution to optimize chamber distribution
- Development and comparisons of alternate technologies with regard to precision, tolerances, cost, and schedule for fabrication.

Trigger Development

- Electronics and algorithms for generation of trigger using position detectors
- Development of fast trigger elements.

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5

TRIGGER, DATA ACQUISITION & COMPUTING

5 - TRIGGER, DATA ACQUISITION, & COMPUTING

The design of the EMPACT detector places balanced emphasis on the measurement of electrons, muons, jets, and neutrinos (missing energy). To ensure that a broad range of physics can be successfully addressed, the trigger system must be correspondingly general. Moreover, it must be flexible enough to respond to evolving physics interests and to accommodate changes in running conditions, most notably increases in luminosity.

Although the design of the trigger and data acquisition system for any SSC detector is a daunting technical challenge, the conceptual simplicity of the EMPACT detector will help to streamline the trigger design. In particular, the plan is to capitalize on the unique features of the design: field-free central tracking and an air core toroidal magnet system for the detection of muons. The latter feature will permit accurate measurement of muon trajectories for luminosities well above the nominal $L = 10^{33} \text{ cm}^{-2}\text{s}^{-1}$ and will provide the ability to optionally increase the muon p_T trigger threshold to values high enough to screen out semi-leptonic decays of c , b , and possibly even t quarks. Furthermore, the comparatively open geometry of the detector will afford some freedom in situating the electronics, easing somewhat the constraints of limited space, power dissipation, the need for access, and radiation hardness.

The uniformity of technology for measurement over the full solid angle of interest for triggering (typically $\eta < 3$), provides the capability for simple trigger technology dependent only on critical variables (i.e., p_T or E_T), and not on polar angle or azimuthal regions. This is true for electrons, photons and jets whose trigger comes primarily from the calorimeter; and for muons where the angular deflection is everywhere proportional only to p_T , a unique characteristic of the toroidal configuration.

The basic architecture of the trigger system will be standard, consisting of three levels arranged in order of increasing sophistication and decision time:

- Level 1 will operate in real time to reduce the input 10^8 Hz raw data rate by a factor of 10^3 or 10^4 . Effectively deadtimeless operation will be achieved by holding the detector signals in pipelined delay elements while the Level 1 trigger is being formed. Level 1 triggers will be limited to readily formed signals corresponding to single high p_T leptons, jets, missing energy, or combinations thereof.
- Level 2 will use special purpose processors to make more sophisticated tests and will correlate disparate trigger elements to reduce the rate by an additional two to three orders of magnitude.
- Level 3 will employ a general purpose processor farm operating on fully assembled events to further reduce the events in both size and number. This approach is represented schematically in Fig. 5-1 and described in additional detail below.

5.1 LEVEL 1

The Level 1 trigger will be based mainly on analog sums from the calorimeter and struck wire data from the muon system, although use of TRD signals at Level 1 is also under study. In each case the triggering information will be picked off before the signals enter analog or digital delay pipelines, where they will be stored until a valid Level 1 trigger causes transfer to Level 2.

5.1.1 The Pipeline Delay

The formation of Level 1 triggers based on coincidences between different detector subsystems requires that trigger signals from remote parts of the detector be routed to a central location and that the Level 1 trigger signal be redistributed to all Level 1 storage pipelines, which will be mounted on

Fig. 5-1 Data Acquisition Schematic

or in close proximity to the detector. The large spatial extent of the detector results in a substantial roundtrip time and sets a floor of 600 ns on the delay time between the occurrence of an interaction and the return of the trigger strobe. Adding in the time for trigger formation and the propagation delays of the numerous circuits in the fan-in/fan-out tree will result in a Level 1 pipeline delay time of 1 – 2 μ s. The tradeoffs involved in setting this delay time for EMPACT await systematic study. For purposes of discussion, a value of 1 μ s is assumed.

5.1.2 Level 1 Primitives

Level 1 triggers will be constructed from any number of separate triggers, here called primitives, combined in logical expressions. There will be four types of primitives: muon, electron, jet, and missing E_T . For each type of primitive, signals corre-

sponding to a number of different transverse momentum or energy thresholds will be generated. In principle, calculations of arbitrary complexity could be performed in generating these primitives. In practice, however, the calculations will have to be kept simple, so that the length of the delay pipeline does not get too unwieldy. This means that only simple functions such as analog sums will be implemented and that complicated looping and correlations among detector elements will be avoided.

5.1.3 Level 1 Trigger Formation

As previously mentioned, Level 1 triggers will be formed at a central location on or near the detector. Since the number of signals that can be routed to this location is clearly a small fraction of the total number of detector elements, a great deal of logical OR-ing will be done locally on the detec-

tor, and only highly summed signals will be passed on to the Level 1 trigger box. For example, the muon subsystem might report that there were two high p_T muons in the third octant of the forward muon system, or the central calorimeter might report single high p_T electrons in the second and seventh octants.

A trigger will be any combination of trigger primitives that can be constructed by counting, or with standard Boolean algebra operators such as AND, OR, NOT, etc. Physics processes of interest will be addressed by setting up those combinations of primitives that provide the best reduction in background with least penalty to the signal. Since it will be difficult to anticipate all aspects of the trigger performance in detail and since physics goals will evolve over the life of the experiment, the Level 1 trigger will be fully programmable. Nonetheless, extensive study will be needed to ensure that a sufficiently flexible set of primitives is made available.

Table 5-1 shows how a representative set of primitives might be combined to provide sensitivity to various physics processes. The first signal column means "at least one lepton with at least 100 GeV/c of transverse momentum," etc. Leptons can be either electrons or muons. Note that physics channels are generally addressed by more than one combination of primitives. The last two entries are calibration triggers. In some cases, additional rejection will be obtained by requiring the logical AND of combinations. Also, the number of thresholds has been sharply reduced to simplify the table.

5.2 LEVEL 2

The rate of events passing Level 1 will be in the range $10^4 - 10^5$ per second. Level 2 will reduce this rate by an additional factor of 100 to 1000 by:

- Refining the lepton and jet criteria imposed in Level 1. In the case of muons, this will mean including more muon chamber layers in the calculations to eliminate spurious tracks and to correct for event vertex effects. In the case of

Table 5-1 Physics Processes And Level 1 Trigger Primitives

PHYSICS	SIGNALS (units in GeV)				
	$\#(p_T^l > 100) \geq 1$	$\#(p_T^l > 20) \geq 2$	$\#(p_T^{\text{jet}} > 100) \geq 1$	$\#(p_T^{\text{jet}} > 20) \geq 2$	$E_T^{\text{miss}} > 100$
$H \rightarrow l^+ l^- l^+ l^-$	X	X			
$H \rightarrow l^+ l^- \nu \bar{\nu}$	X	X			
$H \rightarrow l^+ l^- q \bar{q}$			X	X	
COMPOSITENESS			X	X	
$Z' \rightarrow l^+ l^-$	X	X			
$W^\pm \rightarrow l^\pm \nu$	X				X
$\tilde{g} \rightarrow p_T^{\text{miss}}$			X	X	X
$\tilde{g} \rightarrow l l$	X	X			
HEAVY QUARKS	X	X		X	
$W^\pm \rightarrow l^\pm \nu$	X				
$Z^0 \rightarrow l^+ l^-$	X	X			

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electrons and jets, this will mean using finer segmentation and/or cleaning up the cases where a shower extends over more than one trigger tower. Corrections of this nature will sharpen the p_T resolution in the measured quantities, thereby allowing higher thresholds to be applied without loss of efficiency.

- Requiring appropriate correlations (or anti-correlations) between detector subsystems. This will allow us to distinguish, for example, between jet associated and isolated leptons.
- Calculating quantities such as jet-jet or lepton-lepton invariant mass combinations.

In contrast to the fixed decision times of Level 1, Level 2 decision times will vary from event to event, spanning the range from a few to a few tens of microseconds. The asynchronous nature of Level 2 will allow for a variety of technologies, ranging in complexity from Level 1 type cuts that require just slightly longer than the allotted $1\ \mu\text{s}$, to sophisticated calorimeter pattern recognition or straw tube track finding analyses carried out by special purpose processors. Although Level 2 trigger elements may combine information from different detector subsystems, this will be done only in an ad hoc way, e.g., TRD information might be combined with calorimeter information for purposes of electron identification. Full scale event building will be left to Level 3.

5.2.1 Storage Consideration

The data from events satisfying the Level 1 trigger must be saved as they leave the $1\ \mu\text{s}$ delay pipeline. For detector elements with pulse widths (or drift times) greater than the $16\ \text{ns}$ corresponding to a single bucket, each store operation will mean saving the information from more than one bucket. Also, to minimize the deadtime it will be necessary to store events that arrive before Level 2 has dispensed with the last Level 1 trigger. The depth of storage required is presently an open question, but a rough idea can be garnered from Fig. 5-2, which shows the livetime fraction as a function of the dimensionless quantity $R_{\text{trig}} T_{\text{trig}}$, the average trigger rate multiplied by the time it takes to process a

Fig. 5-2 Live time Fraction vs the Product of the Average Trigger Rate Times the Time to Process a Trigger for Different Number of Data Buffers

trigger (in practice T_{trig} is variable). The different curves in Fig. 5-2 correspond to different numbers of buffers. Two trends are evident: (1) adding a second buffer produces a substantial improvement for most values of $R_{\text{trig}} T_{\text{trig}}$, but the returns diminish after that point, and (2) no amount of buffering will compensate for a trigger decision time that exceeds $1/R_{\text{trig}}$. Indeed, to evade the latter limit the Level 2 calculation would itself need to be pipelined. Although this option has not been ruled out, it would appear to place an overly stringent constraint on the design of all Level 2 triggers.

5.2.2 Level 2 Technologies

The development of Level 2 hardware and algorithms represents an interesting technical challenge that may be amenable to a number of intriguing solutions. Since these calculations must be performed on a very short time scale, any system will need to operate with a high degree of parallelism. A specific Level 2 trigger solution has not been determined at this point. However, it is clear that such a trigger will be of the custom processing class. There are several candidates in this class and a significant R&D effort will be required to sort out the appropriate solutions. Two candidates are discussed below:

- **Image Processors**—These systems are custom-built arrays of special purpose microprocessors

that execute non-standard instructions on multiple streams of data. Typical functions of these processors include the identification of features (e.g., reconstructing jets from calorimeter data) or recognition of incomplete patterns (e.g., electron tracks in a TRD). Quite simply, image processors attempt to emulate the human eye's ability to pick out "interesting events" in the presence of background. Significant work on the application of image processors has already been done [1]. We plan to expand on this work through informal collaborative efforts, adapting it to the EMPACT trigger/DAQ architecture.

Solid State Neural Nets – The field of neural nets has undergone rapid expansion in the last few years, and new hardware and software tools are now available. Neural nets are normally touted for their ability to be trained to recognize specific patterns and minor variations on such patterns. Of particular interest is the high degree of parallelism they allow, which will potentially enable the construction of fast Level 2 triggers. There are currently efforts to use neural nets in existing detectors. These approaches will be followed closely to identify the potential areas of interest and gain.

5.3 LEVEL 3

The rate for events passing Level 2 will be in the range of 100 to 1000 per second. The event size in EMPACT could be as large as several Mbytes. Therefore, it will be necessary to ensure that data can be transferred from the Level 2 buffers at average rates approaching 10 Gbytes/s. Such transfer rates can be achieved through massive parallelism of the bus structure (fiber optic links will be investigated for this purpose) connecting Level 2 buffers to the event builder – the location where data are collected into complete events. Once events have been assembled, high level filtering will be performed by programmable microprocessors, where an additional rejection of about a factor of 100 will be achieved prior to sending events to mass storage for subsequent offline analysis.

5.3.1 Event Building

The assembly of complete events for Level 3 filtering is a potentially complex task due to the size of events, the mix of data from different detectors, and the rate at which the task must be performed. Architectures have been proposed that appear capable of coping with the data flow rates well beyond those anticipated in EMPACT (e.g., the barrel switch of BCD) [2, 3]. An event builder utilizing dual port memory, similar to ones developed for BNL E791 or the D0 Level 2 trigger [4], configured so that input data from Level 2 enters at one port and is sent from the other port on busses to Level 3, appears to be the most straightforward approach for a high p_T detector, where significant trigger rejection (at least 10^5) should be achieved in Levels 1 and 2. This is an aspect of data acquisition design that will require extensive simulation and study before a particular approach is adopted. Detailed study of the event builder is one of the areas of focus of data acquisition subsystem R&D [5].

5.3.2 Processor Farm

Any estimate of the computational power required for Level 3 filtering is very uncertain. Rough scaling from present day collider experience suggests that a 100 MIPS machine should be able to handle about one event per second. That implies a need of about 10^5 MIPS in the processor farm. Fortunately, modern RISC processors are evolving so rapidly that single processors with speeds well beyond 100 MIPS appear likely within a few years. A processor farm of 1000 nodes, or more if needed, does not seem prohibitive. Therefore, while the Level 3 processor farm for an SSC experiment could not be assembled today, well established trends make it likely that sufficient computing power will be available when needed.

5.4 TRIGGER RATE

Detailed rate estimates with a realistic simulation of the EMPACT detector remain to be made. One can, however, get a rough idea of how realistic the design goal rate reduction of 10^4 for Level 1 is by considering the dominant sources of leptons,

both real and apparent. The Level 1 muon trigger has been discussed in Subsection 4.4.2 so that this Subsection will concentrate on the somewhat different question of Level 1 electron identification.

Figure 5-3 shows the expected trigger rates for single leptons as a function of p_T threshold, assuming a luminosity of $10^{33} \text{ cm}^{-2} \text{ s}^{-1}$. The solid line results from a sample of two-jet events ($5 < p_T^{\text{JET}} < 2500 \text{ GeV/c}$) where only information from the EM calorimeter is used (trigger towers $\Delta\phi \times \Delta\eta = 0.1 \times 0.1$). Adding the requirement that there be no more than 5 GeV of transverse energy in the hadronic tower behind the EM tower, a condition that could be employed at Level 1, results in the rate curve denoted by long dashes. The dotted line, shown for reference, gives the rate for prompt electrons from c , b , t ($M_t = 140 \text{ GeV}/c^2$) and W decays. As discussed in Subsection 4.4.2, the muon rates are quite low and are dominated by b and c decays at all but the lowest p_T values, where π and K decays and hadronic punchthrough are important.

Fig. 5-3 Integrated Single Electron Rates as a Function of P_T Threshold. The curves show the rate from two-jet events at $L = 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$ for: (i) all EM-calorimeter energy depositions (solid line), (ii) EM-calorimeter energy depositions not accompanied by more than 5 GeV of E in the corresponding tower of the hadronic calorimeter (long dashes), and (iii) the rates from b , c , t , and W decays. TRD information has not been used for (i) and (ii).

The curves in Fig. 5-3 demonstrate that single lepton p_T thresholds in the 20 to 40 GeV/c range are

plausible at Level 1. The role of Level 2 will be to further reduce these rates by using the TRD information (unless that is done at Level 1) and by the application of isolation cuts.

The power of multiple-lepton triggers is illustrated in Fig. 5-4, where the rate as a function of the second largest p_T electron candidate is plotted. The solid curve shows the rate for all EM energy depositions, while the dashed curve shows the rate for EM depositions that are not accompanied by more than 5 GeV of transverse energy in the corresponding hadronic tower.

Fig. 5-4 Integrated Rates for Two Electrons Plotted as a Function of the P_T of the Lower P_T Electron. The solid curve shows the rate when all depositions in the EM calorimeters are used, and the dashed curve shows the rate when only depositions with less than 5 GeV E_T in the corresponding hadronic tower are used.

5.5 COMPUTING

Computing is one of the most rapidly advancing technologies in the world today. The intent is to take full advantage of likely future developments leading to increased processing power, reduced cost, and enhanced functionality over the next decade.

An EMPACT computing advisory committee has been established to coordinate and interact with the SSCL and to help to refine a strategy for EMPACT. Items that are being addressed by this group are listed below.

5.5.1 Organization & Standards

To take full advantage of new hardware technology and to expedite the development and maintainability of EMPACT software will require the establishment and enforcement of a set of well-thought-out software standards. The sooner the existing software can be brought into this framework, the better, though it is important to understand the direction that will be established by the SSCL computing organization on certain issues. EMPACT is providing input to the Laboratory as it decides the form that this organization will take. From initial discussions it seems that the SSCL will start with a CERN Library-based, primarily FORTRAN 77 environment, on both VAX/VMS and UNIX systems; EMPACT will presumably follow this direction.

The goal is to separate structural aspects of the code (which will probably be the responsibility of a central EMPACT computing group) from applications aspects, so that either may evolve without major dislocation to the other. In addition, there will be minimal machine dependence, in view of the strong likelihood that the technology will advance significantly between the time the proposal is approved and the time operation begins at the SSC. This strategy should aim to minimize the necessity to procure or develop software to translate between various platforms and software packages. In addition, existing software packages will be used as much as possible to minimize the amount of code duplication and take advantage of the software maintenance resources expected to be in place at SSCL.

5.5.2 On-Line System

While the detailed specification of the requirements of the on-line system will constitute a major effort, a number of goals for the system can be listed now. The system will be modular, multi-user, and hierarchical in nature so that the lowest level detector subsystems can be operated in isolation; in parallel, for purposes of testing, debugging, and calibrating; and then combined to form higher level subsystems and eventually a single system. The

structural parts will, where possible, exploit commercially available technology in both hardware and software, and will be the responsibility of a single centralized group. While the development of on-line application code is expected to be distributed more widely across the collaboration, the integration of that code into a working system, including the verification that coding and performance standards have been met, is probably best accomplished by a central group located at the SSCL. This central computer group will require many full time computer professionals for the on-line structure and support activity, beginning as early as possible after approval of the project and continuing through to data taking.

Early iterations of on-line software will be exercised in test beam operations and will be used to perform subsystem verification at the sites where such systems are assembled and tested. This is important both in terms of iterating the specifications of the system and of familiarizing users with the on-line system as it will be at the SSC. The implication of such an iterative approach is that a complex specification must be prepared that describes not only direct functionality but the staged availability of that functionality and a series of points in the implementation schedule at which certain design options will be selected and existing specifications changed within limits.

5.5.3 Detector Monitoring

In addition to the on-line system for monitoring detector performance by examining the data, it will be necessary to monitor various static parameters, such as power supply voltages, gas flows, etc. The need for such monitoring is particularly acute for a detector the size of EMPACT, since the number of sensors will be too large for a manual or partially automated approach.

The need for this sort of function is common in industrial applications and a number of solutions, such as CAMAC or token ring schemes, exist. We plan to borrow heavily from existing designs so as to devote as much as our manpower as possible to

problems unique to SSC detectors. Nonetheless, the scale of the task is large and will probably require the full time efforts of two or three engineers.

5.5.4 Off-Line Computing

Currently EMPACT computing is basically concerned with the simulation of the detector (see Section 6), and with its engineering design (see Sections 2 through 4). Computing resources in terms of hardware for the short term (next 12 months), will require 100 to 200 MIPS to be available at member institutions for Monte Carlo simulation and sufficient 3D modeller/CAD capability. An attempt is underway to evaluate how the hardware requirements (CPU's, disk space, and tape storage) and personnel needs will grow after this period, and the best way of satisfying these needs.

A great deal of computing will need to be done in support of the detector design effort, and it is important that this aspect of the software be well planned and merged as seamlessly as possible into the off-line computing done as the detector becomes operational. The goal will be to produce at a relatively early stage in the design cycle of the detector, a flexible plan for off-line computing software that includes implementation in stages. The off-line structure and support efforts are expected to require a number of computer professionals, beginning as early as practical after project approval (in addition to the many physicists who will contribute to the simulation and design efforts).

5.5.5 Networking

EMPACT is a decentralized collaboration without a single dominant computing center of gravity, and considerable emphasis is being placed on the availability of adequate connectivity among the various institutions, and between them and the SSCL. This will become even more important if the considerable computing resources (4000 MIPS) expected to become available at the SSCL over the next year to two years are to be used effectively. Existing ESnet connections are generally of reasonably high standard on the pathways concerned,

a number being T1 lines, but a careful review of network needs is required. A first step in this process will be the submission of a proposal to the Texas National Research Laboratory Commission for a system of engineering workstations to be installed at the collaborating universities. These workstations will facilitate broader university participation in the engineering aspects of the detector design process. The network enhancements put in place at this stage will undoubtedly be useful through later stages of the project as well.

5.6 DEVELOPMENT ISSUES

At this point only a fraction of the questions that must ultimately be decided have been considered. Although the broad features of the trigger/DAQ architecture have been tentatively settled, many aspects of the system must be explored in much greater depth. For example:

- The front-end designs for the TRD, calorimeter, and muon chamber readouts must be reviewed with an eye toward compatibility. The goal will be to strive for as many common elements as possible. Initial prototypes must be fabricated and tested under realistic conditions at an early date.
- The location of the readout chains, and attendant tradeoffs between cabling and mounting costs, cooling, and ease of access must be studied in a systematic way. Although it is clear that nearly all of the electronics will be mounted on or near the detector, an integration of the electrical and mechanical designs remains to be done. The TRDs present a special challenge in this regard, since there is little room for bringing out individual signals, yet little space for detector-mounted electronics. Alternate strategies, such as fiber optics, will be considered.
- The length of the Level 1 delay pipeline must be determined. Although it will probably not be possible to fix this time with precision until the system design is well along, it is important to develop an early feeling for the tradeoffs involved since they may themselves have a profound influence.
- Level 2 triggers schemes have to be specified

and evaluated. This will not be easy in view of the wide range of possible technologies.

- Although the current thinking is that with the exception of the TRDs, the Level 1 delay pipelines should be analog (most likely switched capacitors), the nature of the Level 2 storage remains to be determined. If analog is best, the appropriate level of multiplexing for analog to digital conversion must be determined.
- The readout paths between the Level 2 buffers and the Level 3 event building must be established and analyzed to ensure that logjams do not develop.
- Since the design will be driven in large measure by the physics goals, realistic simulations of the trigger signals must be developed. This work will be part of a larger and more general simulation effort, which will encompass a simulation of the physics and detector performance as well as detailed modeling of the DAQ system's behavior.
- R&D on the Level 3 processor farm will address such issues as systems integration and whether the optimal configuration is parallel processors, hypercube type computers, etc. A common problem for all SSC experiments will be the proper choice of large storage media.

A number of these issues will be addressed as part of an ongoing SSC Subsystem R&D effort [5] in which a number of EMPACT collaborators are involved. An important feature of this subsystem R&D effort is the recognition that systems with this level of complexity will require careful simulation at all levels to ensure

successful operation. In keeping with this philosophy, we intend to carry out such simulations before any circuit fabrication takes place. Also, collaborators from LeCroy will be joining the system design effort. Since many of the items above are of a generic nature, the same solution will probably be applicable to more than one experiment. It is anticipated that many of the developments needed for the EMPACT system will be accomplished in cooperation with other groups [6]. Such cooperative efforts will maximize productivity (by avoiding duplication of effort) and minimize costs.

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6 SIMULATION

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6 - SIMULATION STUDIES

6.1 INTRODUCTION

Work is in progress to simulate a number of SSC physics processes. The physics topics being studied were selected partly for their physics interest, but primarily because they test important aspects of the EMPACT detector design. The immediate goal of this activity is to quantify the potential of the EMPACT detector discussed in this document. It is expected that the continuation of these initial investigations will significantly affect the evolution of the detector design. Most of the effort to date has involved setting up the various simulation tools required for these studies, and as a consequence the results are quite preliminary. In the following subsections some details of this work are presented. The sense of these studies is that, while much work remains to be done to arrive at a detailed detector design, this detector will be capable of addressing the important physics processes at the SSC and will be able to tap the unexpected discovery potential of the SSC.

A primary goal in the design of EMPACT is to have a detector with muon resolution comparable to the electron resolution over the full η acceptance. The potential of the present design in this regard has been studied both for the four muon decay of the standard Higgs and for Z' production. The conclusions, discussed below, are that the resolution for both electrons and muons permit reconstruction of Z^0 's from Higgs decay at close to the natural width and that the muon acceptance and resolution is matched to the discovery of a Z' and to the measurement of its decay asymmetry.

EMPACT is conceived to be a hermetic detector. This property is being investigated through the Higgs decay $H \rightarrow Z^0 Z^0 \rightarrow l^+ l^- \nu \bar{\nu}$ and in the search for gluinos. A detailed GEANT study of the transition at $\eta = 3$ will be used to improve the present calorimeter resolution function so that more realistic calculations can be carried out.

Calorimetry will play a major role in EMPACT physics. Issues such as the optimal segmentation, depth, inner radius, e^+ are being investigated via the process $H \rightarrow Z^0 Z^0 \rightarrow l^+ l^- Q \bar{Q}$ and in the requirements for identifying leptons near jets such as in the decay of b 's from top. The question of b -tagging is also being studied for the specific process $pp \rightarrow HWX$ where $H \rightarrow b\bar{b}$.

A study of τ lepton signatures for EMPACT is in progress. At present the focus is on the Higgs decay $H \rightarrow Z^0 Z^0 \rightarrow l^+ l^- \tau^+ \tau^-$ but the work will eventually be expanded to include Z' decays and jet physics. Since identifying τ 's requires the identification of isolated leptons or low multiplicity jets with large missing p_T , it will require good hadron calorimetry and hermeticity as well as good TRD/Tracker correlations.

In EMPACT, the signs of muons but not of electrons can be measured. The implications of this decision are being studied in a variety of ways. The cleanest signature for t decays is thought to be μe final states. Given the expected high rate for this process, it is unlikely that the sign of the electron will be required to extract the signal, and there

should be no limitation on the study of top physics using this detector. This is also true for the same sign dilepton signature for high rate processes such as gluino production. One might be less confident of the physics potential for very low rate processes, such as same sign W production from the strong interactions of vector bosons. Since the sign of only muons can be measured in EMPACT, one might naively expect a reduction in acceptance of a factor of four compared to detectors that can also measure the electron sign. However, the difference is unlikely to be so large given the limited rapidity range over which electron signs can be measured in sole-noid configurations compared with the large acceptance for muons in EMPACT. In addition, for very low rate processes it will almost certainly be necessary to run at higher than the nominal luminosity, where it is likely that signs of only muons can be measured with high efficiency. Since EMPACT is being designed to handle high luminosity, it will be an appropriate detector for studying very low rate processes with a same sign lepton signature.

6.2 SIMULATION TOOLS

At present a number of the simulations are at the event generator level or use a simple calorimeter. However, wherever possible, resolution functions appropriate to the EMPACT detector are used, and in some cases detailed simulation at the GEANT/GEISHA level have been developed. For the muon studies discussed below, an analytic resolution function for the toroid system has been derived (Section 4). A simple analytic form (Fig. 6-1) is in agreement with the full analysis form and is adequate for the present studies. A calorimeter energy resolution function [1] has been derived from a study (Section 3) of the actual 3D engineering model of the calorimeter constructed at Martin Marietta. Rays traced at various η are used to determine the amount of active and passive material

Fig. 6-1 Muon Momentum Resolution

traversed by particles in the calorimeter. Using a longitudinal shower parameterization, these ray tracings have been converted into appropriate resolution functions for different particle species. This study covers the region $\eta < 3$ and in the present analysis is used for the whole calorimeter coverage that is taken to be $\eta < 5.5$. This treatment is thought to be adequate for the transition in the $\eta = 1.5$ region between the central and end calorimeters, but less appropriate for the $\eta = 3$ region where there is a transition between the end calorimeter and a forward calorimeter quite far behind the end calorimeter. The extension of this resolution function into the forward region is being studied using a GEANT/GEISHA simulation.

Detailed simulations are in use or are being developed for some of the simulation studies. For example the TRD/Tracking system (Section 2) has been simulated in great detail. This simulation uses a full geometrical specification of the TRD detector and detailed tracking with appropriate dE/dx loss and x ray production and detection. This analysis, which is not GEANT based, is being used to study the electron identification efficiency and hadron rejection capabilities of the system and the potential

for high energy muon identification. As noted above, a full muon Monte Carlo (again not GEANT based) and track reconstruction analysis has been used to study the muon resolution of the proposed toroid spectrometer system. Work is in progress to study the calorimeter system using a GEANT/GEISHA simulation. A fast shower algorithm is being used to study the basic parameters (inner radius, average interaction length, segmentation, etc.) of the calorimeter. This algorithm [2] uses the full GEISHA interaction code until a track from an interaction has energy less than a cutoff energy (at present $E_{\text{cut}} = 500$ MeV) and then the remaining energy is parameterized. This allows one to retain most of the fluctuations in hadron showers while running up to 20 times as fast as the standard GEANT/GEISHA package. An example of simulation of a jet event in the EMPACT calorimeter is shown in the illustration at the front of this section.

Work is in progress to develop an overall EMPACT simulation package by integrating the present muon and TRD simulations into the ZEBRA based framework of the calorimeter GEANT simulation. Once this is operational, detailed studies of the interrelation of the subsystems can be done to improve the present disjoint approach. The simulation tool based on the engineering model of the detector will be enhanced and developed to provide input to the experimental proposal. A number of extensions to the present simple ray tracing algorithm will be implemented. Transverse shape will be added to the parameterized showers. In addition, an option that some or all of the shower development can be done by Monte Carlo tracking of secondaries rather than by parameterizations will be included. This will allow for fluctuations to realistically treat possible non-Gaussian tails. Calorimeter readout segmentation schemes will be implemented, and input from event genera-

tors such as ISAJET or PYTHIA will be supported. This development will make available a sophisticated simulation code with the great advantage of working directly upon the detailed 3D model created in the engineering CAD/CAE system. It is expected that this program will continue to mature along with the EMPACT detector, but it should be a useful and working tool at all stages. For the immediate future, the standard simulation program will be GEANT based. It might be possible in the future to build the GEANT geometry directly from the 3D engineering model. How this transfer can be implemented will be investigated in light of future GEANT developments and the SSCL's computing strategy.

6.3 $H \rightarrow Z^0 Z^0 \rightarrow 4\mu$

The cleanest signature for the standard heavy Higgs will be its decay via $Z^0 Z^0$ to 4 leptons. The rate of this decay is very low, as can be seen in Table 6-1. It shows the number of $H \rightarrow Z^0 Z^0$, $Z^0 \rightarrow e^+ e^-$ or $\mu^+ \mu^-$ events for various Higgs masses at $10^{33} \text{ cm}^{-2} \text{ s}^{-1}$ luminosity if the coverage of the detector is $\eta < 2.5$. These numbers are quite optimistic since no estimate is yet available for the effects of cracks or other detector related acceptances. A study [3] has shown that to reduce the potential background, a cut on the Z^0 of $\eta_z < 1.5$ will be required. In this case the event rate, where again one requires all 4 leptons to have $\eta < 2.5$, is even lower (Table 6-1). The

Table 6-1 $H \rightarrow Z^0 Z^0$ ($Z^0 \rightarrow e^+ e^-, \mu^+ \mu^-$)

MASS (GeV)	EVENTS/ 10^{40} cm^{-2} $ \eta_l < 2.5$	EVENTS/ 10^{40} cm^{-2} $ \eta_z < 1.5, \eta_l < 2.5$
150	168	116
300	476	328
500	180	108
800	56	32

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acceptance as a function η is shown in Fig. 6-2 for various masses. Clearly it will be necessary to confirm this statistically weak signal by looking for other decay modes. Perhaps even more necessary is the construction of a detector such as EMPACT that is conceived as being capable of handling higher luminosity.

The present simulation is focused on the decay $H \rightarrow Z^0 Z^0 \rightarrow 4\mu$, as this represents an important test of the design criteria for EMPACT. For this study, samples of events for Higgs masses of 400 and 800 GeV were generated using ISAJET. These events were then reconstructed using the muon resolution function (Fig. 6-1). The dimuon mass spectra

obtained (Fig. 6-3) show that the EMPACT goal of attaining muon resolution comparable to electron resolution can be achieved. This good resolution is important to ensure good acceptance for Z^0 's in the presence of high mass dimuon backgrounds such as those from $t\bar{t}$ production, especially if high luminosity degrades the information available from tracking or calorimetry [4,5].

In Fig. 6-4, the 4μ invariant mass for Higgs decays in the presence of a $Z^0 Z^0$ continuum background is shown. In reconstructing these events, no mass constraints have been used, but a rapidity cut $\eta < 2.5$ which represents the physical limits of the toroids has been imposed [6].

Fig. 6-2 The Geometrical Acceptance for $H \rightarrow Z^0 Z^0$, $Z^0 \rightarrow ee$ or $\mu\mu$ for Various Higgs Masses. The Solid Curves are for decays with $\eta_z < 1.5$, While the Dashed Curve is for all Decays

Fig. 6-3 Dilepton Mass Spectra for $Z^0 \rightarrow l^+ l^-$ from $H \rightarrow Z^0 Z^0$. $M_H = 800$ GeV (A) $Z^0 \rightarrow e^+ e^-$, (B) $Z^0 \rightarrow \mu^+ \mu^-$, $M_H = 400$ GeV (C) $Z^0 \rightarrow e^+ e^-$, (D) $Z^0 \rightarrow \mu^+ \mu^-$. The integral of these curves gives the number of Z^0 from accepted Higgs for integrated $L = 10^{40} \text{ cm}^2$.

6.4 $H \rightarrow Z^0 Z^0 \rightarrow l^+ l^- \tau^+ \tau^-$

The rate for $H \rightarrow Z^0 Z^0 \rightarrow l^+ l^- \tau^+ \tau^-$ ($l = e, \mu$) is equal to the rate for e, μ decays alone. Present indications are that, with EMPACT, it is likely that one can reconstruct the τ neutrino. Since such modes represent more than half of the τ decays, their detection

could be very important in confirming an observation of the Higgs through its cleanest decay into only μ or e particles. The signature for this process would be a reconstructed Z^0 ($Z^0 \rightarrow e^+ e^-$ or $\mu^+ \mu^-$) with large missing p_T and either another isolated lepton or low multiplicity jet characteristic of τ decay. For

Fig. 6-4 Invariant Mass Spectra for $H \rightarrow Z^0 Z^0 \rightarrow 4\mu$ for (A) 400 GeV (B) 600 GeV Higgs, Plus the $Z^0 Z^0$ Continuum Background

example, in the case of the semileptonic τ decay the missing p_T spectrum is shown in Fig. 6-5 and the p_T of the lepton from the τ decay is shown in Fig 6-6.

Fig. 6-5 Missing p_T Distribution for $H \rightarrow Z^0 Z^0 \rightarrow \ell^+ \ell^- \tau^+ \tau^-, \tau \rightarrow \ell x$

Fig. 6-6 The p_T Distribution for the τ Electron in $H \rightarrow Z^0 Z^0 \rightarrow \ell^+ \ell^- \tau^+ \tau^-, \tau \rightarrow \ell x$

For good lepton efficiency, it will be necessary to detect leptons with p_T as low as 20 GeV/c with good efficiency.

If the τ jets are identified via their decays to low multiplicity jets (or leptons), the event can be reconstructed by accounting for the missing transverse momentum carried away by the τ neutrinos. As a result of the small τ to Z^0 mass ratio, the τ neutrinos lie close to the axis of the observed jets. The

neutrinos can be apportioned to the two components of missing transverse momentum, and the energy can be found assuming a τ parentage for the two jets, allowing for a subsequent kinematic test that the dijet invariant mass is consistent with the Z^0 mass.

The success of this measurement will depend on the ability to select the low multiplicity τ jets, while suppressing the copious background due to Z^0 + jet production. ISAJET studies [7] have shown that about one in a thousand high transverse momentum jets will mimic a τ hadron jet, which provides roughly a factor of 10^6 rejection of Z^0 + jets. For EMPACT, the level of background rejection achieved will depend on the effective multitrack resolution of the TRD/Tracking system.

A study in progress [8] is aimed at simulating the response of EMPACT in a measurement of $H \rightarrow Z^0 Z^0 \rightarrow l^+ l^- \tau^+ \tau^-$. The simulation has so far focused on $l = \mu$ and $\tau \rightarrow \pi^- \pi^0 \nu_\tau$. Jets, with electromagnetic and hadronic energy deposition, selected by a modified version of the UA1 [9] algorithm, are found in events with a high transverse momentum $Z^0 \rightarrow \mu^+ \mu^-$ and large missing transverse momentum. Parameterized energy resolutions are employed to determine the resolution of the kinematic reconstruction. The simulation code developed for the TRD/Tracking system (and tuned for electron identification) will be employed to evaluate jet multiplicity response. Similarly selected background events (Z^0 + jets) will be used to determine the signal to background ratio.

In addition to increased capability for heavy Higgs boson searches, this study will also serve as a proving grounds for the capability of EMPACT to study signatures involving τ leptons such as those suggested in the context of searches for compositeness [7] and new heavy vector gauge bosons [10].

Apart from its obvious physics interest, this study also addresses the capabilities of and requirements on the TRD/Tracking system for hadron jets.

6.5 $H \rightarrow Z^0 Z^0 \rightarrow l^+ l^- \bar{\nu}$

This decay mode for the Higgs boson offers the potential of increased statistics due to the large ($\sim 20\%$) $Z^0 \rightarrow \nu \bar{\nu}$ branching fraction. At the same time there are significant background contributions from physics processes involving real Z^0 's [11]. An initial study has been performed to estimate the importance of various background processes and to indicate which detector parameters have the largest effect on the observed signals for a range of Higgs masses (400, 600, and 800 GeV). The results presented here are for the muon channel, but a study for electrons should yield similar results [12].

The invariant mass of the Higgs boson can not be reconstructed when half the final state energy is in the form of neutrinos. Instead, the missing transverse momentum of the event is used. This distribution displays a Jacobian peak at about half the Higgs mass. The background comes from the production of (transversely polarized) Z^0 pairs and single Z^0 's plus QCD generated jets. A mismeasurement of the p_T of the jets in the latter process produces an unbalanced p_T of the observed Z^0 which contributes to the transverse momentum background.

The missing p_T sensitivity of the calorimeter is likely dominated by the response to showers with $\eta > 3.0$. A realistic study of this region of the calorimeter will require a detailed GEANT simulation including shower crossover. This is the case where a shower starting in a tower near the $\eta = 3$ cone contributes to another tower as much as 180° away in azimuth. As a first approximation to this cone problem the magnitude of the Z^0 plus jets background was estimated by assuming perfectly

measured "pencil" jets up to an effective η cutoff, past which the jet is assumed not to be measured at all. Figure 6-7 shows a signal from a 400 GeV/c² Higgs plus this background for effective η cuts of 3, 4, and 5.

Fig. 6-7 The Effect of the Calorimeter Hermeticity for a Higgs with $M_H = 400$ GeV and the Background from $Z^0 + \text{QCD Jets}$

The second significant background is the continuum production of Z^0 pairs where one of the Z^0 's decays into neutrinos. This background is independent of the detector configuration and is more significant for larger Higgs masses. The combinations of these two backgrounds with the signal is shown in Fig. 6-8.

The signal to background ratios, assuming a conservative coverage for jets of $\eta < 4.0$, along with the estimated number of muon events surviving geometrical acceptance and tight cuts on the Z^0 transverse momentum is summarized in Table 6-2. No detailed attempt has been made to optimize the cuts.

It is clear from Fig. 6-7 that the signal to background ratio for a low mass Higgs could be substantially improved by carefully planned forward calo-

Fig. 6-8 The Higgs Signal Plus QCD Background for $H \rightarrow Z^0 Z^0 \rightarrow l^+ l^- \nu \bar{\nu}$ as a Function of the Measured $Z^0 p_T$

Table 6-2 Higgs Production for an Integrated $L = 10^{40} \text{ cm}^{-2}$ for $H \rightarrow Z^0 Z^0 \rightarrow l^+ l^- \nu \bar{\nu}$

HIGGS MASS (GeV)	EVENTS	SIGNAL/BACKGROUND
400	837	0.46
600	149	0.31
800	71	1.13

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rimetry. The high mass Higgs backgrounds are, however, dominated by Z^0 pair production and are insensitive to detector parameters. There is clearly a window of opportunity for this Higgs signature. A realistic description of the transition region is obviously needed, and is one of the important optimization parameters required for EMPACT.

6.6 $H \rightarrow Z^0 Z^0 \rightarrow l^+ l^- Q \bar{Q}$

The rate for this Higgs decay is 24 times that for the Higgs decay into 4 leptons (e or μ). However, it is still unclear whether or not one will be able to extract this signal or indeed any Z^0 signal from the Z^0 decay into jets. Even so, this process is extremely useful in trying to evaluate the likely performance of the calorimeter with regard to the various design parameters such as inner radius, total depth, seg-

mentation, etc. In particular for EMPACT, it is essential to understand the physics implications of starting the calorimeter 1 m from the beam. This is a non-trivial problem requiring a full GEANT simulation, as it clearly involves the competing effects of the opening angles of the particles in the shower and the effects of shower sizes and segmentation.

No attempt has yet been made to simulate full events. The present study [13] concentrates on the decay of a single Z^0 from Higgs decays (Higgs masses of 400 GeV and 800 GeV are being used) into the central calorimeter ($\eta < 0.5$ for the Z^0). Once this simple process is understood, full signal and event simulation will be carried out. For simplicity, the present analysis does not attempt to reconstruct jets, but rather the reconstructed mass is obtained from the 4 vectors of cells with non-zero energy deposits. In Fig. 6-9, the difference in the

Fig. 6-9 Mass Difference Between Reconstructed Mass and Generated Mass for $Z^0 \rightarrow jj$ from 800 GeV Higgs Decays

reconstructed mass and the PYTHIA Z^0 mass is shown for a sample of 400 Z^0 decays to jets from an 800 GeV Higgs. In this example, the calorimeter inner radius is 1 m, the η and ϕ segmentation is 0.05, and the average density of the calorimeter is 13.6 gm cm^{-3} . A summary of the means and widths of similar distributions for variations of the segmentation is shown in Fig. 6-10a, while the radius dependence is shown in Fig. 6-10b. In generating these plots, only Z^0 's with $\eta < 0.5$ and decay particles with $\eta < 1.0$ were used. The present indications are that

Fig. 6-10 Means (M) and Widths (RMS) of Difference Distributions (see Fig 6-9) as a Function of (A) Calorimeter Segmentation and (B) The Inner Radius Of The Calorimeter For Z^0 's, From 400 GeV and 800 GeV Higgs

the ability to reconstruct the Z^0 mass from jets changes slowly with changes in the parameters and that having a calorimeter starting at 1 m is not a handicap in the detector design.

6.7 $p p \rightarrow H W + X$

Finding the Higgs at the SSC will be most difficult if its mass is in the intermediate mass range (80–170 GeV). If its mass is larger, it will be more easily extracted [14] from the background due to its dominant decay to W^+W^- and Z^0Z^0 . However, if the Higgs mass is in the intermediate range, it will decay mostly to heavy quarks, and it will be extremely difficult to extract the signal from the background of QCD jets. To suppress this enormous background, it has been proposed to look for Higgs production in association with a W^+ or W^- [15,16]. Even in this case the production of signal events,

$$pp \rightarrow H^0 W^\pm X (H^0 \rightarrow Q\bar{Q})$$

is still orders of magnitude less than the backgrounds ($qg \rightarrow W^\pm Q$, $q\bar{q} \rightarrow W^\pm g$, $q\bar{q} \rightarrow W^\pm Z^0$) which feed this channel.

The feasibility of detecting the intermediate mass Higgs boson through its decay to two b quark jets at the SSC has been studied using the Monte Carlo program PYTHIA 4.8 to generate both signal and background event samples [17]. Identifying b decays required identifying electrons with large transverse momentum (j_T) with respect to the jet axis. Close in tracking permitting impact distance measurements is important, but modest vertex detector performance is sufficient. EMPACT is evaluating a vertex detector to provide these measurements (Section 2). With these capabilities, detection of this process, may be possible.

This earlier study has been extended to determine the transverse segmentation requirements for the EMPACT electromagnetic calorimeter. In this

new study [18] the effects of shower spreading are not included, but rather the closeness of other particles in the event to the targeted high j_T electron is evaluated. Figure 6-11 is a typical result from this study. The relevant high j_T electron has been selected for each event and the energy of all other particles in an $\eta - \phi$ cone of radius $R = 0.03$

Fig. 6-11 The Ratio of the Total Energy in a cone of Radius $R = 0.03$ to the Electron Energy vs the Electron Energy for Selected High j_T Electrons from b Decays

calculated. Figure 6-11 shows the ratio of the energy in this cone to the selected electron energy as a function of the electron energy. As expected for b decays the electron energy distribution peaks relatively low (≈ 40 GeV). However, it is worth noting that the energy in the cone is essentially independent of the electron energy and that the selected electrons are quite isolated. The fraction of events for which the energy contained within the cone exceeds 10% of the electron energy is shown in Fig. 6-12. Only 10% of the electrons exceed this value for an R cut of 0.03. At a radius of 1 m, this corresponds to a transverse dimension of 3 cm. The required transverse segmentation of the calorimeter is, of course, somewhat finer than this. These studies will continue to ensure that the design of the

Fig. 6-12 The Fraction of Events for which the Energy in a Cone of Radius R Exceeds 10% of the Energy of the Selected High p_T Electron

EMPACT calorimeter retains a good prospect for finding $H \rightarrow b\bar{b}$ should it occur with manageable background. The issues relevant to a vertex detector will also be studied.

6.8 Z' DETECTION

The detection of a new, heavy, neutral gauge boson, generically labelled Z' , has been discussed in several previous studies [19-21]. The decay $Z' \rightarrow l^+l^-$, if present, is thought to have little or no background. The discovery of a Z' then depends primarily on the event rate and less on the dilepton mass resolution. However, the task of uncovering the nature of the Z' places greater demands on the detector design. In this subsection the issue of the Z' discovery potential for EMPACT and the question of understanding the Z' are discussed [22].

The Z' is expected to be quite narrow with a width that scales with $M_{Z'}$. For the various models considered, the Z' width is 1 – 3% of the Z' mass. The ability to observe the Z' is thought to rest solely on evaluating the statistics of a bump in the dilepton invariant mass spectrum. Figure 6-13 shows the

expected number of $Z' \rightarrow \mu^+\mu^-$ events in a canonical SSC year for different rapidity coverages. There is clearly a statistical advantage in extending the lepton coverage to $\eta = 2.5$. EMPACT should be able to observe a Z' if $M_{Z'}$ is less than about 6 TeV.

The Z' rate depends on the couplings of the particular model. For example, the calculation used to generate Fig. 6-13 assumes that the Z' is simply a heavy Z^0 , as in the PYTHIA Monte Carlo. In superstring inspired models based on $E(6)$, the rate also depends on whether the new “exotic fermions” present in the model are kinematically accessible in Z' decay. Table 6-3 indicates the range of events,

Fig. 6-13 Number of $Z' \rightarrow \mu\mu$ Events Expected for $L = 10^{40} \text{ cm}^{-2}$ as a Function of Z' Mass.

Table 6-3 Expected Number of $Z' \rightarrow \mu^+\mu^-$ Events for an Integrated $L = 10^{40} \text{ cm}^{-2}$

$M_{Z'} \text{ (TeV)}$	1	2	3
MODEL			
HEAVY Z	27×10^3	2.5×10^3	0.52×10^3
$E(6)$	$9 - 30 \times 10^3$	$0.9 - 3 \times 10^3$	$0.2 - 0.6 \times 10^3$
L-R SYMMETRIC	15×10^3	1×10^3	0.3×10^3

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assuming perfect acceptance, expected in one SSC year for various models. Depending on the model, the mass reach for one SSC year could be as high as 4 TeV.

The narrowness of the Z' implies that the observed shape will, in most cases, be dominated by experimental resolution. Figure 6-14 shows the expected mass peak from Monte Carlo simulations for $M_{Z'} = 1$ TeV. In this calculation the muon resolution function shown in Fig. 6-1 was used. The mass peaks for $Z' \rightarrow e^+e^-$ and $Z' \rightarrow \mu^+\mu^-$ could be used to identify the Z' signal. However only muons are considered here as the lepton charge is required for the asymmetry measurements. Once the peak has been observed, the study of the underlying physics is largely a question of measuring asymmetries, or related quantities. As an example the measurement of a forward-backward asymmetry, A_{FB} is considered. In pp collisions at high energy, the usual A_{FB} is an odd function of rapidity. If $y_{\pm}$ refer to the rapidity of the final state $\mu^{\pm}$ muons, then if $y_+ + y_- > 0$

$$A_{FB} = A_{FB}^{++} = \frac{\sigma(y_- > y_+) - \sigma(y_- < y_+)}{\sigma(y_- > y_+) + \sigma(y_- < y_+)}$$

For $y_+ + y_- < 0$, $A_{FB} = -A_{FB}^{++}$. Clearly, the determination of the sign of electric charge at high momentum is essential.

Following Rosner [23], A_{FB} as a function of dilepton mass in the vicinity of $M_{Z'}$ is shown in Fig. 6-15, while A_{FB} atop the Z' peak is calculated as a function of the rapidity of the Z' in Fig. 6-16. Figures 6-15 and 6-16 indicate that A_{FB} is quite sensitive to the underlying physics. Therefore, even a rather low statistics measurement of A_{FB} can be useful for eliminating models. The other important point to note from Fig. 6-16 is the substantial increase in A_{FB} with rapidity. This means that in addition to the moderate statistical gain of extending the rapidity coverage for muons to 2.5, there is

Fig. 6-14 Reconstructed $\mu^+ \mu^-$ Effective Mass for $Z' \rightarrow \mu^+ \mu^-$ with $M_{Z'} = 1$ TeV with the EMPACT Muon Resolution

Fig. 6-15 Forward-Backward Asymmetry as a Function of the Dilepton Invariant Mass for $M_{Z'} = 1$ TeV at $y = 2$. θ defines the model of $E(6)$ breaking.

Fig. 6-16 Forward-Backward Asymmetry as a Function of the Rapidity of the Z' for $M_{Z'} = 1$ TeV. The particular manner in which $E(6)$ is broken is defined by the parameter θ .

also a large gain due to the increase of the asymmetry itself. Table 6-4 summarizes the results of calculations for several Z' cases, giving the expected A_{FB} and its error for $y_{max} = 1.5$ and 2.5. For $1.5 < y < 2.5$, where the A_{FB} measurement is most critical (see below), a muon of momentum 5 TeV/c is measured in EMPACT with a resolution ranging from 10-25%. One clearly sees the advantage of having good muon coverage to a rapidity of 2.5.

Table 6-4 Calculated A_{FB} and Its Expected Statistical Error for an Integrated $L = 10^{40} \text{ cm}^{-2}$: (δA_{FB} varies approximately, as $1/\sqrt{N}$, where $N = N_F + N_B$)

MODEL $M_{Z'} \text{ (TeV)}$	θ	$A_{FB} \pm \delta A_{FB}$	
		$y_{max} = 1.5$	$y_{max} = 2.5$
1	38°	-0.004 ± 0.011	-0.011 ± 0.008
1	128°	-0.034 ± 0.011	-0.086 ± 0.008
3	38°	-0.01 ± 0.06	-0.02 ± 0.05
3	128°	-0.09 ± 0.06	-0.22 ± 0.05
5	38°	-0.01 ± 0.18	-0.03 ± 0.14
5	128°	-0.16 ± 0.18	-0.33 ± 0.13

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Because of the excellent muon momentum resolution in EMPACT, it is interesting to consider what is to be gained by measuring A_{FB} as a function of the dimuon mass, $M_{\mu\mu}$. This can be important statistically for some models where A_{FB} is an odd function in $M_{\mu\mu}$ about $M_{Z'}$ (see Fig. 6-15). In this case $M_{\mu\mu} > M_{Z'}$ and $M_{\mu\mu} < M_{Z'}$ can be considered separately. If the asymmetry can be measured away from the Z' peak, the interference between Z' and Z^0 becomes increasingly important. Here, the dependence of A_{FB} on the couplings will be different than on the peak and new information can be extracted [23]. The cross section off-resonance is roughly a factor 10 – 100 smaller than on-resonance. If an integrated luminosity of 10^{41} cm^{-2} becomes available, then such studies will become feasible for even reasonably high $M_{Z'}$. There is still an ambiguity that results from such measurements, in which the right- and left-handed couplings can be inter-

changed [19]. This can be resolved in a polarization measurement, for example using $Z' \rightarrow \tau^+ \tau^-$.

6.9 TOP

The search for the top quark is still a critical quest in the Standard Model. If its mass is light ($\leq 180 \text{ GeV}$), it may be discovered at Fermilab. But even if it is discovered there, the SSC will produce $\geq 10^3$ times as many top events which will allow detailed studies of its properties – for example, a precision determination of the mass. Since the top is so much heavier than the other quarks, it may exhibit quite different physics. This makes it interesting to investigate rare top decays. No concrete studies in this area are yet in progress, but these decays will typically involve combinations of signatures that EMPACT will be in a position to exploit. A detailed study of top physics at Fermilab [24] indicates no problem identifying top decays into μe final states, which is the cleanest signature. The background rates are low and the sign of the electron is not a necessary constraint. Also it appears likely that one can tag the b from the t decay, either through its μ or e decay, with reasonable acceptance. An extension of that study for EMPACT is currently underway and it is probable that the same conclusions will be valid at the higher SSC energies. Of particular interest to the EMPACT design is the ability to identify leptons in the vicinity of jets. Since it is now known that $M_t > M_w$ [25], new strategies need to be developed to identify the top [24]. The lepton from the W decay is quite energetic and isolated, while the lepton from the b decay is often obscured. A study was done at the ISAJET level to see the effect of calorimeter cell segmentation on the identification of this lepton. Figure 6-17 shows the percentage of top events that have a lepton from the b decay or subsequent c decay as a function of the amount of extra energy in a cone of size R. The lepton has $p_T > 2.5 \text{ GeV}$ and the isolation cut demands $\sum E_T < 2.5 \text{ GeV}$ in the R cone. The efficiency is better for smaller segmentation, but this study did not include transverse shower spreading, which is important. There is a factor of 2 improvement from $R = 0.2$ to

Fig. 6-17 Efficiency for Detecting Electronics from T-Decay The electron has $P_e > 2.0$ GeV and the $\sum E_T$ in a cone of size R is < 2.5 GeV in both the electromagnetic and hadronic calorimeters. The open squares are the electrons directly from $W \rightarrow e\nu$. The open circles are from b- or c-decays. The triangles are Dalitz backgrounds that can be removed by the TRD.

Fig. 6-18 Efficiency for Detecting Electronics from b or c Decay, from $t \rightarrow Wb$ as a Function of p_T^e . $\sum E_T < 2.5$ GeV in a cone $R = 0.05$.

$R = 0.1$. This would suggest that a cell segmentation of 0.05×0.05 is beneficial. Figure 6-18 shows the efficiency as a function of the p_T^e cut on the electron. It may be necessary to demand a higher cut on these electrons, and the figure shows how the efficiency falls with an increasing cut. The study will be repeated with a full GEANT simulation.

6.10 GLUINO SEARCHES

Present searches for SUSY particles have a rather limited mass reach and therefore assume that gluinos decay directly into photinos ($\tilde{g} \rightarrow q\bar{q}\gamma$). Since the photino has a neutrino-like cross section, it escapes the detector. This produces the characteristic large missing p_T signature that one expects in such processes. For the SSC, the mass reach is greatly extended and one must take into account other modes that become dominant for heavy gluinos [26]. Here there is the possibility of cascade decays into the lightest, and undetectable, neutralino. This has two consequences for SUSY searches at the SSC. First, there is the question of whether the missing p_T signature is still valid in light of the decay channels available. Second, there is the addition of interesting new signatures. For example, in the model being considered here [27,28] the gluino will decay almost 30% of the time to the chargino $\tilde{\chi}_2^\pm$, which in turn decays to a Z^0 , 40% of the time, giving rise to final states with a Z^0 and large missing p_T . In addition, since gluinos are Majorana fermions, one can have same sign dilepton final states. All these signatures put constraints on the detector design, and that is the primary focus of the present EMPACT studies. Clearly the viability of the missing p_T signature is not just a function of the cascade decays of the gluinos but also of the hermeticity of the detector, and the question of same sign dileptons is important for this detector as it can only measure the sign of muon tracks.

There has already been considerable work in this area [27-29]. However it is important to evaluate it in light of the specific properties of the EMPACT detector. The signal and background samples being used in the present study were generated using ISAJET. The background considered is from heavy quark jets. Since gluino production is a strong process the rates, even up to masses of 2.0 TeV, are more than 1000 events per canonical year at the SSC. If one requires that there are only

Fig. 6-19 Gluino Cross Section as a Function of Gluino Mass. Lower curve for Two and Only Two Muons with $p_T(\mu) > 20$ GeV/c and $\eta_\mu < 2.5$

two leptons in the final state, that they are same sign muons with $\eta < 2.5$, and with $p_T > 20$ GeV/c, then the event rate is still more than 10 events per year in the same mass range (Fig. 6-19).

Other issues considered here are whether the missing p_T signature is significant, and whether the lower rate signatures of Z^0 plus missing p_T and same sign leptons plus missing p_T are observable. Only a brief summary of the present status of the analysis is presented here [30].

The missing E_T and P_{out} (P_{out} is the momentum vector out of the plane of the beam and the highest p_T jet) signatures for 750 GeV gluino events and the appropriate background events are shown in Figs. 6-20 and 6-21. The background is for heavy quark jets. The heavy quarks decays were generated with ISALEP, a special version of ISAJET which is optimized for the generation of heavy quark decays with large lepton (e, μ , or ν) p_T . Even with this fast generator, one needs considerably more background

Fig. 6-20 Missing E_T Distribution for 750 GeV Gluinos

Fig. 6-21 $p_{T,out}$ Distribution for 750 GeV Gluinos

events to understand the missing p_T signatures for gluinos. This work is continuing to generate adequate background. In addition, one has to include the expected EMPACT resolution and hermeticity to fully understand the potential for this search at SSC energies. The present conclusions are similar to those of earlier studies in that for $E_{T,miss} > 300$ GeV there is likely to be an observable gluino signal.

The same samples discussed above were also used to study the potential lepton signals and backgrounds. The high p_T leptons from gluino decay come primarily from W and Z^0 decays and are isolated. Various effective mass calculations have been proposed to isolate the gluino signal and to

Fig. 6-22 Effective Mass Distributions for the Two Same Sign Lepton & the Four Highest P_T Jets for Gluino Events with (A) $M_{\tilde{g}} = 750$ GeV & (B) $M_{\tilde{g}} = 1500$ GeV

extract the gluino mass. In Fig. 6-22 the gluino system mass (defined to be the effective mass of the two highest p_T leptons and the four highest p_T jets) for same sign dileptons is shown for both 750 and 1500 GeV gluino production. This distribution is clearly sensitive to the gluino mass. An alternative distribution to consider is the effective mass of the second lepton and the closest two jets. Again the

distribution is sensitive to the gluino mass. Work on the backgrounds to these distributions is still in progress.

6.11 STRONG $W_L W_L$ INTERACTIONS

If there is no Higgs boson and no other new physics then the interactions of longitudinally polarized $W^\pm$ and Z^0 bosons must become strong at a mass scale $M_{WW} \approx 1$ TeV. In this scenario, the new physics of the SSC would be to observe the strong interaction dynamics of these W_L , which behave like the pions of the SU(2) electroweak theory. Chanowitz *et al.* [31] have estimated the cross sections for the various $W_L W_L \rightarrow W_L W_L$ channels, assuming a simple model. The cross section is taken from low energy theorems up to the point where unitarity is violated and it is assumed to be

Table 6-5 Number of Events for Integrated $L = 10^{40} \text{ cm}^{-2}$ from Strong $W_L W_L$ Interactions & Number of Real Background Events in Various Channels.

CHANNEL	DECAY MODES	M_{WW} LIMIT	SIGNAL/BKG
$Z^0 Z^0$	$l^+ l^- l^+ l^-$, $l^+ l^- \nu \bar{\nu}$	1.0 TeV	17/12
$W^\pm Z^0$	$l^\pm \nu l^+ l^-$	0.8 TeV	9/9
$W^\pm W^\pm$	$l^\pm \nu l^\pm \nu$	0.8 TeV	53/34

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constant thereafter. The effective W approximation is then used to calculate the results for pp scattering. The number of events into the leptonic channels predicted by this calculation per canonical SSC year is exceedingly small, as can be seen from Table 6-5.

Since a generator for strong $W_L^\pm W_L^\pm$ scattering is not available, $W^+ W^-$ events with $M_{H} = 2$ TeV were used. This should have similar kinematics and general features, although the backgrounds are quite different. In Figs. 6-23 and 6-24 the lepton rapidity and p_T distributions for $W_L^\pm W_L^\pm$ events from ISAJET with a large Higgs mass, $M_{H} = 2$ TeV, are shown.

Fig. 6-23 The Lepton Rapidity Distribution for $W^+ W^-$ Events from Higgs Decay with $M_H = 2000$ GeV

Fig. 6-24 The Lepton p_T Distribution for $W^+ W^-$ Events from Higgs Decay with $M_H = 2000$ GeV

The kinematic coverage of EMPACT is well suited to this physics, and given the small numbers of events in all the channels and the significant backgrounds, EMPACT's goal of utilizing luminosity greater than $10^{33} \text{ cm}^{-2}\text{s}^{-1}$ will be beneficial.

The $W^\pm W^\pm$ channel is particularly interesting because it avoids the backgrounds from $q\bar{q} \rightarrow W^+ W^-$ and especially from $t\bar{t} \rightarrow W^+ W^-$. But the backgrounds from $W^\pm$ radiation from quarks produced in QCD processes and from $W^+ W^+ \rightarrow W^+ W^+$ scattering in the standard model are not negligible,

as can be seen in Table 6-5. One might hope to suppress the first background by making an isolation cut. Since the W is radiated from a quark, there should be a nearby jet. To investigate this, a sample of single W 's radiated from QCD jets using ISAJET is compared with W 's from Higgs events with $M_H = 2$ TeV. In this analysis, only the partons generated by ISAJET were used and no detector effects have been included. The W 's from QCD

Fig. 6-25 The E_T in a Cone of Radius $R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$ About the Lepton
(A) W 's From 2 TeV Higgs
(B) W 's From QCD Jets

events are less isolated, as can be seen from Fig. 6-25, but a large fraction of events are still isolated even for $p_T^\mu > 100$ GeV. The isolation should improve for higher p_T^μ , but it is not visible within the limited Monte Carlo statistics. In any case, it does not appear that isolation will dramatically decrease the background. At present the feasibility of a measurement of W^+W^+ events has not yet been demonstrated. Alternative approaches to the study of strong vector boson scattering will also be investigated [32].

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7

INTEGRATION & ASSEMBLY

7 - INTEGRATION & ASSEMBLY

7.1 INTRODUCTION

This section describes how the major elements of the EMPACT detector form an integrated concept with provisions for signal cables, mechanical supports, service, and assembly access. An assembly plan is presented which determines baseline concepts for the detector hall and surface facilities. Consideration is given to the use of these facilities for the data taking phase of the experiment and during periods of routine maintenance, unscheduled major repairs, and detector upgrades. The baseline has been developed in sufficient detail to determine the critical requirements. Trade studies for future optimization are indicated here. Realistic detector models have been developed in response to the detector physics goals. An in depth discussion

of these issues appears in the "EMPACT SSC Resource Requirements" document that is being prepared in cooperation with the SSCL [1].

7.2 INTEGRATION

The EMPACT detector design philosophy incorporates systems integration requirements and constraints from the start of conceptual development. This is accomplished by using the tools and talents of industrial engineering partners experienced in developing large, high technology systems. Requirements driven by component designs, assembly, installation, and maintenance govern evolution of the total system. The 3D model in Fig. 7-1 and on the back cover shows the EMPACT assembly supported from an external structure that

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Fig. 7-1 Cut-away 3D view of the EMPACT detector showing parts of the overhead support frames from which the detector is suspended.

minimizes losses in the detector coverage. The relatively low weight of the detector (5600 metric tons) permits suspension of the major assemblies with adjustable tension members from above rather than from massive internal columns required for support from below. The tension members pass between muon chamber panels and require only local truncation of panel corners or edges in the upper detector quadrants. A double-walled tube supports the calorimeter and forms the inner vacuum vessel wall of the central toroid and the outer vacuum vessel wall for the LAr barrel. The inner barrel muon chambers are located between these two walls. The number of cavities around the circumference for muon chambers is driven by issues of structural strength vs thickness and spacing of stiffening ribs and optimization of the number of muon channels.

The dimensions of the detector elements and the spaces between them provide room for support members, signal cables, high voltage cable, low voltage cables for electronics, muon chamber gas feeds, cryogen feeds, vacuum lines, etc. The utilities that interpose dead material in the sensitive volume of the detector have been included in the physics models to determine degradation of detector performance and some sizing and routing optimization has been performed. Services that are routed between the central and end toroids exit from the upper 135° azimuth sector. This preliminary concept provides minimal interference with muon coverage. Further optimization of the interaction between the supports and the muon chambers will be necessary, especially questions regarding the overlap of the barrel and plug muon chambers. Table 7-1 summarizes the salient physical specifications of the EMPACT detector, and Fig. 7-2 shows a dimensioned cross section.

The interaction between the forward calorimeters and the collimators protecting the first quadrupoles of the low beta interaction region is not well understood at present and is under joint study with the SSCL.

Table 7-1 Specifications of EMPACT Detector

COMPONENT	WT (MT)	DIMENSIONS (M)				INSTR CHAN COUNT (K)
		L	W	H	D	
EMPACT TOTALS FOR:						
LAC	5588	37.1	26.2	26.2		1159
SPACAL	5208	37.1	26.2	26.2		959
SPACAL/SILICON EM	5208	37.1	26.2	26.2		1265
CENTRAL TRACKER	1	6.1			2.0	384
CALORIMETER OPTIONS:						
LAC	2830	14.0			7.0	273
BARREL	1710	3.6			7.0	156
ENDCAP	1120	3.3			5.7	117
SPACAL	2500	13.4			7.0	73
BARREL	1200	5.1			6.8	39
ENDCAP	1300	4.0			6.5	34
SPACAL/SILICON EM	2500	13.4			7.0	379
BARREL	1135	5.1			6.8	10
ENDCAP	1272	4.0			6.5	9
SILICON EM-CENTRAL	65	5.1			2.4	260
SILICON EM-ENDCAPS	28	0.2			2.6	100
AIR CORE TOROID	1808					
CENTRAL TOROID	752	16.6			16.6	
END TOROIDS	1056	5.6			18.6	
MUON DETECTORS	349	37.1	26.2	26.2		500
FWD DETECTORS - LAC	600	3.9			4.1	2
FWD DETECTORS - SPACAL	550	2.7			3.6	2
MP90-3180-011B						

The transitions between the endcap calorimeters and the forward calorimeter coverage at $\eta = 3$ require further study. This transition degrades the hermeticity but continuing the endcap calorimeter to smaller angles drastically increases the radiation load for elements in the central tracking region, and limits the rapidity coverage.

7.3 ASSEMBLY PLAN

The point-of-departure detector assembly plan and the corresponding hall concept [2] incorporate above ground fabrication, assembly, and test of all major detector components, followed by integration and system tests below ground in a minimum size hall. Initial studies indicate this concept offers lower overall facility and installation costs through minimization of high cost hall volume, coupled with some increase in low cost surface facility volume. Detector construction proceeds in surface buildings in parallel with hall construction to pro-

Fig. 7-2 Quarter sections of the EMPACT detector with dimensions (cm). On the left is a section through the interaction point normal to the beam line. The right is a section along the beam line. The calorimetry chosen for this figure is the LAr.

vide maximum schedule flexibility. In contrast, an alternative plan where most fabrication and assembly work is performed in the hall is relatively inefficient and costly, and the hall must be enlarged to provide space for parallel construction tasks. Detailed trade studies in cooperation with the SSCL will evaluate alternative hall and assembly concepts.

Figure 7-3 is a cutaway view of the integrated EMPACT detector in the collision hall with one end toroid pulled back as required during construction or maintenance phases. The barrel and endcap calorimeter, and central toroid components are supported from stationary overhead frames, while the end toroid assemblies and forward calorimeter assemblies are supported from movable frames. The integrated model of Fig. 7-3 contains significant detail, and detail will be added for the support frames, muon chamber support structures, and interfaces for vacuum, cryogenics, and electrical services to support trade studies. These details will also

be included in plant design surface models, illustrated on the front cover, which provide complementary tools for studying detector integration, assembly, and service requirements.

7.3.1 Surface Activities

Most assembly operations use modules and subassemblies fabricated at the vendor's site or at the collaborator's institution, which are then assembled in surface facilities near the collision hall. The calorimeter modules, fabricated offsite, are installed in a surface building. The toroid modules and muon chambers are assembled in adjacent buildings. All completed assemblies are moved to one of two $9\text{ m} \times 27\text{ m}$ vertical access shafts over the collision hall on a track-mounted transporter and lowered using a temporary, heavy-lift device. A temporary portable enclosure provides protection during the transport and lowering operations.

Surface facilities include construction sheds for the central and end toroids, the muon chambers, and

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Fig. 7-3 Perspective cut-away view of the EMPACT detector in the collision hall. One end toroid with attached muon cap chambers and forward calorimeter is pulled away from its normal position as might occur just before completion of assembly or during maintenance. Parts of the overhead cranes are shown. One bearing wall for the overhead support frames shows clearly in the foreground. Not shown are the rails on which the arch supports for the end assemblies move along the beam line.

the calorimeters. The calorimeter shed contains clean rooms for installation of the calorimeter modules into the barrel, end, and forward calorimeter assemblies. The full model showing surface facilities, underground hall, and detector is shown in the illustration at the beginning of this section. Figure 7-4 and the illustration at the front of this section show a perspective cutaway view of the collision hall with the EMPACT detector in place at the interaction point; it also shows the access shafts.

Two large shafts (9 m × 27 m) are for lowering major components and two smaller shafts (7.2 m inside diameter) are for routine access of equipment, personnel, and services. Also shown are a plan view and scaled elevation view perpendicular to the beamline. The assembly approach shown here minimizes the size of the costly collision hall. Some of the surface buildings can be converted to control room, office, and laboratory space after the construction phase.

Fig. 7-4 The EMPACT collision hall, access shafts, and surface facilities. The perspective cut-away view shows the collision hall as in Fig. 7-3 but with the two large access shafts centered on the beam-line, the rail system for moving assemblies to the shafts, the smaller utility shafts, and the surface sheds. The large shafts are shown with covers in place. The surface sheds are indicated with their intended use during the assembly phase. Below is a plan and elevation view normal to the beam line. In the plan view one can see the cross tunnel between the horizontal tunnels at the base of the smaller access shafts. This will be used for high voltage and other electronics that require access and proximity to the detector.

The baseline approach is to install the barrel calorimeter into the double wall support tube before being lowered into the hall. The total weight of this 16 m long assembly is 1710 metric tons. The fully assembled endcap calorimeters are also lowered, each weighing 560 metric tons.

7.3.2 Hall Activities

Eight central toroid modules are delivered to the site as 45° octants. The modules are within the

size and weight limitations for water and ground transport. The 94 metric ton octants are lowered into the hall where they are assembled into the complete central toroid using temporary fixtures. During these operations the overhead support frames for the central toroid/calorimeter assembly and the end toroids are installed in the hall. Tie rods are attached to the overhead frame structure to support the toroid/calorimeter barrel assembly prior to dismantling the temporary fixture. All of the hall

operations use two independent 55 metric ton bridge cranes for routine lifting.

The support tube with or without the central calorimeter can then be installed in the central toroid using movable beams.

In conjunction with the assembly of the central toroid octants in the collision hall, the end toroid magnets are assembled in a surface building using the same 45° octant approach. They are approximately 18 m in diameter and each weighs 528 metric tons.

While the assembly operations for calorimeters and toroids are underway, the muon chambers are assembled in the surface facility. Upon completion of the muon chamber sets, each pair is joined in a truss structure and initially aligned prior to lowering into the hall. The largest muon chamber assemblies (27 m diameter cap ends) determine the access shaft dimensions. They are moved to the hall prior to lowering the end toroids. After the toroids are in the beamline position, the muon chambers are installed and aligned on their respective support structures.

The barrel muon chambers may be installed on the central toroid structure any time after the toroid is fully assembled in the hall. This also applies to the inner barrel muon chambers, provided the end toroids are moved to their extreme hall positions.

Service equipment such as vacuum pumps, cryogenic lines, electrical cabling, and various instrumentation are the last items to be assembled and installed in the collision hall. Much of this equipment will be located on platforms and routed on cable trays that are part of the central, fixed support structure. These are not shown on the drawings in this document.

When the EMPACT detector is fully assembled, the beam line elements within the collision hall can

be installed on their rigid platforms [3]. Assembly schedules for the EMPACT detector indicating readiness for beam by 1999 are shown in Section 8.

A lateral gallery connecting the horizontal sections of the access shafts close to the interaction region houses controls, trigger electronics, and power supplies requiring minimal cable lengths and access during operations. Shielding doors allow occupancy during beam operations.

7.3.3 Assembly Issues

A number of issues are being investigated to optimize the assembly scenario and reduce building requirements. The primary driver for the large shaft size is surface assembly of the cap muon chambers. We are now studying the option of fabricating smaller subassemblies on the surface and installing them on their support frames in the hall. This will reduce the shaft dimensions and may simplify subsequent maintenance and disassembly operations of the cap chambers.

We are also considering the option of installing the double-wall cylinder into the assembled central toroid without the barrel calorimeter. This may simplify assembly and handling operations in the hall. This also provides the option of completing either the central toroid or central calorimeter first.

Finally, an area of concern is the penetration of the upper three octants of muon chambers by the overhead tie rod supports. Alternate configurations for these chambers are being considered to further minimize these localized regions of lost tracking.

7.4 FACILITIES/SERVICES

The size of the collision hall, access shafts, and surface buildings necessary for the EMPACT construction phase were described in the previous section and are shown in Fig. 7-4. Space requirements during the running of the experiment, during routine maintenance periods for major unscheduled repairs, and for significant upgrades require no

additional space. Surface construction space will be converted to offices and maintenance labs as needed.

Table 7-2 lists utilities required during operation of the experiment.

Table 7-2 EMPACT Utilities Requirements During Operations

UTILITY	REQUIREMENTS
ELECTRICAL	
• DC POWER FOR ELECTRONICS	1000 kW AVG
• DC POWER FOR TOROIDS	1000 kW AVG @ 12 V
• AC POWER FOR REFRIGERATION	450 kW AVG
• AC POWER FOR HEATERS, VACUUM PUMPS, ETC	250 kW AVG 600 kW PEAK
LIQUIDS	
• LIQUID ARGON FOR CALORIMETERS	43 kgal
• LIQUID NITROGEN FOR CAL CRYOSTAT	3600 l/hr
CHAMBER GASES	
• XE/CO ₂ GAS FOR INNER TRACKER	2.0 m ³
• 88% ARGON/9.5% ISOBUTANE	400 m ³
• 2.5% CO ₂ FOR MUON CHAMBERS	1200 m ³ /DAY
MP90-3180-012D	

REFERENCES

1. EMPACT SSC Resource Requirements Document.
2. L. Mason and J. Rutherford, "EMPACT Detector Assembly Scenario," EMPACT Note 216 (1990).
3. J. Rutherford, "Accelerator Constraints in an SSC High Luminosity Collision Hall," EMPACT Note 215 (1990).

8

COST & SCHEDULE

8 - COST & SCHEDULE

As part of the effort to iterate the design from baseline concept to optimum detector, tradeoff studies must be conducted to estimate both the total cost of the EMPACT candidate configurations and possible schedules for construction. These baseline estimates and schedules are essential in order to perform cost-benefit analyses of alternative detector technologies and to identify critical path items. It is emphasized that the estimates and schedules given here are to be considered as points of departure only.

Estimated baseline costs and schedules are given below for the total EMPACT detector system and for the period of time during which the R&D and engineering is performed that leads to the Detailed Design Report (pre-DDR). The DDR is the key milestone which establishes readiness for procurement and fabrication of all systems. It assumes detailed specification of all engineered systems and proven performance from the essential detector elements. The DDR must be complete by the end of 1992 in order for EMPACT to be operational by late 1998.

The estimates and schedules have been established by technical experts from EMPACT industrial, national lab, and university team members. To facilitate the systematization of cost estimates and ensure inclusion of all cost factors, EMPACT has initiated a Work Breakdown Structure (WBS), which has been constructed by comparison to existing detector projects. Cost estimates for the calorimeter and toroids have been made by the Martin Marietta and Grumman engineers that developed the designs, using established industrial estimating and scheduling models. LeCroy has estimated front end electronics costs. It should be noted that the calorimeter estimates and schedules are consistent with the tradeoff studies made by Martin Marietta for the Physics Research Division of SSC.

8.1 BASELINE EMPACT ESTIMATES

The summary cost estimation given in Table 8-1 indicates that the cost range of the systems of the

Table 8-1 Baseline EMPACT Detector System Costs
(Thousands of FY90 \$)

DETECTOR	
Tracking	
TRD	15 087
2-D Options	
1 - Vertex	14 000
2 - Pads	4 340
Calorimetry Options	
1 - LAr	
Central	55 503
End Cap	42 992
Forward	15 296
2 - SPACAL	
Central	77 418
End Cap	76 261
Forward	23 866
3 - SPACAL/Silicon EM	
Central	84 090
End Cap	77 640
Forward	23 866
Superconducting Toroids	
(includes calorimeter & detector support system)	
Central	63 120
Ends	99 908
Muon Detectors	20 250
Signal Handling	
Front End (LAr)	68 560
Front End (SPACAL)	49 401
Front End (SPACAL/Silicon EM)	46 079
Data Acquisition	24 104
TOTAL (LAr)	409 160
TOTAL (SPACAL)	453 754
TOTAL (SPACAL/Silicon EM)	458 484

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EMPACT baseline is between \$409M and \$458M in 1990 dollars, depending on the choices of technology. Given in Table 8-2 are related costs such as R&D, and Engineering, Design, and Inspection (EDI), as well as estimates for the experimental facilities baseline described in Section 7. These baseline cost estimates will, in conjunction with guidance from the SSC as to the scope of the U.S. funded detector program and financial commitments from foreign collaborators, aid progress towards the optimization of the EMPACT detector system over the next year. It is the intent of the collaboration to seek non-U.S. contributions to the detector at a level proportional to the foreign participation in EMPACT – currently estimated at one-third of the total. These costs do not include such critical factors as contingency or inflation, which are not appropriate until later in the design cycle, since major cost

swings can be accomplished by changes in technology choices or channel counts, and the final choices in technology control the risk assessment studies needed for contingency analyses.

Figure 8-1 presents schedule and funding profile estimates for the EMPACT baseline detector along with the published major milestones of the SSC Detector Program. The funding profile presented here shows average levels for six month intervals, and was calculated for the EMPACT baseline described in earlier sections. It reflects assumptions about assembly methods and sequences described in Section 7. Figure 8-1 graphically illustrates the magnitude of the task and emphasizes the importance of funding and performing significant R&D and engineering design, especially on the calorimetry and muon toroids, if the experiment is to be operational by late 1998.

Table 8-2 Baseline EMPACT Related Costs
(Thousands of FY90 \$)

RELATED COSTS	
Facility	
Structure (Surface & Underground)	45 000
Equipment/Services (LAr)	18 714
Equipment/Services (SPACAL)	14 986
Detector Installation	9 388
Engineering	
EDI (LAr)	62 374
EDI (SPACAL)	67 677
EDI (SPACAL/Silicon EM)	79 791
Integration	21 138
Research & Development	
Tracking	1 960
LAr	7 023
SPACAL	4 178
SPACAL/Silicon EM	1 523
Superconducting Toroids	12 629
Muon Detectors	1 013
Signal Handling	4 633
Detector Equipment	2 015
Integration & Management	3 339
Physics Detector Simulation	5 920
Total R&D	44 233

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8.2 DEVELOPMENT OF THE DETECTOR DESIGN

A critical point to emphasize is the significant funding needed for advancement of the detailed design during the period late 1990 to early 1993. This involves the R&D and engineering design that leads to the DDR. In Fig. 8-2 estimates are presented of the schedule and funding profile during the detailed design period, averaged for each six month period. Total R&D needs are estimated at \$44M, and the engineering design costs at about \$83M – \$100M, depending on technology. As fractions of the overall estimated system costs, R&D at 10% and engineering design at 20% are historically justifiable levels for a one-of-a-kind project of this magnitude.

Figure 8-3 shows the key events in the pre-DDR period of EMPACT, along with EMPACT milestones and SSC Detector Program milestones. Consistent with the EMPACT philosophy of iterating the design based on physics performance, technical feasibility, and cost, we anticipate evolving the initial baseline presented here to an intermediate baseline design in March-April 1991, and a final

Fig. 8-1 Schedule and Funding Profile for EMPACT Baseline Configurations

Fig. 8-2 Schedule and Funding Profile for EMPACT Detailed Design Development

Fig. 8-3 EMPACT Detailed Design: Key Events

baseline just before the proposal is due in the late fall of 1991. Also identified in Fig. 8-3 are EMPACT milestones involving the specification of long-lead procurement after first stage approval, and the submission of a DDR in late fall 1992. Key events in the development of the DDR, such as selection of the radius of the tracker-to-calorimeter transition, the calorimeter technology, the muon detector technology, and the experimental hall configuration, are also found in Fig. 8-3. Black lines indicate items on the critical path to a particular decision, and open lines indicate other important activities. The shaded lines represent the ongoing physics performance, engineering feasibility, and cost/schedule analyses that are central to the iteration of the designs. It is important to emphasize that significant parallel paths in R&D must be followed to select technologies for EMPACT (e.g., calorimetry and muon detectors). This is reflected in the plans and schedules shown in Figs. 8-2 and 8-3.

8.3 1991 FUND REQUESTS

Table 8-3 shows the 1991 fund requests, by institution, for the work necessary to initiate the

detailed design of EMPACT. These activities are consistent with the cost and schedule estimates presented in Figs. 8-2 and 8-3, and are crucial to designing and building EMPACT for operation by 1999. The university and laboratory requests incorporate technology R&D, critical simulation and analysis efforts, and operating support including post docs and travel.

The collaboration will rely on its industrial collaborators for engineering R&D, engineering design, and systems integration. Engineering R&D is work in support of technology development; engineering design is focused on detector baselines and systems. The industrial fund requests shown in Table 8-4 reflect the bulk of the estimated 1991 costs of EMPACT engineering related activities delineated in Fig. 8-2. These fund requests result from trade study cost estimates and are not to be construed in any way as bid prices. It is anticipated that specific statements of work, memoranda of understanding, and contracts will be negotiated between collaborating institutions or industries and the SSCL at the appropriate time.

Table 8-3 1991 University & National Laboratory Requests
(Thousands of FY 90 \$)

INSTITUTION - TASK	EQ	WS	TR	SS	ENG	PD	MISC	EQ \$	OP \$	Total
Adelphi - Simulation			5					0	5	5
Arizona - Sim/Cal	85	45	20	15				130	35	165
Boston - TRD	150		28		280	70	38	169	397	566
- Parallel Processor	15		10	45			26	28	68	96
Brookhaven - LAr	80			173	70			80	243	323
- Muon	70			60			51	70	111	181
- Simulation		60						60	0	60
- Trigger	80		73	40	280			80	393	473
UC San Diego - SPACAL	235		20			70	150	310	165	475
Carnegie Mellon - Silicon	50		16					50	16	66
Florida State - Simulation			10	25				0	35	35
Houston - Muon Detector	44		15			70	52	70	111	181
Indiana - Muon Simulation		45	30	40				45	70	115
Kansas - Simulation		45	15	12		70		45	97	142
Lehigh - Simulation			5					0	5	5
Louisiana State - Muon/Simulation		45	15	25				45	40	85
Mass, Amherst - Trigger/Simulation	10	45	30	15			6	58	48	106
MIT - Muon Detector	210	45	50	25	140		30	270	230	500
Michigan State - Trigger/Magnets		45	5		140			45	145	190
NYU - Simulation			5					0	5	5
Northeastern - Simulation			5					0	5	5
Oak Ridge - Superconductor				240	101		90	45	386	431
Oregon - Sim/Sil/FwdCal	75	45	40			210		120	250	370
Princeton - Trigger	41	45	24	15				86	39	125
Rochester - LAr	35	45	15		35	70	20	95	125	220
Stony Brook - Toroid/Simulation	90	45	50	25			70	170	110	280
Texas, Austin - Trigger		45	15	25	140	70		45	250	295
Vassar - Simulation			5					0	5	5
Washington - Vertex Det/Sim	5	45	10		140	70	40	70	240	310
Wm&Mary - SPACAL	150	45	20	25		140		195	185	380
Yale - Muon/Simulation	7	45	24	15			4	54	41	95
TOTAL	1432	735	555	820	1326	840	577	3782	2504	6285
EQ = Equipment (Equipment \$) ENG = Engineers (Operating \$) WS = Workstation (Equipment \$) PD = Post Docs (Operating \$) TR = Travel (Operating \$) MISC = Materials, supplies, shops, etc. SS = Support: programmers, technicians, (50% Operating \$, 50% Equipment \$) graduate students (Operating \$)										

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Table 8-4 1991 Industry Requests
(Thousands of FY 90 \$)

INDUSTRY - TASK	ENGINEERING R&D	ENGINEERING DESIGN
Grumman - Toroid Development	2755	4352
- Detector Support & Alignment	1667	
- Systems Integration		617
LeCroy - Electronics Systems		280
Martin Marietta - LAr	3636	3537
- SPACAL	2948	5054
- Systems Integration		552

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9 MANAGEMENT

9 - MANAGEMENT

EMPACT is a collaboration of scientists who have similar physics interests at the SSC and who believe that the EMPACT detector is the best way to pursue this physics. EMPACT is also an enormous high-technology project that must be designed, fabricated, assembled, and commissioned at the SSC before experimentation can begin. There must be an overall collaboration organization that ensures the scientific integrity of the experiment, and a project organization that ensures that the detector system meets technical, cost, and schedule goals.

9.1 EMPACT COLLABORATION ORGANIZATION

The collaborative and project EMPACT organization is illustrated in Fig. 9-1.

The primary elements of EMPACT are the collaborating institutions, from locations shown on the maps on the facing page. Each group has designated a contact person who will serve on the Collaboration Council. The Collaboration Council is comprised of one representative from each institution – university, laboratory, or industry – participating in the experiment. The Council has responsibility for all scientific reports and publications and is required to ratify any major changes in the scope of the detector or the physics program of the experiment. The Council is run by a Chairman who is elected by majority vote. It is the responsibility of the Chairman to bring issues to the Council for consideration. The Council has the authority by two-thirds vote to amend the management structure of the collaboration. The

Fig. 9-1 EMPACT Organization

Council will also elect representatives to a Scientific Policy Committee (SPC) on a rotating basis.

The SPC is comprised of members elected by the Collaboration Council from the collaboration on a basis intended to represent fairly the scientific views of the collaboration and also to provide a balanced representation of institutions by their geographical distribution and by their contribution of resources and manpower to EMPACT. The SPC sets the physics goals of the experiment and is responsible for insuring the integrity of the physics program by reviewing and approving all major decisions regarding the performance capabilities of the detector. The SPC also acts in an advisory role to the Experiment Coordinator (see below) on all other matters. Those issues that are deemed to alter the scope of the experiment will be brought to the Council for ratification, with a recommendation from the SPC. The SPC will elect a Chairman by majority vote, who will also function as a Deputy Experiment Coordinator.

The detector consists at present of six major subsystems: tracking, calorimetry, toroidal magnets, muon detectors, electronics, and computing. Each of these systems has a Manager who is appointed by the Experiment Coordinator with the approval of the SPC. The Managers are responsible for coherence and adequacy of their systems design, adherence to schedules for their systems, fiscal responsibility for their system, and liaison between their system and the Systems Integration Group for the experiment.

The Technical Advisory Committee (TAC) acts in an advisory role to the SPC and the Experiment Coordinator. It is composed of the six Systems Managers, plus one representative from each industrial partner, the Systems Engineering and Integration Manager, and a budget representative from the Project Support Group. The TAC is charged with oversight for all technical decisions concerning the design, optimization, development, fabrication, test, and commissioning of the detector. This Committee will review the technical progress of all systems

concerning performance, cost, schedule, and safety and will report the results of these reviews to the Experiment Coordinator and the SPC. The EMPACT Project Manager is the chairman of the TAC and will also function as Deputy Experiment Coordinator.

The experiment will be managed by an Experiment Coordinator and the two Deputies representing the Scientific Policy and Technical Advisory Committees. The Experiment Coordinator has the prime responsibility for the design, fabrication, and commissioning of the detector and for ensuring the capability for extraction of high quality physics data in a timely manner. The Experiment Coordinator has the responsibility and authority to carry out the functions required to achieve the technical, cost, and schedule goals of the experiment. The Experiment Coordinator provides the link between the collaboration and the SSCL. The Experiment Coordinator will be nominated by the SPC and must be ratified by a majority vote of the Council. The Experiment Coordinator will normally serve for a term set by the Council. The Experiment Coordinator will be assisted by the Project Support Group, responsible for budgetary, scheduling, and systems integration functions, as well as by the Collaboration Secretary, responsible for communications within the collaboration, including announcements, technical notes, and meeting notices. The Experiment Coordinator will be empowered to provide budgets for all technical systems and to negotiate agreements between the collaborating institutions and the experiment.

9.1.1 Joining the Collaboration

In order to maximize participation of the community, the EMPACT collaboration will remain open to high energy physicists from any university, laboratory, or industry. Prior to submission of this document, joining the collaboration could be accomplished solely by letter to the Collaboration Secretary stating an interest in the physics goals of EMPACT. As the Collaboration structure and institutional responsibilities become formalized, future applications for collaboration will be negotiated by the Experiment Coordinator and ratified by the

Council to ensure that new participants constructively contribute to expediting the completion of the project and extracting high quality physics.

9.2 EMPACT PROJECT MANAGEMENT

The scale of EMPACT is such that a clear, direct project management structure is necessary to ensure schedule and cost performance. This structure must, however, recognize the international nature of particle physics and be flexible enough to accommodate the evolution of the collaboration's scientific goals. We propose a structure that provides strong scientific and technical oversight while using proven project management and systems integration techniques to assure EMPACT's technical, schedule, and cost performance. This structure, represented in Fig. 9-1, is directed by an overall Project Manager, and features safety, planning, cost control, and procurement functions that are well integrated with parallel organizations in the SSCL, as well as central systems engineering and integration, and independent quality assurance. Subsystem groups (e.g., tracking, calorimetry, etc), each under the direction of a Manager, consist of individual physicists or engineers responsible for R&D, development of major detector elements, and important engineering functions.

The roles of major elements of the project management are described in the following paragraphs.

Project Manager – responsible to the Experiment Coordinator and Collaboration Council for the overall execution of the EMPACT Project from design through assembly and commissioning. The Project Manager is also the chairman of the TAC and Deputy Experiment Coordinator. We anticipate that the EMPACT Project Manager will be resident at the SSCL upon approval of the EMPACT proposal. EMPACT physicists, engineers, and support staff will be located at the SSCL, as appropriate.

Quality Assurance Group – responsible for independent verification that the hardware is built, tested, and assembled in accordance with overall

and detailed designs and plans. This group also independently verifies that software is developed and documented according to design and to agreed upon standards.

EMPACT Project Support Functions – report directly to the Project Manager, and include safety, planning, cost control, accounting, procurement, and contracting. These functions will be closely coordinated with related offices at the SSCL, both in the execution of their functions and in the tools and methods used. Support functions such as planning, cost control, and safety are also represented on the TAC.

Systems Engineering & Integration Group – will employ industrially proven systems engineering and integration methodologies that have been specifically tailored to the development of a large particle physics detector system in an international environment. This group's manager will also serve on the TAC. The group will be responsible for the integration of the EMPACT detector system and will work closely with the SSCL to interface EMPACT with the Collider. The SE&I Group will consist of physicists and engineers representing each subsystem, as well as the necessary systems engineering personnel. SE&I functions include:

- Development of a Systems Engineering Management Plan (SEMP), Work Breakdown Structure (WBS), and specification trees
- Requirements verification and validation
- Interface and change control
- Configuration and data management
- Reliability and maintainability
- Procurement and fabrication
- Logistics
- Parts, materials, and standards
- Overall integration and assembly of subsystems.

The development of each major subsystem (i.e., tracking, toroids, calorimeters, muon detectors, electronics, and computing) is the responsibility of a System Manager. These Managers also serve on the TAC. Under each Manager, individual physicists or engineers will oversee development and

fabrication of major elements of the subsystem. Engineering, test, and assembly functions required by the group and subgroup leaders will be the responsibility of engineering team leaders. The Computing Manager will ensure coherence, use of common configurations, and efficient software development for data acquisition, simulation, monitoring, controls, and off line analysis. The simulation group forms the core of the postproject experimental data reduction and analysis group. The development of individual subsystems will occur at the appropriate physical locations – be they collaborating universities, laboratories, industries, or the SSCL itself – as determined by cost and availability of facilities.

9.3 ORGANIZATION FOR INITIATION & PROPOSAL PERIOD

To facilitate the initiation of the EMPACT experiment and to manage the collaboration during

the proposal preparation phase, we have set up a modified version of this plan that provides for an Experiment Coordinator and two Deputies, named on the title page, who will have the responsibility of managing the collaboration affairs. The SPC will be elected after approval of the EMPACT experiment. Until that time, its role will be assumed by the Collaboration Council, thus allowing the entire collaboration to have a voice in the initial decisions regarding the configuration of the experiment. If the collaboration becomes too large to allow this group to function effectively, the Council may choose to elect and initiate the SPC. An interim TAC, composed of the EOI section editors, has been formed to manage the activities leading to a formal proposal. After the actions of the PAC in November 1990, it is the intent to convene the Collaboration Council to ratify or alter the initial structure and list of management personnel. This meeting should occur no later than 30 November 1990.

- END -

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