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THE SSC: PROGRAMME AND SEARCHES FOR NEW PARTICLES

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1. Introduction

The Superconducting Super Collider (SSC) Laboratory is under construction. Many critical components have been designed, small and full scale prototypes built and successfully tested, and in some cases samples have been produced by industry. The 'Project', as we call the task of building the SSC Lab, is well under way. In this talk I will describe the Project and give an idea of what its status is to date.

The physical potential of the SSC is extraordinary. Whatever is responsible for the spontaneous breaking of the electroweak symmetry, it must loom at the energies accessible at the SSC. It will produce top quarks copiously. And, most significantly, it will probe the shortest distance scales ever, opening up a new frontier in High Energy Physics. Also in this talk, I will touch on some of the physics of the SSC.

I end the introduction with a disclaimer. This talk is about subjects outside my field of expertise. Describing the Project would be better left to an administrator or manager, while a discussion of what could be found and how, could certainly be done more properly by one of the many brilliant experimenters involved in the design of the major detectors for the SSC. Not all is lost, though. You will get what I hope is an interesting and peculiar, if not illuminating, insider/outsider's view. Insider's because I am employed by the SSC, and so I am embedded in the day to day discussions about the Project. Outsider's because I am neither a manager nor an experimentalist.

Most of the material covered in this talk comes from conversations with my SSC colleagues and from their transparencies. I have also used some technical documents.[1,2]

2. The Project

2.1 The accelerator systems

The SSC is a facility for producing two counter-rotating high energy and high intensity proton-proton beams, and for studying their collisions. The design of the facility was made on the premise that interesting physics would be accessible to the laboratory if the center of mass energy were to be at least 20 TeV, and that integrated luminosities of $10^{40}\mathrm{cm}^{-2}$ would be needed to make discoveries possible. The design parameters of each of the two collider rings were chosen to meet these criteria; see table 1.

Table 1. SSC Parameters

Proton Energy	20 Tev
Circumference of Rings	87 Km
Protons per r.f. bunch	0.75×10^{10}
Bunch Spacing	5 m
Number of Bunches(per ring)	17,424
Total Particle Energy (per ring)	418×10^{6} J
Emittance (RMS)	1π mm-mrad
Interaction Region Focal Spot Size RMS Radius ($\beta^* = 0.5$m)	5×10^{-6} m
p-*p* collisin rate	60 MHz
Luminosity	1×10^{33} cm^{-2} sec^{-1}
Synchrotron Radiation Power	8.75 KW (per ring)

Four stages of injection will accelerate protons from zero to 2 TeV, for delivery into the collider rings. The parameters of these accelerators are given in table 2.

The first stage, the linac, is really an array of several systems that work in series. An Ion Source is followed by the Low Energy Beam Transport. The 2.2m long Radio Frequency Quadrupole accelerates the H$^-$s from 35 keV to 2.5 MeV, which are then accelerated to 70 MeV in the 23m Drift Tube Linac. The last system of the linac is the 120m Coupled Cavity Linac which boosts the ions to an energy of 600 MeV. Three days before this talk was given news came out of a $4.9 million general construction contract awarded to Sedalco, Inc. of Fort Worth, Texas, to begin construction of the facilities that will house the Linac.

Table 2. Injector and Collider Parameters.

	Linac	LEB	MEB	HEB	Collider
Kinetic Energy (GeV)	0.6	11.1	180–200	2,000	20,000
Circumference (Km)	(length)0.11	0.54	3.96	10.89	87.12
Cycle Time	0.1sec	0.1sec	3sec	2min	~24 hr
Protons per Cycle	—	10^{12}	8×10^{12}	2×10^{13}	1.3×10^{14}
Protons per Bunch	—	10^{10}	10^{10}	10^{10}	0.75×10^{10}
Normalized RMS Emittance (π mm-mrad)	< 0.5	0.6	0.7	0.8	1.0

The Low and Medium Energy Boosters use warm magnet systems, while the High Energy Booster and the Collider use cold magnets. The design of the High Energy Booster is both interesting and challenging: to provide protons to the two collider rings it must handle rotating and counter-rotating beams, and this is accomplished by quickly alternating the polarity of the dipoles.

It is interesting that the location chosen for the collider has rather favorable geological attributes. Most of the collider tunnel will be bore through a layer of

Austin Chalk, a type of limestone. Below this lays some Eagle Ford Shale. My knowledge of geology is very limited; my son reads to me from his book that 'limestone is made of shells all pressed together, sandstone is made of grains of sand all pressed together, shale is made of mud and clay all pressed together'. The point is that, under pressure, shale behaves like mud but limestone is more like concrete. Earlier this year a decision was made to locate the experimental halls for the large multipurpose detectors (see below) on the east side. With the main campus on the west side, this is certain to make it inconvenient to the users of those east side facilities. The reason for the decision is that experimental halls for large detectors on the west side would reach down into the shale, making it hard to stabilize a very heavy detector.

2.2 Magnet Systems

The success of this enterprise lies heavily on the ability to produce industrially high quality superconducting dipoles. So not only must dipoles be designed and constructed in laboratories that will conform to demanding specifications, but the technology has to be transfered to industry.

Table 3 displays the characteristics of the collider's dipoles. The performance of dipoles constructed both by FNAL and BNL, and by technicians from industry working at these labs is superb. Typical quench sequences (at 4.35°K) involve at most one quench below the operating current of 6500 Amps (on the first ramp up), with every subsequent quench occurring always at currents exceeding 7000 Amps.

Table 3. Parameters of SSC Superconducting Dipoles (and Quadrupoles)

Operating Field	6.6 T
(Operating Gradient)	206 T/m
Operating Current	6.5 kAmps
Stored Energy	1.58 MJ (1.32 MJ)
Length	15.8 m (13.3 m)
Inner Coil Aperture	50 mm
Cold Mass	12,700 kg (10,800 kg)
Conductor	NbTi
J_c (5T, 4.2°K)	2750 Amps/mm
Filament Diameter	6 μm
Operating Temperature	4.35°K
Dipoles (Quads) per Ring	4230 (832)

The Accelerator Systems String Test (ASST) has as objective operating a half cell of five collider dipole magnets, one quadrupole magnet, and two spool pieces at the design current of 6500 Amps. It is housed in a long structure built to reproduce precisely the (almost imperceptible) actual curvature of the tunnel. A half cell is the minimum reproducible unit of which the collider arcs are built. Meeting the AAST objectives successfully is necessary to demonstrate that the many different systems that go into a minimal collider unit can work together.

2.3 Other systems and facilities. Schedule

The SSC Laboratory will be a complex array of very many systems. It is impossible to properly describe them here, so I won't. Just as an example of what is involved, the cryogenic systems for the collider will collectively perform as the biggest cooling plant in the world. There are also satellite facilities with important functions. For example, in collaboration with Southwest Medical Center a medical applications station has been planned. It will use H^- beams from the linac for cancer therapy, among other applications.

Table 4. SSC Baseline Schedule: Major Project Milestones.

Description	*Schedule*
Baseline Validation Complete	July 1990
A-E/CM Letter Contract & NTP	August 1990
CDM Authorization to Incur Costs	November 1990
SEIS Record of Decision (ROD)	February 1991
Begin Conceptual Design for Detectors	February 1991
Start SSC Civil Construction	February 1991
Accelerator String Test Complete	**September 1992**
Notice to Proceed Experiment Halls	June 1993
Full-rate Production Decision on Magnets	April 1994
Start First Half Sector – CDM Delivery	April 1994
First Collider Half Sector – Start Installation	June 1994
LINAC Start Commissioning (600 MeV)	October 1994
First Collider Half Sector – Start Cooldown	March 1995
LEB Start Commissioning	October 1995
Beneficial Occupancy of Large Experimental Halls	January 1996
MEB Start Commissioning	June 1996
HEB Start Installation	August 1996
MEB Test Beams Available	January 1997
HEB Start Commissioning	September 1998
West Detectors – Start Commissioning	March 1999
Collider – Start Commissioning	March 1999
Beam to Experiments (End of Project/Begin Ops.)	September 1999

At the beginning of time (1990) a document, the 'SSC Baseline' was created. (As far as the Project is concerned, the beginning of time *is* the baseline). In varying degrees of detail, the baseline specs out the project, its timetable and cost. Table 4 lists the major project milestones together with their baseline schedule. Of note is that the Accelerator Systems String Test (see 2.2, above) met its objectives six weeks ahead of schedule (at 11:39 AM, on Friday, August 14). The cooldown for the key test began in June and the current was slowly raised in the string, testing the quench protection system along the way. The test demonstrated the quality of the industrially assembled magnets and the associated power, cooling, and control equipment to operate together successfully as a system.

Also of note, beam should be delivered to experiment by September 1999. Of course, it will take some additional time before the beam to experiment achieves design luminosity. Studies of operation procedures are currently under way.

3. Experimental Program

3.1 Generalities

The initial experimental program of the SSC should match the physics potential and the investment in such a discovery machine. It was therefore decided, upon recommendation of the advisory panels, that the initial program should involve:

- ▷ Two major, complementary detectors aimed at the physics opportunities opened at multi-TeV energies; and
- ▷ Several smaller experiments, adding diversity and coverage of phenomena at low transverse momentum and B-physics.

The experimental program of the SSC is proposal driven. Expressions of Interest were called for starting in May 1990. By the time this talk was given 21 Expressions of Interest had been submitted, involving some 2300 collaborators from about 350 institutions worldwide. They include large all purpose detectors and smaller specialized detectors. The latter include, among others, a proposal for study of "Low p_T Physics at the SSC", four for studies of B decays (and CP violation), one proposal for "A Very Long Baseline Neutrino Oscillation Experiment" and one for "A Full Acceptance Detector for SSC Physics at Low and Intermediate Mass Scales".

(If I understand correctly) Decisions on the experimental program are made by the Director of the Laboratory upon recommendation from advisory panels (the Scientific Policy Committee and the Program Advisory Committee), constituted from renowned international experts.

3.2 Status of the Two Major All Purpose Detectors

The Program Advisory Committee stated (July 1990) that "A healthy initial program requires two detectors with complementary as well as overlapping strengths that address the physics at high p_T". That their strengths be complimentary has the obvious effect of increasing the total capabilities and discovery reach. Overlapping strengths allow for cross checks of discoveries. And, of course, that there are two experiments with some overlapping capabilities introduces that element of competitiveness that brings the best out of scientists!

Out of the many Expressions of Interest for major detectors eventually two were selected to proceed forward with Letters of Intent and then Technical Design Reports:

GEM Its design Goals emphasize identification and precision measurement of gammas, electrons and muons, with capabilities for higher luminosity. The Letter of Intent was submitted on November 29, 1991, and in January 1992 was given approval to proceed towards a Technical Design Report. At present detector R & D and Engineering is under way, with some major decisions for calorimetry to be made by the fall of 1992.

SDC Its design Goals emphasize charged particle tracking, hermetic calorimetry, lepton energy measurement and identification and vertex detection. Letter of Intent was submitted on November 30, 1990, and in January 1991 was given approval to proceed towards a Technical Design Report. This was submitted on April 1, 1992. Detector R & D and Engineering is under way.

3.3 Physics

As an example of the physics that can be studied at the SSC, we focus on discovery of a standard model higgs. By 1999 LEPII will have either discovered the higgs or set a lower bound on its mass of about 80 GeV. Theoretical upper bounds on the standard model higgs mass are in the 600 GeV to 800 GeV range. Therefore a strategy for higgs discovery at SSC needs only cover the 80 GeV to 800 GeV mass range.

The main problem for almost any SSC experiment is the enormous two jet cross section. This translates into large, often unmanageable detector backgrounds. For example, the rate for higgs production anywhere in the above mass range is at least five orders of magnitude smaller than the rate of two jet events. Thus discovery in (or study of) purely hadronic decay channels, such as $H \to b\bar{b}$ is nearly impossible.

Discovery strategies are driven by the higgs decay fractions. For masses above $2M_Z$ the dominant decay modes are into pairs of weak vector bosons. The cleanest channel is higgs $\to ZZ \to \ell^+\ell^-\ell^+\ell^-$, but it is statistically limited. Not as clean is higgs $\to ZZ \to \ell^+\ell^-\nu\bar{\nu}$. Much more abundant are the processes higgs $\to ZZ \to \ell^+\ell^- + 2\text{jets}$ and higgs $\to W^+W^- \to \ell\nu + 2\text{jets}$, which are respectively 20 and 150 times more frequent than the four charged leptons mode. They are less clean, as they involve backgrounds from $W/Z+$jets and $t\bar{t}$, so in the end they give smaller signal to background ratios. The main backgrounds to higgs $\to ZZ \to \ell^+\ell^-\ell^+\ell^-$ are from $q\bar{q}$ or $gg \to ZZ$, $Z + Q\bar{Q}$ or $Q\bar{Q}$. An additional complication comes from the fact that the width of the higgs boson increases from 1.4 to 30 to 270 GeV as the mass increases from 200 to 400 to 800 GeV. Except at the upper end of this mass range, simple cuts seem to ensure discovery of the higgs boson in the four lepton channel in 1 SSC year (1 year of running at design luminosity, i.e., 10^{40}cm^{-2}). At the upper end of the mass range either the inclusion of other channels, or additional integrated luminosity, or both, would be necessary for discovery.

Below $2M_Z$ decay into two bottom quarks quickly becomes dominant, but the decay into ZZ^*, i.e., into Zl^+l^-, $Z\nu\bar{\nu}$ and $Zq\bar{q}$, is still significant and can be used for discovery in the range 120 GeV $\leq M_h < 2M_Z$. (The branching fraction into ZZ^* dips to a minimum at $\sim 2M_Z$, reaching a maximum at $\sim$ 150 GeV). The most important backgrounds for higgs $\to ZZ^* \to e^+e^-e^+e^-$ come from production of $t\bar{t}$, $Zb\bar{b}$ and $Zt\bar{t}$; it seems possible to bring these under control through simple transverse momentum and rapidity cuts. The situation is similar for other channels. The combined signal for $4e$, 4μ and $2e2\mu$ seems very significant after 1 SSC year.

In the lowest end of the mass range, 80 GeV $< M_h <$ 130 GeV, the decay mode of choice is into two photons. Although its branching fraction is small (approximately constant and $\sim 10^{-3}$ in the range 80 Gev$< M_h <$ 150 Gev), it is a relatively clean mode. Directly produced higgs with subsequent decay into two photons seems hard, if not impossible, at SDC and GEM; the irreducible backgrounds from $q\bar{q} \to \gamma\gamma$ and $gg \to \gamma\gamma$ are several orders of magnitude larger than the signal. If the higgs is produced in association with another particle which may be used to tag the event the prospects of discovery seem brighter. Studies by both SDC and GEM indicate that the combined $W+$ higgs and $t\bar{t}+$higgs signals may yield a 4-sigma discovery limit in this mass range within 1 SSC year. The mass resolution in this range clearly depends critically on the specific choices made for electromagnetic calorimetry, and is estimated to be somewhere between 0.5 GeV and 2.5 GeV.

Space limitations preclude us from discussing the many other discovery potentials of the SSC experiments. The list is long (Supersymmetric partners of standard particles, technicolor resonances, new gauge bosons, multiple higsses, and on and on), *but hopefully incomplete!* What makes the SSC so unique among present day accelerators is that it is designed to probe the dynamics underlying the breaking of the electroweak symmetry, the stuff of which matter is made. The mechanism responsible for this could be completely new and unanticipated!

4. Concluding Remarks

The odyssey has begun. Tunnels are being dug, magnets are being fabricated, systems are being tested. Two gargantuan experimental collaborations have been formed and are quickly transiting from the design into the development stage. The SSC counts with over 2200 employees, and $517 million in funding for Fiscal Year 1993 has been signed into law. If everything proceeds according to plan (and so far it has), we may very well have a first look at a completely new repertoire of high energy phenomena by 2001.

5. References

1. Technical Design Report, Solenoidal Detector Collaboration, 1 April 1992, SDC-92-201
2. Letter of Intent, GEM Collaboration, November 30, 1991, GEM-92-49