Review of High Energy pp Colliders

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Abstract

An outsider's view is given of the LHC (CERN) and the SSC, but based on up to date information provided by the two laboratories. Topics discussed include status, general layouts, number of experiments, injector chains, magnets, tracking studies, error assumptions, lattice corrections, beam cleaning systems, beam screen requirements, radiofrequency systems and luminosity potentials.

1. INTRODUCTION

The LHC and the SSC were reported separately [1,2] at the 1990 EPAC in NICE. Since that time, basic parameters have changed little, and the designs of both projects have advanced steadily. The LHC has continued development of model magnets, produced a 'pink book' design report [3], undergone a detailed design review, and is to move towards a decision during 1993. The SSC has advanced on many fronts, and the priority that it set in 1990 to establish working 50 mm dipole magnets, suitable for industrial production, and to incorporate them in a string test of two half cells by the end of 1992, is well on the way to being realised.

To an outsider, the features of the LHC and SSC that first attract attention, apart from their sheer scale are:

- the extent of the tracking studies to establish the long-term 'injection' dynamic aperture of the collider rings;
- the small fraction of the ~ 50 mm aperture that is able to sustain motion with the required long term stability;
- the values of brightness required for the stored proton beams so that the design luminosities may be achieved;
- the effects due to the synchrotron radiation emitted by the stored protons at the collision energies;
- the need for a dedicated halo cleaning system to avoid quenching superconducting magnets; and
- the overall optimisation of the colliders, magnet systems and injector chains.

These features are discussed and the way they impact on the overall and individual component designs. The status and some general aspects of the two projects are also described.

2. PROJECT, RING AND MAGNET STATUS

At the time of the NICE conference, it was hoped that a final executive decision to proceed with the LHC would be taken during 1992. This will not now be the case; at the CERN Council meeting of December 1991, the Director General was asked to provide detailed information on technical feasibility, best estimates of cost and duration, financing, including non member states' participation and the experimental programme, before the end of 1993, to allow a move to be made then towards a final decision.

The LHC R&D programme continues as planned, but additional studies are underway following a detailed technical design review held at CERN during May 1991. Points were raised which require detailed evaluation, even though many had already been identified by LHC staff. Among these are a reconsideration of the machine aperture and the separation of the two dipoles, the use of separate collars for the twin magnets, the detailed design of the inner liner synchrotron radiation absorber, and the probable need for momentum (in addition to betatron) scrapers.

An important step in the development of the high field superconducting magnets came in October, 1991. A 1 m model of the twin dipole magnet produced a field then of 10 T in its two apertures at the design temperature of 1.8°K. Longer models, of length 10 m, are being produced by four suppliers and will be delivered to CERN this year for further measurements. In parallel, other magnets continue to be investigated, and one of these is a 10 m model twin magnet made with HERA-style coils. This has operated as expected at 4.5°K and reached 8.3 T at 1.8°K. Features of the magnets will be discussed elsewhere at the conference [4].

At the SSC, the first large scale construction has commenced with the drilling of an exploratory shaft and one of the magnet delivery shafts. The tunnel construction schedule has been evaluated and completion is planned for the end of 1998. The magnet development laboratory is built and the string test facility is well advanced with helium tanks and cryogenic refrigerator compressors installed.

An initial string test was undertaken at FNAL in 1991, using five 17 m dipoles with the earlier 40 mm design aperture. The string was tested successfully for safety and quench performance characteristics at approximately 4°K. Recently, five full length dipoles, with the revised length and aperture of 15 m and 50 mm respectively, have given impressive results under stringent tests. These are to be included in the string test at the SSC later in the year. The number of collider dipoles has now been reduced, with some units removed from the arcs to provide space for correction schemes.

Improvements are still being sought in the performance of the SSC collider quadrupoles, which currently have a 40 mm aperture. Linked to the question of the quadrupole design is the possible need for a vacuum liner synchrotron radiation absorber. A decision on the inclusion of a liner will not be made for some time, but the quadrupole design must take into account that it may be needed. The mechanical design of the liner and the question of its beam coupling impedance have led to discussions concerning a possible increase of the quadrupole aperture from 40 to 50 mm, but this is only at the discussion stage.

3. LAYOUTS AND EXPERIMENTAL REGIONS

The collider rings of the LHC have the same overall shape as LEP and the same circumference. There is a horizontal separation of 180 mm between the apertures of the twin magnets, and as the proton beams progress between the eight ring sectors, they are transferred either between an inner and outer or between an outer and inner orbit. A sector contains an arc and an insertion, and initially there were 25 regular cells per arc, each with 8 dipoles and 2 quadrupoles. These numbers have been changed recently to 24, 6 and 2 respectively. The dipole length has changed from 9 to 13.15 m, with an increase of 5% in the total bending strength.

All eight insertions are 886 m long and contain a long straight section, centred at the crossing point, and two dispersion suppressors. There are 10 quadrupoles on each side of the centre point, with 3 for an inner triplet, 3 for an outer triplet and 4 for a dispersion suppressor. With this arrangement, ten-parameter matching may be obtained between the arcs and insertions for a wide range of lattice parameters at the interaction point. The free space for experimental equipment is ~ ± 16 m, with the space between the inner triplets ± 20 m. Details are given in [3] of the insertions for p-p (or ion-ion) collisions, for injection, for halo cleaning, for the beam dump and for e-p collisions.

A schematic layout of the insertions is given in Figure 1, and is self-explanatory apart from not showing the injection scheme in the straight sections 1 and 8. Newly excavated caverns are planned for straights 1 and 7; dedicated straights for halo cleaning and the beam dump are at straights 3 and 5 respectively, and the remaining four straight sections may alternate for LEP and LHC experiments. The standard p-p collision insertion has a β^* minimum adjustable in the range 0.5 to 15 m, corresponding to p-p design luminosities of 1.65 10^{34} to 5.5 10^{32} cm $^{-2}$ s^{-1} respectively, at each of three intersection regions.

At the SSC, the colliders have a circumference of approximately 87 km and a periodicity of two, formed from two nearly semi-circular arcs and two clusters of straight sections. Each arc is formed from four sectors, and each cluster contains one 'utility' straight and one 'diamond' bypass region containing the intersection regions. Recently, the arcs have been modified and 2 x 26, 15 m spaces created by removing certain dipoles. These gaps are for correctors, scrapers, special diagnostics, beam damping systems, or 'snakes' for maintaining beam polarisation. The spacing is sufficient and uniform enough for polarisation criteria.

Each insertion cluster is composed of the sequence: D-U-D-H-D-<>-D, where D is a dispersion suppressor, U a utility straight, H a region of twelve bending half cells and <> the diamond bypass region, There is an outer and an inner branch for each bypass, and each branch contains two identical intersection regions, with either low, medium or high β^* at the crossing points. With the bypass arrangement, there is no need to move detectors around nor to have large additional experimental halls. The utility straights are required for injection, abort and radiofrequency systems.

The overall arrangement of the SSC is shown in Figure 2, and the first magnet delivery shaft is being excavated near the northernmost end of the western cluster of straight sections. The possible interaction points are marked on the figure. Nominal β^* values are 0.5, 10 and 1300 m for the low, medium and high β^* locations, with ranges of 0.5 - 8.0, 10 - 60 and 1300 - 7920 m respectively. Design luminosities are discussed later in the paper.

4. INJECTOR CHAINS

The injector chains proposed for the LHC and the SSC both include an RFQ, a linear accelerator and three boosters. Existing CERN accelerators are proposed for the LHC, but with some modifications, whereas at the SSC, a new chain has to be built. Design features are described in the references [3, 5, 6] and the main parameters are compared in the following table. The numbers of particles per bunch, N/b, are given in units of 10^{10} and the normalised emittances quoted, ε_n, are the estimated values in µrad m for the normalised rms transverse phase space areas $(\div \pi)$.

LHC INJECTION	T (or p)	N/b	ε_n	SSC INJECTION	T (or p)	N/b	ε_n
RFQ	0.75 MeV	-	0.5	RFQ	2.5 MeV	-	0.2
LIN	50. MeV	-	1.2	LIN	0.6 GeV	-	0.4
PSB	1.4 GeV	175	2.5	LEB	12. GeV/c	0.91	0.6
PS	26. GeV/c	10	3.0	MEB	0.2 TeV/c	0.86	0.7
SPS	0.45 TeV/c	10	3.75	HEB	2. TeV	0.85	0.8
LHC	7.7 TeV	10	3.75	SSC	20. TeV	0.84	1.0

Related to these parameters are the following features:

1. modifications to the existing CERN proton accelerators,
2. transition crossing in both the PS and the SSC-MEB,
3. the need of lower ε_n for the SSC than for the LHC,
4. the higher brightness initially for the LHC than SSC, and
5. longer filling for the SSC due to larger rings and the use of a superconducting HEB.

CERN injector modifications for the LHC include:

1. installation of the recently completed RFQ-2 as a preinjector for the 50 MeV linac,
2. an increase of linac current to 180 mA, for 7 μs pulses,
3. single turn injection into each of the four PSB rings,
4. an increase of the PSB top energy from 1 to 1.4 GeV, with improvements in power supply and cooling,
5. changing the PSB harmonic nos. from 4 & 8 to 1 & 2,
6. acceleration of 1.75 10^{12} protons per ring to 1.4 GeV,
7. a transfer of the single bunches from the four PSB rings to one half of the PS circumference,
8. new extraction and combining systems for item 7,
9. capture of the four bunches in the PS by tuning its present rf system to harmonic number 8,
10. a second PSB-PS transfer of four bunches 1.2 s later,
11. acceleration of 1.4 10^{13} protons in eight PS bunches through transition up to 26 GeV/c,
12. debunching of the beam and rebunching in the PS with a new 0.6 MV, 66.8 MHz rf system at h = 140,
13. transfer of 135 bunches to the SPS, each with 10^{11} protons per bunch, at a bunch spacing of 15 ns,
14. capture of the 135 bunches in a new 2.1 MV, 66.8 MHz rf system in the SPS,
15. transfer of a second and third batch of 135 bunches from the PS to the SPS at 3.6 s intervals,
16. acceleration of the beam occupying 28% of the SPS with the 66.8 MHz rf , until the bunches damp to 4 ns ,
17. further acceleration in the SPS to 0.45 TeV/c with both the new 66.8 and the old 200 MHz rf systems,
18. transfer of 3 x 135 bunches from the SPS to the LHC with new extraction systems and transfer lines, and
19. twelve transfers of 3 x 135 bunches, at 16.8 s intervals, to each LHC ring.

Filling the LHC is estimated to take 7 mins, and space charge tune depressions in the injectors are no higher than in current operation. The estimate assumes a horizontal to vertical emittance aspect ratio of 2 to 1 in the PSB, together with an increase in beam brightness by a factor of three. Preliminary measurements in the PSB, using 3 turn in place of 1 turn injection, suggest the brightness increase is achievable. Estimates for the maximum space charge tune shifts in the PSB and PS are -0.35 and -0.2 respectively.

To obtain the lower normalised emittances at the SSC, the plan is to use a higher energy, lower current, 600 MeV, H^- linac, followed by H^- charge exchange injection into the LEB. A few injected turns are introduced via a bump magnet system and a central stripping foil, and there is a rapid collapse of the bump when injection is over. The latter is required, together with low lattice β-values at the foil, to minimise scattering effects.

In both the PS and MEB, there is transition crossing, with the danger that the short duration bunches of large momentum spread may lose some transverse beam brightness. This is of more concern for the MEB because of its low ε_n value. However, the beam intensity and tune depressions are relatively low in the MEB and transition should only be a potential bottleneck if and when attempts are made to raise the SSC luminosity above the design value.

Filling time for the SSC is estimated at 72 mins, ten times larger than for the LHC. A factor of three is accounted for by the larger circumference, and a further factor is due to the 120 s cycle time of the HEB. The higher initial brightness for the LHC than SSC results from the injection schemes, and an increased brightness for the SSC may be realised by extending its injector chain. The estimated maximum space charge tune shift in the LEB is somewhat higher than for the CERN-PSB.

5. TRACKING AND MAGNET ERROR ASSUMPTIONS

Large computer codes are used to study the LHC, HERA, SSC and HEB. Dynamic apertures are defined from the maximum betatron oscillations that a particle survives for n turns, with distinctions between the short (n = 400), medium (n = 10^4) and long term (n > 10^6). Factors involved include magnetic field and beam-beam non-linearities, synchrotron motion, closed orbit errors and ripple in the orbit fields. Details are entered in the codes for the arcs and insertions, the particle coordinates, and expectation values for the magnet errors, corrections and ripple components. Injection differs from colliding beam operation as the persistent currents and beam sizes are a maximum for the former, while the beam-beam forces and insertion β-values are important for the latter, and the form of the non-linearities is different in the two cases.

Tracking is used first to find the short term and linear dynamic apertures. The detuning, ΔQ, and smear, S, are found and a criteria is set for a linear aperture, eg $\Delta Q < 0.005$ and $S < 0.1$. The former is due mainly to systematic and the latter to random errors, and the latter is defined as a normalised standard deviation of amplitude. There is long term stability of particle motion within the linear aperture, though some diffusion does occur. The next step is to extend the tracking for 10^4 turns to find the medium term dynamic aperture and the boundary between regular and chaotic motion. Lyapunov exponents may be found and predictions made for long term stability. A few long term trackings may be made to verify the Lyapunov aproach and additional confirmation may be obtained through specific experiments on existing colliders.

Experiments at the SPS and Tevatron have studied the diffusion due to higher order resonances and ripple field components. Sextupoles have been used to control the dynamic aperture, ripple introduced in the quadrupole currents, and loss rates measured for different collimator settings. A random spectrum for the ripple usually has a larger effect than discrete frequencies, and the value of the synchrotron frequency is important. Ripple tolerances need to be less than a few parts in 10^4. In general, short term to be less than a few parts in 10^4. In general, short term effects agree well with the tracking predictions, but long term effects are not entirely understood. Islands associated with loss may be identified, but often they are larger than predicted. Octupoles have been used to increase ΔQ and have led to increased dynamic apertures, as expected.

For the superconducting magnets, the designs have been influenced by model magnet measurements and the tracking studies. Dipoles are bent to suppress sagitta, and their length is linked to that of the arc cell. This length is a compromise, with a short cell giving a small beam size but also reduced bending. The choice of the inner coil diameter of the dipoles and quadrupoles is linked to their associated normal and skew multipole error fields, and also to the beam size. Studies at the SSC [6] have led to a cell reduced from 228.5 to 180 m, a dipole aperture increased from 40 to 50 mm, and an injection energy increased from 1 to 2 TeV to reduce the persistent currents during injection. A sorting of the dipoles leads to a reduced effect for random sextupole errors and corrections may be applied for systematic errors. Skew quadrupole correction is important and special compensation may be applied for quadrupoles at high-β positions. The resulting magnet error assumptions, when used in the tracking codes, lead to predictions for the SSC long term injection dynamic aperture at 10 σ, with σ the rms beam size. An equivalent figure for LHC injection is 4.5 σ, but the SSC has a smaller ε_n and a longer filling time and has to consider possible luminosity upgrades.

6. BEAM HALO COLLIMATION

In both the LHC and SSC, a beam halo cleaning system is required to prevent the quenching of one or more of the superconducting magnets. The halo arises due to intrabeam scattering, non-linear diffusion, and elastic scattering effects. The beam-beam collisions provide most of the elastic scattering, though some occurs when protons collide with residual gas molecules. The predicted steady-state proton loss rates due to the halo growth are, at the design luminosities, ~ 4 10^9 s^{-1} for the LHC and about a factor 4 less for the SSC. For a magnet quench to be avoided, the local loss rate must be at least 2 orders of magnitude less, at no more than ~ 10^7 s^{-1}. Beam loss halo collimators of very high interception efficiency are thus required for both projects, and they have to be housed in dedicated areas, devoid of superconducting magnets. In addition to loss of halo, beam is lost due to inelastic collisions and equipment malfunctions, and these are handled separately by other collimators and beam abort systems, respectively.

Two or more stages of halo collimation are proposed for the LHC [3], in long insertion 3. The first collimator is a 3 m block of tungsten, with its inner face parallel to the trajectories of the halo particles. Downstream, there is a second collimator to catch diverging outscattered particles and 2 further collimators to catch inelastically produced secondary particles. For colliding beam operation, the first collimator is placed to intercept particles of amplitude 6 σ, well within the 10 σ minimum aperture acceptance of the rings. The estimated impact parameter at the first collimator is 1 μ, which leads to a specification of 0.3 μ for the surface polishing. With such a small impact parameter, there is a large emergent flux, so necessitating the downstream collimators. Interception and collection efficiencies are under study at both the LHC and SSC, and include effects such as the thermal expansion and deformation of collimators and variations in closed orbits. One suggestion at the SSC is to replace the first collimator by a scattering target, located at a high - β or high dispersion point, with the latter also providing momentum collimation.

7. SYNCHROTRON RADIATION ABSORBER

A separate perforated screen is to be installed inside the stainless steel vacuum chambers of the LHC. The screen will be cooled to 5 - 10°K by pipes containing liquid helium, and the chamber walls will be in contact with superfluid helium at 1.9°K. The functions of the screen are to absorb the power from the synchrotron radiation and beam induced wall currents, provide a cryopumping surface and also allow the 1.9°K walls to provide some continuous pumping through the holes in the screen. A similar system, though at different temperatures, is under study at the SSC.

The screen is an added complication, but it appears the only solution for problems related to gas desorption. This occurs when synchrotron radiation, ionised residual gas molecules or electrons strike its inner wall. Gas is released, mainly hydrogen, and an equilibrium vapour pressure of ~ 10^{-12} Torr exists unless a monolayer of gas builds up, creating a pressure rise. The formation of such a monolayer is prevented as the holes in the screen allow the additional distributed pumping. Desorption coefficients are being measured at the EPA ring at CERN, and the mechanical design of the inner liner is still evolving. The structure must withstand the deformation stresses due to eddy currents if the surrounding superconducting magnet quenches. Also, it must have an acceptable electromagnetic beam coupling impedance. Elliptical and diamond shaped screens are being considered, with no line of sight through the holes to the 1.9°K surfaces. The screens are to be made of stainless steel, and special techniques are being examined for copper plating the inner surfaces.

8. RADIOFREQUENCY (rf) SYSTEMS

The main factor influencing the rf system design of the colliders is the level of beam loading. At the LHC, the circulating current per beam is 0.85 A , while at the SSC it is 0.072 A (or 0.3 A for an upgrade). The loading at the rf frequency is mainly reactive and there are also revolution frequency harmonics due to the beam gaps for injection and aborting. Superconducting cavities are favoured for handling the reactive and transient beam loading. A relevant figure of merit for a cavity is the ratio V/(R/Q), where V is the amplitude of the cavity voltage and R/Q is related to its potential stored energy. The ratio is about an order of magnitude larger for a superconducting than a room temperature cavity, assuming optimised designs. To avoid beam loading instabilities, it is planned to use an rf feedback loop around each high power klystron - feeder - cavity system.

9. LUMINOSITY POTENTIALS

The 1991 LHC review committee considered luminosities of 1.7 10^{34} cm^{-2} s^{-1} a realistic aim. The nominal design values at the SSC are 10^{33} cm^{-2} s^{-1}, but thought has been given on how to approach the LHC figure. One possibility is to increase both the number of protons per bunch and the transverse emittances so that the brightness and space charge levels remain unchanged. A maximum increase is a factor of 4, set by the synchrotron radiation power and by the ratio, at injection, of beam size to dynamic aperture. The gain in luminosity is also 4, and two ways are available to attempt the increase, either to raise the ion source and linac H^- current, or to 'paint' more injected turns. The latter is easier, and the larger emittances accommodate the enhanced foil scattering.

Another possibility is to raise the bunch intensity and beam brightness, using a modified injector chain to prevent an increased space charge detuning. Two options have been considered; in the one, the linac energy is raised to 1 GeV for a further potential gain of 1.75; in the other, an extra booster is introduced between the 600 MeV linac and LEB, eg a 3-ring, 10 Hz, 0.6 to 2 GeV booster, one third the size of the LEB, for a potential gain of 3. The total luminosity gains are 7 for the first example and 12 for the second, but to achieve these, there must be no loss of brightness due to other factors, such as MEB transition crossing effects, or enhanced foil scattering.

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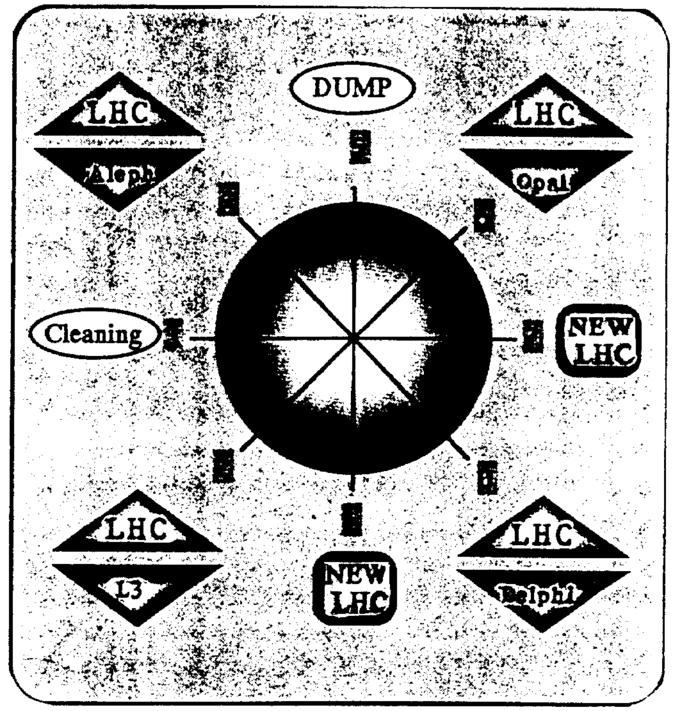

Straights 1 and 8 : injection from SPS.
Straights 2, 4, 6, 8 : LEP & LHC expts.

Figure 1. LHC Layout

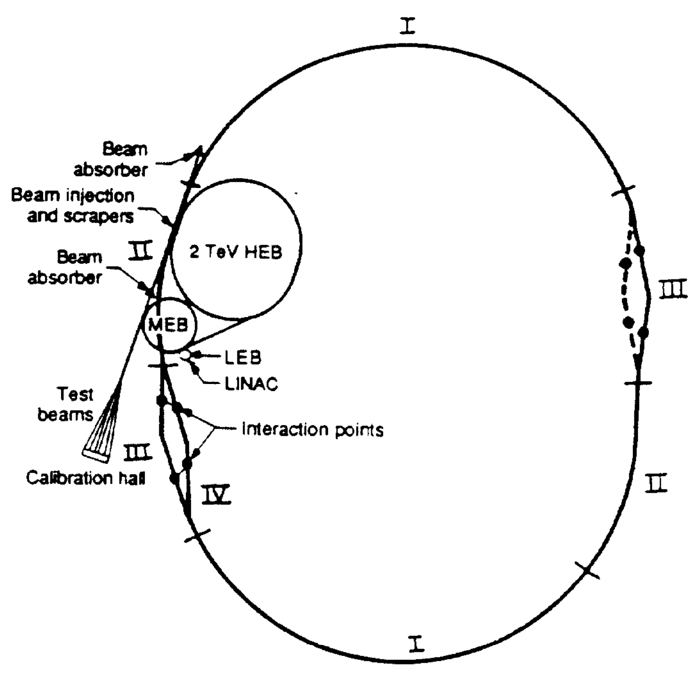

Figure 2. SSC Layout