Report of the Task Force on Detector R&D for the Superconducting Super Collider

June 1986

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on Detector Research and Development
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CHAPTER 1

Summary

Detector research and development requirements for experiments at the Superconducting Super Collider (SSC) have been examined in detail. Our conclusions are that substantial basic R&D is required in the following general areas:

(1) Radiation resistance:

The combination of high luminosity and large particle multiplicities expected at the SSC will present a new class of problems for tracking devices, electronics, and some aspects of calorimetry operating in the high radiation environment near the collision points at the SSC. Research and development is required to find preventative cures for radiation damage to wire chambers, silicon detectors, fiber systems, scintillator, and electronics.

(2) Faster response time devices:

The interaction rate at the SSC at design luminosity is sufficiently high that development of tracking and calorimetric detectors with very short integration times is essential.

(3) Improved granularity:

At any luminosity, the particle density in most of the interesting events at the SSC will require the development of tracking devices, and to a lesser extent calorimetry, with substantially finer granularity (e.g., double track separation) than present devices.

(4) Improved performance of electronics systems:

Large scale detectors at the SSC will require sophisticated electronics systems with up to 10^6 elements. The cost of large SSC detectors will be prohibitive unless substantial improvements are made in the performance

per unit cost of electronics systems. This will require the effective use of custom designed integrated circuits on a scale not yet realized in high energy physics.

(5) Improvements in computing:

The computing requirements of experiments at the SSC could easily equal the combined requirements of all experiments running in the world by the early 1990s. It is essential that parallel computing systems of the one event per processor type, including software, be developed for both on-line and off-line use at the SSC. At present it is clear that cost effective development of such systems will not proceed without substantial support from the high energy physics community.

(6) Improved performance for momenta/energies in the TeV range:

The measurement of momenta or energy and identification of leptons in the TeV range will be of crucial importance at the SSC; the identification of hadrons may also be important. This will require substantial extensions of existing techniques for muon identification and light hadron (π , K, p) identification and, to a lesser extent, electron identification. In some cases, large improvements in spatial resolution will be required to measure momenta of particles over the full kinematic range accessible at the SSC.

In addition to the R&D on hardware and software outlined above, there is also a need for continued development of Monte Carlo programs to simulate high energy pp or $\bar{p}p$ collisions and the responses of detectors to them.

A research and development program to address items (1)-(6) should begin within the next year to match the time scale proposed for the design and construction of the accelerator complex at the SSC. We note that the construction

time for large detectors is substantial and therefore R&D must be completed in the next few years to provide guidance in the choice of major detector subsystems. The initial cost of such a program of generic R&D, not tied to a specific experiment design, depends on the interest of the community and the number of parallel efforts, but is likely to amount to a few million dollars per year. Investment in such a research and development program now is essential to the timely implementation of large detectors and experiments at the start-up of the SSC.

CHAPTER 2

Introduction

The Central Design Group (CDG) for the Superconducting Super Collider (SSC) set up a Task Force on Detector Research and Development for the SSC late in April of 1985. A preliminary report (SSC-SR-1009) was produced by an ad hoc version of the Task Force for the May 25, 1985, HEPAP meeting at SLAC. It was realized during the hurried preparation of this preliminary document that the subject of detector R&D for the SSC required an in-depth review of current R&D throughout the world and additional assessment of R&D needs for the SSC. The membership of the full Task Force was chosen to provide the ability for such a review and critical assessment.

The Task Force members were

Alan Astbury	TRIUMF
Brad Cox	Fermilab
Friedrich Dydak	CERN
Murdock Gilchriese	Cornell(Chairman)
Howard Gordon	Brookhaven
Donald Groom	CDG
Don Hartill	Cornell University
John Jaros	SLAC
Takahiko Kondo	KEK
Paul Kunz	SLAC
Stewart Loken	LBL
Shigeki Mori	University of Tsukuba
Dave Nygren	LBL
Frank Paige	Brookhaven
Abe Seiden	University of California, Santa Cruz
Albrecht Wagner	Heidelberg
Stan Wojcicki	CDG

In addition we received advice and assistance from many consultants to the Task Force; a complete list is given in Appendix A. In some cases the consultants wrote parts of the initial draft of this report. The conclusions and recommendations presented here, however, are those of the Task Force members. The Task Force held meetings on three occasions: September 26-27, 1985; January 13-15, 1986; and April 3-4, 1986.

The Task Force was charged with surveying detector R&D of possible relevance to experiments at the SSC, and with making recommendations for future directions in detector R&D for the SSC. In order to accomplish this goal, working groups were formed with specific charges and membership as given below. Underlining indicates the chairman of the working group.

(1) Tracking Devices (Jaros, Kondo, Nygren, Seiden, Wagner)

Review current R&D in the areas of semiconductor devices, wire tracking chambers, glass/plastic fiber detectors, and related software. Review the status of radiation damage to tracking devices. Make recommendations, including priorities, for future directions for R&D for tracking detectors.

(2) Calorimetry (Astbury, Cox, Dydak, Gordon)

Review current R&D for calorimetry, emphasizing those aspects which are most relevant for the SSC. Investigate fast response calorimetry, new sampling media, compensation, and the viability of known techniques. Make recommendations, and assign priorities, for future directions in R&D for calorimetry.

(3) Electronics, Triggering, Data Acquisition and Computing (Hartill, Kunz, Loken)

Review R&D in these four areas, emphasizing those aspects which will be relevant for the SSC. Outline the likely scale for SSC detectors in these

areas. Make recommendations, assigning priorities, for future support and R&D in these areas.

(4) Particle Identification - Electrons, Muons, and Hadrons (Gilchriese, Groom, Mori)

Review the needs for particle identification at the SSC and indicate those areas in which R&D is required. Review, when necessary, current efforts in these areas.

(5) Large or High Field Superconducting Magnets (Mori)

Explore the feasibility of very large (≥ 2 times presently planned magnets) and of large, high field ($> 1.5T$) superconducting magnets. If possible, develop "scaling laws" to estimate costs for such magnets. Assess the need for R&D in the case of large, high field magnets.

(6) Monte Carlo Development (Paige)

Review the status of present Monte Carlo programs for high energy hadron-hadron collisions, emphasizing those aspects which are most relevant to detector design. Make recommendations, if necessary, for future support of Monte Carlo development.

A common goal among the working groups was to determine the limitations of the various techniques under study in the high luminosity, high energy environment at the SSC. The working groups were also asked to include among their recommendations suggestions, if any, for workshops or study groups. The inclusion of a working group on superconducting magnets was believed to be necessary because such magnets could be limiting factors in detector design for the SSC. Monte Carlo simulations are often used to optimize the design of detector elements or justify the choice of detector techniques. For this reason we included a working group to survey critically Monte Carlo programs for high energy pp collisions.

The primary motivation for the SSC is to discover new large mass particles and/or new forces at short distances. New particles can decay only into other new particles or into the quanta of the standard model. Hence the search for new particles at the SSC must rely on the detection of signatures which are already familiar:

- jets;
- charged leptons;
- missing energy;
- single photons;
- $W^\pm$ and Z^0 decaying into jets or leptons;
- jet flavor identification.

This list certainly does not include all possible interesting experiments at the SSC. The study of rare decays of B mesons might uncover new physics at a mass scale beyond that which can be probed directly. Measurements of the particles within jets and of the properties of low- p_T events may help to understand QCD, and will certainly be needed to test the models for signatures and backgrounds. But the list probably does contain all of the tools available for the discovery of new heavy states.

A great deal of work on these topics has already been done, and recently significant progress has been made on the detection of W bosons decaying into jets. If this progress continues, then the major remaining problem will be the identification of flavors for jets, especially heavy quark jets.

Jets

QCD jets are expected to be the dominant source of transverse energy and certainly of localized E_T . Measurement of them with a calorimeter is a straightforward extrapolation of existing experiments. Indeed, a central problem for SSC physics is to reject the QCD jets, since the rate for jets with $p_T > 1$ TeV is about 1 Hz.¹

Measuring the cross-section for jets provides a limit on new interactions among quarks and gluons, such as would be expected in composite models.² The accuracy is probably limited not by the detector resolution but by the uncertainty in reconstructing the momentum of a jet by clustering the observed hadrons. Possibly it is better to select only a special class of jets, such as very narrow ones, but then it is necessary to know the acceptance as a function of p_T . These are issues which deserve more study both for present and for future experiments.

At the high luminosity needed to reach the interesting mass scales at the SSC, pileup of multiple interactions to fake rare signatures is a potential problem. Careful studies have shown that for the present design parameters low- p_T interactions do not produce clustered transverse energy resembling jets.³ The pileup of several jet events is not a very serious problem since the cross-section falls like a power of p_T , so the convolution is dominated by the single scattering term. But since the jet cross-section is large, the pileup of jet events with other rare events to fake even rarer signatures must also be considered, and this has not yet been done.

Charged Leptons

Measurements of isolated $e^\pm$ and $\mu^\pm$ are also extrapolations of existing experiments, although the problems change at high energy (see the report of the Particle ID Working Group). The use of transition radiation for the separation of electrons and pions starts to fail in the 100-200 GeV range, and muons start to lose energy at a significant rate in matter by mechanisms other than ionization. Simply measuring the momentum of the muon may be difficult; with a rather conservative criterion the discovery limit⁽¹⁾ is 6.5 TeV for a heavy $W' \rightarrow \mu\nu$. Identifying and measuring $e^\pm$ and $\mu^\pm$ inside jets is more difficult, but is clearly important to understand the production of heavy

quarks and their contributions to missing energy and other signatures. A lepton near a jet, but still with rather high p_T relative to it, is the best known signature for a t quark. At an even more ambitious level, a veto on $e^\pm$ and $\mu^\pm$ in jets would significantly reduce the background for missing energy from neutrinos.

The decay $W^\pm \rightarrow \tau^\pm \nu$ has recently been observed at the $Spp\bar{S}$.⁴ At high energy the separation of a $\tau^\pm$ from a QCD jet clearly becomes much easier because the average jet multiplicity increases, but it is unclear if existing Monte Carlo programs can accurately estimate the remaining background.

Missing Energy

There will be missing energy and momentum in events containing particles decaying into neutrinos or into new non-interacting particles. In a colliding beam detector it is nearly impossible to measure the missing energy, since there are often beam jet particles with large fractions of the total energy and small transverse momenta, but it is possible to measure the missing transverse momentum p_T . A detailed study of such signatures and backgrounds has been done for supersymmetric models.⁵ In such models each ordinary particle has a partner with the same quantum numbers but differing by $\pm 1/2$ unit of spin. These partners can only be produced in pairs, and the lightest, here assumed to be the photino $\tilde{\gamma}$, is stable and generally noninteracting. Thus a typical process of interest is the production of pairs of gluinos $\tilde{g}$,

$$\begin{array}{ccccccc}
 g + g & \rightarrow & \tilde{g} & & + & & \tilde{g} \\
 & & \downarrow & & & & \downarrow \\
 & & q + \bar{q} + \tilde{\gamma} & & & & q + \bar{q} + \tilde{\gamma}
 \end{array} \tag{1}$$

The missing p_T is given by the vector sum of the $\tilde{\gamma}$ momenta and is typically of order the gluino mass $m_{\tilde{g}}$. The dominant background comes from neutrinos from heavy quark decays, especially from processes like⁵

$$\begin{array}{c}
 g + g \rightarrow \tilde{g} + \tilde{g} \\
 \downarrow \\
 b + \bar{b} \rightarrow \nu + X
 \end{array}
 \quad (2)$$

For the total missing p_T the background dominates, but since the $\tilde{g}$ is produced with $p_T \sim m_{\tilde{g}}$, the signal has large components of $p_{T,miss}$ out of the event plane, so the signal can be extracted from the background. If supersymmetric particles exist, then it should be possible to observe them at the SSC.

Isolated Photons

Single isolated photons provide a good test of perturbative QCD, since the order- α_s corrections to the processes

$$q + \bar{q} \rightarrow \gamma + g \quad \text{and} \quad g + q \rightarrow \gamma + q \quad (3)$$

are known⁶ and since measurement of a photon is much less ambiguous than measurement of a jet. Like all such tests, this one also provides a probe for new interactions. The reaction

$$q + \bar{q}' \rightarrow W^\pm + \gamma \quad (4)$$

tests⁷ the non-Abelian coupling of the $W^\pm$, particularly its magnetic moment α . The channels $\gamma\gamma$ and γZ^0 are likely decay modes for any new scalar or pseudoscalar particles with branching ratios of order 1%.

The dominant background to an isolated γ comes from a jet fragmenting into one or more π^0 and no charged particles. To suppress this background existing experiments either have used very fine segmentation to identify $\pi^0 \rightarrow \gamma\gamma$ or have relied on an analysis of the starting point of the electromagnetic shower to separate one from two photons on a statistical basis. At higher p_T the required segmentation becomes increasingly prohibitive, especially if a large solid angle is desired to observe $\gamma\gamma$. Since the charged multiplicity of a jet grows rapidly with p_T , the probability for a jet to give no charged

particles decreases, so it may be sufficient to observe an electromagnetic shower with no high- p_T charged tracks near it. But it appears difficult⁸ to make a precise measurement of α .

WW Pairs

In the standard model with $m_H > 2m_W$ the dominant decay of the Higgs boson is into W^+W^- and Z^0Z^0 pairs, with⁹

$$\Gamma(H \rightarrow W^+W^-) = \frac{G_F m_H^3}{8\pi\sqrt{2}} (1-x_W)^{1/2} (1-x_W + \frac{3}{2}x_W^2), \quad (5a)$$

$$x_W = 4m_W^2/m_H^2,$$

$$\Gamma(H \rightarrow Z^0Z^0) = \frac{G_F m_H^3}{16\pi\sqrt{2}} (1-x_Z)^{1/2} (1-x_Z + \frac{3}{2}x_Z^2), \quad (5b)$$

$$x_Z = 4m_Z^2/m_H^2.$$

These widths are proportional to m_H^3 because the longitudinal components of the $W^\pm$ and Z^0 arise from the Higgs mechanism and have couplings proportional to mass. As a result, a heavy Higgs is very wide,

$$\Gamma_H \approx 0.5 \text{ TeV} \left(\frac{m_H}{1 \text{ TeV}} \right)^3, \quad (6)$$

and the branching ratio for $H \rightarrow t\bar{t}$ is small for any t quark mass. Any mechanism of electroweak symmetry breaking must provide the longitudinal $W^\pm$ and Z^0 , so measurement of these channels is a high priority at the SSC.

The Z^0Z^0 channel with both Z^0 decaying into e^+e^- or $\mu^+\mu^-$ is straightforward to measure and has very little background, but the Higgs branching ratio into this mode is only 0.12%, giving for a 1 TeV Higgs only about 10 events per year. Chanowitz¹⁰ has suggested using the mode

$$H \rightarrow Z^0 + Z^0 \quad (7)$$

$$\begin{array}{ccc} & \downarrow & \downarrow \\ e^+e^-, \mu\mu^- & & \nu\bar{\nu} \end{array}$$

with a branching ratio of 0.72%, an improvement by a factor of six. Of course some information is lost by measuring only the Jacobian peak in $p_{T,Z}$, but a heavy Higgs is so wide that the mass peak is not a strong constraint. The dominant background other than the Z^0Z^0 continuum is probably the production of a Z^0 plus a jet which fragments into a hard neutrino: a calculation with ISAJET indicates that this is small.

Cahn¹¹ has pointed out that the WW fusion mechanism,¹² which dominates for high Higgs masses, produces extra jets with $p_T \sim m_W$ and hence gives a larger average p_T than the background processes. This effect has not been implemented in any of the Monte Carlo programs, but it should be possible to extend the backwards evolution formalism used for initial state QCD radiative corections to include it.

The W^+W^- mode with both $W^\pm$ decaying leptonically gives two missing neutrinos and so cannot be reconstructed. A single missing neutrino can be reconstructed with a zero-constraint fit, and the branching ratio for

$$H \rightarrow W^\pm + W^\mp \quad (8)$$

$$\begin{array}{ccc} & \downarrow & \downarrow \\ e^\pm \nu, \mu^\pm \nu & & \bar{q}q \end{array}$$

is 16.6%. Unfortunately there is a large background from the QCD production of a $W^\pm$ plus jets, including

$$g + g \rightarrow W^\pm + \bar{q} + q' \quad (9a)$$

$$g + g \rightarrow W^\pm + q' + g, \text{ etc} \quad (9b)$$

For $p_{T,W} \gg m_W$ these processes are approximately given by the branching approximation. The first analysis¹³ was done using ISAJET 4.10, which contained the branching approximation only for final state jets, for $p_{T,W} = 500$ GeV. It was found that a mass resolution of about 5% could be achieved with a very good calorimeter for $W^\pm \rightarrow qq'$, but this was not sufficient to eliminate the background. However, it was possible to reduce the approximate background to about the level of signal by making a complicated set of cuts based on the shape of the jet structure.

The full perturbative QCD calculation for the production of $W^\pm$ plus two jets has now been carried out by Ellis, Kleiss, and Stirling¹⁴ and by Gunion, Kunzst, and Soldate.¹⁵ From these calculations it is found that the backgrounds for the modes in Eq. (5) are large for all WW masses even after the jet-jet mass is required to be within 5% of m_W . (The 5% resolution was estimated without initial-state QCD radiation, but its effect seems to be small.) However, much of the background comes from events in which one jet is soft, whereas $W^\pm \rightarrow qq'$ tends to give more equal jets. A set of cuts at the parton level have been found¹⁶ which use this fact to reduce the background to roughly the signal level with reasonable efficiency. For an integrated luminosity of 10^{40} cm^{-2} the number of events surviving all cuts is as follows:

<u>$m_H(\text{GeV})$</u>	<u>Higgs Signal</u>	<u>Background</u>
300	1400	1800
800	340	560

While still preliminary, these results are very encouraging, especially since the side bands in the jet-jet mass can be used to measure the background.

Since the branching approximation agrees quite well with the exact three-jet cross section and contains all of the graphs for $W^\pm$ plus two jets, there is reason to hope that it will approximately reproduce the exact cross-sections for $W^\pm$ plus two jets. If so, then the existing Monte Carlo programs can be used to study the effects of higher order QCD corrections and of hadronization on these results. This needs to be done, but the situation appears promising.

Jet Identification

Many sorts of new particles will either decay equally into all quark flavors or decay preferentially into the heaviest flavor. The background of QCD jets is dominantly gluons and light quarks; the spin and color factors give for $s \gg m_q^2$ and $\hat{t} = \hat{u} = -1/2 \hat{s}$

$$\frac{d\sigma}{dt}(gg \rightarrow \bar{q}q) = \frac{7}{1458} \frac{d\sigma}{dt}(gg \rightarrow gg). \quad (10)$$

Thus identifying the flavors of jets and especially of heavy quark jets is potentially a powerful tool.

Two possible methods of identifying t quarks have been investigated. The first is to use the semileptonic decays, demanding an isolated energetic $e^\pm$ or $\mu^\pm$ close to a jet. For $m_t = 40$ GeV the following rejections and efficiencies can be obtained:¹⁷

$p_{T,t}(\text{GeV})$	Rejection	Efficiency
100	180	0.19
300	44	0.12
500	31	0.10

This method works fairly well for moderate p_T but fails for $p_T \gg m_t$ because the lepton is too close to the jet.

The second possibility is to detect the presence of a short-lived b particle from the t decay. Even if this can be done technically it does not provide much identification, because unfortunately the multiplicity of b particles in gluon jets is of order one and the z distributions are not very distinctive.¹⁸ This is not to say that vertex detectors are useless, but a successful algorithm for using them to identify t jets has not yet been found.

To observe these or any other signatures for new physics, experiments at the SSC will require extensions of detection techniques to higher energies, greater particle fluxes and higher rates than present or near future experiments at the CERN $\bar{p}p$ collider, the FNAL $\bar{p}p$ collider or e^+e^- machines. The required energy range for particle detection and/or identification may be crudely identified by using Fig. 2.1, a plot of momentum vs transverse momentum (p_T) for different values of rapidity. Production of massive new states in the central rapidity range can yield particles with momenta in the few TeV region. The study of relatively low p_T processes, 1-10 GeV, in the large rapidity region, $y \geq 4$ say, yields particles with momenta from ~ 30 GeV to upwards of 10 TeV. In short, the study of relatively low mass physics may also require detection of particles in the TeV range.

Charge and neutral particle fluxes at the SSC will be much higher than at present machines as a result of the higher center-of-mass energy and the greater luminosity. Although there are uncertainties in the inelastic cross section and charged particle multiplicity expected at 40 TeV, reasonable values are $\sigma_{inel} \approx 100\text{mb}$ and $d\langle n_{charged} \rangle/dy = 6$. This yields very large fluxes of charged and neutral particles. To operate in such a high flux environment, particle detectors near the beam axis must be fast, radiation resistant, and have high granularity. For $\sigma_{inel} = 100\text{mb}$ and a time between crossings of 15ns, the average event rate is 1.5 per crossing at the design

luminosity and the total event rate is 10^8 Hz. Detectors with good time resolution will be essential for operation at these rates.

The need to measure jet energies or particle momenta in the TeV range will require detectors of larger size than at present. Increased granularity in response to large particle fluxes will yield detectors with more elements and hence more associated electronics. A reduction in the cost of electronics at the same or better performance level than at present is highly desirable and may be required for some detectors to keep cost within reasonable bounds. The computing demands for SSC detectors will also be very large.

To summarize, detector improvements at the SSC will be required in the general areas of:

- measurement and identification of jets and single particles in the multi-TeV region;
- radiation resistance;
- granularity;
- speed of response;
- cost per performance of electronics;
- computing capacity and capability.

In the sections that follow these requirements and others are discussed in detail for various detector elements.

Fig. 2.1. Momentum vs. p_T for different rapidities

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CHAPTER 3

Report of the Working Group on Tracking Devices

3.1 Introduction

Although the role of calorimetric detectors may become pre-eminent in the search for the new physics of the TeV domain, tracking devices will be indispensable both for revealing the detailed structure of these events, and for reconstructing crucial kinematic parameters. However, the desired performance characteristics of tracking devices for the SSC exceed in some important respects what can now be gracefully achieved. The most challenging aspects are direct consequences of the SSC luminosity and energy:

- interaction rates of 10^8 Hz;
- high multiplicity interactions;
- wide range of rapidity coverage;
- high particle density within jets;
- high transverse and longitudinal momenta;
- high complexity in event topology.

In addition to these general concerns, tracking devices will be required to provide more specific information such as:

- primary vertex location;
- correlation of tracks with calorimetric detectors;
- topological definition of jet directions and jet structures;
- high resolution momentum measurements of all interesting tracks up to highest possible momenta;
- sign determination at all energies;
- particle identification for electrons in association with EM calorimeters;
- separation of photon conversions from single electrons;

- particle identification of muons by tracking correlations with absorbers;
- calibration of hadron and EM calorimeters by isolated tracks;
- secondary trigger information;
- reconstruction of secondary vertices;
- rejection of multiple event pile-up;
- accurate association of all track information with the event time origin;
- clean separation of charged and neutral event components.

The diverse physics program accessible at SSC energies will require methods to reject the hadronic jets copiously generated by ordinary QCD processes. The separation of quark and gluon jets and the identification of t quarks will be very important. The search for the Higgs boson or new heavy quarks and leptons may require detection of the hadronic decays of the standard electro-weak intermediate bosons. The possible appearance of technicolor, supersymmetry, or manifestations of compositeness will most likely require a large detailed data sample to allow distinctions to emerge. In each of these cases, a high level of tracking power is important.

Determination of the sign of charged particles near the interesting kinematic limit (≈ 5 TeV) in the central rapidity region presents a difficult challenge. In order to keep tracking devices to a reasonable size and magnetic field strengths within reasonable bounds, large, high precision (including systematic uncertainties) tracking devices will be required. Large wire chamber systems of 2-3 times better resolution than at present will be needed; an alternative is the use on a large scale of very precise devices such as silicon strips or scintillating fibers.

In order to understand better some of the rate and particle density questions, a study was performed using ISAJET and minimum-bias Monte Carlos. The conclusions confirm the presently marginal match of today's tracking techniques to physics. The Working Group on tracking devices considered the current status of familiar drift chamber techniques, their likely potential for further development, and two emergent technologies that have received considerable recent attention, silicon strip detectors and scintillating fibers. In addition some thought was given to software and the importance of optimization of hardware-software systems.

The group was impressed with the steady progress achieved to date and with evolving ideas in the broad domain of wire chamber technologies. The current level of performance, however, still generally falls far short of extracting the intrinsic information content of a track image in gas. In fact, modern drift chamber designs emphasizing two-track resolution systematically reject most of the drifting electrons. If the track information can somehow be efficiently utilized, resolutions smaller than 10 microns appear possible. In addition to encouraging general wire chamber R&D, specific developments such as the induction chamber, modular multicell drift chamber, and the high rate CF_4 -based chambers are seen as particularly promising. Other areas singled out for improvement are radiation hardness, the enduring problem of z resolution, and on-line data compression. The development of cheap, fast, low-power, radiation resistant on-chamber electronics is imperative.

Although a number of problems or uncertainties exist in the application of parallel-plate avalanche counters for detection of minimum ionizing particles, their natural characteristics of high rate capability, fast signals, and flexible geometry attracted the group's attention. It was a general consensus that these devices merit a sustained systematic investigation to understand

their behavior in detail and to cure the diseases of instability and field/rate-induced sparking.

Scintillating fibers of both glass and plastic composition have been made recently with interesting characteristics. Apparently radiation-hard to the Mrad level, these fibers could, in principle, serve as a central tracker, as well as a vertex detector. However, the group concluded that the present short attenuation lengths and long fluorescence decay times observed with glass fibers, and difficulties in fabrication of small-diameter plastic fibers, are serious problems. Common to both materials are questions of event information buffering (for triggering) and fast readout. Increases in scintillation efficiency, if possible, would offer valuable headroom in the design of a complete system. An active program of development is under way to address these problems and should be encouraged as a possible solution to the challenges of the SSC.

Silicon devices offer the prospect of unmatched spatial and track-pair resolution combined with fast response. Microstrip detectors, drift structures, and CCDs have all been shown to offer resolutions of a few microns. Priorities include the development of low-noise, low-power, radiation-hard signal processing ICs for microstrip and drift device readout, improved processing technology for radiation-hardness, increased yield, and stereo readout.

CCDs do not seem to have an obvious role at the SSC because of the extremely long readout times needed to scan all pixels. New architectures will be needed which in effect self-address those pixels hit by particles. This concept has at present no concrete proposal, but efforts to develop such attractive new devices are encouraged and may have widespread application beyond (and before) the SSC.

In the area of tracking software, several broad recommendations are given with the aim of sharpening the requirements for trackers, and optimizing the

tracking design including software as part of the system a priori. An isolated hardware configuration may or may not lend itself to efficient data compression or track reconstruction. As the costs of software development and data processing are large, a systems approach is recommended. Because of the enormous flow of raw data from trackers, highest priority is given to the study of the problems of data compression to track vectors.

In summary, the group sees a broad range of important developments needed for efficient exploitation of the SSC. What has been omitted, of course, is the description of completely new and unforeseen ideas which may transform our perspective on the enduring challenge of reconstructing particle trajectories.

3.2 The Use of Wire Chambers for Tracking at the SSC

3.2.1 Introduction

All major tracking detectors used over the last decade in colliding beam experiments have been wire chambers, ranging from small size, high resolution vertex chambers to the very large main tracking chambers of the multicell, the jet chamber, or the TPC design. Most chambers have proven during many years of operation to be very reliable, and are considered an established technique.

Space resolutions down to $100\mu\text{m}$ in the large chambers and $50\mu\text{m}$ in vertex chambers have been reached in the coordinate relevant for momentum measurement, resulting in a momentum resolution of $\sigma_p/p = 1 \times 10^{-3} p$ (p in GeV/c^2). Using high resolution vertex chambers, the impact parameter of tracks at the vertex can be measured with an accuracy of $25\mu\text{m}$. The availability of high speed flash ADCs has made it possible to reach a two track resolution of 2mm in large chambers, and a two track resolution of $500\mu\text{m}$ has been obtained in vertex chambers with sample restricting or focusing electrodes. Multiple sampling of energy loss has been used to help in particle identification. Several techniques are applied to measure the track coordinate in the beam direction (z). The two most commonly used are a small angle stereo arrangement of different wire layers, yielding a resolution of a few millimeters, and charge division, where the absolute resolution depends on the wire length. Here, values of $\sigma_L/L = 1\%$ have been obtained. An exceptionally good z resolution of $200\mu\text{m}$ is reached in a TPC by measuring the drift time required for ionization to reach the end plate.

Therefore two questions must be asked: 1) is this performance adequate for SSC needs? 2) under what conditions can wire chambers operate in a high repetition rate and high luminosity environment? The first question, to

what extent drift chambers with their present resolution can meet the requirements as defined by physics, such as vertex identification, momentum and charge measurement etc., is not addressed in this section. However, by reviewing current R&D, an attempt is made to point out those areas where more R&D might help to make them one possible option for tracking at the SSC. The review is therefore restricted to types of chambers which could possibly work at a bunch crossing rate of 15ns, eliminating from the discussion all big chambers as used today.

3.2.2 Current research and development

3.2.2.1 Basic research related to wire chambers

Stimulated by the construction of many large tracking facilities in recent years, substantial research has been invested into the understanding of the basic properties of wire chambers. This has led to a better understanding of the underlying mechanisms as well as to the development of a number of tools which will be of great use for the design and the optimization of future gaseous detectors. In this chapter a few of those developments are briefly described.

3.2.2.1.1 Drift properties of electrons in gases under the influence of a homogeneous electric field

The drift properties of electrons in gases under the influence of a homogeneous electric field are characterized by three transport coefficients; the drift velocity, and the longitudinal and the transverse diffusion. Through the measurement of two of these transport coefficients (drift velocity and longitudinal diffusion) as functions of the electric field for methane and methane-noble gas mixtures it has become possible to derive the microscopic parameters (momentum transfer cross section, inelasticity, and vibrational

excitation) of these gases which are relevant for the solution of the Boltzmann transport equation.¹ It is now possible to calculate the drift properties of all methane-noble gas mixtures with good accuracy. In Fig. 3.2.1 the measurements and absolute predictions of the drift velocity for several mixtures of noble gases and CH_4 are shown. To achieve this also for other molecular gases their cross sections and inelastic properties have to be determined in the same manner. This is not a problem in principle, but has to be done very carefully, since in this case collisions with thermally excited vibrational levels must be taken into account. Work in this direction is in progress, as well as similar studies in the presence of a magnetic field.

Applying this technique one can look for gases which are optimized for use at the SSC in terms of their drift velocity, diffusion, and Lorentz angle.

3.2.2.1.2 Use of gases with high drift velocity

Because of a time between bunch crossings of 15ns, and in order to reduce the probability for multiple occupancy of a single drift cell, gases with a high drift velocity are of great interest for wire chamber operation at the SSC. Very fast multiwire proportional chambers of low mass for very high counting rates were developed by J. Fischer et al.² The group obtained anode signals of an effective duration of 8ns after pulse shaping, and a time jitter of only 4ns FWHM. This performance was achieved with a gas mixture of CF_4 and a hydrocarbon at atmospheric pressure in a MWPC with a small interelectrode distance ($< 1\text{mm}$). The gas mixture of CF_4 with about 10% of a hydrocarbon as quencher has a high primary specific ionization density and a saturated drift velocity of $> 100\mu\text{m/ns}$.³ Measurements of the longitudinal diffusion¹ in CF_4 show that up to very high values of the reduced electric field the diffusion is close to the thermal limit. The high ionization, combined with fast low noise signal processing, provides full efficiency at gas gains of a

few times 10^4 . Under these conditions, the chambers can operate at rates of 10^6 s^{-1} per centimeter of anode wire.

3.2.2.1.3 Signal propagation in multiwire chambers

The signal propagation of current signals in a multiwire proportional chamber has been studied theoretically by solving the multiwire telegraph equations.⁴ Electromagnetic coupling between all wires and an infinite number of signal reflections at the wire ends have been taken into account through a complex termination resistor matrix.

As result the pulse shapes and the charge division on the sense wires can be calculated, as well as the amplitudes and shapes of all cross talk signals. A series of test measurements has been performed which show that the measured pulse shapes agree well with the theoretical predictions. This technique has successfully been applied to determine the optimal electric termination of large drift chambers, including a cross talk compensation circuit. The proper electrical termination, obtained by this technique, is of great importance in chambers exposed to very high rates, as in the case of the SSC.

3.2.2.1.4 Radiation damage to wire chambers

In a workshop on radiation damage to wire chambers⁵ recently held at the Lawrence Berkeley Laboratory, a consistent qualitative pattern began to emerge concerning the rate tolerance of wire chambers. However, a quantitative picture of the limiting process of gas polymerization cannot yet be given, since the underlying processes depend on too many variables, of which only a few are known. J. Va'vra in his summary talk⁶ has tried to extract a consistent picture from the many results presented at the workshop, and has reviewed the parameters one can control and which are of influence for the chamber life time, as well as the presently known rate limits.

Various test measurements on two widely used gases, A-C₂H₆ (50:50) and A-CO₂-CH₄ (89:10:1), have shown that after a collected charge of 1C/cm a

gain drop of less than 10% occurs. This performance can be reached either by using very pure gas (99.999%) or by adding a small quantity of alcohol (e.g., 1.5% ethanol) to the gas. One should note however that all these tests have been made in an environment which does not correspond to the typical situation in big chambers, the difference being the amount of organic material in the chamber, the gas flow, etc. No gain decrease has been seen so far in the big chambers used at storage rings, but the total collected charge even in the worst case has not exceeded 0.3C/cm.

From these results one can conclude that for the most common drift chamber gases a collected charge of 1C/cm would yield a gain drop of less than 10%. Gas mixtures containing large amounts of CF_4 exhibit an even higher resistance to radiation damage.⁵ Further systematic studies on aging will certainly help to improve these numbers.

The consequence of these results for the operation of wire chambers at the SSC can be obtained by calculating the secondary particle flux in pp collisions.⁷ At a luminosity of $10^{33} \text{ cm}^{-2} \text{ s}^{-1}$ with 6 particles per rapidity interval, the total collected charge per wire, cm and year at a gas gain of 2×10^{-4} , as function of the radial distance from the beam, is

<u>Radial distance from the beam</u>	<u>Q [C/cm*year]</u>
20cm	1.6
30cm	0.7
50cm	0.3

The numbers are calculated for a cell size of 2cm width and 1cm height. As a result, tracking with wire chambers from the point of view of radiation damage seems feasible even at highest luminosity at radii $> 30\text{cm}$. A further increase in lifetime can be obtained by a reduction in gas gain; however, the measurement resolution of the z coordinate by charge division would deteriorate

as gain is reduced. As noted in Section 3.3, there are limitations to chamber operation other than radiation damage.

3.2.2.2 High rate / high precision chambers

3.2.2.2.1 Straw tube chambers

Thin walled proportional tubes, stacked in large counter arrays, have been successfully used as vertex chambers in high rate environments close to the interaction region of colliders.⁸ Such chambers have become known as straw tube chambers. They are constructed of 5 to 10 mm diameter tubes of aluminized mylar with a wall thickness of $< 0.1\text{mm}$, and with one sense wire in the center. The chambers are simple to build and very reliable, since the failure of one tube does not affect the overall performance. In addition, measurements⁹ have shown that, due to their flat cathode structure, these tubes are particularly radiation resistant: at an integrated dose of 4C/cm in dimethylether no deterioration of amplification has been observed. The space resolution obtained in tests in these chambers has been better than $50\mu\text{m}$, depending on the gas and operating conditions.

With high rate capability, a straw tube array is a candidate for a tracking chamber at the SSC, especially when operated with a fast gas. This might however lead to a decrease in resolution. Furthermore one must investigate if a double track resolution of a few millimeters can be reached with tubes and if, by an appropriate arrangement of subsequent chamber layers, in-time tracks can be separated from those coming from an earlier or later interaction. The maximum tube length built so far is below 50cm. For applications other than a vertex detector one must therefore investigate if longer tubes can be made or if a longitudinal subdivision must be used.

3.2.2.2.2 Chambers with sample restricting geometry

Recently several groups have worked on chambers with a sample restricting or focusing geometry.¹⁰ Here, the detector volume is subdivided into a drift

and an amplification region, allowing for a controlled charge collection. Only those electrons drifting through a narrow window can reach the sense wire, which reduces considerably the spread in arrival time. The restricting geometry is in most applications defined by one additional wire plane on each side of the sense wire plane.

All groups have operated these chambers at a very slow, unsaturated drift velocity, using chiefly CO_2 as the main counting gas, and have reached a space resolution of better than $50\mu\text{m}$ and a two track resolution of about $500\mu\text{m}$. Application at the SSC excludes the use of a slow gas, but the sample restricting geometry should, even in combination with a fast gas, provide a two-track resolution of better than 1mm and a good space resolution.

3.2.2.2.3 The modular multicell drift chamber

Following a similar approach to enhance the rate capability of wire chambers, R. Bouclier et al.¹¹ have recently built and tested a modular drift vertex detector. It consists of an 80cm long multiwire drift tube with 128 independent anodes, each centered inside a hexagonal drift cell of 1mm radius, defined by six cathode wires, and mounted within a light hexagonal carbon fibre tube of 3cm diameter. By recording the drift times to the anodes, accuracies better than $100\mu\text{m}$ per wire and a two-track resolution of about $500\mu\text{m}$ have been measured. A picture of a two-track event is shown in Fig. 3.2.2. The longitudinal coordinate can be obtained through charge division. Several modules of this type can be assembled together to build a compact, fast track detector. The readout of such a dense sense wire structure requires highly integrated electronics consisting of amplifiers and charge storage, similar to the electronics presently being developed for microstrip detectors.

3.2.2.2.4 The induction chamber

The induction drift chamber as proposed by Walenta et al.¹² is designed to resolve high counting rates and to obtain good spatial resolution. The

optimization for high counting rates is achieved through a narrow spacing of anode and potential wires (300 μ m). The high spatial resolution is obtained by recording in addition to the anode signal also the difference of the signals induced on the two neighboring potential wires. In Fig. 3.2.3 the schematic design of the chamber is shown together with the readout principle. First test measurements with a chamber of this type have recently been performed yielding a position resolution of 25 μ m. It was found that with the gas mixture used (A-C₄H₁₀, 80:20), the limit on the resolution was given by the signal to noise ratio of the induced pulses. Further investigation showed that the resolution can be further improved to 10 μ m by using different gases.

An intrinsic advantage of such a chamber with a small interwire and cathode distance is a considerably increased rate capability. Walenta estimates that for the chamber shown in Fig. 3.2.3 the gas amplification begins to collapse at a rate of 10⁷s⁻¹ per centimeter of anode wire.

3.2.2.3 New Developments.

In recent years developments in the field of wire chambers have mainly been devoted to the understanding and improvement of existing techniques. Very few completely new schemes have been proposed. Here, two ideas are mentioned which could be of potential use at SSC.

Parallel plate counters can be considered interesting alternatives to wire chambers for two reasons: they have a very fast time characteristic and a high rate capability. Because of the uniform velocity of ions in a constant electric field, their contribution to the detected signal can be removed easily by electronic differentiation. The remaining electron component is only a few nanoseconds wide, ideally suited for a high repetition rate machine. The high rate capability is due to the fact that the feedback of positive ions into the drift region is strongly reduced because of the configuration of the electric fields. It has been pointed out by Sauli¹³ that for these reasons parallel

plate detectors look interesting for applications in high rate particle detectors.

One major known drawback of such chambers is breakdown due to sparking, which prohibits stable operation. In recent work by the same group¹⁴ the parallel plate detector was studied in a magnetic field. It was found that the sparking in these chambers depends on the ionization density. The sparking probability increases with the gain, the magnetic field, and with the density of primary ionization. Such an ionization density dependent sparking leads to a bias in detectable physics. It is therefore not at all clear if multistep parallel plate chambers can be considered possible candidates for an SSC tracking device, even more so since no realistic conceptual design has been presented so far. If the sparking process can be suppressed their further development would be appropriate.

Several groups¹⁵ have proposed to build a tracking detector based on the observation of gas scintillation. When electrons from some primary ionization drift towards a region of high electric field they can excite the gas atoms, producing a very high light output with or without gas multiplication. The main advantage of a chamber without gas amplification lies in the resulting absence of space charge effects. Considerable R&D work is required on the readout of the scintillation light, one idea being to collect the light with a hodoscope of plastic rods doped with wavelength shifter.

3.2.2.4 Electronics and on-line data processing

3.2.2.4.1 Electronics

There has been a rapid development of readout electronics for drift chambers, ranging from work on low noise amplifiers,¹⁶ to high speed wave form digitization¹⁷ and large scale integration of on-chamber electronics, the last being mainly performed in connection with the readout of silicon strip detectors.¹⁸

In view of the high repetition rate of the SSC the FADC readout of the chamber signals or a multihit TDC coupled to a shift register seem to be possible options. However, in order to achieve a reasonable resolution for very short pulses ($< 10\text{ns}$), the sampling rate should possibly be increased to $> 200\text{MHz}$. The development of GHz waveform sampling using GaAs ADCs and memories is of great interest in this respect.¹⁹ The readout system would work in a common stop mode and the digitized data would be written into a cyclic memory, allowing a large flexibility in timing for the trigger, yet still retaining the time structure of the event. As an alternative to the storage of digital data, the signal charge can be stored in an analog way, for example in the Analog Memory Unit²⁰ or in CCDs.²¹ It is not clear at present which of these techniques is better suited for SSC applications.

3.2.2.4.2 On-line data processing

In order to keep the amount of information per event as low as possible, an on-line compression of the raw data delivered by the track detector should be performed. This technique has recently been explored in connection with the FADC readout of drift chambers:²² chamber pulses are digitized in 3000 channels of FADCs, the data are stored in fast memories, and the valid data are found in hardware by scanners and read out under the control of 32 microprocessors. Subsequently these processors perform an online analysis of the digitized pulse shapes, and convert the information into a time and a charge measurement, thereby providing per hit the space coordinate and ionization loss (r, θ, z, Q). In order to keep the dead time as low as possible all processors operate in parallel in the analysis.

At the SSC it seems advisable to go considerably further. The next two steps in data reduction could be first, an on-line pattern reconstruction with the aim of generating one four-vector per track and second, an elimination of

all tracks with transverse momenta below a given cutoff, e.g., $p_T < 1...10$ GeV/c, depending on the physics.

3.2.3 Recommendations for R&D

As wire chambers have been used for many years, their behavior and limitations are quite well understood. Nevertheless, their use at the SSC requires considerable R&D work. The order in the following list of recommendations represents our estimate of the relative priorities.

1) The recent ideas for chambers with high rate capabilities, resolutions below $100\mu\text{m}$ and a two track resolution of $500\mu\text{m}$, such as indicated above, have to be studied in detail and certainly need further development.

2) A central wire chamber at the SSC will have a large number of sense wires because of the very small cell size. This requires the development of cheap, compact, low power, radiation resistant electronics which could include digitization at the chamber. This is especially true for a chamber type like the modular multicell drift chamber.

3) A quantitative understanding of radiation damage to wire chambers has to be worked out which could lead to a development of possible cures allowing an increase in the limit for tolerable radiation.

4) Serious efforts should go into online data compression in a multi-processor front end system. This is true for any type of tracking detector. The processing strategy is likely to affect strongly the chamber design.

5) The basic research on drift chambers should be continued and encouraged. The progress achieved in the past has been steady and substantial.

3.2.4. Application of wire chambers at the SSC

It is clear that the performance of wire chambers in terms of space, momentum, and two-track resolution is inferior to that of solid state detectors. The assets of wire chambers however are also clear: the long term stability is well proven, they are fairly easy to construct even in large sizes, and the detector itself is cheap.

From the rate estimates given above, and from knowledge about radiation damage, one extrapolates that "standard" wire chambers can survive at a radial distance from the beam of $> 30\text{cm}$. The cell total width should not exceed 1cm in order to keep the radiation exposure small. The wire arrangement must allow separation of in-time from out-of-time tracks.²³ A realistic estimate of the achievable resolution is $100\mu\text{m}$ with a two-track resolution of 2mm . The development of new ideas should be aimed at a resolution of $20\mu\text{m}$, a two track resolution of $500\mu\text{m}$, and at an increased radiation tolerance.

The question of the z resolution in wire chambers at the SSC has barely been discussed in this report. The reason is that the two techniques presently used in wire chambers might no longer be adequate. Charge division (which provides, together with the drift time measurement, genuine space points) requires a good signal to noise ratio and therefore a large gas amplification, which is undesirable from the point of view of chamber lifetime. The small angle stereo technique allows one to measure only projections. This technique might therefore become inefficient for local track densities as they occur inside collider jets. Because of the importance of a good z resolution for identification of events with multiple vertices for example, the issue of the z measurement requires a considerably more detailed study of the hardware and software aspects.

Wire chambers certainly remain one possible way to build a tracking chamber for the SSC which would fulfill a large number of the requirements asked of a

tracker. It should be noted however that all considerations mentioned here were mainly concerned with tracking in the central region ($\eta < 2$), an admittedly small part of the entire rapidity range of interest. In the region of larger rapidity, wire chambers can only be considered as a possible technique for tracking when located at sufficient distances from the interaction region to avoid radiation damage.

Fig. 3.2.1 The measured and calculated drift velocity as function of the electric field for several mixtures of CH₄ and noble gases. The points represent the measurements, the curves are absolute predictions.

Fig. 3.2.2 A picture of a two track event as seen in the multicell drift chamber. The dots indicate the position of the sense wires, the circles the measured drift times.

Fig. 3.2.3 The schematic design of the induction chamber. The lower curve shows the functional dependence of the ratio of the induced signals (Δp), divided by the anode signal, on the track position x .

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3.3 Secondary Charged Particle Fluxes

3.3.1 Introduction

It is well known that at the SSC, the interaction rate is as high as 10^8 Hz for the expected luminosity of $10^{33} \text{ cm}^{-2} \text{ sec}^{-1}$. Tracking devices such as drift chambers will potentially encounter rate problems in this environment. A rough estimate of the charged particle rate is made analytically as well as with a Monte Carlo in order to estimate the effects on tracking detectors.

3.3.2 Secondary Particle Fluxes

The secondary charged particle rate for so-called minimum bias pp interactions is given by

$$\frac{dn^{ch}}{dy} = 6 \frac{\text{particles}}{\text{rapidity}}, \quad (1)$$

where y is the (pseudo)-rapidity

$$y = -\ln \left(\tan \frac{\theta}{2} \right). \quad (2)$$

Eq. (1) can be transformed to

$$\frac{dn^{ch}}{d\Omega} = \frac{1}{2\pi \sin^2 \theta} \frac{dn}{dy} \approx \frac{0.95}{\sin^2 \theta} \quad (3)$$

If the detector element is located at radius r and polar angle θ , then

$$r_{\perp} = r \sin \theta \quad (4)$$

$$d\Omega = \frac{dS}{r^2}$$

and therefore,

$$\frac{dn^{ch}}{dS} \sim \frac{1}{r_{\perp}^2} \frac{dn^{ch}}{dy} \sim \frac{1}{r_{\perp}^2} \frac{0.95}{\sin^2 \theta} = \frac{0.95}{r_{\perp}^2} \quad (5)$$

per interaction. It is noted that the particle flux per unit area is a function only of the distance from the beam pipe and does not depend on the angle θ . If 10^8 interactions occur per second,

$$\frac{dn^{ch}}{dr_{\perp}} \approx \frac{1 \times 10^8}{r_{\perp}^2} \frac{\text{particles}}{\text{cm}^2 \text{sec}}, \quad (6)$$

where $r_{\perp}$ is in cm. Figure 3.3.1 shows the charged particle rate/cm² as a function of distance from the beam pipe. Assuming that one year of operation corresponds to 150 days $\approx 10^7$ seconds, we can estimate the total number of secondary particles/year/cm² as indicated in the right-hand column of Fig. 3.3.1. In the same figure, total doses are indicated using the relation 1 rad $\approx 3 \times 10^7$ particles/cm².

3.3.3 Monte Carlo Simulations

A Monte Carlo study has been performed to estimate charged particle fluxes at 90°, as well as at the extreme forward region, in high energy pp interactions at $\sqrt{s} = 40$ TeV, with a luminosity of $10^{33} \text{ cm}^{-2} \text{ s}^{-1}$.

jets:

ISAJET Version 4.11

two jet (gg, gq, qq mixture)

EHLQ structure functions

minimum bias events:	Minimum Bias Rockefeller Generator
	hardcore 38.4%
	single diffractive 38.4%
	double diffractive 23.3%

Both programs were provided by the Fermilab CDF Group. In the present Monte Carlo simulation, no magnetic field is considered.

3.3.3.1 Rates from minimum bias events

Figure 3.3.2 shows momentum spectra of charged secondary particles for various angle intervals generated from minimum bias events. These distributions are consistent with a flat rapidity distribution.

In Fig. 3.3.3 we assume 10^8 interactions/sec, corresponding to $L = 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$. The rate obtained in the present simulation confirms previous analytic calculations.¹ Except for the extreme forward region, the rates yield a universal curve. This is expected from a flat rapidity distribution.

3.3.3.2 Charged particle density of QCD jets

The jet axis is assumed to be in the direction of original quarks or gluons. One of the two QCD jets is forced to be at $\theta=90^\circ$ in order to minimize effects of charged particles from beam jets. A detector element is assumed to be located 100 cm from the interaction point. Figure 3.3.4 shows the average charged particle density (particles/cm²) at this detector surface. As one goes away from the quark jet axis, the particle density decreases as expected. Figure 3.3.5 is the same kind of plot, but expressed in terms of mean separation of charged particles. It should be noted, however, that these figures represent only averaged quantities over many generated jets.

The event-by-event fluctuations of high- p_T QCD jets are seen in Figs. 3.3.6-8. In these figures, the cross section views of jets at $r = 1m$ are shown at the top, while the projected views of the jet around $r = 1m$ are shown at the bottom. Strongly correlated clusters of charged particles are clearly present, although these clusters do not necessarily follow the original quark direction.

3.3.4 Effects on drift Chambers

Suppose we use an ordinary drift chamber with wires running parallel to the beam pipe. The wire is assumed to be long enough to cover the solid angle from $\theta=30^\circ$ to 150° as indicated in Fig. 3.3.9. The cell size perpendicular to the sense wire is assumed to be d cm high and $2d$ cm wide, where d is the drift distance.

Then, with simple integration, we can calculate

- (1) hit/wire/sec (hit/sec),
- (2) hit/wire/maximum drift time (hit within drift time),
- (3) hit/mm/sec (local hit rate for space charge limit),
- (4) current drawn by a wire,
- (5) total electrons/mm/year,

as shown in Figs. 3.3.10-14. In the calculations, we have assumed that the wire gain is 2×10^4 , the drift speed is $5 \text{ cm}/\mu\text{sec}$, and the ionization rate in the gas is 100 electrons/cm .

Table 3.3.1 summarizes these rates for three typical cases ($r_0 = 10, 50$ and 100 cm) in order to compare with the approximate limits of ordinary drift chambers. These limits are estimated from current operating drift chambers.

It is apparent from the Table that radiation damage itself is not the main limiting factor in the application of wire chambers. The dominant problem stems from the very high hit rate per wire, which can probably be handled by

the electronics but which poses severe problems for the weeding out of all out-of-time hits. Reduction of the hit rate could be accomplished by smaller cell size, shorter wire length, or faster gases. On the other hand, current limitations and/or space charge limitations could be improved by reducing the wire gain, which in turn requires low noise, high gain, but still high speed, amplifiers.

Table 3.3.1
Drift Chamber Limitations at $L = 10^{33} \text{cm}^{-2} \text{s}^{-1}$

Item	Limit	$r = 10\text{cm}$ $d = 0.1\text{cm}$ $L = 35\text{cm}$	$r = 50\text{cm}$ $d = 0.5\text{cm}$ $L = 175\text{cm}$	$r = 100\text{cm}$ $d = 1.0\text{cm}$ $L = 350\text{cm}$
1 hit rate/wire	2-20 MHz	5MHz	5MHz	5MHz
2 occupancy in maximum drift time	uncertain	0.08	0.45	0.9
3 occupancy in beam crossing time (15ns)	~0.05	0.08	0.08	0.08
4 current drawn per wire	1 μ A	0.16 μ A	0.8 μ A	1.6 μ A
5 accumulated number of e^- C/cm/yr	1.0	0.046	0.046	0.046

Fig. 3.3.1 Charged particle rate at $L = 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$.

Fig. 3.3.2 Momentum spectra of charged particles for minimum bias events at $\sqrt{s} = 40$ TeV.

Fig. 3.3.3 Charged particle flux vs. distance from beam axis.

Fig. 3.3.4 Charged particle density for jets of different p_T .

Mean separation (cm) of charged particles in jets at $r = 1$ m

Fig. 3.3.5 Mean separation of charged particles for different $p_{T,jets}$.

Fig. 3.3.6 QCD jet ($p_T = 1000 \text{ GeV}/c$)

Fig. 3.3.7 QCD jet ($p_T = 1000 \text{ GeV/c}$)

Fig. 3.3.8 QCD jet ($p_T = 1000 \text{ GeV/c}$)

Fig. 3.3.9 Wire geometry

Fig. 3.3.10 Hit rate (hits/wire/sec).

Fig. 3.3.11 Occupancy of hits within maximum drift time.

Fig. 3.3.12 Local hit rate (hits/mm/sec).

Fig. 3.3.13 Current drawn by a wire with gain of 2×10^4 .

Fig. 3.3.14 Total electrons on mm length of wire.

Reference

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3.4 Scintillating Fiber Detectors - Prospects for Use at the SSC

3.4.1 Introduction

The art and science of small diameter scintillating fiber detectors has advanced to the point that experiments at Fermilab and CERN are building precision tracking devices based on this technique. Scintillating fiber detectors are a potentially interesting alternative to more traditional tracking devices in the SSC environment, principally because they can survive Mrad radiation doses, but also because they have good spatial and track-pair resolution and are reasonably fast. The technique is in its infancy, however, and several fundamental advances are needed before scintillating fiber detectors can be realistically contemplated as SSC detectors. Even so, they have captured the fancy of several experimental groups and progress in the last few years has been rapid.

3.4.2 Status of Scintillating Fiber Development

Work in the "modern" era on scintillating plastic fibers was initiated by Borenstein and Strand¹ at BNL with recent developments at Saclay². Work on glass fibers was pioneered by Ruchti and collaborators³ at Notre Dame. A few other groups, at Fermilab, CERN, and Rutherford, are working in close conjunction with glass and fiber manufacturers. It is a new field of research with only a few groups worldwide participating.

3.4.2.1 Glass Fibers

Scintillating glass fibers have been made⁴ using Cerium based glass. The most successful glass to date is GS1/SC20 manufactured by Levy-Hill Laboratories and SES Technology Consultants in the U.K. The individual fibers have been made square in cross section, 25, 30 or 40 μm on a side. They typically have a few microns of lower refractive index cladding and capture about 7%

of the scintillation light through internal reflection. The fibers are produced in a coherent matrix which maintains straightness and fiber-to-fiber parallelism, and includes an outer absorption layer around each fiber to prevent absorption and re-emission of the scintillation light by the "wrong fiber". The light output for minimum ionizing particles is about 4 photoelectrons per mm of track length for fibers a few centimeters in length. The scintillator's fluorescent time constant is around 50ns, which gives the fibers a moderately fast response. Cerium based glasses were developed for radiation hardness, and in bulk, samples can tolerate MRad exposures with acceptable changes in light output. Figure 3.4.1 shows the change in light transmission with accumulated dose.

Tracks and interactions have been observed by two groups^{4,5} in fibers made with GS1/SC20. A typical event is shown in Fig. 3.4.2 and is noise-free and rich with information. Images have been recorded by placing highly sensitized film or CCDs behind image intensifiers with photon gains of order 10^5 . The resultant images have been fit with straight lines to determine the spatial resolution. Resolutions around 20μ have been achieved, and the intrinsic resolution ($d/\sqrt{12}$) is expected to be within reach after correction for distortions in the image intensifiers. The track-pair separation capability is also very good, around two to three fiber diameters.

The principal shortcoming of the glass fibers is the short attenuation length. Figure 3.4.3 shows light transmission versus fiber length in long multifiber bundles of GS1. The attenuation is worse than that observed in bulk glasses, so in part seems to be due to the process of making fibers. The present attenuation lengths limit fibers to lengths of 10cm or so. Attempts to improve this performance by controlling the cerium content and oxidation state are under way.

The relatively low light output of the glass fibers also needs improvement. Present light yields require each detecting layer to be several millimeters thick to allow some margin of safety for efficient light collection. An entire tracking chamber might easily be a quarter of a radiation length thick.

3.4.2.2 Plastic Fibers

Plastic scintillating fibers, consisting of polystyrene doped with a scintillator and wave length shifter, have also been shown to work in calorimetric and coarse gained tracking applications. Fibers are typically⁶ one millimeter in diameter, have short (few ns) fluorescence decay times, good light yields (12/mm) and moderate absorption lengths (~1m). The fibers show increased attenuation with radiation, and can tolerate a dose of about one Mrad. The UA2 detector is being fitted with a new scintillating fiber tracking and pre-converter system of length about one meter incorporating 60,000 fibers.

The principal shortcoming of the plastic scintillating fibers is the comparatively large diameter and consequent poor spatial and track-pair resolution. The fiber diameters have been limited to about 1mm by the requirement that the diameter be matched to the absorption length of wavelength shifter in the fiber. If that is not the case, the light yield will drop markedly or the scintillation light will become non-local, neither of which can be tolerated. Several groups are trying to produce working fibers of considerably smaller dimension. One interesting development is the proposal by Bross⁷ to add 3-Hydroxyflavone to the plastic, with the intention of wavelength shifting more locally. 3HF might also increase the radiation hardness of the fibers.

3.4.2.3 Readout Systems

Scintillating fiber bundles have been read out with multi-stage image intensifiers coupled to very sensitive film or CCD or SIT cameras. A system

used by Ruchti et al is shown in Fig. 3.4.4. It consists of a sensitive photocathode to which the fiber bundle is optically connected, and several stages of image intensifiers using fast phosphor screens. A microchannel plate can be used at an intermediate stage to allow the device to be gated on or off in less than 100ns. The final phosphor image can be transferred to film or a CCD. Typical CCDs require 10ms to be read out, and 1-2 μ s to be fast-cleared. Other readout alternatives, such as a SIT-vidicon, wherein a photodiode array is directly bombarded by the photoelectrons produced in the also stage of the image intensifier, can be read out at 100MHz rates, but do not have fast clear options. The comparatively long time required before accessing the data is a definite drawback to this technique in high-rate applications.

3.4.3 Scintillating Fibers at the SSC

Several of the features of the scintillating fibers are a good match to the SSC tracking environment. Radiation hardness, especially in the glass fibers, is excellent and alone makes the technique worth consideration. The readout devices, image intensifiers, phosphors, and perhaps optical fiber delay lines, can also be hard to radiation, and unlike the electronics associated with silicon or drift chamber devices, need not dissipate much heat. Glass fibers have demonstrated excellent spatial resolution and two-track resolution and could provide very dense tracking information. Both characteristics will be essential at the SSC, where very dense hadronic jets will need to be untangled and high momenta measured. Small angle stereo could be used to measure the coordinate along the fiber direction.

There are, however, fundamental limitations in today's devices that must be overcome before one could imagine a working scintillating fiber detector at the SSC. These must be addressed with suitable research and development.

3.4.4 R&D Priorities for Scintillating Fiber Detectors

1. Develop small diameter (say $\leq 100\mu$) long attenuation length ($\lambda > 1\text{m}$) scintillating fibers with good resistance to MRad radiation dosages. Present glass fibers have attenuation lengths an order of magnitude worse than this; present plastic fibers do not have reasonable light output in small diameters.
2. Demonstrate readout capability at 100MHz event rates.

Readout of the fibers in the SSC environment poses several very difficult problems: (a) event integration time is too long; (b) signals must be delayed until trigger decisions can be made; (c) events take too long to read out.

(a) Integration Time. Fluorescence decay times in the glass fibers and in the fastest phosphors used for image intensification are about 50ns. Since the SSC event rate is 100MHz, the fibers will integrate over about ten events. It is conceivable that ten events could be untangled, given the large granularity of a scintillating fiber detector, but it is certainly a very difficult and problematic exercise. Fibers and phosphors with very short decay times ($< 15\text{ns}$) are needed to handle the high event rates.

(b) Optical Delay Line. Current readout systems employ CCDs as the final encoding element. Since there is substantial overhead (about $2\mu\text{s}$) in fast-clearing a CCD, the maximum rate at which information could be strobed to the CCD is about 100kHz if dead times are to be kept manageable. This requires a very effective level 1 trigger decision, and enough fiber-by-fiber delay to allow the trigger to be formed and distributed to gates in the image intensifier systems. Binnie, Kirby, and Ruchti⁸ proposed the use of 30m or so of coherent (non-scintillating) fiber bunches as a suitable optical delay line, but no practical and economic system has been demonstrated. (The current generation of experiments operate at substantially sub-SSC data rates). Obviously, the development of a very fast live trigger or a readout device

with fast clearing capability well under a microsecond would ease the requirements on the delay line. In any case, an existence proof is required for an economic means of delaying the fiber signals until a trigger decision can be made.

(c) Event Readout Time. It takes roughly 10ms to read out a CCD. This time essentially precludes the use of information from the scintillating fibers from participating in any level of triggering. It is important to reduce readout times as much as possible. What readout time can be tolerated depends directly on the performance of the trigger, but should certainly be below 1ms.

3.4.5 Conclusions

The future of scintillating fiber detectors in the SSC environment is by no means clear. Several fundamental advances must be made before they are suitable for general charged particle tracking devices or vertex detectors. However, the facts that they are radiation hard and capable of very good track-pair and spatial resolution, make them interesting and worth pursuing.

Fig 3.4.1 Transmission in bulk GS1 vs. wavelength. Measurements by the CERN-Max Planck-Rutherford Appleton collaboration (see ref. 5). The GS1 emission spectrum is shown for comparison.

Fig. 3.4.2 Interaction of 50 GeV/c π in 25 μ GSI Cerium glass fibers with extra mural absorber. (Data from ref. 4).

Fig. 3.4.3 Light output vs. fiber length in scintillating glass fibers made with GS1. (Data from ref. 5).

Fig. 3.4.4 Gatable image intensifier used to read out scintillating fibers (from ref. 4).

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3.5 Silicon Semiconductor Detectors

3.5.1 Introduction

There are three types of semiconductor tracking devices potentially available for high energy physics experiments:

- silicon microstrip detectors;
- silicon drift chambers;
- pixel arrays.

Compared with wire tracking chambers, silicon semiconductor devices have attractive intrinsic properties such as:

- fine spatial resolution;
- good two particle separation;
- fast response;

as summarized in Table 3.5.1.¹ Because of these features, semiconductor detectors are promising tracking devices for SSC applications.

On the other hand, these devices are still in the early stages of development, and there are many difficulties to be studied and overcome for realistic applications, including the associated electronics. A technical review of aspects of large-scale semiconductor systems, including electronics, is given in ref. 2.

Table 3.5.1. Tracking Properties¹

	<u>Strip Detector</u>	<u>Silicon Drift Chamber</u>	<u>CCD</u>	<u>Wire Chamber</u>
Spatial Resolution	3 μ m	5 μ m	4-6 μ m ²	30 μ m
Two particle separation	50 μ m	80 μ m	40 μ m	500 μ m
Response Time	10ns	1-10 μ s	50ns	50ns

3.5.2 Silicon Microstrip Detectors

3.5.2.1 Present status

After the successful application of the planar process to the fabrication of solid state nuclear detectors,³ silicon microstrip detectors have been used as precision vertex detectors in many fixed target experiments.⁴

A position resolution of $4.5\mu\text{m}$ has been achieved so far with a $60\mu\text{m}$ read-out pitch for $20\mu\text{m}$ strip detectors.⁵ Capacitative charge division has been successfully employed in order to overcome the readout density problem.⁶ The effect of magnetic field has been studied and is less than a $10\mu\text{m}$ effect on position resolution at $B = 1.6$ Tesla.⁵ Silicon microstrip detectors are now commercially available with sizes up to $91\text{mm} \times 35\text{mm}$ and strip pitches as small as $25\mu\text{m}$.⁷

Rapid progress has also occurred with respect to readout electronics of microstrip detectors. Minimum ionizing particles traversing $200\mu\text{m}$ of silicon generate 16000 electrons (2.5fC). Therefore the equivalent noise charge (ENC) of amplifiers has to be smaller than about 2000 electrons to result in a reasonable detection efficiency. In order to accommodate the small pitch size, amplifiers must be compact and low power. Several hybrid preamplifiers have been developed and used in experiments.⁸⁻¹⁰ However, hybrid types are too bulky for colliding beam experiments.

J.T. Walker et al. have successfully developed an NMOS amplifier and sample-and-hold circuit (Microplex), with an input pitch of $47.5\mu\text{m}$, to read out silicon detectors of $25\mu\text{m}$ strip-to-strip pitch (Fig. 3.5.1).¹¹ They have performed a successful beam test with a signal-to-noise ratio of more than 15 to 1, as shown in Fig. 3.5.2. Other current efforts include sample and hold circuits¹² similar to the Microplex and CCDs.^{13,14}

3.5.2.2 Requirements for SSC

As a model, we assume that an SSC vertex detector will consist of 5 layers of silicon microstrip devices with the same number of small-angle stereo layers. Their basic configuration is:

microstrip detector	:	9.09cm(L) x 3.3cm(W) x 0.02cm(T)
strip pitch	:	32 μ m on both sides forming small angle stereo, 1024 strips/face
angle coverage	:	30° - 150°
detector radii	:	5.25, 7.88, 10.50, 13.13, 15.75 cm
total strip area	:	27000cm ²
number of strips	:	921k
total detectors	:	450
number of readout channels	:	307k (charge division)
total radiation length	:	1% (silicon only)

We assume the use of 3-strip charge division to lower the readout electronics channels while keeping the good spatial resolution. With a luminosity of $10^{33}\text{cm}^{-2}\text{s}^{-1}$, we get

	$r = 5.25\text{cm}$	$r = 15.75\text{cm}$
hit rate	80kHz/strip	8kHz/strip
integrated dose	1Mrad/year	110krad/year

Therefore, with time slicing every 50ns in the readout electronics, the random occupancy would be of less than 1%. It should be noted that number of readout channels definitely requires integrated circuits with extremely low power dissipation.

3.5.2.3 R&D recommendations for silicon microstrip detectors

Priority 1: Radiation resistant integrated circuits with time slice readout capability.

Although the Microplex circuit successfully developed at SLAC is a good starting point, its simple sample-and-hold scheme does not work for the SSC.

Our recommendations for readout electronics based on the above mentioned requirements for SSC are:

- radiation resistance up to 10Mrads;
- parallel-in serial-out analog or digital memory (see Fig. 3.5.3);
- 20MHz time slicing capability;
- ENC less than 0.5fC;
- low power dissipation less than 10mW/ch.

Priority 2: Study of radiation damage to silicon detectors

There is some evidence that (a) ion-implanted pn-junction detectors are more resistant to radiation than surface barrier detectors and diffused pn-junction devices¹⁵ and (b) silicon microstrips can survive up to 10^{13} - 10^{14} particles/cm.^{16,17} In addition, there is an interesting observation (not yet confirmed) that (a) the damage strongly depends on the dose rate and (b) a silicon detector with low resistivity is more resistant to radiation.¹⁸ The initial indication of radiation damage is thought to be an increase of leakage current corresponding to the reduction of minority carrier lifetimes due to the creation of intergap levels.¹⁹ Points of study for radiation damage are:

- study of the causes of the damage, for example, separation of surface and bulk damages;

- damage dependence on types of detectors (surface barrier, ion-implanted and diffused junctions), resistivity, and dose rate;
- study of cures such as annealing and operation at low room temperatures.¹⁷

It has been repeatedly pointed out that associated electronics could not survive even if the detectors are alive.²⁰ It is generally said that MOS circuits die at around 100 krad, while bipolar circuits survive to 1 Mrad.^{21,22} There exist radiation damage studies in the fields of nuclear power plants, and for space and military applications, which are useful, if not always directly applicable. A systematic survey should be performed together with a carefully planned experimental program.

Priority 3: Techniques for better wafer processing:

1. Readout strips on both sides of wafers: This reduces the necessary number of detector planes by a factor of two, reducing the radiation length, photon conversion probability and multiple scattering. One could form small angle stereo for two-dimensional pattern recognition. Ideas are needed to get around the bias voltage problem in this geometry.

2. High production yield: Commercially available microstrips are not yet in the state of best quality control. They reveal defective strips at the few per cent level.²³ It is imperative to improve the production processing technique not only for detectors with no defective strips but also for low cost mass production.

Priority 4: Software study of track reconstruction:

Figure 3.5.4 illustrates one of the fixed target events in 800 GeV pN interactions. With limited numbers of detector planes, one encounters great

difficulties in pattern recognition. Software studies have to be performed to find the optimal configuration of strips for SSC detectors.

3.5.3 Silicon Drift Chambers (SDC)

Gatti and Rehak proposed the novel idea of silicon drift chambers. The present status is well summarized by P. Rehak.²⁴ They have achieved $\sigma = 4\mu\text{m}$ under laboratory conditions and $11\mu\text{m}$ in a beam test, with unambiguous two dimensional resolution of $20\mu\text{m}$ in the beam test.²⁵ Thus it can be said that SDCs are demonstrated to work in experimental conditions. With SDCs one may reduce the number of electronics channels required by at least a factor of 100. Two dimensional readout can be easily accomplished by segmenting the anode. Their ultralow capacitance for large area devices provides excellent noise performance.

The drift velocity in silicon is an order of $10\mu\text{m}/\text{ns}$. Therefore it takes a maximum of $1\mu\text{s}$ to drift 1cm in an SDC. Event overlaps due to such long drift time will be a problem for the SSC at high luminosity.

So far SDC of 1cm^2 have been made. The wafer processing is not trivial. There are many R&D items required, including electronics and radiation damage tests, directed towards SSC applications.

3.5.4 Pixel Devices

Since there are potential difficulties in the straightforward application of silicon microstrip detectors as vertex detectors because of complex projection patterns at SSC, pixel devices could provide a powerful means for pattern recognition and tracking.

3.5.4.1 Present status

CCDs are the only devices available at present as a working pixel-type detector. The Rutherford group has demonstrated that standard optical imaging

CCDs perform well as particle detectors.²⁶ They have obtained excellent results such as

spatial resolution	4.3 μ m x 6.7 μ m
two track resolution	40 μ m
efficiency	98 $\pm$ 2%

However, the application of CCDs to high luminosity SSC detectors seems to be impossible because of their readout scheme. Even at a clock speed of 100MHz, it takes at least 2ms to readout a CCD with 500 x 500 pixels.²⁷ During the readout cycle, more than 1000 particles hit the CCD, generating background. Also, the operation at liquid nitrogen temperatures makes application of CCD's to SSC vertex detectors impractical. CCD architecture requires that every pixel be addressed and tested for hit content, but even the most dense jet will occupy only about 10^{-4} of the available pixels. Given the unacceptably long readout time, CCDs as currently produced will therefore have no foreseeable role in SSC tracking.

There are a number of incomplete proposals to alleviate the readout problems of CCDs. Such R&D work should not be discouraged since their superior capability of pattern recognition is of extreme importance in track recognition, but their applicability to the SSC is unclear.

3.5.4.2 R&D recommendations for pixel devices

1. For straightforward application to the SSC challenges, new architectures for pixel devices will be required. Owing to the extreme sparseness of the hit content, an architecture which allows a struck pixel to propagate a signal promptly to an address encoder (with time slice buffer for trigger formation) seems to be essential. How this new architecture might be realized is

not yet concrete, but rudimentary concepts are currently under development.^{28,29} Special purpose devices made by industry for aerospace and other applications may provide part of the solutions needed.³⁰ Successful development of large area pixel devices with architectures optimized for sparse data fields could have a major impact in many experimental applications in high energy physics, nuclear physics, X-ray imaging, etc.

2. CCDs: For completeness, we mention a few interesting possibilities for improvements. The pile-up problems of CCDs can be ameliorated (but not solved) for the SSC by implementing a fast clear, gating off sensitivity after a trigger is formed, and by some fast decision scheme to sense an entire line for hits present or absent. These developments should be encouraged as possible short-term improvements in the expanding use of pixel arrays within high energy physics, but with lower priority than the development of new devices with architectures appropriate for the SSC.

Fig. 3.5.1 Block Diagram of the circuit.

Fig. 3.5.2 Probability of finding one or more strips above threshold for delayed (background) and on-time (data) triggers. Pulse heights have been corrected for pedestal and baseline shifts. No background counts above 39 BADC units were seen on the 130 strips in 800 triggers. For data, an efficiency of 98% was determined at a cut level of 42. The inefficiency was due to a single defective strip in the 75 included in the beam profile.

Fig. 3.5.3 Parallel-in/Serial-out circuit for readout of microstrip detectors.

Fig. 3.5.4 800 GeV p-N interaction with silicon microstrip detectors (E653).

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3.6 Tracking Software

3.6.1 Introduction

With regard to tracking software we see several areas in which progress should be made. These areas are: (1) clarification of the parameters required of a tracking system, and their relation to SSC physics; (2) use of what we have learned about tracking with drift chambers to optimize the arrangement of novel tracking systems (silicon or glass fibers), and specification of what a minimal system must look like; (3) exploration of what can be done on-line with information from a tracker to minimize the very substantial off-line computational load; (4) continued optimization of tracking algorithms and exploration of benefits of code vectorization and new computer architectures.

As a general remark, it should be noted that the volume of information from an SSC detector makes data taking and off-line processing sufficiently complicated that the on-line and off-line software aspects of a detector design should be important considerations in choosing an optimum design.

3.6.2 Parameters for a Tracker

Although a substantial amount of work has been done in this area, a more focused study would be useful. The two most pertinent features of a tracking system are the momentum resolution achievable and the typical angular separation between tracks for them to be reconstructed correctly. As examples of physics constraints on these parameters: (a) measurement of the sign of the charge for an electron requires $\Delta p/p \approx 40\%$ at the electron momentum; (b) separation of B from D particles using the invariant mass of charged tracks from a secondary vertex requires a modest mass resolution, $\sim 10\%$, which therefore requires $\Delta p/p \approx 10\%$ for the secondary particles from B or D decay; (c) reconstruction of the particles and thereby the secondary vertex for a 1 TeV b

jet requires an angular segmentation of a few tenths of a milliradian for the tracker; (d) reconstruction of the tracks and the B vertex coming from a top jet of 1 TeV requires an angular segmentation of about 1 milliradian.

Clarification of goals for these physics dependent parameters is a high priority. It is important to go beyond looking at quantities like the angle between all tracks and to look more closely at the tracks which might help determine the physics producing particular types of jets. Once the desired parameters are specified, the tracker radius, number of layers, and magnetic field can be specified for a given position resolution. This will also help clarify the physics motivation for novel trackers. In particular, the need for an angular segmentation of a few tenths of a milliradian, which would probably allow most charged tracks to be reconstructed, would argue for a novel tracker.

3.6.3 Tracker Organization

In the case of novel trackers, the necessity of minimizing the size will probably still make the hit density quite large and pattern recognition challenging. Important questions to answer would be how many layers are needed to find most of the tracks, how layers should be grouped (for example equal spacing of all layers versus group of layers, which provide local track vectors which then need to be linked), and how the z coordinate is measured. Important trade-offs need to be made between frequent sampling and the amount of material present and the radius of the device and the magnetic field.

In the case of large drift chamber detectors, substantial work has been done on the questions of cell size and organization. Further software-related work to be done is discussed below.

3.6.4 On-line Data Compression

Several schemes have been suggested to allow suppression of out-of-time hits on-line. These involve staggered jet cell layers or tilted jet cells. In addition, the measurement of a track segment in a jet cell allows a calculation of momentum, assuming the track comes from the origin. One could thus eliminate all low momentum (<5 to 10 GeV for example) track segments on-line as well. The above strategies could substantially reduce the amount of information which has to be permanently stored.

Problems to be solved are the implementation of an on-line algorithm which chooses the good track segments and the extent to which high track densities cause the loss of information which could have been retrieved had all the information from the tracker been saved. Also, the interaction of the chamber design and the possibilities for data compression should be clarified.

3.6.5. Track Reconstruction

Initial estimates of the computer power needed for event reconstruction for SSC events are very large (see Section 6). This can be minimized by putting some of the reconstruction on-line (for example segment finding), by the suppression of information from low momentum tracks on-line, by improvement of algorithms, and by better use of new computer architectures.

In the area of new algorithms, progress has been made this year by both the MARK II and SLD (SLD note # 135 by W. Atwood) experiments. These exploit the information given by groups of wires to link track tangent vectors. The speed-up in track finding for the Mark II case seems to be about a factor of four over estimates based on extrapolating old PEP programs. Experience gained here would be useful in organizing the layers of a novel tracker to optimize pattern recognition.

In the case of computer architectures, two examples of large gains due to vectorization have recently been demonstrated. The first is the vectorization of an event generator, FOWL, by K. Miura of Fujitsu, giving a factor of 3.5 speed-up. The other is the track reconstruction program of Fermilab and Florida State experiment E711 where a factor of ten speed-up was achieved using a CYBER 205. As experience grows in vectorization, it would be useful to understand the relationship of the tracker design to the speed-up achievable.

3.6.6. Conclusions and Recommendations

We have outlined above several areas requiring study, all of which would influence the design of a tracker. Most pressing is the need for a study of on-line and off-line algorithms for data suppression and fast track reconstruction, as all trackers present very large amounts of data. Such a study should include recommendations on tracker design and how it interacts with the software analysis.

CHAPTER 4

Report of the Working Group on Calorimetry

4.1 Introduction

Calorimetry will form the heart of most SSC experiments. It will be essential for determining the four momenta of jets and missing transverse momenta, and will provide the means for the basic first level trigger.¹ Since it is so important, and since calorimetry is among the most costly and time consuming of the various detector R&D areas, some of this R&D must be pursued in an experiment-independent environment if any of the new techniques are to be available in time for the SSC. After some deliberation, the calorimetry subcommittee of the SSC Detector Task Force has compiled a list of techniques to be considered for the major calorimeters which will be needed in experiments at the SSC. The committee reviewed previous efforts to select criteria by which the various methods should be judged, and made a new assessment of the most appropriate selection.² These criteria were then used to determine areas of research and development which should be pursued for each of the techniques considered.

Nine general techniques of calorimetry were considered in some detail by the committee:

- A1. Liquid Argon Calorimetry
- A2. Warm Liquid Calorimetry
- B1. Silicon Calorimetry
- B2. Heavy Scintillating Glasses
- C1. Gas Calorimetry
- C2. Barium Fluoride Calorimetry
- C3. Plastic Scintillator Calorimetry
- C4. Heavy Scintillating Liquid Calorimetry
- C5. Scintillating Crystal Calorimetry

No one technique provides an ideal solution to the problem of calorimetry at the SSC, but each has its special advantages. In many cases some critical attributes of a specific technique are simply unknown. In evaluating each possibility the committee gave special weight to the consideration that the majority of the calorimetry in a given detector (i.e. the electromagnetic and fine hadronic calorimetry) should use the same technique. While hybrid calorimetry is possible, high resolution hadronic calorimetry will be difficult to achieve if electromagnetic and hadronic sections are constructed using different techniques. The pulse height equality of hadronic and electromagnetic shower components and, at a higher level, of jets is hard to achieve in hybrid constructions. However, it will be possible, with little degradation of performance, to construct the hadronic leakage sections of calorimeters at the SSC using a technique (such as gas calorimetry) different from the primary hadronic calorimeter.

The committee grouped the various techniques into three categories as indicated by the list. Category A seemed to the committee to comprise the methods which are presently receiving the most attention from experimentalists. Liquid argon plate calorimetry is a mature technique and will certainly work at some level at the SSC. While warm liquid calorimetry in high energy physics is clearly in its infancy, some of the construction techniques and operational aspects of these calorimeters are similar to those of the liquid argon devices. Although these methods are receiving attention from existing large collaborations^{3,4} and are likely to have considerable R&D effort expended on them, major pieces of research needed for these types of detectors, including studies of compensation in warm liquid calorimeters and the determination of relative and absolute sizes of electromagnetic and hadronic pulse heights in uranium or Pb-liquid argon calorimetry, are only partially completed. In addition, it

seems clear that critical research needed for the SSC (for instance, increasing the speed of response of the detectors and electronics to cope with event rates of the SSC) will receive little or no consideration in the current round of experiments. Additional R&D will therefore be required in the A category, although to a lesser extent than in the B category.

Category B contains promising new techniques which at present offer hope of significant advances in one or more aspects of calorimetry, such as improvement of hadronic resolution (heavy scintillation glasses), or more compact construction using higher density materials (silicon plate calorimetry). At present, the techniques in category B are speculative and require too much development work to receive the backing of a currently approved experiment.⁵ Long-term, experiment-independent R&D is needed for these techniques to be adequately evaluated.

Category C techniques were judged by the committee to have serious drawbacks for 4π calorimetry at the SSC, where electromagnetic and fine hadronic calorimetry will use the same technique. These problems, which appear insoluble even with further R&D, were deemed serious enough to prevent any of these calorimetric methods from being the first choice for a non-hybrid detector operating in the SSC environment. A notable exception to this may be gas calorimetry, whose low cost and flexibility in construction may, in a given 4π detector, override the serious difficulties perceived by the committee. In addition, these category C techniques may be the best option for certain specialized detectors, and will require further R&D for complete development.

For each technique, an attempt was made to estimate both the likelihood of success and the need for encouragement of R&D. While R&D is needed in all categories to realize fully the potential of the techniques, category A and B should receive preference, with special attention being given to category B because of its speculative nature.

Evaluation criteria were developed by the committee without regard to any particular technique. In this report no attempt was made to give a comprehensive discussion of all the techniques with respect to all the criteria. Rather, the aim was to highlight the strong points and shortcomings of each in the context of the high energies and luminosities of the SSC. This examination led quite naturally to the definition of potential areas for R&D. For some of the less developed methods, potential areas of R&D not specific to the SSC are also pointed out in this report. Finally, not all techniques are discussed to the same depth. More attention was given to those that seemed more promising for the SSC.

The criteria given below form a background for the report. In no particular order they are:

1. Speed - This criterion is extremely important in the high luminosity environment ($L \approx 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$, 10^8 interactions/sec) of the SSC. The time interval between bunch crossings is presently planned to be 15ns. Each technique must be evaluated not only for integration time but also for time slewing of the signals. While the exact effect of pileup on resolution for masses, missing energy etc., is a complicated and extensive question, it is clear that fast response times are highly desirable. To some extent, finite differencing charge integration systems will circumvent some of the problems for calorimeter triggers, even for relatively slow techniques such as liquid argon. On the other hand, the solution to the problem of reconstructing precise energies and pulse heights in calorimeters in which serious pileup occurs is not clear. The smaller the pulse height that must be analyzed, the worse the problem. The ability to tag single bunch crossings ($< 15\text{ns}$) is essential, and integration or sampling times of less than a "few" bunch crossings are desirable.

2. Resolution - The energy resolution is important not only for single particles but also for jets and missing transverse momentum. Major contributions to the energy resolution (equality of electron and hadron responses, signal to noise, statistics on collected charge, etc) should be evaluated for each technique. Since new particles at the SSC are expected to have typical masses of a few hundred GeV/c^2 , a jet-jet mass resolution of a few percent in this mass range is desirable. This implies energy resolutions better than $50\%/\sqrt{E}$, and necessitates e/π close to one. If significantly better resolution than this could be achieved, major breakthroughs might be possible in the search for such objects as the Higgs boson.

3. Granularity - Historically, this criterion has been set by requirements for electron identification close to jets. At the SSC, the effect of granularity on jet angular resolution must also be considered. A crude estimate is that granularity of $\Delta\theta \approx 0.03$, $\Delta\phi = 0.03$ is needed to achieve two-jet invariant mass resolution of a few percent. In addition, it was shown⁵ at Snowmass 1984 that it is beneficial to reach this level of granularity in order to separate $W \rightarrow$ jets from the QCD backgrounds. Each calorimetry method must be evaluated as to the difficulty of making a tower structure with this granularity.

4. Absolute Calibration, Stability and Monitoring - Calibrations should be good to 1%. Stability after corrections should be good to 1% over a few weeks.

5. Uniformity of Response - The uniformity of response of the detector, element to element or tower to tower, should be of order 1% so that the non-uniformity does not dominate the energy resolution at high energy.

6. Density - Densities of $> 8 \text{ g/cm}^3$ are desirable to allow compact calorimetry.

7. Containment - The calorimeter should be thick enough to contain a reasonable percentage of the shower energy and to minimize non-interacting punch-through, thus allowing the most sensitive measurement of missing p_T . We have set this thickness to be $24\lambda_0$ and $12\lambda_a$ total for the electromagnetic and hadronic calorimetry. The fine hadronic calorimetry should provide at least $6\lambda_a$ of the total hadronic calorimeter thickness. The remainder of the calorimetry can be provided by a cheap alternative such as gas calorimetry.

8. Radiation Hardness - No calorimeter with appreciable degradation at doses of 10^6 rad or less is adequate for high luminosity operation at the SSC. This includes any electronics associated with the calorimetry.

9. Linearity of Response - It is desirable to avoid saturation up to 5 TeV.

10. Hermeticity - Practicalities of mechanical construction must be considered. It is necessary to cover $\Delta\eta \approx \pm 5.5$ for 4π detectors. A reasonable criterion for hermeticity, which has been used in 4π detectors at present energies, is that the missing p_T must be small compared to the missing energy due to ν 's. Estimates of cracks and dead regions inherent in particular calorimetric techniques should be made.

11. e/π Separation - A separation of 10^3 is possible using the longitudinal and transverse shower development as measured by the calorimetry alone. Each technique should be evaluated for its ability to measure proper transverse and longitudinal shower development.

12. Homogeneity - The fine hadronic and electromagnetic calorimetry should be as homogeneous as possible to minimize calibration problems.

13. Associated Electronics - Special problems associated with the electronics for particular types of calorimetry should be evaluated.

14. Costs - The competitiveness of each technique must be evaluated according to the cost of meeting all the criteria listed above.

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4.2 Liquid Argon Calorimetry

4.2.1 Introduction

Since the pioneering work more than 10 years ago¹ many experiments²⁻⁴ have quite successfully used liquid argon calorimetry with a variety of plate materials. In the past, the calorimeters have been used mainly for electromagnetic shower detectors, but now several large detectors are being designed with large solid angle calorimetric coverage for both electromagnetic and hadronic particles. Among these are D0 at Fermilab,⁵ SLD at SLAC⁶ and H1 at HERA.⁷ The calorimetry group at Snowmass 1984⁸ concluded that the default choice for an SSC detector would be a uranium-liquid argon calorimeter. Liquid argon calorimetry has several clear advantages: it has been demonstrated to work; it has superior density, nearly equal electromagnetic and hadronic response,⁹ and good energy resolution; it is simple to calibrate and segmentation is easy.

While electron drift in pure liquid argon is not fast (drift times are $\sim 200\text{ns/mm}$ and a lower limit with some additives is $\sim 60\text{--}80\text{ns/mm}$), information about the energy deposited in argon can be obtained in a shorter time by observing a fraction of the total charge. A limit to the counting rate is posed by the time required to transfer the charge from the electrodes into the amplifier. This charge transfer time is proportional to the length of the connections between the electrode and the amplifier, and its lower limit is of the order of 50ns per meter of the length of connections. (This is not a simple transmission line propagation, but rather a transfer of charge from a large electrode capacitance through the line onto the amplifier, while preserving the signal to noise ratio.)

For example, a large calorimetric system, such as that envisaged for D0, would not work in the high luminosity environment of the SSC because of the

long sampling times. DO has been designed to use a $2.5\mu\text{s}$ sampling time and 10m long cables to bring signals to the preamplifiers. In order to have an acceptable transfer time in a large calorimeter, the amplifiers would have to be located close to the electrodes, i.e., they would have to be able to operate in the liquid argon. Fine segmentation of the electromagnetic part (and to a lesser extent of the hadronic part) of the calorimeter poses problems in the electrode design with the capacitance and inductance of the connections, cross-talk, and the application of the electric field. One consequence of the large dynamic range is that the charge preamplifiers have to be operated at much higher power, which is then dissipated in liquid argon. An ionization chamber calorimeter can have a very high intercalibration accuracy (better than 0.5%), but this requires a system for accurate charge injection into all signal channels. These and other important issues are being addressed on a relatively small scale in the development of a liquid argon calorimeter for the HELIOS (NA34) experiment at the CERN SPS. Further research and development of these ideas and problems is necessary for calorimetry at the SSC.

There are difficult questions concerning readout and signal processing in large calorimeters with many readout channels. Usually the information in the calorimeter is processed in two ways. One is the formation, in the shortest time possible, of linear and weighted sums (E , E_T , p_T) for trigger purposes. The other is the storage of information from selected events in each channel. To reduce the number of feedthrough connections on the calorimeter vessel it is tempting to think of performing both functions inside the liquid argon vessel, and bringing out only the sums (of which there is a small number) and the multiplexed readout of the temporarily stored information from part or all of the channels. This would pose many problems, such as power dissipation and the inaccessibility of virtually all of the electronics, but the only alternative is to cope with a large number of feedthrough connectors.

It should be noted that very accurate timing can be performed with liquid argon calorimetry. The charge (or current) signal has very small fluctuations in shape due both to the high density of ionization (~ 9000 ion pairs per mm for a single minimum ionizing particle track) and the large number of samples (track segments) constituting a shower. The timing error is then determined only by the signal and noise and is given by

$$\sigma_t \approx \frac{\sigma_{ne}}{E} \left(\frac{1}{A} \frac{dA}{dt} \right)_{zc}^{-1},$$

where σ_{ne}/E is the ratio of the electronic noise to the particle energy and $(1/A dA/dt)_{zc}$ is the normalized slope of the signal at zero crossing after an appropriate bipolar pulse shaping. Assuming a relatively "slow" shaping of 100ns for the first lobe of the bipolar output, the slope is $(1/A dA/dt)_{zc} \approx 3 \times 10^{-2} \text{ ns}^{-1}$. The electronic noise appropriate to a section of the calorimeter covering a solid angle large enough to form a sum signal (corresponding to a volume of perhaps 1m^3) may be $\sigma_{ne} = 3 \text{ GeV}$. At an energy of 100 GeV, this would give a timing error $\sigma_t \approx 1\text{ns}$, which is sufficient to assign the signal to a particular beam bunch. Since statistical fluctuations in the shape of the signal are negligible, simple shape analysis can be used to find out if there was significant pile-up of events from other bunches within the width of the calorimeter response. Accuracy increases for events at higher energies.

4.2.2 Equalization of Hadronic and Electron Pulse Height/Compensation

Recently much discussion and effort has gone into resolving the question of whether uranium-liquid argon calorimetry truly exhibits compensation. A Workshop last year at the California Institute of Technology on Compensated Calorimetry⁹ was devoted entirely to that subject. In high-Z calorimeters there is a trend toward equalization of the response to electromagnetic and

hadronic showers through suppression of the electromagnetic response. This arises from inefficient sampling of the electromagnetic energy when, for a finite sampling thickness, the Z of the absorber is much larger than the Z of the sampling medium. This inefficiency is frequently referred to as the transition effect or Lande factor.

True compensation for hidden energy in the plates would arise if the energy lost in nuclear breakup were replaced with fission energy products, which would be visible in the active medium. In plastic scintillator, compensation appears to take place largely through energy transfer from fission neutrons to protons and carbon atoms in the scintillator. In a sampling medium of liquid argon, this process appears to be negligible as a means of energy transfer because of both the larger Z of the argon and recombination. To the extent that compensation is present in liquid argon it must come from the fission photons. These very low energy photons are sampled very inefficiently; just how much energy is transferred depends on experimental details and the question is yet unresolved by data or calculation.

Equalization does not contribute to the energy resolution in the same way that compensation does. Fluctuations in the response due to variations in the energy lost in nuclear breakup are not reduced by equalization. However, fluctuations in response from variations in the amount of electromagnetic energy in a hadronic shower are reduced by equalization. True compensation improves the resolution in both of these cases.

There was general agreement at the workshop that the near equality of response to electromagnetic and hadronic showers in high- Z calorimeters is due mostly to the suppression of the electromagnetic signal. This applies to uranium-liquid argon as well as to lead-liquid argon as measured by the SLD

collaboration. An unresolved issue is whether fissions induced in a uranium calorimeter contribute significantly to the energy resolution. The DO collaboration claimed a better energy resolution for 10 GeV hadrons after subtraction of electronic noise than was measured by SLD. SLD found little difference between the response of lead-liquid argon and uranium-liquid argon. There were, however, significant differences between the tests, making comparisons difficult. The DO calorimeter had six absorption lengths of uranium for their uranium-liquid argon tests, while SLD had only three. In addition, the two test calorimeters used opposite polarities of electric field, which could also affect the results.

Results from the HETC and GHEISHA hadron cascade Monte Carlo programs were presented at the workshop. The agreement with experimental data is not perfect. For example, HETC does not accurately reproduce the observed longitudinal development of hadronic showers in the SLD data. The development of Monte Carlo programs which correctly simulate hadronic cascades and which can be used as a design tool for calorimetry is an extremely important project in the immediate future.

4.2.3 Suggested R&D

Much R&D on compensation is still needed, and would best be done using a set of well designed tests which are not under pressure to provide information for an imminent experiment. These tests should decide the precise role of each effect contributing to the equality of electron and hadron pulse heights in uranium and lead liquid argon calorimetry, and should determine the contribution of fission to the improvement of hadronic resolution. Issues such as the effect of electric field polarity and the thickness of uranium plates on hadronic response should be addressed. The data from such tests

would reduce the degree of empiricism in the design of liquid argon calorimeters. In addition, novel measurements, such as those discussed by R. Wigmans at the Compensation Workshop, should be encouraged to provide more information on hadronic shower composition for the benefit of Monte Carlo developers. Development of hadronic shower programs must have high priority so that they become reliable guides to calorimeter design.

Finally, work needs to be done to increase the response speed of liquid argon calorimeters. To arrive at an optimal calorimeter, the electrode design, the charge transport mechanism, and the electrode readout must all be considered together. Extension to 4 π geometries of the approach of NA34 for cold amplifiers must be studied, in order to design schemes which are crack free. R&D on the effects of adding methane or other hydrocarbons, not only on response speed but also on compensation and resolution, should be performed.

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4.3 Warm Liquid Calorimetry

4.3.1 Introduction

There are good reasons¹⁻³ why a calorimeter with a room temperature liquid as the ionization detecting medium is of considerable interest for an SSC detector. All the advantages of a unity-gain ionization sampling device known from liquid argon calorimetry apply to such a device: these are homogeneity of response, stability of operation, ease of calibration, and ease of longitudinal and transverse segmentation. These properties are very important for calorimetry at the SSC, where systematic fluctuations in the cell response, rather than statistical fluctuations, are expected to dominate the uncertainties in measuring the four-momenta of jets, and where there is no easy in situ calibration. The use of room temperature liquids may offer further advantages over liquid argon:

- no bulky cryogenic equipment means fewer dead zones;
- there are no time-consuming cryogenic operations;
- time resolution is better;
- prospects for an e/π response near unity are better with depleted U as absorber.

In contrast to these advantages, there are also some serious problems: in comparison with liquid argon:

- the pulse-height is lower by a factor of four;
- the safety hazard is increased;
- purification requirements are tougher;
- steeper dependence of collected charge on electric field than in liquid argon leads to a higher sensitivity to space charge, due to positive ions at high rates.

The advantages of a room temperature liquid appear sufficiently interesting to justify extensive R&D efforts in this area, with a view to demonstrating the feasibility of a large-scale warm liquid calorimeter for an SSC detector, and exploring its properties.

4.3.2 Which Warm Liquids?

In order to serve as a useful ionization detection medium, the liquid must have a large free ion yield from the passage of ionizing particles, a high electron mobility, and a long electron lifetime.

The free ion yield, $G_{fi}(E)$, denotes the number of ion pairs released by 100 eV of deposited energy that escapes recombination and can be collected by the electric field E . The higher $G_{fi}(E)$, the better is the signal-to-noise ratio. The drift velocity of the electrons is proportional to the mobility μ , where $v_e = \mu E$. A high mobility is of particular interest for the SSC environment, with bunch crossings every 15ns. Finally, in order to allow an efficient collection of the charges, electron trapping impurities must be minimal.

Several room temperature liquids are known which exhibit the required properties. They all have non-polar molecular structures. Many interesting liquids have tetrahedral structures of the type $X(CH_3)_4$, where X is a four-valent atom such as C, Si, Ge, Sn or Pb. The simplest is Neopentane, $C(CH_3)_4$, but its low boiling point of 9°C renders it unsuitable for room temperature calorimetry. Replacing the central C atom by Si yields $Si(CH_3)_4$, Tetramethylsilane (TMS), which is under close examination for use in large calorimetric devices. Replacing Si with still heavier metals yields Tetramethylgermanium ($X = Ge$), Tetramethyltin (TMT, $X = Sn$), and Tetramethyllead ($X = Pb$). Of these, Tetramethylgermanium appears too expensive,

Tetramethyltin is somewhat toxic but might still be usable, and Tetramethyllead, also toxic but perhaps usable, is of low stability.

Other liquids of similar structure have been tested, in particular 2,2,4,4 Tetramethylpentane (TMP), and Hexamethylethyldisilane (double TMS, DTMS). Still more liquids may exist with similar properties, and should be sought and studied.

Table 4.3.1 lists some of the relevant properties of candidate warm liquids. For comparison, the properties of liquid argon are also given.

Table 4.3.1¹⁻⁴

Properties of Some Warm Liquids, and of Liquid Argon

	<u>TMS</u>	<u>TMP</u>	<u>DTMS</u>	<u>TMT</u>	<u>LAr</u>
Density [g/cm ³]	0.65	0.72	0.75	1.31	1.40
Boiling point at 1 bar [°C]	26.5	122	151	78	-186
Vapor pressure at 20°C [Torr]	650	15	<10	-	-
G _{fi} at 15kVcm ⁻¹ (a)	1.4	1.5	0.9	-	4.2
Min. ion. dE/dx [MeVcm ⁻¹]	1.4	1.6	1.7	1.7	2.2
μ [cm ² V ⁻¹ s ⁻¹]	100	24	47	70	50 (b)

a) number of free ions per 100 eV deposited energy

b) at E = 10 kV/cm

4.3.3 Warm Liquid R&D at Karlsruhe

At the Kernforschungszentrum Karlsruhe (Fed. Rep. Germany) intensive R&D on warm liquid calorimetry using TMS is under way. Small quantities of Tetramethyltin have also been successfully tested.

At present, about 200 liters of TMS are under test. A relatively simple purification plant has been built, combining vacuum distillation and the use

of molecular sieves. The purification is not considered a major problem. It is important to build and maintain the whole system vacuum-tight at the level of 10^{-8} Torr-liter/sec, to prevent oxygen from leaking into the system. Once purified, the liquid retains stable properties as an active ionization sampling medium over a period of months, provided it is kept under high voltage.

Karlsruhe has tested a 400kg iron calorimetry module with 35 liters of TMS.⁹ The construction of a total absorption hadron calorimeter, with depleted uranium as absorber and TMS as sampling medium, is under way. Its main features are summarized in Table 4.3.2.

Table 4.3.2

The Karlsruhe Hadron Test Calorimeter

Structure	5 modules of one λ_{abs} thickness each
U plates	60cm x 60cm, 3mm thick
Liquid	TMS, 5mm sampling gap
Schedule	Ready for beam tests in autumn 1986
Readout electronics	From the CELLO liquid argon calorimeter

The aim of this test is to demonstrate the feasibility of a total absorption hadron calorimeter using TMS, and to measure the energy resolution of hadron showers. In particular, the question will be addressed whether compensation works in a uranium-TMS calorimeter. Since TMS is a hydrogenous material, one might expect compensation by thermalized fission neutrons to occur. Doubts exist, however, as to what extent the ionization produced by slow knock-on protons is actually measurable. Recent experimental results quoted by Holroyd and Anderson⁴ suggest that the observable ionization from low energy protons is an order of magnitude smaller than for minimum ionizing

particles, owing to enhanced electron-ion recombination occurring in the track. However, the data are scarce and the crucial question of compensation in an uranium-warm liquid stack needs detailed study in properly designed test experiments.

4.3.4 Warm Liquid R&D at CERN (UA1 experiment)

The UA1 Collaboration has embarked on a large-scale program to upgrade its calorimeter. They plan to replace the present electromagnetic calorimeter, a lead-scintillator sandwich, by a construction using uranium plates as the absorber, sampled with a warm liquid. The chief reason for choosing uranium is to squeeze as much absorbing material as possible into the available space. At 90°, 23 cm of uranium (= 2 absorption lengths) can be accommodated. While it has been decided to use uranium as the absorbing material, and the delivery of the material and the mechanical construction has started, it is still unclear which warm liquid will finally be used. TMS has been discounted because its large vapor pressure at room temperature, in conjunction with the flammability of uranium, makes its use hazardous. The choice between TMP and DTMS is likely to be decided in favor of TMP.

In accordance with the experience at Karlsruhe, the problem of purifying the liquid is considered difficult but technically feasible. However, experience has shown that ultra high vacuum techniques must be used in building the calorimeter. Specifically, the liquid can only touch stainless steel or ceramics - plastics or epoxies are not allowed. The main features of the UA1 uranium-warm liquid calorimeter are listed in Table 4.3.3.

An intensive R&D program on warm liquid technology has been carried out by the UA1 group over the last two years. The efforts have concentrated both on the understanding and measurement of the basic electronic properties of

candidate warm liquids, and on techniques for purification. As an example of the good quantitative understanding of the electronic properties of warm liquids,⁶ Fig. 4.3.1 shows the measured pulse for minimum ionizing muons as

Table 4.3.3

The U-warm Liquid Calorimeter of UA1

Absorbing material	2mm and 5mm U-plates approximately 10cm x 10cm Total weight: 300 tons
Warm liquid	TMP or DTMS; gap width: 2.5mm Total volume: 15m ³
Longitudinal segmentation	6 samples
Transverse segmentation of readout pads	Approximately 10cm x 10cm

a function of the electric field, in satisfactory agreement with the expectation from the Onsager theory. The time-scale for the new UA1 calorimeter is exceedingly tight: at least part of the calorimeter should be ready towards the end of 1987 when the new antiproton-proton source ACOL is scheduled to come into operation.

4.3.5 Other R&D Efforts on Warm Liquids

There are at present no large R&D efforts on warm liquids going on besides the ones at Karlsruhe and CERN. Some measurements of ionization by particles are being performed or are going to be performed in Portugal (Coimbra⁵), in Japan (Tokyo⁵), in the USSR (Moscow), in the US (LBL), in Switzerland (SIN, Villigen⁷), and in Germany (Hamburg⁸).

4.3.6 Suitability of Warm Liquids at the SSC

While the speed of charge collection in warm liquids cannot compete with the response of fast scintillators, warm liquids tend to be faster than liquid

argon. The drift velocity of electrons is proportional to the electric field E up to 20kV/cm, and in TMS attains 1mm/50ns at 20kV/cm, whereas the drift velocity in liquid argon saturates at about 1mm/200ns. While the correlation of the response of a particular calorimetric cell with a given bunch crossing is not easy, it appears to be possible if suitable pulse shaping is employed. However, the dependence of the collected charge on the electric field is much steeper than in liquid argon (even liquid argon with a few tenths of a percent of methane to increase the drift velocity). This leads to a higher sensitivity to space charge because of positive ions at high rates.

The need for fast readout is in conflict with the collection of full charge. Fast charge collection means that one cannot wait for full charge integration, and becomes dependent upon the cell capacitance. With a drift length of 2mm, two thirds of the charge is accumulated within 40ns. The cell-to-cell capacitance variations must then be minimized by construction, or corrected for by calibration to better than 3%, in order to achieve an overall cell-to-cell uniformity of ~1%.

Fast readout means high noise levels. Present experience from the Karlsruhe tests indicates a noise level of $\sigma \approx 600$ MeV for 30ns integration time, which would make the observation of the minimum ionizing muon pulse next to impossible. The development of fast low-noise preamplifiers is imperative, especially since the electric signal in warm liquids is typically a factor of four smaller than in liquid argon (see Fig. 4.3.2). On the other hand, it is not obvious that observation of the minimum ionizing pulse height is necessary.

The purification requirements are much more stringent for warm liquids than for liquid argon. Electron trapping impurities must be kept as low as a few parts per billion to ensure an electron lifetime longer than the gap transit time. Today, the problem of purification is solved in principle, but

after achieving the required level of purity, it is non-trivial to maintain it in a large calorimetric set-up.

The granularity of the system is defined by the pad size, and can be tailored to almost any desired figure. Also, the longitudinal segmentation can be chosen at convenience to minimize π/e misidentification, to measure separately the electromagnetic and the hadronic component, and/or to allow weighing techniques to achieve a ratio of the e/π response close to unity.

The calibration of the system can be done to better than 1% accuracy by injecting charge into the preamplifiers or directly into the calorimetric cells. The absolute calibration must come from the calibration of a small subsample of cells in suitable particle test beams. Properly designed, the system should exhibit good uniformity at the 1% level, and stability with time.

The use of a warm liquid allows an easy separation into a fine-grain front calorimeter made of depleted uranium, and a coarse-grain back-up calorimeter made of iron plates. The latter would serve at the same time as a flux return for the magnetic field.

Warm liquids seem to be very radiation resistant. Indeed, high radiation doses have been utilized to purify the liquids. In the worst case, it is always possible to replace the liquid. Quantitative tests on radiation hardness are going on both at Karlsruhe and at CERN. Preliminary results indicate that radiation hardness is not a concern for the use of warm liquids at the SSC.

The linearity of the response should be next to perfect, although there might be a non-linearity problem due to volume recombination of ion pairs in

the core of electromagnetic showers of very high energy. This should be tested experimentally.

With 3mm thick uranium plates as absorber, and anticipating an e/π response ratio of 1.1 (which could be improved by weighting techniques), one might expect a hadron energy resolution of

$$\Delta E_h/E_h \approx 45\% / \sqrt{E_h[\text{GeV}]} + 1\% .$$

4.3.7 Summary and Recommendations

There is a considerable R&D effort on the use of warm liquids in calorimetry at Karlsruhe and especially at CERN. The UA1 collaboration is committed to the use of a warm liquid for its calorimeter upgrade.

The committee would like future R&D efforts on warm liquid calorimetry strengthened to include aspects which are important to the SSC. In a first step, a large total absorbing calorimeter, utilizing several absorber media and trying out several warm liquids, should be built. Further searches should be carried out, in collaboration with expert chemists, for new candidate liquids which might yield more charge and be less hazardous to use. At the same time suitable low-noise electronics mounted near the calorimeter cells (to avoid the cost and the additional capacitance and inductance of long cables) should be developed.

Fig. 4.3.1 Pulse height of cosmic ray muons as a function of the electric field. The full line denotes the expectation from Onsager's theory.

Fig. 4.3.2 Ratio of free electron yield of liquid Argon and TMP vs. electric field, taking into account the specific ionization dE/dx .

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4.4 Silicon Calorimetry

4.4.1 Introduction

Silicon microstrip detectors and multilayer silicon targets have been in operation for several years in high energy experiments. More recently, large area silicon detectors have been successfully used as active sampling devices in electromagnetic calorimeters.¹⁻⁴ Silicon detectors have several properties which make them attractive for use in calorimetry at the SSC.

- They have fast response. For standard detectors of 300 μ m thickness the electron collection time is 30ns and the hole collection time is about 60ns.
- They allow construction of very compact calorimeters: indeed, the silicon detector thickness (around 300 μ m) and its support allow sampling gaps of about 1.3-1.5mm.
- They also allow a flexible and very fine longitudinal and lateral segmentation, providing precise angle measurements and separation of very close jets and photons. Silicon allows flexible construction and optimum utilization of the available space, minimizing detector dead space.
- Silicon detectors have been shown to be insensitive to magnetic fields. No change in pulse height has been observed up to 1.7T;⁵
- Silicon detectors have unity gain and therefore gain stability is potentially very good.

4.4.2 Present Status

Recently, the SICAP0,^{1,2} Tokyo,³ and Hamburg⁴ groups have published test results on electromagnetic calorimeters using silicon detectors as sampling devices. Table 4.4.1 summarizes these test results. Comparisons among

these test results are made in detail in ref. 5. It should be noted, as indicated in Table 4.4.1, that the three groups use quite different types of silicon detectors. However, all three show more or less consistent performance and energy resolution. It can therefore be said that the principle of silicon sampling calorimetry has been experimentally verified.

Table 4.4.1
Silicon Detector Test Results

<u>group</u>	<u>SICAP0</u> ⁶	<u>TOKYO</u> ⁷	<u>HAMBURG</u> ⁸
detector type	undepleted pn-junction	Lithium drifted	surface barrier
depletion depth	200 μ m	1000 μ m	180-200 μ m
sensitive area	25cm ²	38cm ²	8cm ²
resistivity	2k Ω cm	?	1.2k cm
absorber	W and U	Pb	Pb
sampling frequency	2X ₀	0.9X ₀	1X ₀
total X ₀ length	24X ₀	10X ₀	12X ₀
energies tested	4-49GeV	0.25-0.75GeV	1.5-5GeV
energy resolution	17.6% $\sqrt{(\tau/E)}$	16.5% $\sqrt{E}$	20.7% $\sqrt{(\tau/E)}$

The approach taken by the SICAP0 group is new and potentially promising; they have developed a technique of so-called "undepleted" silicon detectors. At present, large active area silicon detectors can be manufactured in 4 or 5 inch wafers. For such active areas an increase in detector thickness is required to give sufficient rigidity. Silicon devices with 400 μ m thick wafers are routinely produced by industry. In order to deplete fully a device with this thickness, the required bias is about 570V for $\rho = 1k\Omega$ cm and about 115V

for $\rho = 5\text{k}\Omega\text{cm}$, where ρ is the bulk resistivity of the silicon crystal. With the current technology of crystal growth, it is extremely difficult to mass-produce large diameter silicon crystals with resistivity as high as $5\text{k}\Omega\text{cm}$. In any case, application of bias voltages higher than 100V is not recommended because of the increase in surface leakage currents.

For bulk resistivities of 1-1.5 $\text{k}\Omega\text{cm}$ and an applied bias of about 100V, silicon detectors are not fully depleted. These undepleted devices have space-charge regions of about 150-200 μm . It has been shown by the SICAPD group that they have a performance equal to fully depleted detectors with the same width of the space-charge region. These undepleted devices have been tested with short integrating-time electronics. Therefore, this relatively low resistivity, low cost silicon may be a viable alternative to the high resistivity silicon. However, there may be severe problems with uniformity from crystal-to-crystal when operating such devices in a non-depleted mode. This issue, along with calibration techniques, must be studied further.

4.4.3 Areas for Research and Development

4.4.3.1 Large active area silicon detectors

The calorimeters at the SSC will require large areas, so it is imperative to establish the technology for mass production of high quality, large area silicon detectors. There are several approaches toward this goal:

- fully depleted pn-junction detectors using silicon wafers of high resistivity (over $5\text{k}\Omega\text{cm}$);
- undepleted pn-junction detectors using silicon wafers of 1-1.5 $\text{k}\Omega\text{cm}$;
- lithium drifted silicon detectors based on silicon wafers with low resistivity;

Collaborations with silicon manufacturers must be initiated in order to produce large crystals with high resistivity, which are needed for all these approaches.

It is also important to establish very clean processing facilities and to collaborate with VLSI manufacturers on efficient and high quality detector production, regardless of the approach. Because of the relatively large area of each detector element compared with VLSI chip size, it is quite difficult to produce detectors with sufficiently high yield. For this reason, any simplification of wafer processing is very attractive.

4.4.3.2 Electronics

A fast hybrid charge amplifier has been developed for the silicon active target of the NA-14 experiment at the CERN-SPS.⁶ It has a signal base-time of about 60ns and can operate up to input capacitances of about 0.5nF. Its response is stable to better than 1% up to $1-2 \times 10^6$ counts/s. Low noise operation with such high detector capacitances in a high rate environment is a problem which must be studied further.

4.4.3.3 Radiation damage

The effects of radiation on silicon detectors depend strongly on detector type.⁷ For the pn-junction detector, radiation resistance has been demonstrated for doses up to and beyond 1 Mrad.⁸⁻¹⁰ However, increases in dark current and decreases in the minority carrier lifetime do occur because of incomplete charge collection due to radiation-induced defects. This increases the noise. However, the performance of the detectors is not impaired provided electronics with very short shaping times is used. It has also been observed that cooling the damaged silicon detector reduces the leakage current due to radiation damage by a large factor.¹⁰

An increase in the bias voltage is necessary to obtain full depletion and charge collection from the intensely disordered small volumes created by the radiation. The NA-34 group has observed a change of resistivity due to radiation damage.

Detectors made of relatively low resistivity material are expected to have better resistance to radiation than high resistivity detectors, but additional R&D is needed to verify this hypothesis.

It is also very important to study the radiation damage to the readout electronics; such studies are in progress at CERN and Ispra.

4.4.3.4 Hadronic calorimeters

No data on the performance of silicon hadronic calorimeters are currently available. In the next two years a prototype of such a calorimeter is expected to be put into operation by a Genova/Firenze/Hamburg/Tel-Aviv/ Trieste collaboration at the CERN-PS. Measurement of the response of a silicon calorimeter to hadrons is an important goal which must be accomplished to determine the usefulness of this calorimetry technique at the SSC.

4.4.4 Conclusion and Recommendations

Electromagnetic calorimetry with silicon sampling layers has been successfully demonstrated in the pioneering tests of the three groups mentioned above. It has been shown that these calorimeters have an electron energy resolution comparable to that obtained using plastic scintillator or gas as an active element. The advantages of such calorimetry are greater compactness and geometrical adaptability to various experimental conditions and perhaps better resistance to radiation damage than scintillator. Future areas for R&D include:

- development of mass-production capability for low cost, large area silicon detectors;
- study of silicon calorimeter response to hadrons;
- better understanding of the behavior of the silicon detectors under exposure to a high level of radiation;
- development of fast, low noise detector electronics;

- detailed and systematic comparisons of different types of detectors for calorimeters - lithium drifted, surface barrier, fully depleted pn-junction, and undepleted pn-junction;
- development of good uniformity of response and/or appropriate calibration techniques in silicon detectors.

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4.5. Scintillating Glass Calorimetry

4.5.1 Introduction

While heavy scintillating glass is not a recent development,¹ its use in calorimeters for high energy physics is relatively new. Thus far, heavy BaO glasses loaded with the scintillator Ce_2O_3 have been tested for electromagnetic calorimeter prototypes²⁻⁴ for medium and high energy physics, and are currently in use in the substantial electromagnetic detector of Fermilab experiment E-705.⁵ The major advantages of scintillating glass over other transparent media devices are at this point:

- the high light yield relative to Pb glass (~5 times that of Pb glass) insures that the calorimeter does not operate in the photon statistics limited region for most of the pertinent energy range. Because of this, an excellent electromagnetic energy resolution of $\sigma < (\text{constant} + 2/\sqrt{E}(\text{GeV}))\%$ can be achieved (see Fig. 4.5.1);
- the relatively low cost (~\$0.18/cm³ in 1983 when procured in quantity);
- the resistance to radiation damage (see Fig. 4.5.2).

The major disadvantages are:

- relatively low density ($X_0 \approx 4.35$ cm, $\lambda_a \approx 46$ cm, $\rho \approx 3.36$ g/cm³);
- the inherent disadvantage of all transparent media devices, i.e., the difficulty of constructing a fine granularity tower structure to match the desired $\Delta\eta \approx 0.03$, $\Delta\phi \approx 0.03$ criterion.

The major motivation for R&D of heavy glasses is the potential that such detectors may have for significant improvement in hadronic shower energy resolution over that attainable by sampling calorimeters. The basis for this hope is that the factors which degrade and ultimately limit hadronic energy

resolution in a sampling calorimeter will certainly be much different and most probably less important in a calorimeter constructed from a transparent medium.

For example, transition effects due to inhomogeneity, which are present in plate calorimeters, suppress electron shower pulse heights. These effects will be much different in an optical calorimeter made of a transparent medium such as scintillating glass, and will presumably be considerably less than in a sampling calorimeter. In addition, because nuclear breakup products from the interaction of hadrons with the calorimeter plate material should be visible in the transparent medium, hadronic energy loss in plate material, which tends to produce differences in electron and hadron pulse heights in a sampling calorimeter, should be decreased. It is then possible that the hadron and electron responses of such a transparent calorimeter may approach equality. Moreover, sampling fluctuations will not be present in a transparent medium calorimeter. These factors, if verified, could lead to a significant improvement in hadronic energy resolution.

However, there are effects which work to degrade this resolution in a real material such as SCG1-C scintillating glass. There will certainly be imperfect transmission of the scintillation light through finite lengths of the glass; this would make $e/\pi \neq 1$ and add a different kind of shower fluctuation. The sampling fluctuations of plate calorimeters will be replaced in a scintillation glass calorimeter by fluctuations in pulse height due both to differing longitudinal development and to imperfect transmission through differing lengths of glass. The size of these fluctuations will depend on the longitudinal shower fluctuations and on the extent to which the glass is transparent, over long distances, to the emission spectrum of Ce_2O_3 . Extensive large scale prototype work is therefore necessary to measure both the e/π ratio and the hadronic resolution for this type of counter.

To date, the low density of the glass has not encouraged groups to measure the response to hadrons, although the E705 group has measured⁶ 4-14 GeV/c π 's in a relatively short calorimeter ($\sim 2\lambda$). That prototype, which was intended to check electromagnetic properties of scintillating glass, had substantial leakage, as shown in Figs. 4.5.3(a) and (b). The leakage prevents any conclusions from being drawn at this point about e/π response of this glass.

4.5.2 Survey of current scintillating glass R&D

The major drawback to the scintillating glasses that now exist is their low densities. The work^{7,8} on BaO glasses has produced, to date, a series of low cost, moderate density cerium glasses more appropriate for electromagnetic than for hadronic calorimetry. Some of these glasses are described in Table 4.5.1 below.

Table 4.5.1⁹

Characteristics of Some Scintillating Glasses

Glass	BaO	Wt(%) SiO ₂	ρ (gm/cm ³)	n_d	χ_0 (cm)	λ_{max} (nm)	τ^1 (ns)	Relative Light Out ²
SCG1	43	42	3.36	1.61	4.35	430	-	.04
SC56	37	42	3.34	1.60	4.55	407	110	.16
SC58	45	39	3.47	1.63	3.51	430	100	.04
SC59	52	35	3.76	1.61	3.14	425	110	.09
SC60	56	34	3.87	1.64	2.85	430	40	.03
SC61	65	26	4.34	1.66	2.28	458	30	.03

¹ Width of base of pulse between 10% to 90% points

² Scale of light output is BGO=1

Inspection of this table shows that the wavelength of the emission line increases with BaO content and that there is some correlation of BaO content with the speed of the pulse. The parameters of the glass can thus be tailored to some extent. However, the major problem is that, if one is restricted to

BaO, the density of the glass will be small. A low level effort is under way at the moment by A. Spowart⁸ of SES to develop cerium glasses which include dense components such as thorium; it may then be possible to achieve densities approaching the desired 8g/cm^3 .³

4.5.3 Suggested Scintillation Glass Research

Scintillating glass is a relatively new possibility for calorimetry. A sequence of steps must therefore be followed to define the promise of the technique and outline its limitations. These steps are:

1. Research into heavier components which will work with cerium must be pursued with highest priority. If this technique is to fulfill all its promise, it must be capable of use in hadronic calorimeters.
2. Any candidate glass must be produced in large enough quantities for a full scale prototype to be constructed so that the relative size of electron and hadron pulse heights and the hadronic energy resolution can be determined. The relationship of electron and hadron pulse heights must be measured with an array which has a realistic longitudinal segmentation, representative of a real calorimeter.
3. In parallel with the development and measurement of higher density glasses, R&D on the readout of these glasses must continue. Development of photodiodes¹⁰ along with the attendant amplifiers should be pursued, with stability and calibration of such calorimeters in mind.
4. Comparison of various methods of determining shower position must be compared, since in general the granularity of the tower structure will not be adequate to fix the shower position.

5. Another important feature of the readout is that it must be flexible enough to be used with counters whose sizes and shapes will vary with angle. This will not be easy for transparent medium devices since, unlike plate calorimetry where the readout defines the tower structure, the tower structure must be built into the shapes of individual counters and will demand different sizes and shapes of photocathode. There should be research to develop strategies which can overcome this lack of flexibility.

Fig. 4.5.1 SCGI-C Scintillating glass - energy resolution.

Fig. 4.5.2(a) SCG1-C Transmission vs. flux for 55 MeV protons.

Fig. 4.5.2(b) SF5 Transmission vs. flux for 55 MeV protons.

Fig. 4.5.3(a) Response of an SCG1 scintillating glass array to pions and electrons at 4 GeV/c.

Fig. 4.5.3(b) Response of the same array to pions and electrons at 14 GeV/c.

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4.6 Gas Calorimetry

4.6.1 Is gas calorimetry appropriate at the SSC?

Calorimetry with gas as ionization detecting medium ('gas calorimetry') has become a standard tool, and is widely used in large colliding beam detectors. ALEPH and DELPHI have chosen gas sampling devices as electromagnetic calorimeters (high-gain proportional tubes and high-density projection chamber, respectively). For hadron calorimetry, both ALEPH and DELPHI, and also OPAL and L3, have chosen gas as the sampling medium.

The chief reasons why gas sampling is a popular choice for hadron calorimetry are twofold: firstly, the readout is done via pads, a method which lends itself easily to projective tower structures of any desired transverse and longitudinal segmentation; secondly, the gas calorimeter offers reasonable performance at low cost.

All detectors mentioned above are e^+e^- colliding beam detectors: collision rates are low, so speed is no problem. Furthermore, hadron calorimetry plays a less crucial role than electromagnetic calorimetry. The situation at the SSC is quite different. In the following, some of the properties of gas calorimeters are reviewed with an eye to their applicability to an SSC detector with 4 π calorimetric coverage.

Speed should not be a limitation provided the drift length in the gas does not exceed 2-3mm. The intrinsic time resolution of a signal obtained from a tower segment involving several readout layers is then below 10ns, which makes the distinction between successive bunch crossings possible. Hence only thin-gap chambers are of interest for SSC calorimetry. In addition, minimization of dead time prohibits operation in limited streamer or saturated avalanche modes.

The homogeneity of gas calorimetry is a more serious problem. In general, the gas amplification in the proportional mode depends critically on the electric field strength. Small changes of the wire diameter or of the wire-cathode plane distance easily lead to large changes in the response. An individual calibration of each tower being very difficult, the desired homogeneity of 1% must be assured by construction: wire diameter and wire-cathode plane distance tolerances must be very carefully controlled. This requires extremely careful engineering, but may not be impossible to achieve.

Two severe problems of gas calorimetry are the absence of an easy mechanism for the absolute and relative calibration of the response, and the absence of intrinsic stability. The stability with time depends on the gas composition and impurities, gas pressure, temperature, and on the applied high voltage. While present day high voltage power supplies offer sufficient stability (few times 10^{-4}), the temperature must be kept stable to $\pm 0.5^\circ\text{C}$, the pressure controlled to $\pm 0.2\%$, and the gas composition continuously monitored in small test chambers. With a great deal of effort, a stability of order 1% is conceivable through proper design and monitoring. The absolute calibration must be determined by calibrating part of the calorimeter in test beams. The difficulty is, however, that no easy in situ verification of the calibration is possible for the SSC, unlike the case of e^+e^- colliders. How well the test beam calibration can be transported into the detector environment is also questionable.

Two methods have been proposed to overcome this difficulty: strong γ -sources (eg. Co^{60}) moving along the surface of the calorimeter, or a controlled admixture of radioactive gas. Both methods can be used for relative stability monitoring, and for the transport of the calibration. Altogether, the requirements are very stringent, although there is no obvious intrinsic reason why 1% stability, 1% homogeneity, and 1% absolute calibration

accuracy cannot be achieved with gas calorimetry. Considerable attention to engineering details would be required to make this possible.

An important aspect of SSC calorimetry is the e/π response, which should be near unity in order to achieve the best hadronic resolution. The e/π ratio depends in part on the response of the readout medium to neutrons with a few MeV energy, which are produced in the nuclear interactions. This, in turn, depends strongly on the atomic number, Z , and the density of the sampling medium. A hydrogen-rich sampling medium is an advantage. Recent Monte Carlo studies and experimental data indicate that a gas calorimeter can be designed to exhibit an e/π response ratio of unity¹ by a suitable choice of materials, absorber and sampling gap thicknesses, and gas pressure. Relevant measurements by the L3 group are shown in Fig. 4.6.1. They have been performed with a test calorimeter consisting of 5mm thick U plates (with optional shielding by plexiglass or Cu plates) and 6mm thick MWPCs with different gas mixtures of Ar and CH_4 and C_4H_{10} . The strong dependence of the e/π response ratio on the choice of the parameters is apparent, as well as its 'tunability' to unity. Hence from the point of view of optimum hadron energy resolution, a well-designed gas calorimeter may not be much worse than a liquid calorimeter. The gas calorimeter can be made quite hermetic, with no obvious disadvantage as compared to, for example, a warm liquid calorimeter.

Up to now only the more positive properties of gas calorimetry have been listed. There are considerable difficulties in using gas sampling for the primary 4π calorimetry at the SSC. The linearity of the response is not good in gas calorimetry because of the gas amplification is reduced in high-density showers. Electromagnetic showers may be linear to 1% up to ~50 GeV energy, and hadronic showers up to ~100 GeV. Because of the different linearity of the electromagnetic and hadronic components, there will be a serious problem in understanding both the response and resolution of showers in the TeV region.

Another intrinsic problem of gas calorimetry is degradation of response. There must be means to eliminate broken and noisy wires, at the expense of local inhomogeneities in the response which persist forever. Wire deposits which limit the lifetime of the chambers may constitute a very serious problem (see Chapter 3). This is primarily true for calorimetry in the forward and backward directions located near the beam.

In summary, gas calorimetry cannot be considered a prime candidate for high resolution 4 π calorimetry in an SSC detector. The chief arguments against it are: i) its vulnerability to radiation damage; ii) its non-linearity and hence poor resolution in the TeV region; iii) the absence of an easy calibration and monitoring system at the 1% level; and iv) the difficulty of achieving a 1% uniformity.

However, a gas calorimeter may well serve as back-up calorimeter behind a high quality U-warm liquid or U-liquid argon calorimeter, for example. Its chief function would then be to serve as the leakage section for hadron calorimetry, and the chief requirement would be speed. All the arguments listed against gas calorimetry as the main calorimeter would not apply. At the same time, a back-up calorimeter with iron as absorber could serve as a magnet flux return and muon filter.

In the following section, a recent development in gas calorimetry is described which may be of particular interest for use as an SSC back-up calorimeter, from the points of view both of speed and of low cost.

4.6.2 The OPAL thin-gap chamber

The Israeli group of the OPAL Collaboration has designed and tested a thin multiwire proportional chamber working in a saturated high-gain mode.

The overall thickness is as low as 6.6mm. The output pulse is large and independent of the particle species, and the performance is not critically dependent on mechanical non-uniformities. The chamber is suitable for mass production, and will be used in the hadron calorimeter of the OPAL detector.

Figure 4.6.2 shows the construction of the chamber: the anode wire plane consists of 50 micron diameter wires spaced at 2mm. The cathode planes are made of G10 sheets coated with a resistive carbon paint. The distance between the cathode planes is 3mm. Readout is performed by copper pads which can take any desired shape, mechanical stability is achieved by support planes of 1.6mm thickness, made of G10, and electrical shielding is assured by a copper coating on the outer faces of the support planes.

The output signals on the pads are large enough (3pC per minimum ionizing particle) to be fed into standard ADCs without further amplification. The output signals are very fast, with rise time of 5ns and FWHM 15ns. Above rates of $10^3/\text{mm}^2$ appreciable reduction in output signal occurs.

Test results² indicate linearity of response in hadron calorimetry up to ~100 GeV. The saturation effect observed in hadron calorimeters employing the limited streamer tube design is absent because the minimum allowed distance between avalanches is much smaller. This is a consequence of the use of a strongly quenching gas mixture (60% CO² + 40% n-pentane), which localizes the avalanches in space. The response of the chamber to inclined particle tracks is remarkably independent of the angle of incidence, up to 45° with respect to normal incidence.

The radiation resistance of the chamber has so far been tested only with a collimated Sr⁹⁰ source. The total irradiation corresponds to 10^9 particles per mm². The response of the chamber did not show any systematic change larger than ~10%.

A prototype stack of such chambers, interleaved with 8cm thick iron plates as absorbers, was tested in a pion beam. The resolution obtained was $\sigma/E = 117\%/\sqrt{E}$, with no evidence for significant saturation of the response up to 90 GeV (see Fig. 4.6.3).

4.6.3 Summary and Recommendations

Gas calorimetry is not likely to be employed for the main high resolution 4π calorimeter in SSC detectors. However, it may well be used in a back-up calorimeter behind the main calorimeter, or in other applications which do not require optimal energy resolution.

Gas calorimetry can be made fast enough to allow distinction between successive beam crossings. The disadvantages of gas calorimetry are not important in its use as back-up calorimeter. The OPAL thin gap multiwire chambers, for example, allow a compact and reasonably hermetic design, with any desired readout pad structure, at low cost.

The pulses are large enough to drive present day electronics. No substantial R&D effort seems required beyond the current efforts of the OPAL Collaboration, which is committed to the use of thin gap multiwire chambers in its hadron calorimeter.

If gas chambers working in the proportional mode are to be used at the SSC, despite the disadvantages listed above, R&D into the development of fast preamplifiers mounted directly on the towers appears necessary. The tower capacitance is larger, for example, than that of a liquid argon calorimeter, requiring the cable inductance to be as small as possible in order to allow high speed. This is best achieved by reducing the cable length to a minimum. However, no large calorimeter of such a design has yet been built.

Fig. 4.6.1 The π/e response ratio as a function of the hydrogen content of the gas mixture (L3 collaboration).

Fig. 4.6.2 Schematic layout of the OPAL thin gap multiwire chamber.

Fig. 4.6.3 Resolution and response of the OPAL hadron test calorimeter, as a function of beam energy.

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4.7 Barium Fluoride Calorimetry

4.7.1 Introduction

Barium fluoride (BaF_2) is a new scintillator for calorimetry. It has a reasonably high density ($\rho = 4.8\text{g/cm}^3$), a short radiation length ($X_0 = 2.1\text{cm}$) but a long interaction length ($\lambda = 30\text{cm}$), and is non hygroscopic. The major advantage that makes BaF_2 unique and interesting for the SSC is that it has two emission spectra with very different decay time constants¹ (220nm, 0.6ns; 310nm, 600ns). These spectra are shown in Fig 4.7.1. This material has potential for a calorimeter that is very fast but suitable mainly for electromagnetic calorimetry. The density is too low for the material to be applicable to hadronic calorimetry unless it is used between plates of denser material such as uranium. In tests² an electromagnetic energy resolution of $\sigma \approx 2.5\%/\sqrt{E}(\text{GeV})$ has been measured.

The shorter wavelength component with its fast decay constant has been successfully coupled to wire chambers filled with the photosensitive gas tetrakis(dimethylamino)ethylene (TMAE).² This wire chamber readout technique is flexible and can be made with large areas at low cost. It is quite insensitive to magnetic fields. Use of low pressures (1% of atmospheric pressure) makes it possible to take advantage of the speed of the fast component by fast ion collection. In the tests mentioned above, a timing resolution of 1ns FWHM has been measured and signals of $< 20\text{ns}$ at the base have been observed. The positive ions from the gas are collected in about $1\mu\text{s}$. The scintillation light from BaF_2 can also be detected with photomultiplier tubes. Timing resolution of 112ps FWHM has been measured for 1 MeV photons using this readout technique.³ The major disadvantage of using photomultipliers with BaF_2 is that they must have quartz windows, making the readout both expensive and bulky. Since the readout must be insensitive to

the slow component of the BaF_2 emission spectrum, CsTe photocathodes must be used if high rate operation is desired. Finally, photomultipliers are sensitive to magnetic fields.

In addition to its speed, BaF_2 is the most radiation hard of the various crystal scintillators: samples of BaF_2 have been exposed to doses of over 10^7 rads with no visible degradation.⁴ An exposure of 8×10^7 rads produced some visible damage, but there was almost complete recovery after 3 days.⁵ A correlation appears to exist between sample purity and radiation hardness, with lower quality material demonstrating higher sensitivity. The part of the system necessary for this calorimetric technique that is vulnerable to radiation is the wire chamber readout. Further R&D is necessary to determine the extent of the problem.

The major disadvantage of BaF_2 , other than its unsuitability for hadronic calorimetry without the addition of heavy plates, is the cost. Cut and polished crystals presently cost about $\$6/\text{cm}^3$. With its use in Brookhaven experiment E787⁶ the cost is expected to drop to $\$3/\text{cm}^3$, and with increased use and new growth techniques under development, the price of a finished crystal may drop as low as $\$1.0$ – $\$1.5/\text{cm}^3$.

The inherent difficulty with this type of calorimetric technique (and others in the same category, such as scintillating glass, Pb glass, and other crystals) is that there is a limit to the physical size of reasonable towers, and therefore a requirement that at a given angle, in order to satisfy the $\Delta\eta = \Delta\theta = 0.03$ requirement, the tower must be a certain distance away from the interaction point. There is also a requirement that the tower size be compatible with the size of a shower (electromagnetic or hadronic) in the medium. Although BaF_2 , because of its relatively high speed, radiation hardness and high cost, is probably mainly useful for electromagnetic calorimetry at small angles, we have considered the tower configuration for a

detector constructed from this material from 90° down to 1° with respect to the beam. The table of tower distances given below is to some extent also applicable to the discussion of scintillating glass in section 4.5. If a 2x2 cm² BaF₂ crystal sets a minimum reasonable size of a realistic tower, then the distances given in Table 4.7.1 must be maintained between the interaction point and the towers at the indicated angles:

Table 4.7.1

<u>Angle of Tower</u>	<u>Pseudorapidity at the SSC (η)</u>	<u>Distance from Interaction point</u>
90°	0.00	0.7m
45°	0.88	0.8m
30°	1.32	1.3m
20°	1.74	2.0m
10°	2.44	3.8m
5°	3.13	7.7m
3°	3.64	13.0m
2°	4.05	20.0m
1°	4.75	40.0m

This table emphasizes the problem of configuring calorimetry at small angles.

While the problem is not special to BaF₂, stability, monitoring and absolute calibration appear to be difficult, especially with the fast component because of the small number of photons. A technique which may work is to measure the transmission of each individual crystal and to then infer its light output. After determination of the light output of the crystal, the uniformity, gain and response to ultraviolet light of the wire chamber readout must be determined. BaF₂ is different from other crystals in that the light output of the fast component is independent of temperature. For comparison, BGO has a variation of -1%/°C.

4.7.2 Conclusions and Recommendations

We have concluded that, because of the relatively high cost of barium fluoride, the construction of a combined electromagnetic and hadronic calorimeter seems unrealistic at this time, even with a BaF_2 -plate construction technique. For its development for electromagnetic calorimetry at the SSC, there are three areas that need special attention. The first is the need to develop a technique for calibrating such a calorimeter. The second major area of research is the determination of the radiation hardness of the wire chamber readout, and the invention of ways to make it less vulnerable to radiation. Because the photosensitive chambers can work with almost any gas, there is hope that a gas can be found which will work with TMAE and will also have a long life expectancy. Finally, one must be able to obtain large quantities of high grade BaF_2 with uniform properties at a reasonable price.

Fig. 4.7.1 Emission spectrum of BaF_2 .

References

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4.8 Plastic Scintillator Calorimetry

Although many present-day calorimeters are based on scintillator sampling, this approach does not appear to be promising for the SSC. Two limitations stand out: susceptibility to radiation damage and the difficulty of achieving $\Delta\eta \times \Delta\theta = 0.03 \times 0.03$ type of segmentation with reasonable longitudinal segmentation and minimal cracks.

The radiation environment of the SSC was first estimated at the 1983 LBL Workshop.¹ According to the 1983 estimate, acrylic scintillator available at that time would not last a year at angles $< 40^\circ$, while polystyrene would not last a year for angles $< 20^\circ$.

Since then Sirois and Wigmans² have determined that the slow degradation of acrylic scintillators can be lessened by at least an order of magnitude if contact with oxygen is avoided. However, even this improvement would still not permit its use in the forward direction at the anticipated dose of 10^6 rad. New measurements³ at CERN have shown that PVT based scintillators are better than acrylic scintillators at exposures of 10^6 - 10^8 rad, but still show considerable damage.

For application at the SSC, improvements in resistance to radiation damage and the development of new optical readout techniques are required. For large scale applications in a fine-grained calorimeter, replacements for phototubes must be found which ensure hermiticity. R&D in both of these areas should be encouraged.

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4.9 Heavy Scintillating Liquid Calorimetry

Certain heavy metal compounds are found to be soluble in water with the resulting solution reasonably transparent to visible light. Among the most promising that the committee is aware of is the thallium formate-malonate (Clerici) solution, which has been investigated for possible use in electromagnetic calorimeters.^{1,2} Comparisons have been made of this solution with Pb glass as a Cherenkov radiator for electromagnetic showers. The solution, which has a density of 4.24g/cm^3 and a radiation length of 2.57cm , was found to have a high resistance against radiation damage (no damage up to levels of 3×10^6 rad). The resolution for electrons was found to be somewhat worse than that obtained from SF5 lead glass counters of the same number of radiation lengths. To date there has not been much success in including organic scintillators in these heavy metal solutions.³

As far as we are aware, no other promising liquids have been found with densities greater than the Clerici solution, although several other possibilities involving different materials, such as bromine or lead, have been investigated.¹⁻³ In addition, the construction of calorimeters using these fluids poses severe problems because they must be made from individual containers holding these rather toxic materials. In order for this technique to be competitive, the problem of including scintillators without increasing the vulnerability to radiation damage must be solved, the densities must be increased, and formidable construction problems must be solved so that hadron calorimetry becomes feasible.

References

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4.10 Scintillating Crystal Calorimetry

4.10.1 Introduction

Scintillating crystals such as sodium iodide, NaI(Tl), cesium iodide, CsI(Tl), and bismuth germinate, BGO, can provide very high resolution electromagnetic calorimeters. This has been amply demonstrated by the Crystal Ball and CUSB collaborations, who have used these calorimeters at e^+e^- storage rings. For example, the Crystal Ball resolution is $\delta_E/E = 0.025/(E)^{1/4}$. In considering the physics program of the SSC, one should ask whether there is a need for this resolution. Of course, better resolution is always better; but one must balance the price of this resolution against the potential gain. The physics of the SSC is expected to center around the study of high transverse momentum hadronic jets, and the advantages of such superb electromagnetic energy resolution are not apparent in the study of the physics of those jets. However, there may be significant physics in the study of isolated photons and electrons. One can imagine scenarios where precise energy measurements of the isolated photons and electrons open a new world for study. The scintillating crystal calorimeter would be ideal for this task.

Assuming that there are physics problems that will be well handled by a high resolution electromagnetic calorimeter, one must ask whether the phosphor decay time will be a limitation and whether the crystals are sufficiently radiation resistant to withstand the radiation levels anticipated at the SSC. The scintillation light decay times, $0.3\mu\text{s}$ for BGO and for NaI(Tl), and $1.0\mu\text{s}$ for CsI(Tl), are not ideal (see Table 4.10.1). The occupation rates estimated for SSC luminosities of $10^{-33}\text{cm}^{-2}\text{s}^{-1}$ are prohibitive, and one should expect significant resolution deterioration for photon energies below 10 GeV owing to stray particles from low momentum transfer collisions that occur

during the light output integration times. An interaction rate of 10^8 Hz plus an additional rate from beam-beam or beam-wall interactions will have to be tolerated by the detector.

Table 4.10.1
Properties of Scintillating Crystals

<u>Material</u>	<u>NaI(Tl)</u>	<u>CaF₂(Eu)</u>	<u>CsI(Na)</u>	<u>CsI(Tl)</u>	<u>Bi₄Ge₃O₁₂</u>	<u>CdWO₄</u>
Wavelength of maximum emission (nm)	410	435	420	565	480	530
Decay Const. (μs)	0.23	0.94	0.63	1.0	0.30	0.9-20
Scintillation cutoff wavelength (nm)	320	405	300	330	350	450
Density (g/cm ³)	3.67	3.18	4.51	4.51	7.13	7.9
Hygroscopic?	Yes	No	Yes	No	No	No
Scintillation Efficiency (%)	100	50	85	45	8	20

The radiation damage problem is much more serious. Extensive measurements have shown that a 100 rad dose will reduce the light output of these crystals by 10 to 20%. The crystals apparently self anneal at room temperature, but the recovery times are days for BGO and weeks or months for NaI(Tl) and CsI(Tl). Since the expected radiation exposure levels are from hundreds to thousand of rads per day, it is impractical to consider these crystals until one has had the opportunity to design a protective shielding system or unless operation at much lower luminosity is desired.

There are other materials which appear to be much more radiation resistant and which are capable of providing energy resolution comparable to that of

NaI(Tl), CsI(Tl), and BGO. The reason for the good resolution of these materials is the fact that all of the energy is deposited in the crystal lattice and one avoids the statistical fluctuations of sampling. Scintillating glass and barium fluoride can provide comparable resolutions for these reasons. These materials are significantly more radiation resistant. They do not provide as much light per MeV of deposited energy, but this should not be a problem. For example, the light output of scintillating glass is a thousand times lower than that of Cesium Iodide, and the resolution will be limited by electronic noise at energies below 5 GeV when using photodiode readout systems. Using photomultiplier tube readout, there is no difference above a few MeV.

4.10.2 Recommendations

Because of the severe problem that scintillating crystals have with vulnerability to radiation damage at relatively minor doses, it appears that other transparent media materials such as scintillating glasses and BaF_2 are much more likely to prove profitable subjects for R&D. For this reason we recommend a concentration of effort in those areas rather than in further development of scintillating crystals of the type discussed above for SSC applications.

References

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4. Proceedings of the 1983 DPF workshop at Berkeley, p.53.

4.11 Recommendations

The calorimetry subcommittee makes the following recommendations concerning calorimetry R&D for the SSC:

1. R&D in calorimetry for 4 π detectors at the SSC should be pursued immediately in the following areas in an experiment-independent way. R&D for 4 π hadronic calorimetry should begin immediately in the A and B categories listed below.

A1. Liquid Argon Calorimetry

A2. Warm Liquids Calorimetry

(TMS, TMP, others...)

B1. Silicon Calorimetry

B2. Heavy Scintillating Glass Calorimetry

Although category A techniques are being actively investigated and developed for existing experiments, the present R&D programs are not adequate for SSC calorimetry designs. Category B techniques require substantial R&D and should receive special attention because they are more speculative, less mature and are not now receiving as much attention as the category A techniques.

The committee recognizes the incomplete nature of the information that experiment-dependent R&D has yielded for all techniques in all categories, and endorses efforts (such as a complete study of compensation in liquid argon uranium calorimeters) to produce complete information sufficient for future calorimeter design.

2. We recommend that R&D efforts in the following areas be pursued for the SSC, but at a lower priority than items in categories A and B:

- C1. Gas Calorimetry
- C2. BaF_2 Calorimetry
- C3. Scintillator-Plate Calorimetry
- C4. Heavy Liquid Scintillators

It is the committee's opinion that these techniques have disadvantages for use as the primary, precision hadronic calorimetry over large solid angles in the high luminosity environment of the SSC. They may, however, have significant roles in specialized experiments.

3. Overall priority should be given to R&D into techniques for calorimeters in which both the electromagnetic and the precision hadronic calorimetry are implemented using the same medium or technique.

4. The further development of Monte Carlo programs for hadronic shower evolution should be pursued to the point where they can be relied on as a tool to aid the design of calorimeters suitable for experiments at the SSC and elsewhere.

5. The scope of much of the R&D related to calorimetry is large and will require facilities, including test beams, at the national laboratories. Manpower and technical support requirements will likely be equivalent to a small experiment for full scale prototype tests. For these reasons the national laboratories must play a significant role in implementing the crucial calorimeter R&D for the SSC. This is particularly true for tests in high energy (~ 1 TeV/c) hadron or electron beams, for which Fermilab is the only available source in the US. The national laboratories must recognize their pivotal role in large scale calorimeter R&D and assign appropriate priorities to the

allocation of resources to such work. Because of the long construction time for the very large calorimetric systems required for the SSC, basic R&D must be completed in the next few years to provide a foundation for an intelligent choice of calorimeter type.

CHAPTER 5

Report of the Working Group on Muon, Electron, and Hadron Identification

5.1 Introduction

In this section we will discuss the detection and identification of muons and electrons at the SSC, and experimental possibilities and requirements. We will also briefly discuss some aspects of identifying light hadrons (π, K, p) but not charm, bottom, or top hadrons. We conclude each section with a summary of recommendations for detector R&D related to muon, electron, or light hadron identification.

The identification of muons and electrons will be a crucial part of most experiments at the SSC. High energy leptons may be signatures for the production of new gauge bosons, compositeness, new heavy quarks, and a number of other "new physics" processes. The study of production and decay of known particles such as bottom hadrons and W or Z bosons will also require lepton identification and energy measurement; two examples indicate that capability up to lepton energies of about 10 TeV will be required. As an example of new physics, consider the production of new gauge bosons. Assuming that 100 events in an integrated luminosity of 10^{40} cm^{-2} would be sufficient for discovery, then a new W(Z) boson could be produced with a mass up to $\sim 10.5(8) \text{ TeV}$.¹ This would yield leptons up to $p_T \approx 5 \text{ TeV}$. A more conventional process would be the production of Z bosons at large rapidity. The cross-section for Z production² falls rapidly by $y \approx 6$ so for a lepton with $p_T \approx 50 \text{ GeV}$ the resulting momentum is $\sim 10 \text{ TeV}$. To summarize, for the SSC we must understand the requirements for lepton detection up to about 10 TeV, a factor of 10-20 higher in energy than present experiments at $\bar{p}p$ colliders or Fermilab fixed target experiments.

The role of conventional light hadron (π, K, p) identification at the SSC is not as well documented as lepton identification. It seems unlikely at present that such identification will be required for the discovery and study of new high mass states: particle multiplicities would be too large for the conventional mass reconstruction techniques of hadron spectroscopy. On the other hand, the study of rare decays of bottom hadrons or W bosons, and perhaps the study of ordinary exclusive decay modes of top hadrons, will likely require π , K and p identification. If such studies are to be done in the central rapidity region, then the kinematics will be similar to existing or imminent e^+e^- colliders at the appropriate energy, although with substantially higher particle backgrounds. At smaller angles and larger rapidity, such studies would be done with detectors that resemble fixed target experiments but which may need to cover an energy range at least 10 times larger than fixed target experiments at Fermilab. For this reason it is useful to explore the limits of light hadron identification up to the TeV region. In this report we only discuss in detail extensions of ring imaging Cherenkov (RICH) counters for hadron identification. We do not discuss the requirements for conventional Cherenkov counters which might be used in single particle inclusive measurements.

References

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5.2 Muon Detection and Identification

There are three principal methods for identification of muons together with measurement of muon momenta:

- (1) particle tracking in a magnetic field in conjunction with penetration through mostly non-magnetized iron (typical of most present 4 π detectors at e^+e^- colliders);
- (2) absorption of hadrons, followed by magnetic measurements (like the L3 experiment at LEP);
- (3) measurements in magnetized iron, preceded in some cases by non-magnetic or magnetic tracking.

There are two common features for all three techniques: the behavior of muons in material and the characteristics of hadron absorption. We will discuss each of these below.

5.2.1 Muon Interactions in Matter

It is not our intent to derive or review the formulae for muon energy loss in matter but to present an overview of muon energy loss up to the TeV energy region. This summary is taken from the articles of ref. 1. Energy loss by muons traversing material arises from

- ionization,
- pair production,
- bremsstrahlung,
- nuclear interactions.

Ionization losses are only weakly dependent on muon energy, but pair production, bremsstrahlung, and nuclear interactions all depend strongly on energy. This is exhibited in Fig. 5.2.1 (taken from W. Lohmann et al. of ref. 1) showing the calculated energy loss vs. muon energy in iron. Ionization losses

dominate for $E < \text{few hundred GeV}$ but are negligible at 10 TeV, where pair production and bremsstrahlung losses dominate. The average amount of energy lost can be large, as shown in Fig. 5.2.2 for 6m of iron; at 10 TeV about 4% of the initial energy is lost, predominantly producing electromagnetic showers in the absorbing material, in this case iron.

The distribution of energy lost by muons in matter is illustrated in Fig. 5.2.3 (taken from Zupancic of ref. 1), which shows the number of single events per meter of iron, with muon energy loss $> E$, as a function of E for two different muon energies, 100 GeV and 10 TeV. One will notice that, at 10 TeV, the largest energy losses (but not the most probable) result from bremsstrahlung and nuclear interactions. According to this figure, a 10 TeV muon has about a 1% chance per meter of iron of losing 10% (1 TeV) or more of its energy.

The energy loss of muons in material at high energies has two important consequences:

- (1) precision muon spectrometers (e.g., of the L3 type) that aim for an accuracy of a few percent for muon momenta in the TeV range must measure the electromagnetic energy associated with a muon traversing a hadron absorber before the momentum measurement; precise measurement of muons in or near jets in this way will therefore be very difficult to impossible;
- (2) the energy lost by muons in the TeV region will predominantly appear as electromagnetic showers, which will tend to obscure the accompanying muon for tracking detectors, thereby making identification and momentum measurements more difficult.

By relatively modest scaling of the techniques for precision muon momentum measurements proposed by the L3 collaboration at LEP, it seems possible to

achieve an rms momentum resolution of about 5% at 1 TeV.² To preserve this resolution and retain high efficiency, the electromagnetic energy accompanying the muon must be measured (with modest precision). This seems feasible for isolated muons.

The situation is different for measurements of muon momenta in magnetized iron. Multiple scattering for a practical detector limits the momentum resolution to about 10% or greater at all momenta. This is illustrated in Fig. 5.2.4, which shows the momentum resolution expected for 6m of magnetized iron ($B = 1.8T$) interspersed with chambers before and after the iron.³ Energy loss, which has been neglected in the calculation of momentum resolution, will create an uncertainty in the true muon momentum. Although on average this effect will be small compared to the intrinsic resolution of an iron spectrometer, there will be a loss of efficiency from catastrophic energy losses.

Since most of the muon's energy loss is via radiation effects, its track through iron is accompanied by electromagnetic showers, often with energy ranging from tens to hundreds of GeV. The showers develop along the muon path, obscuring it as far as precision tracking is concerned. Effective tracking can only be done with an increased number of tracking elements, very likely every 25-50 cm. Monte Carlo studies using any of the several available muon transport codes,⁴ together with EGS⁵ for the electromagnetic shower part, will be required to optimize designs. Such studies would also investigate the effective angular perturbation of the muon in addition to multiple scattering. It is our recommendation that a detailed study of this type should precede any beam test (at the Fermilab Tevatron for example) which aims to understand muon energy loss in the TeV region. This study could be carried out at the Snowmass 1986 meeting.

We also note that systematic mechanical alignment errors are likely to dominate the position uncertainty for conventional muon chamber tracking systems in iron. Considerable effort will be required to preserve a true 300μ rms error in position measurements (assumed for Fig. 5.2.4) in the very large tracking systems envisaged for the SSC. Active alignment techniques such as those proposed for the L3 detector should be considered. For operation near the design luminosity, the production of $Z^0 \rightarrow \mu\mu$ is copious (about 1Hz) and might be used as a momentum calibration signal for iron muon spectrometers.

As mentioned above, most 4π detectors at present e^+e^- storage rings use tracking in a central drift chamber, in conjunction with penetration through non-magnetized iron (except for magnet return yokes), for muon identification and measurement. This is a viable technique, limited by momentum resolution in a central track chamber (about 1 TeV for a realistic device based on wire drift chamber technology) and by triggering considerations. The inclusive muon trigger rate depends strongly on the p_T of the muon. A trigger based solely on penetrating tracks through a realistic amount of absorber will yield a trigger rate of about 50kHz at the design luminosity of $10^{33} \text{ cm}^{-2} \text{ s}^{-1}$.⁶ This is clearly unacceptable, and other trigger criteria would be required in conjunction with a muon signature, thereby limiting the physics reach. The use of some magnetized iron to allow a p_T dependent muon trigger is required to reach a tolerable single muon exclusive trigger rate for most experiments at the SSC.

5.2.2 Hadron Absorption and Punchthrough

Effective muon identification requires the absorption of hadrons. It is therefore of considerable interest to understand punchthrough and muon production in hadronic showers. A related topic is hadron rejection. By measuring

the angle and/or momenta of tracks entering and leaving a hadron absorber, the hadron rejection factor can be substantially improved beyond what is expected simply from punchthrough. There is considerable variation in published results on punchthrough and hadron rejection, probably as a result of incomplete analysis; punchthrough measurements are seldom the actual goal of any experiment. We have based our conclusions on recent compilations and measurements.^{7,8,9}

The punchthrough probability (P) may be simply defined as the probability that one or more particles, of any location, be detected at a specific longitudinal position in an absorber. A recent compilation of data taken from ref. 7 is shown in Fig. 5.2.5. The punchthrough probability may be parameterized in terms of the incident hadron momentum, the average absorption length in approximately the first four interaction lengths of the absorber, and the remaining length of the absorber which ranges out soft muons produced in the front of the absorber.

The crucial question for the SSC is how to extrapolate from these measurements to the TeV region. A guide may be obtained from ref. 7, which finds that for thick absorbers and high energies the punchthrough probability P may be parameterized by

$$P = (p/350 \text{ GeV})[0.0095e^{-1.42(\sqrt{R}-2)}](0.22+0.59f),$$

where p is the momentum, R is the range in GeV (1.4 GeV per meter of iron), and f is λ/λ_{Fe} , the ratio of the interaction length of the absorber to that of solid iron. The data from which this fit was obtained are shown in Fig. 5.2.6. The author of ref. 7 notes that this formula is approximate and only applies for $4 < R < 9$ GeV and for $p > 75$ GeV. What does this imply at high energies? Taking 6 m of iron ($R = 8.4$ GeV) and $f = 1.1$, the formula yields $P = 6.6 \times 10^{-3}$ at 1 TeV. The impact of the relatively large punchthrough probability at high energies is not clear; these probabilities need to

be folded with charged particle momentum spectra from high energy jets to determine the overall punchthrough probability vs jet p_T , a more interesting number at the SSC. This would be an excellent exercise at the Snowmass 1986 Summer Study. It also seems clear that additional data should be accumulated at the highest possible energies, primarily from experiments at the Fermilab Tevatron.

The hadron rejection factor can be substantially different from the punchthrough probability. The two factors which improve hadron rejection are active sampling in the hadron absorber (calorimetry) and measurement of the exit angle and/or momentum of the muon candidate as it leaves the absorber. A hadron entering an active absorber will usually produce a visible shower and thereby be rejected. This technique will not work for muons close to or within jets. Also at high muon energies, as we have seen above, the muon may sometimes lose substantial energy in the absorber. Comparison of the exit position and angle of the punchthrough track with that expected for a muon candidate can substantially increase the hadron rejection. Recent measurements⁹ in the 50-150 GeV region indicate improvement factors of the order of 100 in hadron rejection by using such criteria. In these measurements the hadron rejection factor improves with energy, even though the punchthrough probability increases. It seems likely that hadron rejection factors in the 100-1000 GeV region can be 10^{-5} - 10^{-4} . These factors do not include contributions from π or K decay before the absorber.

5.2.3 Summary of Muon Identification and Recommendations

Muon identification and momentum measurement are possible over the complete range of muon energies expected at the SSC. The major difficulty in measurement of muon momenta will be the handling of energy losses from pair production, bremsstrahlung, and nuclear interactions. It is also extremely

desirable to reduce the systematic limitations of spatial resolution of tracking devices in magnetized iron spectrometers.

Our recommendation for detector R&D related to muon identification and detection is for further substantial Monte Carlo study and some theoretical work to understand the optimal configuration of a magnetized iron spectrometer for muon energies about 1 TeV and above. Such studies should precede beam tests, which are limited to energies below 1 TeV, to provide a basis for extrapolation to higher muon energies. Information from muon experiments at the Fermilab Tevatron should also be studied before performing an extensive series of new beam studies.

Fig. 5.2.1 The various components of muon energy loss in iron.

Fig. 5.2.2 Muon energy loss in 6m of iron vs. muon energy.

Fig. 5.2.3 The number of single events per meter of iron with muon energy loss $> E$, as a function of the energy loss E . Two muon energies are shown, 100 GeV and 10 TeV.

Fig. 5.2.4 Momentum resolution in an iron muon spectrometer.

Fig. 5.2.5 Punchthrough probability vs. depth of Fe for various momenta as indicated.

Fig. 5.2.6 Punchthrough probability vs. hadron momentum for different absorber thickness (ref. 7).

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5.3 Electron Detection and Identification

Calorimetry with or without association of momentum measurements, transition radiation, and synchrotron radiation, particularly for electron energies above 100 GeV, are discussed below. Our emphasis has been on electron identification requirements at high energies; methods of electron identification are well understood in the energy region below 50-100 GeV.

5.3.1 Electron Identification: Calorimetry

The development of electron cascade showers in matter is substantially different from that of hadronic showers. This property has been widely applied to electron identification and hadron rejection. In particular, the longitudinal development of the electron cascade shower takes place very rapidly and most of the shower particles are contained within approximately 30 radiation lengths.¹ On the other hand, the average hadron shower has a substantially larger longitudinal spread.² In addition, information on the lateral development and fluctuation of the center of gravity of a shower can improve electron hadron separation.

In general, calorimeter systems at high energies may consist of electromagnetic (EM) shower detectors, with hadronic shower detectors behind them. The longitudinal dimensions of EM showers are primarily determined by energies and material thickness in terms of radiation lengths. Materials for EM detectors should have a large ratio of absorption length (λ_0) to radiation length (X_0) in order to minimize energy deposition of hadronic showers inside the detectors. Therefore, high Z materials such as lead and uranium are usually used as radiators in sampling calorimeters. The λ_0/X_0 ratios for iron, lead, and uranium are 9.5, 30.5, and 33.2 respectively. A typical EM detector of $30X_0$ has about one absorption length. The peak of an EM shower profile

appears at a depth of $5X_0$ to $10X_0$ for the energy range of the SSC. Longitudinal segmentation and measurements of lateral shower distributions at various depths can improve electron-hadron separation.

Table 5.3.1 lists some recent reports on π/e separation using EM shower calorimeters. Common techniques used to identify an electron are:

- comparison of the shower energy with the momentum if the particle momentum is analyzed by a magnetic spectrometer;
- ratio of shower energies in EM and hadron calorimeters;
- ratio of the front end energy to the total shower energy in an EM shower detector;
- measurement of the lateral shower profile near the shower maximum of an electron.

A pion rejection factor of approximately 10^{-3} has been obtained at high energies with a reasonable electron acceptance. At very high energies ($>$ few hundred GeV to a TeV), where the momentum resolution of a magnetic spectrometer becomes poor, the total energy of a particle must be measured by a calorimeter system. Therefore, finer lateral segmentation of both EM and hadron calorimeters are required. Among the measurements listed in Table 5.3.1 we describe test results of prototype calorimeters designed for the CDF detector and also measurements made to study effects due to material in front of EM shower detectors.

R. Diebold et al.⁶ studied the performance of the full-scale prototype model of the central calorimeter for the CDF.¹⁵ The EM shower counter consists of 33 layers of lead/scintillator, each having 0.32 cm of lead and 0.64cm of plastic scintillator, $0.6X_0$ per layer, for a total of $20X_0$. Two layers of wire chambers are placed at $2.6X_0$ and $6.2X_0$ depths.

Table 5.3.1

Recent Reports on the π/e Separation Using EM Shower Calorimeters

Group Experiments	Ref.	Methods	E(GeV)	π -rej./e-accep.
J.E. Brau	3	Lead glass columns	4-16	$\sim 10^{-3}/80\%$ @ 8 GeV $\sim 10^{-4}/50\%$ @ 8 GeV
M. Jonker	4	CHARM: Fine grain marble/scinti.	15-140	$4 \times 10^{-2}/95\%$ @ 50 GeV
M. Bourquin	5	WA2: Lead glass array (SF5); σ_p/p	2-35	$\sim 10^{-3}/89\%$
R. Diebold, L. Nodulman	6	CDF: Lead (EM) and iron (hadron)/scinti., chambers, σ_p/p	15-45	$\sim 10^{-3}/70\%$
Y. Hayashide	7	CDF: Lead/conductive plastic tubes, front vs. total PH plots, σ_p/p no hadron calor.	10-40	$\sim 10^{-3}/99\%$ @ 40 GeV
B. Bleichert	8	Iron/scinti. (EM & had- ron), front vs. back PH plots, no hadron calor.	0.5-10	$5 \times 10^{-3}/80\%$ @ 50 GeV
R. Engelmann	9	Segmented extruded lead glass, no energy information	15-45	$\sim 10^{-3}/90\%$
Y. Hayashide	10	CDF: Lead/scinti., chambers, σ_p/p ,/no hadron calor.	17-175	$\sim 2 \times 10^{-3}/80\%$ @ 75 GeV
U. Micke	11	Lead/liquid argon, energy and strip cuts	2-10	$\sim 4 \times 10^{-3}/97\%$ @ 10 GeV
M. Basile	12	Lead/limited streamer tube	0.5-4	$6 \times 10^{-4}/90\%$ @ 1.2 GeV
A. Drescher	13	ARGUS: Lead/scinti., no hadron calor.	0.7-2.5	$2 \times 10^{-2}/80\%$
K. Ogawa	14	VENUS: Lead glass (SF03), σ_p/p	1-16	$2 \times 10^{-3}/95\%$ @ 4 GeV

The hadron calorimeter consists of 34 2.54cm-thick iron plates with 1.6cm gaps containing 1cm thick scintillator. Most of the measurements were made with 7.6cm of aluminum in front of the module in order to simulate the effects of a coil-cryostat. Figure 5.3.1 shows typical pion and electron pulse height distributions in the EM shower counter and hadron calorimeter at 30 GeV. For a momentum resolution of $\delta p/p = 0.002p$ (GeV/c), a pion rejection of approximately 10^{-3} was obtained for an electron efficiency of 70%. Table 5.3.2 gives typical cut efficiencies for 30 GeV e and π . The energy dependence of the pion rejection factor from 15 GeV to 46 GeV was found to be small, although some improvement was observed at higher energies. They also studied the dependence of the pion rejection on the amount of material in front of the calorimeter. The ratios for pion rejection for 14 cm/7.6 cm/2.5 cm aluminum were observed to be $(1.9 \pm 0.3)/1/(1.0 \pm 0.3)$.

Table 5.3.2
Electron Selection Criteria

<u>Cut</u>	<u>Electron Survival</u>	<u>Pion Survival</u>	<u>Remaining Pion Survival After All Other Cuts</u>
EM scintillator	0.87	0.0076	0.29
Hadron calorimeter	0.94	0.013	0.54
W1 pulse height ($25X_0$)	0.94	0.24	0.54
W2 pulse height ($6X_0$)	0.97	0.041	0.90
W1 width	0.99	0.24	0.89
W2 width	0.97	0.23	0.69
Total	0.72	7×10^{-4}	

Y. Hayashide et al.⁷ used another test shower counter of 31 layers of lead/scintillator for the CDF. A proportional chamber is placed at $5.6X_0$ depth, near the shower maximum of electrons. A likelihood method incorporating Fourier analyses of lateral profiles of electron and pion showers was employed

to study π/e separation. In their analysis information from a hadron calorimeter was not included. For a momentum resolution of $\delta p/p = 0.002p$ (GeV/c) the pion rejection factor was determined to be $(2.3 \pm 0.5) \times 10^{-3}$ and $(1.8 \pm 0.4) \times 10^{-3}$, at 50 and 75 GeV respectively, for an electron acceptance of 80%.

A gas sampling EM shower calorimeter using extruded conductive plastic tubes was tested by Y. Hayashide et al.⁷ with high energy electron beams. The calorimeter consists of 32 layers of chambers interleaved with lead plates of varying thickness for a total of $20.3X_0$. The first segment of two layers is $2.3X_0$ thick. Figure 5.3.2 shows two-dimensional plots of the total pulse height (P_{tot}) vs. the pulse height from the first segment (P_1) normalized to P_{tot} . Table 5.3.3 gives results of pion rejection factors against electrons with various energies. At 40 GeV the pion rejection factor was found to be 0.8×10^{-3} with the standard cut alone for an electron acceptance of 99%.

Table 5.3.3

π/e Discrimination Result by Cuts in Lateral Shower Profiles

Cuts	(1)	(2a)	(2b)	(3)
π^- 40 GeV	5.5×10^{-2}	1.7×10^{-2}	1.2×10^{-2}	1.2×10^{-2}
e^- 10 GeV	0.955	0.901	0.900	0.870
π^- 40 GeV	2.8×10^{-2}	1.0×10^{-2}	8.5×10^{-3}	
e^- 20 GeV	0.950	0.949	0.947	
π^- 40 GeV	5.1×10^{-3}	2.5×10^{-3}	2.5×10^{-3}	
e^- 30 GeV	0.956	0.955	0.954	
π^- 40 GeV	0.8×10^{-3}	0.8×10^{-3}	$< 0.8 \times 10^{-3}$	
e^- 40 GeV	0.990	0.988	0.988	

(1) P_{total} vs. P_1/P_{total} .

(2a) Lateral shower spread (second moment) of 2nd segment pad chamber.

(2b) Lateral shower spread (second moment) of 2nd strip chamber (cathode).

(3) Lateral shower spread (fourth moment) of 2nd segment pad chamber.

As discussed by Diebold et al.,⁶ interactions of pions with material in front of the calorimeter can worsen the pion rejection factor. The chance for a zero prong interaction such as $\pi^- p \rightarrow \pi^0 n$ is proportional to the material thickness in terms of the absorption length and is estimated to be 0.8×10^{-3} in 7.6 cm of aluminum at 30 GeV. This should give a rough indication of pion survival rate. The zero prong probability decreases with increasing pion energy.

There scarcely exist systematic measurements of the dependence of the pion rejection on the amount of material in front of sampling shower calorimeters. We discuss experimental results of lead glass shower detectors in order to get some ideas about absorber effects. Figure 5.3.3 shows energy spectra for 3 GeV pions and electrons from a lead glass counter (SF03) of $18X_0$ measured by K. Ogawa et al.¹⁴ When particle energies are determined with accuracy better than the energy resolution of the counter for electrons, only pions which give the same pulse heights as electrons are misidentified as electrons. In such cases the pion rejection factor is about 2×10^{-3} at 3 GeV for the electron acceptance of 96%. Misidentified pions are likely to correspond to those pions which have zero prong interactions in the upstream region of the counter. If effects due to the light attenuation inside the lead glass detector can be compensated,¹⁸ the pion rejection factor is determined primarily by the energy resolution of the counter for electrons.

Material in front of the shower counter generally degrades the energy resolution and pion rejection factor of the counter. Figure 5.3.4 shows the energy resolution as a function of the electron energy for aluminum absorbers with various thicknesses. Above 4 GeV the energy resolution is essentially not degraded by aluminum absorbers thinner than $1.5X_0$. Energy spectra for pions in the lead glass detector were measured to be nearly equal for aluminum absorbers thinner than $1.5X_0$.¹⁷

Micke, Trines, and Wallraff¹¹ studied the pion misidentification probability after inserting 10cm of aluminum in front of their lead liquid argon calorimeter, which corresponds to a total amount of $1.3X_0$ material in front of the active part of the detector. They observed a small increase in the misidentification probability at 2, 5, and 10 GeV. They pointed out that an improvement of π/e discrimination could be achieved by cutting on the pulse height in the first strip system. Combining all cuts they obtained a pion rejection rate of $(4 \pm 2) \times 10^{-3}$ at 10 GeV for an electron efficiency of 97%.

It can be concluded that additional material in front of an EM shower detector can in principle degrade the energy resolution for electrons and the pion rejection factor, but in practice effects due to an aluminum absorber of 1 to $1.5X_0$ are small at electron energies greater than about 10 GeV.

Electron identification can be provided by calorimetry over the full electron energy range expected at the SSC. Pion rejection factors of $\sim 10^{-3}$ can be expected by using combinations of E/p and shower development criteria. At energies above ~ 1 TeV, only shower development is likely to be viable as magnetic tracking resolution becomes very poor, at least in a typical 4π detector. The limitations to measuring shower development in large calorimeter systems will arise primarily from mechanical complexity and cost considerations, not the fundamentals of electromagnetic showers. Finally, for those experiments at the SSC which are investigating high mass/high energy phenomena, the effects of inert absorbing material preceding electromagnetic calorimetry will be small, possibly simplifying the mechanical design of detectors.

5.3.2 Electron Identification: Transition Radiation

A number of reviews^{18,19} of the principles of transition radiation detectors (TRD) exist in the literature and we will not discuss them here. Transition radiation is a well established method of electron identification and

hadron rejection. Our interest is in the limitations of transition radiation for high energies and at large particle fluxes.

A typical transition radiation detector consists of thin foils of, for example, lithium or CH_2 followed by a wire proportional chamber containing Xenon (and other gases) to detect the soft X-ray transition radiation photons. The number of photons detected first changes rapidly with γ , the Lorentz factor for the particle traversing the foil, and then reaches a saturation value. The response of a single module of TRD from a recent experiment²⁰ is shown in Fig. 5.3.5. Since saturation occurs at a particular value of γ , electron/pion discrimination is lost. Indeed pion rejection factors are degraded before saturation is attained. A typical calculation²¹ of the pion rejection vs. momentum is shown in Fig. 5.3.6. Under optimal conditions, the ability of a TRD device to reject pions rapidly becomes poorer for momenta above approximately 200 GeV. However, since backgrounds are typically larger at lower momenta, and because calorimetry (with or without charged particle tracking) is also poorer at rejecting hadrons, additional pion rejection for momenta < 200 GeV could be very useful in many experiments at the SSC.

Since the detection of TRD in a practical device requires a wire chamber X-ray detector, limitations at high particle fluxes will arise as in any wire chamber. Such limitations have been discussed in more detail in the report of the Working Group on Tracking Detectors (section 3). Two problems are particularly severe for TRD detectors: slow gases and the desire to do cluster counting. A typical TRD detector gas is Xenon + CH_4 (for example a 70:30 mix) which has a slow drift velocity of about 2cm/ μs (typical drift chamber gases like 50:50 Argon-ethane have drift velocities of about 5cm/ μs). The absorption of X-rays in Xenon leaves dense clusters of electrons which drift toward the anode wires. Identification of the clusters can be done by analyzing the

waveform on the anode wire. This obviously works best for a thick gas path length for the TRD and slow drift velocities. Neither of these is attractive at high rates at the SSC.

In conclusion, transition radiation may be very useful for electron identification and hadron rejection in the momentum range < 200 GeV. The major technical limitations result from the demands at high luminosity - slow gases in the wire chamber detectors of the X-ray TRD, and also the usual possibility of radiation damage to such chambers. Our recommendation is to search for faster gas mixtures appropriate for use in a TRD detector, and to test the gases now in use for their susceptibility to radiation damage.

5.3.3 Electron Identification: Synchrotron Radiation

The idea of using synchrotron radiation for electron identification has been explored for many years at various workshops,²² most recently at the Snowmass 1984 Workshop by R. J. Morrison.²³ The energy lost by an electron traversing a magnetic field is approximately given by

$$\Delta E(\text{in KeV}) \approx 0.013E^2B^2L,$$

where E is the electron energy in GeV, B the magnetic field in kG, and L the path length in meters. The critical energy is defined to be²⁴

$$E_c(\text{in KeV}) = 0.133E^2B.$$

The number of photons radiated (N) is independent of E and is given by

$$N = 0.6BL.$$

The radiated photon spectrum²⁵ is shown in Fig. 5.3.7. The energy lost and the critical energy are plotted vs electron energy for $B = 15\text{kG}$ and $L = 2\text{m}$, reasonable values for a large 4π detector at the SSC, in Fig. 5.3.8. The

energy lost is substantial in the TeV region, greater than 10 GeV for $E > 1$ TeV.

Since the number of radiated photons does not depend on E , the photon energy spectrum merely shifts to higher energies as E increases. Applications of synchrotron radiation heretofore have concentrated on detecting the X-ray photons emitted from electrons of energy of the order of 10 GeV. At higher electron energies this is not feasible, since the number of photons which have energies within the detection range of an X-ray detector, typically a Xenon proportional chamber, decreases with energy.

At high energies it has been proposed²⁴ to convert the synchrotron radiation photons in a thin converter (10-20% of a radiation length) or series of such converters. The photon conversion probability is substantial for photons of energy greater than 5 MeV. In Fig. 5.3.9 the number of synchrotron radiation photons with $E > 5$ MeV is plotted vs. electron energy. The number becomes usable at about 100-150 GeV. These converted photons would be spread over distance d from the electron track approximately given by $d/\text{mm} \approx 15 BL^2/E$, or about 9mm at $E = 100$ GeV. Converted photons could possibly be detected by the presence of additional ionization in tracking detectors placed after the converters, spatially correlated with the electron track. Since the converters and the tracking devices would most likely be located within the magnetic field, the curl-up of the soft electron-positron pairs from the converted photon must be accounted for in any calculation. The radius of curvature of a 5 MeV electron in a 15kG field is about 1cm. There will, of course, be radiation from the passage of the electron which will also aid in identification.

The presence of considerable additional ionization near an electron track could yield a substantial rejection against hadron tracks. This technique of using synchrotron radiation at high electron energies deserves additional study

with shower simulation programs such as EGS, including the effects of magnetic field. If such studies indicate that this technique has promise, then beam tests for high energy electrons should be done. Such tests would be rather modest in cost since they require little apparatus. If this method is viable, it would be a rather cost effective way of enhancing hadron rejection at high electron energies and could be designed to operate at high luminosity.

5.3.4 Summary of Electron Identification and Recommendations

The effective electron energy coverage of calorimetry, transition radiation, and synchrotron radiation (assuming that using synchrotron radiation at high energies is a viable technique) is shown in Fig. 5.3.10. Neglecting rate limitations for the moment, at least two methods span the entire energy range accessible to the SSC with the assumption above.

Our recommendations for detector R&D related to electron identification are modest and follow below.

- (1) Additional workshop-type studies of detector parameters (calorimeter granularity, hadron rejection factors, trigger requirements, etc.) for electron identification and detection in SSC experiments are needed. Such studies would to some extent serve as guides to future detector development.
- (2) Transition radiation detectors share the same limitations as all wire chamber devices at the SSC; susceptibility to radiation damage and possibly inadequate operation at high rates. Gas mixtures traditionally used in transition radiation detectors should be tested for radiation damage and operation at high rates. New gases should be developed if necessary.

- (3) The possibility of using synchrotron radiation to identify electrons for electron energies greater than 100 GeV should be investigated. Monte Carlo studies should be done and must show promise for this technique before beam tests are performed.

30 GeV/c

Fig. 5.3.1 Typical pulse height spectra in an electromagnetic and hadronic calorimeter for electrons and pions at 30 GeV (ref. 6).

Fig. 5.3.2 A two dimension plot of the total pulse height (p_{tot}) vs. the pulse height from the first segment (p_1) normalized to p_{tot} ; (a) for 10 GeV electrons, and (b) 40 GeV pions. The dotted line indicates a cut in the scatter plots (ref. 7).

Fig. 5.3.3 Energy resolution of and SF03 lead glass counter (18X₀) with aluminum absorbers of different thickness in front (ref. 14).

Fig. 5.3.4 Energy spectra from 3 GeV pions and electrons for an SF6 lead glass counter (ref. 14).

Fig. 5.3.5 The number of detected photons in a TRD module vs. γ (ref. 20).

Fig. 5.3.6 Pion rejection vs. momentum for a TRD system (ref. 21).

Fig. 5.3.7 The synchrotron radiation spectrum (ref. 25).

Fig. 5.3.8 The total energy lost (solid line) and critical energy (dashed line) vs. electron energy from synchrotron radiation.

Fig. 5.3.9 The number of synchrotron radiation photons of energy $> 5 \text{ MeV}$ vs. electron energy.

Fig. 5.3.10 A summary of the energy range of various techniques for electron identification.

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Note that there exist different definitions of critical energy. The definition often used in synchrotron radiation work and discussion of accelerators uses a coefficient of 0.067 instead of 0.133.
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5.4 Hadron Identification

We now discuss some aspects of light hadron identification using ring imaging Cherenkov counters.

5.4.1 Ring Imaging Cherenkov Counters

The current (1986) limits on resolution for ring imaging Cherenkov (RICH) detectors are presented below. The rms error $\Delta\theta$ to which the Cherenkov angle θ can be measured is ultimately limited by chromatic effects in the radiator gas medium. This error is:

$$\Delta\theta = \Delta\theta_{\infty} / \sqrt{1 - \gamma_t^2 / \gamma^2} \quad \text{with } \Delta\theta_{\infty} = (dn/dE)(\Delta E / \sqrt{12})(\gamma_t - 1 / \gamma_t), \quad (1)$$

where n is the radiator refractive index, E the photon energy, and $\gamma_t = n / \sqrt{n^2 - 1}$ is the threshold Lorentz factor of the radiator medium. The quantity dn/dE is the dispersion of the medium and ΔE the full width energy acceptance of the detector. Measurements show that for the best radiator media (He, Ne, CF_4 , C_2F_6 , C_3F_8 etc.)

$$\Delta\theta_{\infty} / \theta_{\infty} = 5 \times 10^{-3} \quad (2)$$

for photons in the energy interval 6.2 to 7.8 eV. This interval is the energy acceptance of a RICH detector with TMAE as the photosensitive gas, the best quality quartz window and the highest reflectivity UV mirror. Under these conditions a Cherenkov quality factor $N_0 = 150 \text{ cm}^{-1}$ is obtainable. The number of photoelectrons, N , on a ring image is given by the relation

$$N = N_0 L \sin^2 \theta, \quad (3)$$

where L is the radiator length. Note that the Cherenkov angle θ may be

written

$$\sin^2 \theta = (1/\beta^2)[(1/\gamma_t^2) - (1/\gamma^2)],$$

or

$$\theta = \theta_\infty \frac{[1 - \gamma_t^2/\gamma^2]^{1/2}}{[1 - 1/\gamma^2]^{1/2}} \quad (4)$$

with $\theta = 1/\gamma_t$ the Cherenkov angle at $\gamma \gg \gamma_t$.

At a given momentum p the quantity $(\theta_\pi - \theta_k)/\Delta\theta_\pi$ represents the number of standard deviations n_σ to discriminate against a pion being misidentified as a kaon. For N points on an image, the angular error $\Delta\theta_\pi$ is reduced by a factor $\sqrt{N}$ hence

$$n_\sigma = \frac{\theta_\pi - \theta_k}{\Delta\theta_\pi} \sqrt{N}. \quad (5)$$

Using relations Eqs. (2), (3), (4) and (5) gives

$$n_\sigma = [(\theta_\pi - \theta_k)/\Delta\theta_\infty] \sqrt{1 - \gamma_t^2/\gamma_\pi^2} \sqrt{N_0 L} \theta_\infty \sqrt{(1 - \gamma_t^2/\gamma_\pi^2)/(1 - 1/\gamma_\pi^2)} \quad (6)$$

$$n_\sigma = [\sqrt{N_0 L}/5 \times 10^{-3}] (\theta_\pi - \theta_k) (1 - \gamma_t^2/\gamma_\pi^2) / \sqrt{1 - 1/\gamma_\pi^2}.$$

The last factor rapidly approaches unity when $\gamma_\pi \gg \gamma_t$. From Eq. (4) the angle difference $(\theta_\pi - \theta_k)$ may be expanded as a power series in $1/p^2$ i.e.,

$$\theta_\pi - \theta_k = [(m_k^2 - m_\pi^2)/2p^2] [\gamma_t - 1/\gamma_t] [1 + (1/4)(\gamma_t^2 - 1)(m_k^2 + m_\pi^2)/p^2 + \dots] \quad (7)$$

Substituting Eq. (7) into Eq. (6) and neglecting the last factor in each yields

$$n_\sigma = 100 \sqrt{N_0 L} \gamma_t (1 - 1/\gamma_t^2) (m_k^2 + m_\pi^2)/p^2 \quad (8)$$

For a fixed number of photoelectrons N on the image, γ_t is fixed as

$$\gamma_t = \sqrt{N_0 L/N}. \quad (9)$$

Hence, Eq. (8) becomes

$$p^2 = (100/n_\sigma)(N_0 L / \sqrt{N})(1 - N/(N_0 L))(m_K^2 - m_\pi^2) \quad (10)$$

from which it is seen that the momentum p for a given separation n_σ scales like $\sqrt{L}$. This means that if the counter length is increased by a factor 4 the upper momentum limit for separation increases only by a factor 2. Taking as a numerical example $N_0 = 150\text{cm}^{-1} = 15000\text{m}^{-1}$ and $N = 25$, $n_\sigma = 4.2$ (corresponding to 1% misidentification) gives $p^2/L = 1.65 \times 10^4 \text{GeV}^2/\text{m}$. For $K\pi$ discrimination the factor is 4.53×10^4 , for πe 1.4×10^3 and for $\pi\mu$ 6.86×10^2 . The momenta at which 1% misidentification occurs (p_1) are plotted in Fig. 5.4.1. At momenta below p_1 the number n_σ rises as $1/p_2$ and rapidly becomes larger.

The detection of the ultraviolet photons from the Cherenkov radiation is done in a wire chamber device using TMAE (or a similar photoionizing material) to convert the photons to electrons. The liberated electrons are then detected in wire chambers of a variety of designs.¹ The detection of the Cherenkov rings requires at least two dimensional space coordinate information and detection in depth of the photon conversion point in the TMAE gas mixture may also be required. This imposes some severe requirements on RICH detectors for high luminosity operation at the SSC. Measurement of one of the space coordinates by drifting long distances (as in DELPHI and SLD)¹ is not a viable option for luminosities even 10-100 times less than the design luminosity of the SSC; too many events would overlap within the drift time. While it is technically feasible to construct wire chambers with pad readout that can quickly determine in two dimensions the location of the electrons from photoionization, the resultant cost in electronics to read out each pad individually is extremely large with present techniques. Also, because wire

chambers are used as the Cherenkov photon detectors, the usual problems of high rates and radiation damage discussed in Chapter 3 will also arise at high luminosity.

5.4.2 Recommendations for Hadron Identification

Our recommendations regarding light hadron identification using RICH detectors are given below.

- (1) Additional study is required to quantify the requirements (momentum range, spatial segmentation, etc.) for light hadron identification for experiments at the SSC. If studies indicate a need for such light hadron identification, then R&D as outlined below will be needed.
- (2) The development of RICH detectors with much shorter response time will be required for the SSC, and R&D in this direction should be encouraged. As part of such R&D efforts, studies of radiation damage to gases used in RICH counters should be done. The development of detectors with greater photon detection efficiency, particularly of lower energy photons, should be encouraged.
- (3) We note that a major limitation to the viability of RICH counters at the SSC may be the electronics systems required for chamber readout. The development of cheap, highly integrated wire chamber readout is likely to be required.

Fig. 5.4.1 The momentum at which 1% misidentification occurs vs. RICH counter length.

Reference

1. See D. W. G. S. Leith, SLAC-PUB-3829 for a recent review.

CHAPTER 6

Report of the Working Group on Electronics, Triggering, Data Acquisition and Computing

6.1 Introduction

The charge to this subgroup was to review the present R&D in the four named areas, with special emphasis on aspects of particular relevance to the SSC. In addition to this review, estimates of the scale of these items in likely SSC detectors were requested, as well as projections of the R&D in these areas needed for successful construction and operation of the detectors at the SSC. If possible, priorities for the different R&D needs were to be assigned, as well as likely support levels necessary to carry out this R&D in time to be applied to the detectors. With the exception of the Electronics section, the recent FNAL Workshop on "Triggering, Data Acquisition, and Computing for High Energy/High Luminosity Hadron-Hadron Colliders" has provided most of the up-to-date information on the current status of R&D in the areas covered by this chapter. For that Workshop and for the purposes of this report, a reference detector for the SSC consists of the following elements:¹

- Coverage in rapidity between ± 5.5 units.
- Charged particle tracking with 100 samples per track and with drift times of 100 ns: 175,000 wires instrumented with drift time measurement and pulse height measurement at both ends (charge division for the coordinate along the wires).
- Calorimetry with 50,000 towers of 3 longitudinal segments each. Wide dynamic range pulse height measurement is provided by two gain ranges with some means of separating signals from nearby crossings.

- Muon tracking using 100,000 wires with drift time and charge division measurements.
- Total electronics channel count of 850,000.
- Some technique of waveform sampling to be used for signal digitization in all detector types, providing the multihit capability necessary for tracking devices and the pulse shape information necessary to deconvolve calorimeter pulses. The total information content of all samples before zero suppression will be 20-80MBytes, depending on the details of the detector. After zero suppression and encoding of the data, an accepted event is estimated to be about 0.4MBytes in size.
- Vertex detection is to be treated as a special case and is not considered here.

Reference

1. A. Lankford and G. Dubois, Overview of Data Filtering/Acquisition Working Group - Subgroup A: Requirements and Solutions, Proceedings of the FNAL Workshop on Triggering, Data Acquisition and Computing for Higher Energy/High Luminosity Hadron-hadron Colliders, (Mar. 1986).

6.2 Electronics

The three generic detectors studied at Snowmass in 1984 set the scale of the detectors which will be proposed for use at the SSC. This scale is a total capital cost of approximately \$250M to \$350M, with the electronics, data acquisition, and computing systems representing one third to one half of this total. There are typically 200K to 850K electronic channels in these detectors, with the model detector outlined in the introduction at the upper end of the scale. If the present day technique of transporting the signals by cable from the detector element to remote electronics was to be employed, the cross section of the cables coming from the central tracking system alone would be one square meter, which would necessarily be inert as far as the calorimetry is concerned.

The earliest development of custom integrated circuits for High Energy Physics was carried out by the MPS Group at Brookhaven National Laboratory. E. Platner and his collaborators first developed an LSI level gated memory (TTL) for triggering the MPS detector, and subsequently developed a two chip set (amplifier-discriminator and fast shift register TDC) for drift chambers in silicon on sapphire (SOS) technology.¹ RCA designed this latter chip set to BNL specifications. Recently, a number of custom devices have been successfully developed to meet specific detector needs. T. Walker of Stanford, S. Parker of U. of Hawaii, and their collaborators have developed the microplex chip, a 128 channel amplifier, double sample and hold, and readout multiplexer for silicon strip detectors;² the SLD collaboration has developed the micro-store analog memory chip set.³ These recent devices have been implemented in 5μ feature size NMOS technology and are at the LSI to VLSI level of complexity. 5μ NMOS is a widely accepted industry standard, with a large number of vendors willing to transform the design files created from a variety of CAD work stations into working silicon devices. In the near future, 1.25μ CMOS

will be in the same state of maturity, and is more attractive because of the enhanced speed from the smaller feature size and the higher analog gains available from complementary devices. The smaller feature size also improves the radiation hardness of the devices.

As can be seen from these few examples, the cost of development of custom monolithic ICs for HEP detectors is now at an affordable level: it is at the same stage as thick film hybrids were several years ago. As an example, it is now cheaper and more reliable to package typical drift chamber front ends and TDCs as thick film hybrids than as printed circuit boards. There is a large potential payoff in cost savings, reduced complexity and increased reliability to be gained by employing custom VLSI integrated circuits.

6.2.1 Available Technologies and Design Tools for Developing Application Specific Integrated Circuits (ASICs)

As the silicon industry becomes more mature, custom application specific integrated circuits (ASICs) are an increasingly interesting and cost effective alternative to past solutions of detector electronics problems. Generally, there are excellent design tools available, which currently range from CAD/CAE stations (using IBM PCs or microVAXs as the host computer), to design centers with minicomputer, to supercomputer hosts with very powerful placement and routing software and simulation software for both analog and digital circuits. In the recent past, only the latter expensive systems were available, and only industry could afford them. This precluded their direct use by designers of HEP electronics. That situation has now changed. The spectrum of technologies available today ranges from 5μ to 1.25μ NMOS and CMOS, and includes bipolar and GaAs devices. Some of the design techniques require little training and only minimal design skills, while a full custom mixed analog and digital design

requires extensive training, special skills and extensive experience to complete the design successfully.

During the recent LBL Workshop on New Solid State Devices for High Energy Physics, the main activities of the Electronics Subgroup were to assess the present high energy physics experience with application specific integrated circuits, to understand the investment necessary to develop full custom linear and digital integrated circuits with VLSI complexity, and to attempt to list devices likely to be developed in the future.⁴ One important consideration in their deliberations was the implication of the likely radiation environment on the designs of fully customized integrated circuits to be used with detectors at the SSC.

The steps necessary to produce a full custom VLSI circuit were outlined by S. Kleinfelder⁵ (LBL), in a talk presented to the Electronics Subgroup at the LBL Workshop. As an example of the low cost end of the CAD/CAE spectrum, the design tools he uses are public domain software which run on any VAX operating under UNIX or under a UNIX shell in VMS. The buy-in cost is then the price of a good color graphics terminal and an account on your local VAX. These programs, the 1985 Berkeley VLSI Design Tools, are:

- MAGIC: a program which enables the designer to create and edit circuits graphically. It verifies that the designed circuit contains no design rule errors, extracts an electrical model of the circuit for simulation, and produces a file (CIF format = Caltech Intermediate Form) from which the circuit can be fabricated.
- PLA TOOLS: a set of programs to generate and optimize programmable logic array layouts.
- CRYSTAL, ESIM, and SPICE: programs to do timing analysis and circuit simulation.

- MPACK, MQUILT: programs to generate personalized semi-regular arrays of subcircuits.
- CIFPLOT: a program to plot layouts from CIF files.

His paper, which includes a full description of the software and the necessary steps to carry out a complete design, is an appendix to the LBL Workshop Report. For copies of the programs and their associated documentation, write to Dr. John Ousterhout, CS Division, Dept. of EECS, Univ. of Calif., Berkeley, CA 94720. They are available free of charge to Universities and to Government agencies.

There are many foundries willing to convert CIF design files into silicon devices. One is MOSIS (Metal Oxide Semiconductor Implementation Service), a fast turn-around prototype foundry located near Palo Alto, CA. They are sponsored by NSF and ARPA and will turn CIF design files into silicon for a cost of under \$6k (perhaps free to NSF supported groups).

There is a variety of commercial CAD/CAE products available which have been extensively used by industry, e.g. the Daisy System, VTI, and others. They are more expensive but may offer considerable advantages in developing a successful custom VLSI design.

One of the first steps in industrial participation in HEP custom IC electronics development outside LeCroy was also presented at the LBL Workshop. This is a European development effort for analog shift register CCDs which was described by Eric Heinje (CERN).⁶ Philips has provided very close industrial support for the project.

6.2.2 VLSI Development for High Energy Physics

The development of the microplex chip is already under way. A group at LBL has begun a project to produce a CMOS version of this chip for the proposed silicon vertex detector in the CDF detector at FNAL. Both of these

projects are specifically aimed at solving the electronics packaging problem for narrow pitch silicon strip detectors. At the moment, these projects, along with the SLD analog memory unit chip set and the SLD digital data correction unit chip, are the principal activities in this country. Efforts at developing optical CCD arrays as precision particle tracking detectors have been omitted from this review because the very long memory time of these devices is inappropriate for SSC detectors.

An excellent candidate for a more advanced project to give experience in developing ASICs for HEP would be a high input sensitivity multihit drift chamber TDC chip, or chip set, providing 120 micron resolution at gas gains of 10^4 . This would be a generally useful development which could also be used in upgrades to present large detector tracking systems. Once the layout is complete, the cost of producing prototypes of the circuit in silicon is less than \$6k. The largest cost would be in the released time necessary to learn how to use the CAD software and to go through the several rounds of design and modification necessary to realize a successful circuit. It would be an excellent way to learn how to produce custom ICs.

One of the conclusions reached at the FNAL Workshop on Triggering, Data Acquisition and Computing was that an essential feature of the front end electronics is the capability of delaying the analog information for at least 500ns, to allow the level one trigger to act in a deadtime-free fashion. As mentioned in the Analog Trigger section below, there are several possibilities to produce this delay. Along these lines, a more ambitious second design project might be to incorporate a fast ADC and memory on the same chip, perhaps combined with a sparsifier to suppress zeros, to provide both the waveform digitization and the delay. It is important to start these second stage

projects as soon as possible to gain the necessary experience for reliable estimate of the effort required to develop the circuits needed for SSC detectors.

6.2.3 Radiation Damage in VLSI

The radiation damage question arises for the large detector systems that will be used at the high luminosity interaction regions of the SSC and for high intensity fixed target experiments where the silicon devices are part of an active target. In contrast to the situation for the electronics in the tunnel of the SSC, where the radiation field is almost entirely low energy neutrons, the radiation field for the detectors has equal numbers of high energy charged particles and photons, with an unknown but probably smaller number of neutrons. For the full luminosity of $10^{33} \text{ cm}^{-2} \text{ s}^{-1}$, the radiation exposure of electronics which might be mounted on the end plate of a large central drift chamber would vary from 10^6 rads per year near the beam pipe to 10^3 rads per year at the outer edge of the chamber. Even the lower level is uncomfortably close to the radiation damage limit for conventional commercial VLSI CMOS which, because of low power dissipation and adequate speed, is the likely choice for the electronics. For modern 1.25μ feature size devices, with careful attention given to the processing steps for the gate oxide layer, this limit is probably a few times 10^4 to 10^5 rads. There are NMOS and CMOS devices available from industry, primarily Sandia and Harris, which have been hardened to $> 10^6$ rads. The cost of these devices, however, is high at the moment because of their low production volume.

In response to this radiation damage issue, a special evening session was organized at the IEEE NSS meeting held in San Francisco, October 23-25, 1985.⁷ A summary of typical SSC detector parameters was given in a talk by

D. Hartill, and a detailed talk on radiation damage in VLSI circuits was given by C. F. Gibbon of Sandia National Laboratories.

One of the questions raised during the IEEE evening session was whether there are any gains to be realized by concentrating on less developed technologies such as GaAs or silicon MESFETS. Gallium arsenide transistors use junctions or Schottky barriers as gates since there is no stable gate dielectric in this material. Published results⁸ indicate that discrete transistors can survive 10^7 rads with similar results for silicon MESFETS⁹. The problem with these technologies is that, at present, GaAs ICs are barely at the LSI stage and are developing very slowly. There has been no extensive commercial development, implying a probable large cost per part. These features make this technology unattractive for high energy physics detectors. Silicon MESFETS are at an even earlier stage of development and are equally unattractive. Neutron irradiation of single crystal silicon and GaAs produces small clusters of point defects which act as recombination centers, reducing minority carrier lifetimes. Since field effect transistors are majority carrier devices, silicon MOS and GaAs ICs have little performance degradation in neutron fluences up to 10^{14} neutrons/cm². The gain of bipolar transistors depends on the minority carrier lifetime in the base region, and gain changes can be seen for fluences as low as 10^{12} neutrons/cm². Fast bipolar devices suitable for VLSI are at least an order of magnitude less sensitive to neutron damage because of their small feature size. Table 6.2.1 summarizes the radiation hardness of presently available technologies suitable for VLSI devices. The upper limits given in the table assume that the devices have been hardened.

Table 6.2.1.

Radiation Damage Characteristics of IC Technologies

Technology	Total Dose (rads)	Upset (rads/sec)	Latchup (rads/sec)	Neutrons (α/cm^2)	Single Event Upset (error/bit-day)
NMOS	10^3-10^6	4×10^7	None	$> 10^{15}$	Sensitive
CMOS	10^5-10^7	10^9	10^{12}	$> 10^{15}$	$< 10^{-8}$
CMOS/SOS	$> 10^6$	10^{11}	None	$> 10^{15}$	$< 10^{-8}$
BIPOLAR	10^4-10^6	2×10^7	Possible	$10^{13}-10^{14}$	$> 5 \times 10^{-5}$
GaAs	$> 10^7$	No Data	None	$> 10^{15}$	3×10^{-6}

6.2.4 High Energy Physics Experience in VLSI Radiation Damage

The development of custom VLSI circuits for high energy physics experiments is in its infancy. There have been several LSI devices developed as preamplifiers, discriminators and timers for drift chamber applications. These have been both bipolar silicon and SOS devices, and their radiation hardness has not been investigated. S. Parker and his collaborators have carried out³ preliminary radiation damage measurements on three microplex chips, and have found a radiation hardness of more than 10^6 rads (Co^{60}) in the power-off state. Powered with a 25% duty cycle to simulate their probable operation in the upgraded Mark II detector for SLC, three other devices failed at 10^5 rads (Co^{60}). This corresponds to a power-on hardness of 2.5×10^4 rads for these devices, which is similar to the performance of commercial 5 micron NMOS VLSI devices. Threshold shifts of several volts were observed during the irradiation, and clock drive voltages had to be changed to keep the devices operating. Two other custom VLSI devices, the microstore and the CDU, have been developed by T. Walker and by the SLD collaboration³ as mentioned

above. Although radiation damage tests have not been carried out for these devices, similar performance is expected since they are also 5μ NMOS devices. Small scale radiation damage tests of commercially available buried channel optical CCD imagers have been carried out, with both Co^{60} radiation and particle beams. These devices are being evaluated for use as precision fine granularity charged particle tracking detectors in vertex detectors in fixed target experiments, and for the SLD detector at SLAC. Performance degradation is observed after a few times 10^4 rads in particle beams because of threshold voltage shifts from trapped charge. Good performance can be regained by suitable operating voltage shifts, but after an integrated dose of a few times 10^5 rads the charge transfer efficiency drops rapidly, rendering the devices useless¹⁰. Radiation hardening techniques may improve CCD hardness to 10^6 rads. In conversations with C. F. Gibbon¹¹ (Sandia), during the IEEE NSS meeting in San Francisco, a non-recurring engineering cost of \$200k was mentioned as the cost of hardening an existing design in 5μ NMOS or CMOS. The production cost is comparable to that of a normal part, but the list of qualified foundries is much smaller. The situation with radiation damage in VLSI devices can be best summarized by the curve in Fig. 6.2.1. The vertical axis is some combination of effort, pain, and cost.

The bottom line is that for the main central tracking chamber electronics, present radiation hardened CMOS ICs have adequate radiation hardness. The only impact is that a working design must be ready a year in advance of production so that the radiation hardening step can be completed.

6.2.5 Electronics - Conclusions and Proposed R&D Program

The era of custom VLSI integrated circuits developed specifically for use in high energy physics is at hand. The available public domain software design tools make the process affordable even by small groups at universities. Potentially, the capability of developing these custom circuits provides the same kind of breakthrough technology as did the original development of multi-wire proportional chambers and drift chambers.

It will be possible to build custom CMOS VLSI devices which are radiation hard to 10^6 rads in time for use in possible tracking systems in SSC detectors. To make this possibility a reality, high energy experimentalists must acquire much more experience in custom IC design in order to develop the desired parts. System reliability studies must be then carried out and design modifications made to accommodate the likely decrease in the mean time before failure of even radiation-hardened parts in the environment of the tracking detectors. Finally, the modified design must be radiation hardened. Development of each hardened part will require at least a year and cost between \$100k and \$200k. It is likely that the list of silicon foundries capable of producing the radiation-hardened part will be short, implying a modest increased cost for the part.

By mounting an R&D effort in electronics in the near future, a successful and affordable SSC detector can be assured. The first step in such an R&D program is to understand the needs and specifications of electronics systems for SSC detectors, for which presently there is no comprehensive picture. It is clear however that the following areas must be addressed by any R&D program:

- study of radiation damage characteristics of presently available commercial CMOS devices, and likely improvements in the near term;

- training of high energy physicists to use semiconductor industry standard CAD tools;
- development of experience in producing VLSI integrated circuits;
- development of simulation techniques to predict the performance of these complex systems at the very high data rate of the SSC.

We would also like to note that industrial participation in the early stages of such an R&D program would be very useful. The identification of a few chips or chip sets to be developed in collaboration with industry should be a near term goal.

Finally, SSC detectors will be large complex devices, and if they are to be successful a much higher level of systems engineering, including particular attention to systems reliability, will be required compared to present-day large hadron collider detectors such as CDF, DO, and UA1. As an example, the mean time to failure for typical solid state electronic components decreases by a factor of two for every 10°C increase in operating temperature. This necessitates careful attention to the cooling systems for large electronic systems in small volumes. The system design includes both the software and the hardware, with the distinction between electronics, data acquisition, triggering and computing becoming very fuzzy in detectors of the SSC class. As a result, the complete system must be optimized.

Fig. 6.2.1 Effort required to achieve a certain radiation hardness.

References

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6.3 Triggering and Data Acquisition

Will it be possible to trigger an SSC detector operating at an interaction region where a luminosity of $10^{33} \text{ cm}^{-2} \text{ s}^{-1}$ causes a primary interaction rate of 10^8 per sec? The FNAL workshop gave a preliminary answer of yes to this important question by using a three level trigger scheme. As an example, two new physics processes, $H \rightarrow W^+ + W^-$ and $pp \rightarrow \text{gluino} + \text{gluino}$, were considered in detail¹ by the SSC Physics Signatures and Trigger Requirements working group at the workshop. In both cases, trigger strategies were found which gave an overall trigger efficiency of greater than 25%, and trigger rates of 0.1 and 0.2 per sec respectively. Table 6.3.1 summarizes the trigger strategy for the first reaction. For the second, the first level trigger requires $E_T(\text{miss}) > 100 \text{ GeV}$, with similar jet requirements by the second and third level triggers.

From the table, by far the largest reduction factor comes from the first level trigger, with substantially smaller factors coming from the subsequent trigger levels. For signatures and trigger strategies looked at so far, this seems to be a common feature. In some sense, it is driven by available technology since it is necessary to throw out quickly as many minimum bias events soon as possible to limit the data flow through the system. After a description of the expected event size, the following sections give a brief summary of the results of the studies carried out during the FNAL Workshop, then a description of the R&D needed to achieve workable trigger and data acquisition systems and off-line computing facility for SSC detectors.

Table 6.3.1

Summary of trigger strategy and ISAJET results for $H \rightarrow W^+W^-$.

<u>Trigger Selections</u>	<u>Rejection Factor</u>	<u>Remaining Cross-Section(nb)</u>	<u>H $\rightarrow$ WW Efficiency</u>
<u>First Level:</u>			
a) Select electron candidate as calorimeter cell with $E_T > 25$ GeV and with at least 80% of the energy electromagnetic	10 ⁴	3x10 ⁴	0.86
b) Require $P_{T,miss} > 40$ GeV for the event	4	7500	0.43
<u>Second Level:</u>			
a) Require the electron candidate to be isolated, with a surrounding region of ± 5 calorimeter cells in both y and θ containing less than 20% of the E_T of the electron candidate cell	1.5	5000	0.37
b) Make a jet requirement of either 1 jet having $E_T > 80$ GeV or 2 jets each having $E_T > 40$ GeV	20	250	0.32
<u>Third Level:</u>			
Require that tracking show a charged particle with $p_T > 10$ GeV pointing to the candidate electron calorimeter cell.	220	1.1	0.32

6.3.1 Event Size

The typical minimum bias interaction event at the SSC is expected to have about six charged particles (and three neutrals) per unit of rapidity. In the model detector, covering 11 units of rapidity, there will be about 66 charged tracks in the tracking detectors and about 100 charged and neutral particles in the calorimeters. For an event with a multijet trigger at a jet threshold of 500 GeV, there may be 30-40 charged particles per jet plus a background which resembles a minimum bias event. For two jets, there will be about 150

charged tracks and for four jets, about 200. Typical event size calculations assume a total of 200 charged particles plus 100 neutrals. The overall event size from the model detector will be dominated by the tracking chambers, where there will be 100 hits per track (as compared with three samples per calorimeter tower). In addition, during the 100ns drift time of the tracking detector, there will be signals from interactions occurring during six other beam crossings. Thus, in addition to hits from tracks in the event of interest, there will be hits from the equivalent of nine minimum bias events. The total number of hits is then equivalent to the number from 800 charged particles, or 80,000 hits. Assuming that the drift time, pulse height, and third coordinate measurements from each wire can be reduced to five bytes, including a wire label, the 80,000 hits will produce 400kBytes of charged particle information. In the calorimeters, there will be about 1200 particles assuming resolving times of about 100ns, with three times as many for resolving times of 300ns. Allowing for an average of two hit towers per particle and three hits per tower, there will be 7200-22,000 hits per trigger. With timing information about the hits causing the trigger, hits from the events from different beam crossings can be rejected, leaving 3200 hits per trigger. At four bytes per hit, there would then be 12kBytes per event. There may be multiple samples per signal if high occupancies demand that signals from different crossings on a single channel be deconvolved;² assuming that this deconvolution is performed in hardware, only one sample per event is counted. It will be possible to pack the information from all three sections of a tower in six bytes with a label, leaving only 6kBytes per event. These numbers are negligible compared to the charged particle data. The quantity of data from the muon tracking system will also be negligible. As a result, 400kBytes of data are expected from a typical event after all reduction.

6.3.2 Analog Trigger and Data Acquisition

The Analog Trigger Working Group led by P. Franzini³ concluded that using only the calorimetry information for the level one trigger, it would be possible to achieve a factor of 10^4 reduction in the primary event rate. The 50,000 calorimetry towers listed in the introduction are or-ed together to form 5000 trigger towers. The average energy deposited per microsecond per trigger tower is 1.5 GeV from minimum bias events. This "noise" level determines the maximum number of trigger towers that can be combined without discrimination to form a single sum signal. This is particularly important in generating E_T and missing p_T signals, since it is possible to generate 100 GeV levels from "noise" if no discrimination is applied before adding the signals. The level one trigger then consists of suitably weighted sums of fast output signals with and without discrimination before the addition. The estimated time to form this trigger is from 500ns to 1 μ s, with a substantial fraction of the delay being in cable runs (250ns) to some common point. The results of the simulations for the first level trigger are listed in Table 6.3.1.

Table 6.3.1
Level One Trigger Rates

Trigger	Rate (kHz)
Isolated electron, $E_T > 25$ GeV	20
Missing $p_T > 50$ GeV	20
Total $E_T > 300$ GeV	10
2 Jets, each with $E_T > 40$ GeV	100

With slightly higher thresholds in each of these categories, and requiring two jets and an isolated electron, it looks possible to achieve an overall trigger rate of 10kHz at this level.

Since the beam crossing time is 15ns, with an average of 1.5 interactions per crossing, it is clear that the data acquisition system must store with each crossing the information from every channel, and keep it until the trigger information is available. This is quite different from the current generation of colliders (either $\bar{p}p$ or e^+e^-) where the beam crossing times are longer than the first level trigger decision times, and the information from every channel only has to be stored for one crossing. There are several techniques which can be used for this storage, including analog delay lines, analog shift registers, analog memory chips (such as SLD's AMUs), fast digitization followed by digital memory storage, or newer devices like surface acoustic wave devices (SAWs). One detector may use different techniques for different parts of the detector, or even a combination of techniques for one component of the detector. These front end systems are feasible but expensive with electronics systems which are either presently available or likely to become available within the next few years. But as mentioned in the electronics section, substantial cost savings may be realized by developing custom VLSI circuits.

Waveform sampling of drift chamber pulses, and the associated R&D being done for the front end systems of the detectors currently under construction, are relevant to future SSC needs. As mentioned above, implementing this capability in a VLSI circuit would be an excellent second stage R&D project to improve HEP expertise in VLSI design. A very important aspect of any fine grain sampling system is that the data be sparsified before leaving the device, otherwise the large quantity of data, mostly zeros, will overwhelm the downstream data acquisition system. One important question which can be answered

by more sophisticated simulation studies is whether this fine grained sampling, with its associated large cost, actually improves the track finding efficiency of the overall system. Because of chamber lifetime problems, small drift cells operating at low gas gain are the likely choice for tracking detectors, in which case fast low noise amplifiers with short clipping times followed by a discriminator and multihit TDCs may make more sense. More simulation studies are clearly needed, and would be an excellent topic of study for a working group at Snowmass 1986.

6.3.3 Medium Level Triggers and Data Acquisition

Once the analog trigger reduces the data rate to 10^5 triggers/sec or less, the problem is similar to triggering the current generation of detectors. The total quantity of data is, however, considerably larger. The second level trigger refines the analog trigger calculations, and can require isolated electrons in combination with a variety of jet topologies. Muon triggers have a large rate reduction at this stage, since the time scale permits crude track linking in the muon chambers. Typical strategies for these triggers use lookup tables in fast memories, programmed logic arrays, digital summing, and, in some cases, limited internal specialized sequencers. The time required to form the second level trigger decision is of the order of $10\mu\text{s}$. From simulations carried out at the FNAL Workshop, typical reduction factors of 30 to 100 can be achieved with little loss of efficiency for events of interest.

While waiting for the second level trigger decision, the data acquisition system must store the data in fast buffers and/or be processing data (sparse data scanning, applying pedestal and gain corrections, etc) with small, fast, dedicated processors. These techniques pose no particular problems in principle and current detectors under construction are prototypes for SSC detectors. The focus of the R&D should be to reduce the costs of the system

by using higher levels of integration. Prototype algorithms and strategies for this level trigger would also be an excellent working group topic at Snowmass 1986.

6.3.4 Third Level Triggers and Data Acquisition

The third level trigger domain will be software running on a large farm of processors operating in the one event per processor mode. After the previous level trigger, the only further filtering that could be done requires track information from the tracking detectors, which requires software programmable processors with floating point precision. The data acquisition system must fill a processor with the entire event and have a bandwidth to the trigger processor farm sufficient to keep up with the previous level trigger.

A. Lankford and G. Dubois nicely summarize the expected requirements in their summary report of the data filtering/acquisition working group at the FNAL Workshop (ref. 1, section 6.1). Figure 6.3.1 provides a flow diagram for the data from the detector to the data summary tapes, and illustrates the scale of the problem. As can be seen from the bottom of the figure, the on-line level three trigger processor farm is at the scale of 1000 VAX equivalents being fed by a 1 GByte/sec data bus. This is a substantial extrapolation from our present day experience of 10 VAX equivalents being fed by a few MByte/sec data bus.

The prototypes of large farms for SSC detectors will be the high level triggers currently being developed for detectors at the Tevatron, LEP, HERA, and SLC. Here, the issues currently being discussed, of code portability, downloading of constants, internal bus structures, I/O rates and so on, will be solved on a smaller scale than for the SSC but on a much larger scale than currently exists.

General Model of Data Flow

Fig. 6.3.1 Flow diagram of the data from detector elements to permanent storage.

References

1. G. Kane et. al., in Proceedings of the FNAL Workshop on Triggering, Data Acquisition and Computing for High Energy/High Luminosity Hadron-Hadron Colliders, (Mar. 1986).
2. P.S. Cooper et al., *ibid.*
3. P. Franzini, *ibid.*

6.4 Farms

Arrays of smaller computers will be used extensively for both on-line and off-line event processing. These arrays, or farms, are cost effective and well matched to the processing of event-structured data. The systems currently under development will provide very useful information on the feasibility of the large farms which will be required for processing data from SSC detectors.

It is possible to model the data flow in processor farms using programs developed to study computer systems and networks. An initial attempt at modeling the performance of a farm that would handle the data flow from an SSC class detector was carried out at the recent FNAL Workshop by D. Cutts and C. Van Ingen¹ using the program RESQ. Their model is shown in Fig. 6.4.1.

Figures 6.4.2 and 6.4.3 summarize the projected performance versus input bandwidth to the farm, and the farm size, respectively. The conclusion is that fifty 40 Mbyte/s cables (= 50 Fastbus cables in parallel) giving an input bandwidth of 2 GBytes/s and a farm of 500 CPUs (1 CPU = VAX 780 with a floating point accelerator) would handle the projected data flow, writing about 1 event/s to permanent storage for subsequent off-line analysis. A simple analytic estimate was carried out by T. Devlin² at the same FNAL Workshop, confirming the above estimates to within a factor of two. This is an extrapolation of more than two orders of magnitude in input bandwidth from present farm experience, and of more than a order of magnitude in the number of CPUs in a farm. The ACP project at FNAL will have 128 CPUs when it comes up during the summer of 1986. It is crucial to apply these models to the systems under construction (the ACP project and the level three triggers for both D0 and CDF) so that the projected and actual system performances can be compared to test the reliability of the models. With this basis, the models can then be used to provide a reliable prediction of the performance and behavior of the much larger systems needed for typical SSC detectors.

There are several development efforts currently under way to realize these farms. Some are described below.

6.4.1 Emulators

These are specially designed processors which match another computer so closely that the portability of code and data from that emulated computer to the processors is trivial. The currently active projects are the SLAC/CERN 3081/E collaboration and the Weizmann/Rutherford 370E collaboration; both are emulators of IBM mainframe computers. These projects are preparing processors for Mark II at SLAC, and for UA1, LEP3, NA32, and OPAL at CERN, to name a few. The older original emulator, the 168/E (= 2 MIPS), has been extensively used for both on-line and off-line applications at SLAC, CERN, DESY, and other laboratories. As an example, UA1 has been using four 168/E's as a third level on-line trigger since 1983.

6.4.2 Microprocessor Farms

These are specially designed boards on which the processors are constructed using commercially available microprocessors with their floating point co-processors. These boards can be made very cheaply because they use components that are made for the mass market of workstations and process controllers. The leading active project in this area is Fermilab's Advanced Computer Project (ACP), which will be delivering farms for on-line use at CDF and off-line use at Fermilab's computer center in the near future.

6.4.3 MicroVAX Farms

These are available from DEC and are compatible with the VAX family of computers. Although higher in cost per unit processing power than emulators or ACP type processors, they do offer trivial code and data portability from

VAX computers. Two active projects with microVAX farms are the DO third level trigger and NYCB Real-Time Computing's FASTBUS VAX project planned for use by SLD.

Fig. 6.4.1 RESQ Model for a simulation of an SSC farm.

Fig. 6.4.2 Farm utilization as a function of input bandwidth.

Fig. 6.4.3 Farm utilization as a function of the number of CPUs in the farm.

References

1. D. Cutts and C. Van Ingen, in Proceedings of the FNAL Workshop on Triggering, Data Acquisition and Computing for High Energy/High Luminosity Hadron-Hadron Colliders, (Mar. 1986).
2. T. Devlin, *ibid.*

6.5 Off-Line Computing

Estimates from Snowmass 1984 and from the Off-Line Computing and Networking Working Group¹ at the FNAL Workshop indicate that a total of 10kMIPS (1 MIPS = 1 VAX equivalent = 1 Million Instructions Per Second) will be required to handle the data flow from the SSC detectors one year after experiments begin. The time evolution of that computing need combined with the mix between farms and large mainframe computers is illustrated in Fig. 6.5.1.

Figure 6.5.2 is a conceptual model of how the central computing for the SSC might be organized. Of particular note is the need for 10 TeraBytes of mass storage and the probable need for optical disk storage to replace conventional magnetic tapes. It is clear that SSC detectors will depend heavily on industrial progress in both mainframe computing and mass storage technology. Because of the specialized needs of event processing, progress in achieving reliable and economic large farm arrays of small processors will be much faster if it is carried out by the HEP community. It should have high priority and adequate R&D funding. The ACP project and the DO microVAX farm are excellent test beds for developing these farms.

Fig. 6.5.1 Projected off-line computing needs as a function of time for SSC detectors.

SSC MODEL FOR CENTRAL COMPUTING

In this model, permanent data storage is done at each IR, and the recording media are manually transported to the Central Facility.

This diagram shows the logical structure but not the actual bus structure. The Farm Manager and Analysis computer are hoped to be as compatible as possible, and may not be distinct physical units.

Fig. 6.5.2 Conceptual model of SSC central off-line computing.

Reference

1. M. G. D. Gilchriese and S. C. Loken, Summary Report of the Offline and Networking Working Group, Proceedings of the FNAL Workshop on Triggering, Data Acquisition and Computing for High Energy/High Luminosity Hadron-Hadron Colliders, (Mar. 1986).

6.6 Software Research

There are two areas where new approaches to software will have a significant impact on the development of SSC detectors and their associated analysis code. These are algorithms, including those for vector supercomputers, and software development methodologies.

6.6.1 Event reconstruction algorithms.

Most algorithms used in the past have the property that CPU time increases dramatically with the charged particle multiplicity in the chambers. Since the charged particle multiplicity will be very high at the SSC, new and significantly faster algorithms will be needed. The geometry of the chambers affect algorithms significantly. These new algorithms must be developed early in the design cycle so that the chamber geometry can be matched to the algorithms.

6.6.2 Use of Vector Processors by Experimental HEP

The vectorization of traditional analysis code leads to only modest speed-up, if any, and sometimes leads to slower code. To take advantage of the vector analytic properties, the code must be rewritten using new algorithms. Recent work by C. H. Georgiopoulos at Florida State¹ has shown that significant improvement is possible for simple detector geometries. There has also been significant success in adapting hadronic shower Monte Carlo programs to vector computers.²

6.6.3 Use of development tools

With the increase in the size and complexity of detectors, the software effort is one of the most expensive elements of any experiment. It is extremely important to improve the efficiency of code development, to reduce the need for code maintenance, and to ensure that the code is correct before it is run in a production mode for event filtering and off-line reconstruction.

The size of collaborations, especially the software group, and the long time scale of the experiments place new demands on the physicist programmer for better communication, better documentation, formal library management and rigorous testing of software before its release for general use.

Over the last decade, the computer industry has developed new techniques to solve many of these same problems. These techniques are now being adopted by some of the large experiments at the Tevatron and at LEP. Use of these techniques by these collaborations will provide information on their applicability to HEP problems and on the benefits to be gained compared to present methods.

These new techniques include software design methodologies (for example, Structured Analysis/Structured Design or SA/SD), code and library management utilities, and automated program analysis and testing.

6.6.4 Structured Analysis/Structured Design

Structured Analysis/Structured Design is a formal design methodology developed by Yordon Inc.³ It has been adopted by ALEPH and D0 for the design of all new software. The technique has been described by J. Linnemann⁴ at the recent FNAL Workshop. Formal design tools such as Data Flow Diagrams and Data Dictionaries provide a systematic way of presenting and documenting the software design. Design reviews, or Walkthroughs, provide an opportunity to detect logical errors before they are coded.

6.6.5 Code and Library Management

It has become increasingly important to formalize the management of software libraries in large collaborations. Many physicists often work on the

same code and changes must be tracked and documented. Libraries must be updated frequently and on many different computer systems. An early effort to systematically do this was PATCHY, which was developed at CERN. More recently, commercial products have become available and are in general use. DEC provides VAX/CMS and MMS for use on VAX/VMS systems. HISTORIAN is a similar product which runs on many different systems and has been adopted by CERN.

6.6.6 Database Management and Structured Storage

The large number of detector elements and electronics channels in experiments has increased the need for database management tools. Many experiments are using commercial software products to manage inventories and calibration information, and to document analysis progress. Products in use include DEC Datatrieve and Rdb as well as ORACLE.

The FORTRAN language, although widely used for HEP programming, has serious failings in its handling of records. To simplify the handling of event data, a number of data structures have been developed and are in widespread use. These include HYDRA, YBOS, and ZEBRA. Because of these special data structure programs, perhaps yet another look at other possible languages would be worthwhile to simplify our handling of event data.

6.6.7 Common Software Libraries

Because of the large effort required to develop new software, experiments will move in the direction of using common libraries. Some of these libraries are Monte Carlo programs such as GEANT, ISAJET, and EGS, and well as utilities for event histograming (HBOOK/HPLOT) and the data management software mentioned above.

6.6.8 Conclusions

The lead time for these complex software systems to reach an adequate level of maturity is very long. To be useful for SSC detector design and utilization the R&D of these software systems must start in the near future. Just as large cost savings are expected by developing new hardware techniques, equally large savings can be expected from implementing new software design tools and strategies.

References

1. C. H. Georgiopoulos, in Proceedings of the FNAL Workshop on Triggering, Data Acquisition and Computing for High Energy/High Luminosity Hadron-Hadron Colliders, (Mar. 1986).
2. LANL Monte Carlo Generators Using Vector Computers.
3. Structured Analysis/Structured Design, Yordon Inc.
4. J. Linnemann, in Proceedings of the FNAL Workshop on Triggering, Data Acquisition and Computing for High Energy/High Luminosity Hadron-Hadron Colliders, (Mar. 1986).

6.7 Networks

The large size and geographical distribution of collaborations require extensive computer networking for communication and for the management of program libraries and databases. This need has spurred the development of a national High Energy Physics Network, HEPNET. The R&D effort for the SSC, the design of new detectors, and the development of proposals for the SSC will place new demands on HEPNET. With the commissioning of SSC detectors, very high-speed networks ($> 100\text{kBytes/s}$) will be necessary to transmit sample events or databases to various institutions. Networking needs are not unique to HEP. Research and development for networking is being carried out by industry, computer scientists, and standards committees. It is likely that HEP networking needs will be adequately satisfied by vendor supported hardware and software.

6.8 Mass Storage

The large volume of data associated with SSC experiments will require improved data storage facilities. An operating SSC detector will generate 0.4 MBytes of data per second, which must be stored on some permanent medium. Using 6250 BPI magnetic tape for storage would mean one tape every 6 minutes or 240 tapes per day. New devices must have significantly more capacity than magnetic tape, preferably provide random access capability and having automated storage media handling. Optical disk devices offer the possibility of satisfying these requirements, but so far are not available and are too slow for real time data recording without the use of many parallel channels.

Optical disks are especially interesting in that they would allow random access to very large data sets. This would permit much more efficient organization of data than is currently possible with serial media. To take advantage of this increased efficiency, however, will require a new approach to data analysis based on modern database handling techniques.

Mass storage devices will be installed at each detector and at the offline computing facility. In addition, many institutions will have similar devices, and storage media will be exchanged frequently. It will be very important to avoid specialized devices that are not easily installed or maintained at these locations. The use of industry standards will be essential.

6.9 Conclusions and Recommendations

Much of the research and development that will be necessary for electronics, triggering, data acquisition, and computing is already under way. It is extremely important for this work to go ahead and for the results to be widely discussed in conferences and in special workshops. Issues of particular interest are the following:

- To realize the expected very significant cost reduction of the front end electronics by employing custom VLSI devices in SSC detectors, a vigorous program must begin now. This would include education in VLSI design techniques followed by the design and development of useful devices for present generation detectors. To perform this program, funding and facilities should be provided to carry out the necessary steps from circuit designs to working prototypes. This support could range from setting up design centers in the major laboratories to providing color graphics terminals for university groups using public domain CAD/CAE software on their local VAX. While it is possible to have industry carry out all aspects of a custom design, it is important to gain HEP experience in custom design in order to learn the limitations of such techniques. Within the next year a workshop of several days duration should be held to assess progress in developing custom VLSI circuits appropriate for HEP and useful for SSC detectors.
- During Snowmass 1986 working groups should be organized to look in depth at:
 1. tracking efficiency of multi hit versus waveform digitization in tracking detectors;

2. continuation of work started at FNAL Workshop on level two trigger strategies;
 3. models of level three trigger systems, with particular attention to interaction with the data bus(es);
 4. investigation of reactions other than those studied at the FNAL Workshop to understand trigger strategy implications.
- Modeling of high level trigger systems should be continued, and comparisons made with hardware performance as the present generation of high level triggers for CDF and DO are commissioned. These high level trigger projects should be strongly supported since they are appropriate scale models of those needed for SSC detectors.
 - The progress of the ACP project at FNAL should be carefully monitored and the actual performance compared against that predicted by the models. As with the high level trigger projects, the ACP is an appropriate scale model for the off-line processing farm needed for SSC central computing. It would be inappropriate at this time to initiate a new farm project directed specifically to SSC needs.
 - An exploration of the use of vector processors for event reconstruction should be started so that any implications for detector geometry, etc., can be included in the detector design.
 - Vector processors may be attractive because of their large capacity and their industrial development. Monte Carlo simulations of detector elements constitute another area where vector processors may offer advantages. The propagation of hadronic showers through detector materials may be a particularly useful area to explore.

- A vigorous program of software research should be started so that any developments will be mature, and therefore useful, by the time they are needed for SSC detector software. As part of that program, the experience of the ALEPH and DO collaborations in using SA/SD should be reviewed to evaluate the usefulness of this software design methodology.

The implementation of front-end electronics, triggering, and data acquisition systems for the SSC will require substantial improvements in performance over current systems and those in construction. R&D in these areas will be of crucial importance to the successful operation of detectors at the SSC, and will result in substantial cost savings if undertaken in the near future.

CHAPTER 7

Report of the Working Group on Superconducting Magnets

7.1 Introduction

Some of the central detector systems for SSC experiments will include a central tracking detector and a large analyzing magnet to determine the momenta of secondary charged particles. Although electron energies can be measured more precisely by calorimeters, a magnetic spectrometer can determine the signs of electrons up to the TeV region.

In hadron colliders both dipole and solenoid magnets can be used, because the background due to synchrotron radiation from beam particles is not appreciable even in the energy range of the SSC. UA1¹ uses a dipole magnet of aluminum coils with a field strength of 0.7 Tesla and a field volume of $7.0 \times 3.5 \times 3.5 \text{ m}^3$. In the case of a dipole magnet, compensation magnets for the beam optics must be added. The main advantage of using a dipole field is the fact that the momenta of charged particles produced in the extreme forward or backward directions can also be measured.

In e^+e^- collider experiments, solenoid magnets with the axis parallel to the beam direction are almost a unique choice because of synchrotron radiation. Such magnets measure the transverse momenta of charged particles; there are many cases in which measurements of transverse momenta have more direct physical significance; solenoid magnets therefore seem to be more attractive than dipoles even in hadron collider experiments.

Members of the L3 group have described a precision lepton detector for the TeV region.² The detector includes a very large solenoid of aluminum coils similar to those of the L3 magnet. The field volume is 8.6m in radius and 20m

in length. One of the main characteristics of the detector is to measure muons precisely, with a goal of $\Delta M/M \approx 1\%$ at $M = 1$ TeV.

UA1-type dipole magnets and L3-type solenoids built with conventional conductors of aluminum or copper can be used in some SSC experiments. In the latter case the dimensions of the magnets are large and there might be some technical difficulties associated with their sizes. In this report, however, we discuss mainly large superconducting solenoids.³

References

1. See, for example, G. Gidal, B. Armstrong, and A. Rittenberg (Particle Data Group), LBL-91, Supplement Revised UC-34D, May 1985.
2. SSC Report, SSC-SR-1020, Feb. 1986.
3. For a recent review of detector magnets see, for example, H. Desportes in the Report of the Int. Conf. on Magnet Technology MT-9, Zurich (1985).

7.2 Large Superconducting Solenoids

Table 7.2.1 summarizes the parameters of large, thin superconducting solenoids which have recently been constructed and tested.¹⁻⁴ The CDF solenoid was built for the TeV $I \bar{p}p$ collider, and the other five for e^+e^- colliders. The first three can be called first generation solenoids and the last three second generation solenoids. Enormous efforts were made to make all these solenoids as thin as possible, not only in radiation and absorption lengths but also in physical thickness. Barrel calorimeters are placed outside the solenoids because some of those detectors are sensitive to magnetic fields and also because the cost and technical difficulties of constructing larger solenoids are much greater. Because of the thinness of the solenoids they employ the forced flow cooling method of two-phase helium, since pool cooling requires a substantially thicker cryostat arrangement. The last three solenoids have been tested very successfully without any difficulty. The most significant technical improvements made for the second generation solenoids are in fabrication methods of aluminum-stabilized NbTi/Cu conductors and in methods of coil winding or assembly. A monolithic NbTi/Cu superconductor is coextruded using pure aluminum, and the boundary between aluminum and copper is made using the friction welding process to give superior mechanical and electrical properties to the conductor. Outward radial magnetic forces are supported with an outer cylinder of aluminum alloy, and no permanent inner bobbin is used. The TOPAZ coil was wound directly on the inside of the outer support cylinder, and no inner mandrel was used.³ By contrast, the CDF and VENUS coils were wound on a temporary mandrel which was removed after the final assembly of the coil and support cylinder.^{2,4}

Test results of the CDF, TOPAZ, and VENUS solenoids indicate that they have excellent thermal stability.

Table 7.2.1
Design Parameters of Recent Large, Thin Superconducting Solenoids

	<u>CELLO</u>	<u>TPC</u>	<u>CLEO</u>	<u>CDF</u>	<u>TOPAZ</u>	<u>VENUS</u>
Inner diameter/m	1.5	2.0	1.9	2.9	2.7	3.4
Overall length/m	3.5	3.4	3.4	5.1	5.4	5.5
Central field/T						
(design)	(1.5)	(1.5)	(1.5)	1.5	1.2	0.75
Number of turns	1400	2000	2300	1200	1300	650
Conductor layers	1	2	2	1	1	1
Current/A	3100	2100	2300	5000	3600	5000
Inductance/H	1.5	4.8	3.7	2.4	3.0	0.9
Stored energy/ 10^6 J	7.0	10.7	9.4	30	19	11
Conductor:						
NbTi/Cu/Al ratio	1:1:11	1:1.8:0	1:3.9:0	1:1:21	1:1:20	1:1:20
Current density/ 10^7 A/m ²	14	88	42	6.4	5	5.2
Al stabilizer	Solder	--	--	Extrsn	Extrsn	Extrsn
Inner bobbin	Yes	Yes	Yes	No	No	No
Thickness/rad. leng.	0.5	0.4	0.7	0.8	0.7	0.5
Cold mass/tons	1.4	1.4	1.6	5.6	4	4
Completion year	1979	--	1982	1984	1984	1985
Installation	DESY	SLAC	CORNELL	FNAL	KEK	KEK

Two larger superconducting solenoids for LEP experiments, DELPHI and ALEPH, are under construction.⁵ The inner diameter, length, field strength, stored energy, and material thickness are respectively 5.2m, 7.4m, 1.2T, 109MJ, and 4 radiation lengths for the DELPHI solenoid, and 4.96m, 7m, 1.5T, 130MJ, and 1.3 radiation length for the ALEPH solenoid. Both are constructed in modules. They use aluminum-stabilized superconductors, in which compact superconducting strand cables are coextruded with aluminum, instead of the monolithic superconductors used in the second generation solenoids. The new

conductors may have the advantages of allowing long unit lengths and of having high performance reliability. These two third generation solenoids are expected to be completed by the end of 1986. We will gain enormous technical experience from the construction of such large superconducting solenoids.

In the following section we will make estimates of the costs and main parameters for three models of superconducting solenoids which are possible choices for SSC experiments. They are:

- (a) Model B: Diameter $\approx$ 5m
Central field $\approx$ 1.5T
- (b) Model A: Diameter $\approx$ 7m
Central field $\approx$ 1.5T
- (c) Big AMY: Diameter $\approx$ 3m
Central field $\approx$ 3 T

The ratio of the diameter to the length is assumed to be 5:8 unless explicitly indicated. The reason for having the two similar cases, (A) and (B), is that the coil structure can be quite different owing to the lopsided aspect ratio of the conductor cross-section in the two cases.

7.2.1 Model B.

This detector is one of two alternative designs for a 4π solenoidal magnetic detector, described in the report of the Detector Cost Model Advisory Panel (DCMAP).⁶ It is based on the CDF detector, in which barrel EM and hadron calorimeters are placed outside a solenoid, as shown in Fig. 7.2.1(a). The diameter of the solenoid is approximately 5m. The advantages of this design are that it can be built with the same structure as the second generation solenoids and that it can probably be transported after construction at an off-site factory. A superconducting coil consists of a single layer

helical winding of aluminum-stabilized superconductor, mounted inside an aluminum support cylinder. The conductor is indirectly cooled by conduction from a single cooling loop, attached to the support cylinder.

The outward radial magnetic pressure, P , and hoop stress, σ , are given by

$$P(\text{kg/cm}^2) = 4.06 B^2(\text{T})$$

and

$$\sigma = P \frac{R}{t_c + t_s}$$

where R is the coil radius, and t_c and t_s are the thickness of the coil and the support cylinder respectively. The thickness of the coil is determined primarily from safety considerations in case of a quench. The maximum voltage and temperature rise in the coil during a quench must be held to roughly 500V and 100K. A large portion of the material of the coil is very soft pure aluminum. Therefore it seems reasonable to assume that the thickness of the coil structure, $t_c + t_s$, is twice the thickness required to support the hoop stress by aluminum alloy (t_{hoop}). The outer and inner wall thicknesses of the aluminum vacuum chamber of the solenoid cryostat, t_o and t_i , are given approximately by

$$t_o \approx (1.5P_a L R^{1.5} / 0.807E)^{0.4}$$

$$t_i \approx 1.5P_a R / \sigma_a$$

where P_a = atmospheric pressure
 L = length ($= 1.6 \times R$)
 E = Young's modulus
 σ_a = allowable tensile stress,

and the safety factor is 1.5.

The total thickness of the solenoid is given approximately by

$$t_{\text{tot}} \approx t_o + t_i + 2t_{\text{hoop}}$$

and is shown in Fig. 7.2.2 as a function of the diameter for various field strengths. The present estimate must be considered a lower limit. In an actual design, more conservative criteria are usually applied and the thickness of a solenoid would probably be 10 to 30% larger than this value. The thicknesses of the CDF, TOPAZ, and VENUS solenoids given in Table 7.2.1 are also somewhat larger than those extrapolated using Fig. 7.2.1.

The cost of a solenoid depends upon many factors. In the first approximation we assume that the cost is proportional to the total quantity of materials used. Therefore, the cost is proportional to the product, DLt_{tot} ($= 1.6D^2t_{\text{tot}}$). Figure 7.2.3 shows the scaling curves of the cost as a function of the diameter for various field strengths.

7.2.2. Model A.

The Model A detector is the other design for a 4π solenoidal magnetic detector described in the DCMAP report.⁶ It is essentially identical to that described in the Snowmass 1984 Summer Study (Fig. 7.2.1(b)). The barrel EM shower detector and the main section of the hadron calorimeter are placed inside the solenoid. The diameter of the solenoid is then approximately 7m and the volume of the flux return yoke becomes substantially larger than that of the Model B detector. The material thickness of the solenoid is not required to be small.

The conceptual design of a 1.5 Tesla superconducting solenoid of 7m diameter and 12m length was made by A. Yamamoto. The design criteria are as follows:

- The coil is made of an aluminum-stabilized NbTi/Cu superconductor and the support cylinder of the coil is made of aluminum alloys. The maximum stresses of pure aluminum in the conductor and of aluminum alloy should be less than 20MPa (2kg/mm^2) and 100MPa (10kg/mm^2), respectively.
- The average temperature rise should be 70K in case the entire stored magnetic energy is dumped in the coil.
- The maximum temperature of the coil should be approximately 100K in case of a quench.

A schematic drawing of the cross section of the solenoid is shown in Fig. 7.2.4. The double layer coil is wound on the inner surface of the high strength aluminum support alloy cylinder using the internal winding method.³ An aluminum stabilized superconductor is fabricated by coextruding a compact strand cable with pure aluminum. The outer vacuum wall of the aluminum alloy solenoid cryostat can have a few stiffening rings made of carbon fiber reinforced plastic (CFRP) or aluminum alloy, as shown in Fig. 7.2.4, in order to reduce the average wall thickness.

The main parameters of the solenoid are given in Table 7.2.2. The stored magnetic energy is 413MJ. A net weight of about 55 tons is required for the coil and support cylinder in order to hold the average temperature rise at 70K. The total thickness is then 78mm. The thickness of the support cylinder is calculated to be 32mm for a maximum stress of 100MPa. The remaining thickness of 46mm is the double layer coil which seems to be better than a single layer coil for keeping a reasonable aspect ratio of the conductor.

Material thicknesses of each item in the radial direction are summarized in Table 7.2.3.

Table 7.2.2

Main Design Parameters of the SCD (Model A) Solenoid

Types		
Conductor		Nb/Ti-Cu composite pure-Al stabilized
Coil structure		Double layer solenoid
Winding		Double internal winding
Cooling (in steady state)		Indirectly forced flow of two phase helium
	(for back-up)	Gravitational convection
Dimensions		
Coil:	Diameter (center)	7m
	Length	12m
Vac. vessel:	Inner diameter	6.8m
	Outer diameter	7.5-7.6m
Magnetic field		1.5T
Absorption length (radial)		0.36-0.4
Radiation length (radial)		1.6-1.8
Current		5000A
Current density	(in Nb/Ti-Cu)	500A/mm ²
		(700A/mm ² in o.c.)
	(overall)	28-20A/mm ²
Number of turns	2 x 1440 turns	
Inductance		33 H
Stored energy		413MJ
BV (field x volume)		693Tm ³
Cold mass		55-70 tons
Thermal load (into the coil)		150W + 301/h
	(eddy current loss)	50-100W (@ 1A/s)
Total weight		120-150 tons

Table 7.2.3.

Material Thicknesses in the Radial Direction of the SCD (Model A) Solenoid

<u>Part</u>	<u>Thickness</u>	<u>Radiation</u>	<u>Absorption</u>
Outer vessel	20-40 mm	0.23-0.45	0.06-0.11
Outer shield	3	0.034	0.008
Support shell	32	0.360	0.086
Conductor (Al)	2 x (22-30)	0.49-0.67	0.12-0.16
(s.c = Cu)	2 x 1.2	0.169	0.016
Inner shield	3	0.034	0.008
Inner vessel	7	0.079	0.019
Total		1.4-1.8	0.32-0.41

A very crude cost estimate was made and is summarized in Table 7.2.4. The unit costs assumed for materials, machining, and manpower are as follows:

superconductor (s.c. + Al + ins.)	5 - 6 kyen/m
aluminum alloy	1.5 - 2 kyen/kg
design	10 - 12 kyen/man h.
machining and assembly	8 - 10 kyen/man h.

The total cost of \$8-11M includes fabrication and initial testing without an iron return yoke, but any auxiliary equipment such as a power supply or a cryogenic system, is not included. The cost given is a basic figure, and should be considered relatively optimistic. The most unknown factor is the factory location and facilities to fabricate such an extremely large solenoid. An extra cost might be required to prepare a special factory near or on site.

Figure 7.2.5 shows cost as a function of the product of the field strength (B) and magnetic volume (V) for large superconducting solenoids either constructed, or under construction, or proposed. The costs of the CDF, TOPAZ, and VENUS solenoids are actual costs paid, but those of other solenoids

Table 7.2.4

Cost Estimate of the Coil and Cryostat of the SCD Solenoid

Superconductor	350 - 450 MY
Materials and parts	250 - 300
Design and engineering	160 - 200
Machining and Assembly	500 - 600
Special tool or machine	150 - 300
First cool down and test	100 - 150
Transportation	100 - 200
Management	190 - 300
Total	1800 - 2500 MY = 8.2 - 11.3M\$ (@ 1\$/220 Y)

are partially guessed, or extracted from proposals or letters of intent. The dashed line corresponds to the assumption that the cost is proportional to the product BV , normalized to the CDF solenoid. The shaded area indicates the uncertainty of the cost estimate. For larger solenoids such as the SCD solenoid the estimated cost is approximately proportional to $(BV)^{0.4}$ and is substantially lower (by a factor of about two) than that obtained from the linear relation shown by the dashed line.

In the cost estimate given in the previous section we assumed that the cost is proportional to $D^2 t_{\text{tot}}$. Since t_{tot} is roughly proportional to D for a fixed field strength, the cost should be roughly proportional to the field volume. This does not seem to be quite consistent with those shown in Fig. 7.2.5. Within a limited range, however, the cost scaling shown in Fig. 7.2.3 seems to be reasonable.

7.2.3 Big AMY.

One of the TRISTAN experiments, AMY,⁷ uses a high field superconducting solenoid of 3 Tesla. Owing to the high magnetic field, the mechanical structure of the coil is substantially different from those of low field solenoids of about 1.5 Tesla. The main parameters of the AMY solenoid are given in Table 7.2.5, and a schematic drawing of the conductor cross section is shown in Fig. 7.2.6. The pool boiling method is used. The cryostat vessel and the vacuum chamber are made of stainless steel. The magnet is cryostable, but for safety reasons it is designed to allow quenches to occur.

High field superconducting solenoids similar to the AMY solenoid could be used in SSC experiments. We estimate parameters and costs for 3m diameter x 4.8m solenoids of 3 and 5 Tesla.

The case of the AMY conductor is made of hard copper, and the allowable stress is about 20kg/mm^2 . It can be increased to about 26kg/mm^2 by using a stainless steel support structure to reduce the conductor thickness. A new type of conductor called "cable in conduit" can be used to allow a higher current density of about 50A/mm^2 . Table 7.2.6 summarizes design values of the current density and coil thickness for the AMY-type and cable-in-conduit conductors. The stored energy of each solenoid is also given. The helium cryostat and the vacuum chamber should be similar for the three solenoids, and their net material thickness in the radial direction is roughly 5cm of stainless steel. Therefore, the overall material thicknesses for 3m diameter x 4.8m solenoids of 3 and 5 Tesla are 10 to 12 cm and 21 to 25 cm, respectively. The materials are mostly copper and stainless steel. Table 7.2.6 also gives estimated costs based upon the two following assumptions:

- (1) the cost is proportional to the product of the field strength and volume; and
- (2) the cost is proportional to $E^{0.7}$, where E is the stored energy.

Table 7.2.5

Main Parameters of the AMY Solenoid

Solenoid parameters:

Current	5000A
Central field	3.0T
Peak field in the windings	4.0T
Coil diameter (inner/outer)	2.386m/2.584m
Coil length	1.540m
Winding:	
Number of layers	8
Total turns of the winding	1080
Stored energy	40MJ
Cryostat: He vessel	
Material	SUS
Wall thickness (inner/outer)	2.0cm/2.5cm
Length	2.12m

Conductor parameters:

Superconductor	Nb-46.6 wt% Ti
Cross section	$9.8 \times 10.2 \text{ mm}^2$
Strand diameter	1.35mm
Number of strands	7
Filament diameter	$30 \mu\text{m}$
Number of filaments per strand	1025
Critical current:	
At 4.4T (4.2K)	11760A
At 6.0T (4.2K)	8610A

Table 7.2.6

Some Parameters and Costs of the AMY Solenoid and the Present Designs
of 3 m Diameter x 4.8 m Superconducting Solenoids of 3 and 5 Tesla

Solenoid	<u>Present Design</u>		AMY
	3 T	5 T	
Current density (A/mm^2)			37
AMY-type	37	22	
Cable in conduit	50	30	
Coil thickness (cm)			10
AMY-type	7	20	
Cable in conduit	5	16	
Stored energy (MJ)	180	500	40
Cost (10^8 yen (M\$*))			5 (0.23)
$\propto B \times \text{Volume}$	24 (10.4)	40 (18.2)	
$\propto E^{0.7}$	14 (6.4)	29 (13.2)	

*\$1 = 220Y

Fig. 7.2.1 4π solenoidal magnetic detectors. (a) Model B and (b) SCD - Model A.

Fig. 7.2.2 Material thickness in the radial direction, in units of radiation lengths, for the Model B solenoid.

Fig. 7.2.3 Estimated relative cost of the Model B solenoid vs. diameter, for different field strengths.

Fig. 7.2.4 Schematic drawing of the middle section of the SCD (Model A) solenoid.

Fig. 7.2.5 Cost of large superconducting solenoids constructed, under construction, or proposed, as a function of the product of the magnetic field and the volume.

Fig. 7.2.6 Schematic cross section of the conductor of the AMY solenoid

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CHAPTER 8

Report of the Working Group on Monte Carlo Event Simulation

8.1 Introduction

This section contains a description and evaluation of Monte Carlo programs for event simulation in pp or pp collisions at high energies. After a brief introduction, the assumptions used in current programs are described and compared in detail. Detector simulation needs and programs are briefly discussed. Recommendations for future support of Monte Carlo development are given at the end of the section.

The SSC will study a wide range of physics, but its principal motivation is to search for new particles or other new phenomena at the 1 TeV mass scale. The standard model, based on the gauge group $SU(3) \times SU(3) \times U(1)$, has been extremely successful in describing all existing data; nevertheless, it is widely believed that there must be some new physics beyond the standard model at a mass scale less than about 1 TeV. This mass scale cannot be studied at any existing accelerator.

If there is neither a standard Higgs boson nor any other new physics below about 1 TeV, then the scattering of longitudinally polarized W bosons will violate unitarity in perturbation theory, giving rise to strong WW interactions and hence to new phenomena.¹ If a standard Higgs does exist with a mass $m_H < 1$ TeV, then the standard model could be correct up to very high masses, perhaps even to the Planck scale. However, since the standard model contains 19 arbitrary parameters for three generations of quarks and leptons, it does not seem to be an acceptable fundamental theory. This large number of parameters arises primarily because of the fundamental Higgs scalars, whose couplings are not restricted by a gauge principle. It is generally expected that there exists some physics beyond the standard model which determines at least

some of these parameters, and the reasonable guess for its mass scale M is the scale of electroweak symmetry breaking,

$$M \sim 1/\sqrt{G_F} \approx 300 \text{ GeV}. \quad (1)$$

In the absence of a numerical accident, radiative corrections will naturally give $m_H \sim M$. It therefore seems likely that M cannot be much larger than 1 TeV; this is certainly true in the models which have been proposed.

It is perhaps remarkable that while there is no clear idea what the new physics might be, the standard model can be used to calculate cross-sections and to describe signatures for any particular case. This is true because the standard model is a gauge theory, so that the charge, color, and weak isospin of a particle determine its couplings to the quanta of the standard model, and because QCD is asymptotically free, so that perturbation theory can be used to describe strong interactions at large mass scales. The cross-section for two partons i and j from two incoming hadrons to make a particle or a system of particles of mass M has, in perturbative QCD, the form

$$\sigma = \int dx_i dx_j \frac{C}{M^2} f_i(x_i, M^2) f_j(x_j, M^2) \delta(x_i x_j - M^2/s), \quad (2)$$

where C is determined by the model and f_i and f_j are the QCD improved structure functions. Cross-sections for heavy particles are intrinsically small because of the $1/M^2$ factor, and there is a tradeoff² between higher energy (which gives smaller x_i and x_j and hence larger cross-sections) and higher luminosity (which allows smaller cross-sections to be observed). The most complete calculations of such cross-sections are those by Eichten, Hinchliffe, Lane, and Quigg.³ For all the models which they consider they find that the design parameters of the SSC yield an adequate number of events for masses up to at least 1 TeV.

It is not sufficient to produce a new particle; it is also necessary to detect it. There must be a possible trigger, an observable signature, and a way to separate the signature from backgrounds. The standard model can also be used to address these questions. Within the general framework of the standard model there is only a limited number of possible signatures for a new heavy particle: it can be stable, and either visible in the detector or invisible, giving a missing energy signal; or it can be unstable, decaying into another new particle or into quanta of the standard model, that is quarks or gluons, which give jets, charged leptons, photons, $W^\pm$, Z^0 , or possibly H.

However, detectors observe not quarks and gluons but the jets of hadrons produced by them. The formation of jets involves nonperturbative aspects of QCD, which must at present be described by models. Following the pioneering work of Field and Feynman,⁴ a number of Monte Carlo computer programs have been developed which combine perturbative QCD and nonperturbative models for jet formation to simulate complete events, and these have been used to study how to detect the possible signatures at the SSC.

Previously, it has been known how to detect jets, leptons, isolated photons, and missing transverse momentum, at least in principle. Recently, significant progress has been made on the question of separating $H \rightarrow W^+W^+$ from the much larger background of $W^\pm + \text{QCD jets}$. The major remaining problem for high-mass physics is that of identifying the flavors of quark jets, particularly heavy quark jets.

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8.2 Simulation of Hadronic Reactions

Perturbative QCD provides a very good description of all available data on hard interactions, those with momentum transfers large compared to 1 GeV. But perturbative QCD describes quarks and gluons, not the observed hadrons. The hadrons are presumed to be formed from the scattered quarks or gluons and from the remnants of the incoming hadrons by nonperturbative QCD processes characterized by small momentum transfers. Thus the events should contain jets of hadrons with limited p_T relative to the direction of each quark or gluon, and low- p_T beam jets from the spectators. The perturbative aspects of the problem are relatively well understood, although perturbative QCD does have subtle features which are not correctly incorporated in existing programs. The fragmentation of quarks and gluons into hadrons involves the physics of confinement, and is not understood in any fundamental sense, but the factorization theorems in perturbative QCD imply that this fragmentation is universal, so that data from e^+e^- reactions can be used to fix the models. Beam jets are poorly understood, and the models for them are primarily phenomenological.

It is convenient to introduce a parameter t_c which both separates the perturbative from the nonperturbative regions of Q^2 and provides a cutoff for the infrared and collinear singularities of perturbation theory. The value of t_c determines what sort of model can be used for jet fragmentation. If t_c is of order 10 GeV^2 or greater, then the fragmentation model must explicitly incorporate scaling in the longitudinal momentum fraction z , limited transverse momentum, and the ratios of particle types. This is what is done in the independent fragmentation models¹ and (in a somewhat more sophisticated way) in the Lund string model.² But if t_c is of order 1 GeV^2 , then the masses of the color neutral clusters are small and a very trivial hadronization scheme such as two-body phase space can be used.³ Presumably

this is successful because the hadronization process is local in phase space and preserves much of the structure from perturbation theory.

If t_c is relatively large, then at moderate Q^2 there will be only a small number of partons, so it is feasible to use the exact n -body QCD cross sections. However, the average number n of partons above t_c grows faster than any power of $\ln Q^2$, and while these partons will usually cluster into a small number of jets, they will lead to an average transverse momentum with respect to the jet axis of order $\alpha_s(Q^2)Q^2$, and to a larger hadronic multiplicity. Hence at SSC energies it is essential to use an approximation scheme which can handle arbitrary n . Fox and Wolfram³ realized that this can be achieved by keeping in the QCD cross-sections only the singular terms which dominate for collinear partons but using exact, noncollinear kinematics. This scheme, which is called the branching approximation, incorporates the essential physics from higher order QCD corrections:

- Leading-log QCD scaling violations in jet fragmentation and in structure functions. The Altarelli-Parisi equations⁴ sum just those singular terms using collinear kinematics and strong mass ordering.
- Leading-log jet shapes. Since a jet mass is typically $M^2 \sim \alpha_s(Q^2)Q^2 \ll Q^2$, the terms which are singular in the collinear region dominate.
- Approximate three-jet cross-sections. The branching approximation contains the correct powers of α_s and of the masses and it must agree with the exact three-jet cross-section at the edges of phase space; in fact it agrees within a factor of about two over all of phase space.⁵

Implementation of the branching approximation is technically feasible because it depends only on cross-sections or probabilities, the natural thing for a Monte Carlo algorithm.

Three programs, COJETS,⁶ ISAJET,⁷ and PYTHIA,⁸ are available for general use to simulate hadronic reactions. All three incorporate perturbative QCD cross-sections, higher order QCD corrections in the branching approximation, and hadronization of jets and beam jets. A number of other programs have been written which contain interesting features but which are either less complete or not generally available. Marchesini and Webber⁹ have done the most careful treatment of coherent effects in the QCD radiative corrections. Gottschalk¹⁰ has investigated the problem of correcting the branching approximation so as to obtain the correct cross-sections for three jets and other processes over all of phase space. Field et al.¹¹ first studied the branching approximation for the initial state. Ali et al.¹² have incorporated the exact three-jet cross-sections, although their approach does not allow the generation of higher order QCD corrections and so is not suitable for SSC energies.

8.2.1. Primary Hard Scattering

The first task in the simulation of an event is to generate the primary hard scattering, generally a two-body process. If the transverse momenta of the initial partons are neglected, then the hadron-hadron cross-section is a function of three variables plus a trivial azimuthal angle ϕ . The choice of variables should include those for which the cross-section varies rapidly. For QCD jets a convenient (but not unique) choice is the common p_T^2 of the two jets and the jet rapidities y_1 and y_2 . Then the cross-section is given by the QCD-improved parton model:

$$\frac{d\sigma}{dp_T^2 dy_1 dy_2} = \sum \frac{d\sigma}{dt} x_1 f_1(x_1, Q^2) x_2 f_2(x_2, Q^2), \quad (1)$$

$$x_1 x_2 = \hat{s}/s,$$

where $\hat{s}$, $\hat{t}$, and $\hat{u}$ are the usual invariants for the two-body parton subprocess, Q^2 is a momentum transfer scale of order $\hat{s}$, $d\sigma/d\hat{t}$ is the parton crosssection calculated in QCD perturbation theory, and $f_i(x_i, Q^2)$ are the structure functions incorporating QCD scaling violations. Generally an analytic parameterization for the structure functions is used. Then it is straightforward to select p_T^2 , y_1 , and y_2 according to this formula, although some care must be exercised to handle efficiently the rapid variation with p_T^2 .

COJETS, ISAJET, and PYTHIA all incorporate the cross-sections for QCD jets including heavy quarks and for $W^\pm$ and Z^0 production. PYTHIA contains essentially all of the possible two-body processes in the standard model. ISAJET contains only a subset of these processes but it includes the correct decay matrix elements for the W-bosons in $W + \text{jet}$ events and in $qq \rightarrow WW$. ISAJET also contains the cross-sections for pairs of supersymmetric particles in the simplest supersymmetric extension of the standard model. With a little imagination it is possible to generate other processes; for example, lepto-quarks can be generated like scalar quarks.

It is actually not necessary to start with the QCD improved parton model. Instead, one can start with the cross-sections calculated from scaling structure functions and reweight them using a product of weights obtained from the initial-state QCD radiation.¹¹ This is equivalent to leading order in $\ln Q^2$, and while it seems somewhat less convenient, it does allow one to study kinematic and other corrections to the leading-log QCD evolution.

8.2.2 Final State QCD Corrections

QCD radiative corrections are generated using the branching approximation, keeping the terms in the cross-section which are singular in collinear limit and using exact, noncollinear kinematics. The collinear limit distinguishes

between initial and final state partons, and while the ideas are similar the algorithms are sufficiently different that they will be discussed separately.

COJETS, ISAJET, and PYTHIA all handle final state radiation in essentially the same way. Consider the radiation of one extra gluon from an external quark line in an arbitrary process

$$q(p) \rightarrow q(p') + g(p''). \quad (2)$$

Because of the collinear singularities of QCD perturbation theory, this cross-section becomes infinite when $p^2 \rightarrow 0$, i.e., when p' and p'' become collinear. The dominant piece of the cross-section σ with the extra gluon is given by the cross-section σ_0 without it times a simple factor,⁴

$$\sigma = \sigma_0 \left[\frac{\alpha_s(p^2)}{2\pi p^2} \right] P(z), \quad (3)$$

where $P(z)$ is an Altarelli-Parisi function,

$$P(z) = \frac{4}{3} \left(\frac{1+z^2}{1-z} \right) \quad (4)$$

and z is the fraction of the momentum p carried by the quark,

$$z = \frac{p'_+}{p_+} = \frac{p'_0}{p_0} = \frac{p'_0 + \vec{p}' \cdot \vec{p}}{p_0 + \vec{p} \cdot \vec{p}} = \dots \quad (5)$$

The various forms for z are equivalent for collinear radiation but give different results when continued to large angles. Equation (3) with different functions $P(z)$ also holds for QCD radiation from a gluon, $g \rightarrow gg$ and $g \rightarrow qq$.

Consider for simplicity only the radiation of n gluons from a quark; the general case is essentially identical. Kinematics obviously forces the masses to be ordered,

$$Q^2 > p_1^2 > \dots > p_n^2. \quad (6)$$

In the leading-log approximation the $\ln Q^2$ factors arise from integrating over the p_i^2 , so the dominant contribution actually comes from the region of strongly ordered masses, $p_i^2 \gg p_{i+1}^2$. Then Eq. (3) can be applied for each gluon separately, giving

$$\frac{d\sigma}{dp_1^2 dz_1 \dots dp_n^2 dz_n} = \sigma_0 \frac{1}{n!} \prod_i \left[\frac{\alpha_s(p_i^2)}{2\pi p_i^2} \right] P(z_i). \quad (7)$$

The simple factorized form of Eq. (7) implies that the probability of radiating each additional gluon depends on the remaining mass of the quark line but not on the previous emissions. Thus the gluon emission can be treated by Monte Carlo methods, making the branching approximation feasible.³

Equation (7) contains both collinear singularities (the explicit $1/p_i^2$), and infrared singularities the $1/(1-z_i)$ in the $P(z_i)$). The infrared singularities cancel in the usual way with those from the virtual graphs; this can be implemented simply by treating $P(z)$ as a distribution containing a $\delta(1-z)$ term such that its integral is zero. The collinear singularities are needed to build up the QCD scaling violations and do not cancel, but they are cut off by the parameter t_c introduced earlier to separate the perturbative and nonperturbative regions of Q^2 .

The physical idea underlying the branching approximation is that soft gluons are to be summed up and included in the nonperturbative model for hadronization. Thus what is needed is the probability $\Pi(t_0, t_1)$ to evolve from an initial mass t_0 to a final mass t_1 , emitting no gluons harder than the cutoff. It is calculated by integrating Eq. (7) over the region of phase space in which all the gluons are below the cutoff. This integral is trivial if the cutoff is taken to be not $t > t_c$ but rather $z_c < z < 1-z_c$. Then the t and z integrals separate, and the result is³

$$\Pi(t_0, t_1) = \left[\frac{\alpha_s(t_0)}{\alpha_s(t_1)} \right]^{2\gamma(z_c)/b_0}, \quad \gamma(z_c) = \int_{z_c}^{1-z_c} dz P(z) \quad (8)$$

The probability for no emission above the cutoff is $1 - \Pi(t_0, t_c)$, and $1 - \Pi(t_0, t_1)$ is the cumulative probability for the first resolvable branching to occur at t_1 . This is used to generate t_1 ; then z_1 is chosen according to $P(z)$, and the whole process is iterated for the next branching. Given t_1 and z_1 generated with a z cutoff, it is possible to use an iterative correction to implement the desired t cutoff. Thus with the branching approximation the quantum mechanical problem of radiating multiple gluons is reduced to a classical cascade process. This remains true when $g \rightarrow gg$ and $g \rightarrow qq$ are also included; it is simply necessary to follow both partons generated by each branching.

The branching approximation correctly generates leading-log QCD scaling violations; that is, it correctly generates all powers of $\alpha_s(Q^2) \ln Q^2$. These terms arise from the region of phase space in which the masses are strongly ordered, and in this region no problems arise. However, the masses generated are not always strongly ordered, and then various ad hoc modifications are needed to carry out the algorithm. These do not modify the leading-log results, but they will complicate any attempts to generate nonleading-log terms correctly. While the branching approximation correctly sums all powers of $\alpha_s(Q^2) \ln Q^2$, which arise from independent radiation from each parton, it does not sum correctly the powers of $\alpha_s(Q^2) \ln(1/x)$, and these are comparable for the multiplicity. This is because the multiplicity is dominated by very soft gluons which are not radiated independently but couple to the total color charge of the system. It is found from QCD perturbation theory

that to leading order in $\ln(1/x)$ the cancellation of the radiation from different partons leads just to the ordering of emission angles,⁷

$$\theta_1 > \theta_2 > \dots > \theta_n, \quad (9)$$

as well as of ordering of the masses, Eq. (6). This gives a multiplicity which grows asymptotically like¹³

$$\bar{n} \sim \exp \left\{ 2 \left[\left(\frac{36}{33 - 2n_f} \right) \ln Q^2 \right]^{1/2} \right\} \quad (10a)$$

compared with the leading-log result

$$\bar{n} \sim \exp \left\{ 4 \left[\left(\frac{36}{33 - 2n_f} \right) \ln Q^2 \right]^{1/2} \right\}. \quad (10b)$$

Angle ordering has been implemented as an option in PYTHIA, and results from it at $Q^2 = (2 \text{ TeV})^2$ with and without angle ordering have been compared.¹⁴ The differences are surprisingly small, apparently because kinematic effects built into the Monte Carlo programs but not into the asymptotic calculations greatly suppress the contributions of soft gluons. This issue clearly requires more study.

8.2.3 Initial State QCD Corrections

The collinear singularities for QCD radiation from initial-state partons have the same factorized form as in Eq. (3); the Altarelli-Parisi equations for the structure functions sum up just these terms with collinear kinematics and with strong ordering of the masses p^2 . The most natural approach to initial state corrections, therefore, is to generate such a shower starting at partons in the incoming hadrons with small spacelike p^2 and evolving towards the large Q^2 of the hard scattering, in analogy with the final state case. This is the approach taken by Field et al.¹¹ Unfortunately, it is very inefficient, essentially because the showers rarely give the desired x and Q^2

for the parton, so that most of them must be discarded. COJETS was the first program to handle initial state radiative corrections efficiently. While it also uses a forward evolution algorithm, it makes an elaborate pretabulation of showers so that it can efficiently select one giving the desired parton.

An alternative approach which achieves reasonable efficiency without the need for pretabulation is to evolve backwards from the hard scattering towards small p^2 inside the initial hadrons. The Altarelli-Parisi equations are usually considered to describe a forward evolution $a \rightarrow bc$ from a smaller space-like mass to a larger one, but Sjostrand¹⁹ realized that they can also be used to calculate the probability that parton b disappears during a backwards evolution from a larger spacelike mass $|t_0|$ to a smaller mass $|t_1|$. The probability that parton b survives is given by¹⁵

$$S_b = \exp \left\{ - \int_{t_1}^{t_0} dt' \frac{\alpha_s(t')}{2\pi t'} \sum_a \int_{z_{\min}}^{z_{\max}} dz \frac{(x/z) f_a(x/z, t)}{x f_b(x, t)} P_{a \rightarrow bc}(z) \right\}. \quad (11)$$

This formula is quite similar to Eq. (8) for $\Pi(t_0, t_1)$ except for the ratio of structure functions in square brackets. Physically, this ratio implies that a branching can occur only if the structure function $(x/z) f_a(x/z, t)$ for the new initial parton a is large enough that finding it in the incoming hadron is not improbable.

Both ISAJET and PYTHIA generate initial state showers based on Eq. (11). From the standard Regge behavior of the structure functions as $x \rightarrow 0$ an upper bound can be found for the ratio of structure functions. Values of t and z are generated with the ratio replaced by its bound, and the ratio is then recovered by rejecting improbable values. A mass for the radiated parton c is generated with the final state evolution algorithm. Then it is possible to solve the kinematics requiring that the two new incoming partons have zero transverse momentum.

This algorithm requires that the structure functions be known as functions of both x and t ; in practice, a simple analytic parameterization is required. Gottschalk¹⁶ has suggested not using the t dependence but calculating it from a product of weights generated by the initial state evolution. This may prove to be slightly less convenient because the primary hard scattering is not generated according to the correct perturbative QCD cross-section, but it does allow study of kinematic and other corrections to the evolution equations.

8.2.4 Jet Fragmentation

After partons are generated according to QCD perturbation theory they must be fragmented into hadrons, involving nonperturbative physics at the confinement scale. It is therefore necessary to rely on models, but the factorization of collinear singularities implies that the same fragmentation mechanism should be operative in all processes, so the models can be constrained by e^+e^- data.

Both COJETS and ISAJET use independent fragmentation, essentially the original model of Field and Feynman.¹ As the name suggests, each parton is fragmented independently by a simple recursive algorithm. For a quark q , a new quark-antiquark pair $q'q'$ is generated with transverse momenta $\pm \vec{k}_T$. A meson qq' is formed carrying a fraction z of the $p_+ = E + p_z$ chosen according to some distribution $f(z)$

$$q \rightarrow (q\bar{q}') \text{ meson} + q' \quad (12)$$

The process is then repeated for the new quark q' with $(1-z)p_+$. The algorithm can be generalized to include baryon production and gluons. Independent fragmentation can correctly reproduce the most important nonperturbative features of jets, including scaling in z , limited transverse momentum, and particle ratios, but it has several obvious defects. Because it fragments a massless parton into a massive set of hadrons, it cannot conserve both energy

and momentum. It cannot conserve flavor because the last quark q' is discarded. Finally, the model is sensitive to the cutoff t_c because splitting a parton into two nearly collinear ones increases the multiplicity.

While PYTHIA contains independent fragmentation as an option, it mainly uses the Lund string model,² which is motivated by the dynamics of a massless relativistic string with quarks at the ends. A gluon is identified as a kink in the string, which represents the confining QCD field. Particle production occurs by the string breaking through the production of a $q'q'$ pair; short lengths of string are identified with hadrons. Thus, while the string model is totally classical, it embodies several of the features expected for quantum mechanical confinement in QCD. For a two-jet system the string model and the independent fragmentation model are essentially equivalent for fast particles, but because the string model treats the two jets simultaneously it conserves energy-momentum and flavor exactly. For multijet systems the color structure of the perturbative QCD cross-sections can be decomposed into terms corresponding to strings in the limit $N_c \rightarrow \infty$. The resulting event structure is less sensitive to the cutoff than with independent fragmentation: a soft gluon gives only a small kink in the string and so contributes negligibly, while two collinear partons are connected by only a short string and so behave like a single parton.

A third class of models³ extends the perturbative QCD evolution down to very low masses, $t_c \approx (1 \text{ GeV})^2$. Then hadrons are produced from color neutral clusters of partons with a simple model such as two-body phase space. This works surprisingly well with very few parameters, presumably because hadronization is local in phase space and preserves the perturbative structure.

Models of all types can describe most of the available data on e^+e^- reactions quite well. The most widely discussed difference among the models

is in the distribution of particles in three-jet events. The data¹⁷ show an enhancement between the gluon jet and the quark ones and a depletion between the quark jets. This is reproduced by the Lund string model and the coherent-branching cluster model; it is not reproduced by other models lacking coherence among the jets. In the string model, however, the effect arises from boosting particles which have energies comparable to their masses or transverse momenta, so it is expected to be negligible at SSC energies. At high energies the more important effect is probably on the jet multiplicity. In independent fragmentation models splitting a parton into two partons increases the multiplicity, even if the partons are nearly collinear, and nearly collinear partons must occur because the lower limit on parton masses must be a constant. This does not occur in the Lund model. Probably none of the models provide a reliable prediction for the multiplicity when extrapolated over a large energy range, but the models with coherence seem less likely to be wrong.

8.2.5 Beam Jets

Beam jets are the most poorly understood part of event simulation for hadronic reactions. There is no known connection among various processes like that provided by the factorization theorems for collinear singularities in perturbative QCD. Furthermore, it seems likely that beam jets are closely connected with unitarity of the S-matrix, since initial-state rescattering corrections can modify them, so they are as difficult to understand as the total cross-section.

Both COJETS and ISAJET currently assume that the beam jets in hard scattering events are identical with those in non-diffractive inelastic events. The exclusion of diffraction seems natural since a hard interaction should

violently disrupt the incoming hadron, but otherwise this assumption is without any theoretical justification. The minimum bias data¹⁸ are characterized by small transverse momenta, $\langle p_T \rangle \approx 0.35$ GeV, a rising plateau in rapidity,

$$\frac{dN}{dy} \approx a + b \ln s, \quad (13)$$

approximate KNO scaling with large fluctuations in multiplicity,

$$\frac{[\langle n^2 \rangle - \langle n \rangle^2]^{1/2}}{\langle n \rangle} \approx 0.5, \quad (14)$$

and strong long-range correlations in rapidity. To reproduce these features COJETS simply uses the experimental multiplicity distribution and phase space with a transverse momentum cutoff. ISAJET uses a model based on Reggeon field theory¹⁹ in which each event contains leading hadrons plus one or more cut Pomerons. Each cut Pomeron is generated with an independent fragmentation model and so has essentially Poisson multiplicity fluctuations and only short-range rapidity correlations. The increase in dN/dy is put into the splitting function by hand, but the rapidity fluctuations and long-range rapidity correlations emerge naturally from the multiple cut Pomerons.

Since PYTHIA uses the Lund string model, it must treat the beam jets as strings just like those in high- p_T jets. The minimal string configuration agrees fairly well with the data at low energies, but since the string model produces a constant dN/dy and essentially Poisson multiplicity fluctuations, it disagrees badly with the data at $Spp\bar{S}$ energies. However, perturbative QCD predicts that, because of scaling violations, structure functions become large as $x \rightarrow 0$, so the cross-sections for jets with $p_T \ll \sqrt{s}$ become comparable to the total cross-section.²⁰ Events at high energies should therefore contain multiple hard interactions. PYTHIA generates a Poisson-distributed number of

extra jets with $p_T > p_{T,\min} = 1.6$ GeV with a distribution proportional to the perturbative QCD cross-section,

$$\frac{dN}{dp_T} = \frac{1}{\sigma_0} \frac{d\sigma}{dp_T}, \quad (15)$$

where σ_0 is a normalization which measures the probability for some interaction. This is the only feasible ansatz,²¹ although strictly speaking the cross-section for n jets depends on unknown n -parton structure functions and not on the usual structure functions. But unlike the Lund model for e^+e^- interactions, this model is sensitive to the cutoff $p_{T,\min}$.

8.2.6 Status

At the qualitative level the existing programs describe the existing data fairly well. The absolute cross-sections are from standard perturbative QCD, which is well tested. In particular, a careful calculation²² for $W^\pm \rightarrow e^\pm \nu$ and the Sp $\overline{p}$ S experiments²³ at $\sqrt{s} = 630$ GeV give respectively

$$\sigma_{\text{theory}} = 0.47^{+0.14}_{-0.08} \text{ nb} \quad \text{and} \quad \sigma_{\text{exp}} = 0.63 \pm 0.05 \pm 0.09 \text{ nb} \quad (16)$$

The initial state QCD corrections in the branching approximation reproduce the measured p_T distribution of the $W^\pm$ quite well.^{7,15,24} The branching approximation for the final state approximately reproduces the measured shape of the jets; this cannot be done by omitting the QCD radiative corrections and modifying the hadronization algorithm, even drastically.²⁵

A more detailed test of the interplay between perturbative and nonperturbative physics requires comparing the shape of jet events with the models over a range of $p_{T,\text{jet}}$. The UA1 Collaboration²⁶ is currently studying the transverse energy flow $dE_T/d\Delta y$ and the multiplicity flow $dN_{\text{ch}}/d\Delta y$ vs $\Delta y = y - y_{\text{jet}}$ for $p_{T,\text{jet}} = 10, 40, \text{ and } 90$ GeV. The very preliminary indication is that the height of the beam jet background under the jet changes very little

with $p_{T,jet}$ and is higher than that in ISAJET 5.10. This is significant because the contribution to the beam jets from initial-state QCD radiation should scale like $p_{T,jet}$ while the contribution from nonperturbative spectator interactions should be roughly constant. Thus the data indicate that the main contribution comes from nonperturbative physics. This is consistent with lower energy hard scattering experiments, in which the beam jets are also found to be higher than minimum bias data. Unfortunately, it also means that present data will not test the treatment of perturbative QCD in the initial state very well.

For SSC energies the increase of the perturbative contributions with $p_{T,jet}$ should completely dominate the nonperturbative contributions. At least the transverse energy flow $dE_T/d\Delta y$ should be reliably calculable. The multiplicity flow $dN_{ch}/d\Delta y$ is much more dependent on the hadronization mechanisms and so much less reliable. In fact, the difference between independent and string fragmentation for the multiplicity at $Q^2 = (2 \text{ TeV})^2$ is greater than that between the coherent and the incoherent versions of the branching approximation.¹⁴ Finally, perturbative QCD effects will become important in the total cross-section for the first time at SSC energies. The structure of QCD perturbation theory for $x \rightarrow 0$ is still being actively studied, and the implications of the theoretical results are not yet understood. Despite these difficulties, the extrapolation of QCD to SppS energies has been very successful, and there is reason to hope that the present models are sufficiently good to study the signatures and backgrounds for new physics at the SSC.

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8.3 Detector Simulation

Event simulation must be combined with detector simulation and an analysis algorithm to obtain useful results. At an introductory level for most physics questions it is probably sufficient to generate Gaussian resolutions for each particle, and the resolutions given here are intended only as rough guides for this purpose. The energy resolution of a good uranium calorimeter is approximately¹

$$\frac{\Delta E}{E} = \frac{0.15}{\sqrt{E}} + 0.01 \text{ for electromagnetic particles} \quad (1a)$$

$$\frac{\Delta E}{E} = \frac{0.40}{\sqrt{E}} + 0.01 \text{ for hadronic particles} \quad (1b)$$

where the constant term reflects calibration and other systematic problems.

The angular resolution for hadronic showers in a large 4π detector is probably limited to¹

$$\Delta y = \Delta \theta = 0.04 \quad (2)$$

For a magnetic detector with a resolution Δx on the sagitta and a field B over a track length L the momentum resolution for high-momentum tracks is

$$\frac{\Delta p}{p^2} = \frac{8\Delta x}{kBL^2}, \quad k = 0.29979 \frac{\text{GeV}}{\text{Tesla m}}; \quad (3)$$

this gives $\Delta p/p^2 \approx 0.0003 \text{ GeV}^{-1}$ for the parameters of a large 4π SSC detector.¹

To discuss physics with any particular detector it is necessary to incorporate simulation of tracking and of electromagnetic and hadronic showers in calorimeters. Typically the transverse and longitudinal shapes of the showers are parameterized in a simple way. Such programs are very complicated and are typically 100 times slower than the physics event generators. CDFSIM describes in considerable detail the CDF magnetic detector; it is difficult for users to

modify but a version is available² with parameters appropriate for SSC energies. DOSIM describes³ the DO calorimeter and allows the user to modify the geometry somewhat more easily.

For really detailed questions such as the effects of boundaries between calorimeter elements it is necessary to track individual particles through the calorimeters. GEANT⁴ provides a framework for doing this, using a parameterization of data for hadronic interactions. However, the interaction of high-energy particles with nuclei is a complicated problem. Particle production is characterized by local interactions in rapidity with small momentum transfers, so an observed hadron is formed at a distance of order 1 fm in its co-moving rest frame, or γ fm in the laboratory frame. What exists inside a nucleus is not hadrons but a highly virtual state which would have produced them in free space; this state is not well understood either theoretically or experimentally. A great deal of caution should therefore be used when extrapolating empirical models for such interactions over large energy ranges. For the SSC the energy range of interest goes well beyond what will be covered in experiments at the Fermilab collider or at fixed target facilities. For this reason one needs to understand on a more fundamental basis the evolution of hadronic showers over a wide range of energies to have confidence in extrapolating into the multi-TeV energy region. Ideally this would come about by using detailed Monte Carlo simulations which have been cross checked with experimental measurements at lower energies - the hadronic shower equivalent to EGS. This need has already been noted in the report of the working group on calorimetry.

It seems likely that the creation of a detailed simulation for various detector configurations at the SSC will inevitably result when interest in such detectors goes beyond workshop level studies. For some workshop-type

studies, however, there is a need for an intermediate level of sophistication in detector simulation. For example, questions related to the identification of the $W \rightarrow q\bar{q}$ decay mode now require at least some simulation of the transverse and longitudinal development of hadronic showers. The implementation of even an approximation to hadronic cascades in a reasonably flexible way such that the user can change granularity and depth of calorimetry should be encouraged for the Snowmass 1986 meeting.

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8.4 Conclusions and Recommendations

Several Monte Carlo programs now exist which incorporate perturbative QCD in the leading log approximation and hadronization of the QCD partons and the spectators, generating complete events. These programs are far from perfect: they do not contain all that is known about perturbative QCD, and they must rely on models for the nonperturbative physics of hadronization. Nevertheless, they do have some theoretical basis, and they probably provide a sensible extrapolation of the standard model to SSC energies. On the basis of existing Monte Carlo studies it appears possible to observe most of the basic signatures of the standard model, providing a foundation for searching for new physics. In particular, significant progress has been made recently on the identification of $H \rightarrow W^+W^-$. Since there are also good reasons to believe that new particles exist in the mass range below about 1 TeV and that they will be produced in a hadron-hadron collider with the parameters of the SSC, the prospects for interesting results seem good.

While the existing studies are encouraging, additional work is clearly needed to complete the scientific justification for the SSC, to give possible guidance for detector development, and to allow changes to be made in the machine design if required. This work requires a collaborative effort between theorists, experimentalists, and experts on event simulation. It appears that the requisite theoretical work is already being done. The following recommendations are made to carry out the other aspects:

Recommendation 1: An environment should be created in which experimentalists can work on SSC physics and related topics over a sustained period. The remaining questions are difficult ones, and progress is unlikely during brief periods in workshops; nor can experimentalists find the required time while

doing their usual work. But it should be possible to find a few experimentalists willing to devote all or part of a sabbatical year to such questions. They should have funding and a place to work together. The SSC Central Design Group would provide the most natural center, but any of the national laboratories or large university groups could also be the host.

Recommendation 2: Additional work on Monte Carlo event simulation should be supported. All of the existing programs could benefit by increased effort, but it is difficult to attract additional people because of limited job opportunities. While most of the work must be done by theorists, the resulting programs are used primarily by experimentalists. It is obviously inappropriate to attempt to dictate to theory groups whom they should hire. However, none of the national laboratories except Brookhaven have anyone working in this area, and since all of them have experiments crucially dependent on event simulation, it would be in their interests to offer more support. This should be encouraged by the funding agencies.

CHAPTER 9

Summary of Conclusions and Recommendations

It is clear from our study of detector R&D needs for the SSC that many areas of investigation should be pursued. Much of the R&D required would be of general use to most experiments at the SSC and, in some cases, will be essential to a successful experimental program. The scale (physical size, channel count, etc.) of 4 π or general purpose detectors at the SSC will require the construction of large and complex detector subsystems. This construction will take many years and therefore R&D is required now so that informed choices concerning major subsystems can be made in time for detectors to be operational at the turn-on of the SSC.

In this section we summarize our conclusions and recommendations. The recommendations below are in approximate order of priority for each subsection.

Tracking Devices - Wire Chambers

1. There are promising methods for constructing high rate/high resolution wire chambers (see Chapter 3) which require additional development for the SSC. Such development of existing ideas should continue, and new ideas should be encouraged.
2. Many applications of wire chambers at the SSC will require systems with a very large number of sense wires. The development of cheap, compact, low power, radiation resistant electronics will be required to utilize such systems.
3. It is imperative to develop a quantitative understanding of radiation damage to wire chambers which will lead to the development of cures for this problem.

4. The effective operation of large central tracking chambers at the SSC will require very effective onboard data compression in a multi-processor front end system. The processing strategy will likely affect the chamber design.

Tracking Devices - Silicon Microstrip Detectors

1. Silicon microstrip detectors are potentially very powerful tracking devices for the SSC.
2. The development of radiation resistant integrated circuits with time-slice readout capability is imperative for effective use of silicon microstrip detectors at the SSC.
3. Radiation damage to the silicon detector itself also needs additional study.
4. The development of methods to allow readout strips on both sides of the silicon wafer would be very useful for SSC detectors. R&D in this direction should be encouraged.
5. The production yield of microstrip detectors must be improved for their use on large scale.
6. The optimal configuration of microstrip detectors for both central tracking and forward/backward detectors is not yet understood for the SSC. Additional software studies are required to determine the optimal configuration.

Tracking Devices - Other Silicon Based Devices

1. The continued development of silicon drift chambers should be encouraged. Studies of radiation damage and integration of electronics are required.
2. The development of fast pixel-type silicon detectors should be strongly encouraged.

Tracking Devices - Scintillating Fibers

1. In order to use either glass or plastic scintillating fibers in a high rate SSC detector substantial improvements to existing techniques must be made in many areas. These include:

- reduction of integration times;
- improved attenuation lengths;
- development of methods for buffering of the optical information;
- considerable reductions in readout time.

All of these problems must be addressed to utilize scintillating fibers in a high rate environment.

Calorimetry

1. Research and development in calorimetry should be pursued in the following areas as first priorities.

A1 - Liquid Argon:

- a) understanding of compensation and equalization;
- b) optimization of electronic readout for a high rate environment;
- c) study of additives to increase the speed of response.

A2 - Warm Liquids:

- a) construction of a total (as opposed to partial) absorbing calorimeter;
- b) same as (b) above in A1;
- c) search for new warm liquids.

B1 - Silicon sampling:

- a) substantial reductions in the cost of silicon;
- b) construction of a hadron calorimeter prototype;

- c) radiation damage;
- d) development of appropriate electronics for large scale application.

B2 - Heavy scintillating glasses:

- a) development of higher density glasses for hadron calorimetry;
- b) study of the hadronic response of a scintillating glass calorimeter;
- c) development of readout techniques e.g., photodiodes;

Although category A techniques are being actively investigated for existing experiments, additional research and development is needed for the SSC. Category B techniques should receive special attention since these techniques, if viable, have substantial promise but are not now receiving the attention of any large scale experiment.

2. R&D efforts in the following areas should receive second priority for the SSC.

C1 - BaF₂:

- a) improved radiation hardness of wire chamber readout;
- b) develop calibration methods.

C2 - Gas sampling:

- a) additional studies are required of saturation and non-linearities and their impact for SSC detectors.

C3 - Scintillator (solid or liquid) sampling:

- a) improvements in radiation hardness are required and should be encouraged;

- b) basic R&D is needed to assess the feasibility of using heavy liquids for hadron calorimetry and what role this might play in SSC experiments.

These techniques have significant disadvantages for use as the precision primary calorimetry for large, high luminosity experiments at the SSC, although they may have significant roles in specialized experiments.

3. Priority should be given to schemes whereby electromagnetic and precision hadron calorimetry use the same technique.
4. Prototype tests of different calorimetric methods will require substantial investments in time and money. Such tests, however, are crucial to the eventual success of most large scale experiments at the SSC and therefore should receive priority in the assignment of test beam time and other resources at the accelerator laboratories.
5. There is a crucial need for a fundamental understanding of the processes involved in hadronic cascades and their implementation in a reliable Monte Carlo simulation. Present codes are not adequate for this task.

Particle ID - Muons

1. Monte Carlo studies of muon transport at TeV energies in an iron spectrometer should and can be done soon to determine the optimum configuration of such a spectrometer. Such studies should precede any beam tests of muon transport in the TeV region; the need for such beam tests is not clear at present.

Particle ID - Electrons

1. Additional study in a workshop setting is required to determine the quantitative requirements for hadron rejection, for a variety of

physics processes at the SSC. The requirements both at low energies ($E < 150$ GeV) and at high energies need investigation.

2. Studies should be made of radiation damage to wire chambers in TRD detectors.
3. The possibility of using synchrotron radiation for identification of high energy electrons (as defined above) should receive additional study, including prototype tests if necessary.

Particle ID - Hadrons

1. The requirements for π , K or p identification need to be better documented before proceeding with an extensive program to improve hadron ID capabilities for the SSC.
2. If the studies suggested in 1 indicate a need for hadron identification, then substantial R&D will be required on ring imaging Cherenkov counters to provide it. This R&D would include the development of high speed RICH detectors, studies of radiation damage to gases used in RICH detectors, and development of devices with greater sensitivity to Cherenkov photons. A major limitation to the implementation of RICH counters at the SSC will be the cost of the associated electronic readout unless cheap, highly integrated readout is developed.

Electronics

1. The cost of electronics subsystems for detectors at the SSC will be a major, perhaps dominant, fraction of the total detector costs. Present techniques are not sufficient for SSC detectors. It is of the highest priority to lower the unit cost of electronics systems while improving performance.
2. To realize the required cost reduction and improvement in performance of front end electronics by employing VLSI devices for SSC detectors,

a program of education and a program of development of useful devices for the current generation of detectors should begin now. This will require the initiation of several design centers within the HEP community and a strong commitment to extensive R&D efforts.

3. A detailed understanding of radiation damage to the electronics systems to be used at the SSC must be pursued. There is substantial overlap with the needs of the SSC accelerator control systems designers in this area.

Triggering

1. Our understanding of the trigger requirements for the SSC, both physics criteria and hardware/software implementation, is at a very early stage. Substantial progress could be made in this area in a Workshop setting, such as at the Snowmass 1986 meeting.
2. Modeling of trigger systems, and comparison in the next few years with the results of the upgraded UA1 and UA2 experiments and with the CDF experiment, will provide valuable experience.

Computing

1. The implementation of very large arrays of microprocessor farms for high level triggering and/or data reduction is presently believed to be required at the SSC. There are a number of projects presently under way for hadron collider experiments which will serve as first level prototypes of the type of arrays needed for the SSC. The performance of these projects should be monitored carefully; initiation of a microprocessor farm project aimed at the SSC is premature at this time. We recommend, however, that ongoing projects be adequately supported in all phases, including software development.

2. Exploration of the use of vector processors should be substantially expanded for experimental HEP by providing access and computer time to interested parties.
3. The continued improvement of networking among the worldwide HEP community will be crucial for the development of large scale detectors for the SSC, particularly those involving international collaboration.
4. There are likely to be many areas of software research which can be profitably used by the HEP community. A current example which is rapidly increasing in use is Structured Analysis/Structured Design tools for code development.

Superconducting Magnets

1. We have no recommendations for R&D on superconducting magnets for experiments at the SSC.

Monte Carlo Development

1. The continued development of reliable, flexible codes for simulating high energy pp collisions at the SSC will be very important for detector design. At present the development of Monte Carlo programs for this purpose is not adequately supported by either the theoretical or experimental parts of high energy physics. There is an urgent need for increased manpower in this area both for theoretical work to extend the Monte Carlo models, and for software support to make them easier for experimentalists to use. We note that two or three additional people in the world in this area would have a substantial beneficial impact.
2. There will soon be a need for means to simulate in some detail detector response at the SSC. The major element lacking in such a simulation will likely be a reliable parameterization of hadronic cascades in the TeV region; such a parameterization must be developed soon.

To summarize, it is our recommendation that a vigorous program of basic, generic R&D related to SSC detector needs should begin within the next year. This program should have as its highest priority the investigation of those areas which will involve major detector subsystems at the SSC, and those areas which require solutions of problems unique to the SSC environment. Such areas of investigation include radiation damage studies of all relevant devices, increases in speed of tracking and calorimetric detectors and of associated electronics, development of new methods of particle tracking and calorimetry in a high particle flux environment, and cost reduction of electronics systems.

Although traditionally detector R&D has, in general, accompanied proposals for specific experiments, we believe that a generic R&D program, not related to specific detector proposals, is required for detectors in the SSC era. First, there are many common problems associated with constructing detectors for the SSC, for example radiation damage and electronics development. Second, the time-scale for the construction of major detector subsystems, tracking and calorimetry, is likely to be long, given the expected complexity of large detectors at the SSC. Decisions regarding the type of such subsystems must be made early in the process of detector design, and basic research on new techniques must be completed before these decisions are made. Third, the extrapolation required from present detector technology to the needs of the SSC is greater than that which is or was required for LEP, SLC, TeVI, HERA or the Sp $\overline{p}$ S collider. Substantially more basic R&D is needed to provide effective solutions to detector requirements than in previous cases. Finally, the SSC will represent an increased opportunity and need for international collaboration in the construction of detectors and operation of experiments. The concomitant organizational scale suggests that

an early start to detector R&D will greatly improve the probability of having effective detectors available at the start of the SSC program.

The Task Force also recommends that the Central Design Group should play a leading role in encouraging the execution of detector R&D for the SSC. At present the CDG is uniquely qualified to act as an advocate for a strong program of detector R&D for the SSC to take place on the international level. We do not, however, recommend that the CDG act as sole coordinator of detector R&D for the SSC at this time. It is our hope that there will be sufficient interest in the international high energy physics community for continuing existing programs of R&D of relevance to the SSC and for initiating new programs where necessary. We wish to emphasize, however, that a program of basic detector R&D is crucial to the success of experiments at the SSC and that future circumstances may require more direct involvement of the CDG or another coordinating agency in facilitating detector R&D. We therefore recommend that the status of detector R&D related to the SSC be reviewed within the next year. Unlike this document, which attempts to outline R&D needs in a general context, a review within the next year should develop, if necessary, a specific program and timetable for completing crucial detector R&D items.

Appendix A - Consultants to the Task Force

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