Summary Report of the IR Working Group

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Summary

The goals of the working group were to

- o determine the dimensions of collision and assembly halls required for experiments at the SSC;
- o improve and expand on the lattice and IR optics designs described in the SSC Conceptual Design Report (CDR);
- o discuss the luminosity vs free space trade-off in the high luminosity IRs;
- o determine machine requirements for experimental magnet compensation;
- o estimate backgrounds and induced radioactivity in the IR regions;
- o formulate lattice designs for the option to build a bypass of either of the clustered IR regions described in the CDR;
- o present arguments for and against such a bypass including experiment staging and scheduling; and
- o make recommendations for future study.

The dimensions of collision and assembly halls required for the 4π detectors which have been described for the SSC are substantially larger than existing halls at Fermilab, LEP, etc. The option of building such large detectors in-place should be given serious consideration. The SSC lattice with clustered IRs is flexible and can probably accommodate most of the experiments described to date, although there may be some scheduling conflicts between experiments desiring very low luminosity and those requiring the maximum luminosity. The variation of luminosity for deviations around the nominal ±20m free space in a high luminosity IR is not substantial for changes of a few meters which may be important to accommodate experimental apparatus. Focusing IR quadrupoles of the maximum feasible gradient should be used. Compensation of solenoidal magnets in experiments is not needed, and dipole experimental magnets can also be handled. The flux of low energy neutrons produced by the interactions in apparatus of particles produced in the pp collisions will be significant but probably manageable; more calculations are needed. Radioactivation of apparatus in the forward direction will occur. Detectors and people must be shielded from the activated elements, in part by temporary shielding, during access periods.

It is technically feasible to construct a bypass for a clustered IR region on either side of the machine. The penalties are an increase in machine circumference, additional tunnel length for the bypass and more magnets and associated systems. A bypass on the same side of the machine as the injector, to put all experimental facilities on one side of the machine, would substantially increase the circumference of the machine unless the number of intersection regions were reduced. A bypass on either side could have a significant impact on the construction of experimental halls and might make it easier to build experiments in-place. Such a bypass would also allow more flexibility in staging the experimental program. A detailed estimate of the required funding, including experimental facilities and staging of experiments, needs to be done very soon. The bypass option has such a large impact on the overall machine and experiment plan that it requires immediate attention by the Central Design Group. While it is not at all clear that constructing a bypass is the proper choice, the concept does require additional study.

Detector Sizes and Collision/Assembly Hall Dimensions

In this section we will discuss the sizes of detectors for the SSC, and the dimensions of collision halls and assembly halls that result from the detector dimensions. The parameters of large 4π detectors for the SSC have been described in previous workshops[1] and reports[2] and at this meeting.[3] Although there are many uncertainties in the nature of 4π detectors for the SSC, many examples exist, a few of which have been explored in some detail. We therefore can use these examples with reasonable confidence to determine the shape and size of collision and/or assembly halls for 4π detectors. Detectors for forward/backward experiments have also been described in reports[2] and at this meeting.[4,5,6] Such experiments roughly fall into three classes, based on physics interest and luminosity requirements: (1) forward, for studies of rare B decays, t decays and other high mass particles, etc.[4]; (2) very forward, some overlap with (1) and studies of diffractive production of new and old particles[5]; and (3) elastic or almost elastic scattering.[6] Because of the many possibilities for experiments in the forward direction, it is more difficult to determine the sizes of the associated collision and assembly halls. In order to have definite examples we have chosen to determine the appropriate hall dimensions for a forward detector such as that described in SSC-SR-1023 or the TASTER experiment described in these proceedings[4] and the quadrupole spectrometer first described by Bjorken.[5] These examples should be representative of needs in the forward direction. The collision and assembly hall needs for elastic scattering experiments are minimal and will not be described here.[6] Many other experimental arrangements are possible at the SSC. For example, detectors[7,8,9] with magnetic spectrometers at 90° will require collision halls with considerable transverse but reduced longitudinal dimensions. We will briefly discuss this possibilty. Other "special purpose" detectors have not yet been described in sufficient detail to determine the appropriate hall sizes.

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TABLE 1. The dimensions in meters of 4π detectors

Detector	Closed Length	Retracted Length	Height Central	Width Central	z Forward	Length Forward	Height Forward	Width Forward	Core Length	Core Height	Core Width
Model A	26	40	19	19	20	11	9	9	14	12	12
Model B	27	40	19	19	20	11	9	9	13	12	12
Iron Muon	25	40	19	19	20	12	9	9	12	9	9
L3'	25	36	24	24							
D1	28	36	15	15	18	11	8	8	15	8	8
CDF'	16	25	12	12	9	9	9	9	11	12	12
D0'	22	33	13	13					12	8	8
UA1'	16	20	13	13					11	9	9

The dimensions of 4π detectors described in Refs. 1-3 are given in Table 1. To understand the meaning of the various dimensions, refer to Fig. 1.

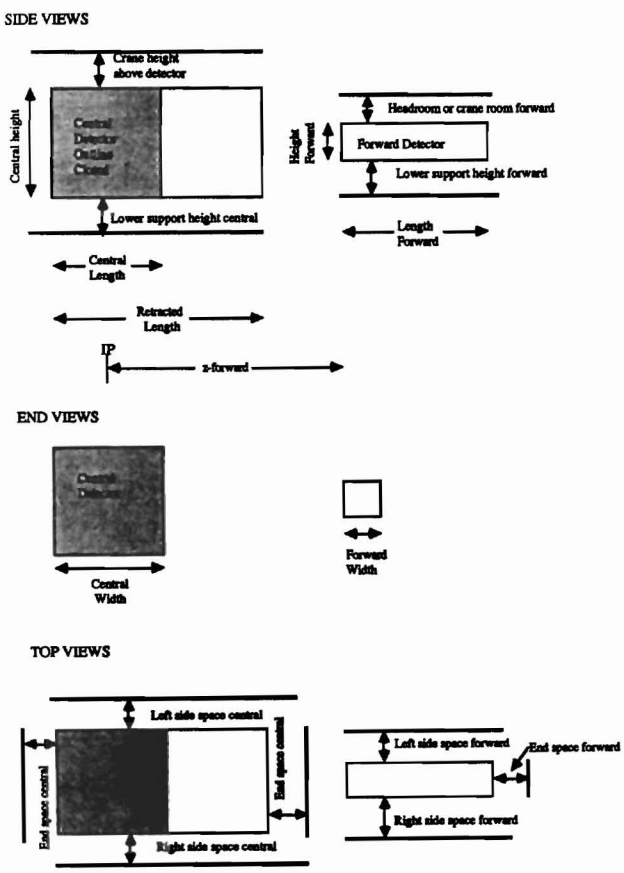

Fig. 1 Explanation of the dimensions given in Table 1, and in the text.

The "core" refers to that part of the central detector which might be rolled out of the beamline. The core does not include magnetized iron for muon measurements, on the sides or in large angle forward direction (intermediate toroids). The dimensions given in Table 1 include electronics, shielding and any other equipment directly attached to the major detector elements except support structures beneath the major pieces of the detector. These dimensions are uncertain to at least ±1m since many of the details of detector construction have not yet been explored.

The dimensions of the collision halls for the 4π detectors can be determined under two different assumptions. In the "traditional" way the detector is assembled in an assembly hall and then moved, piecewise if necessary, into the collison hall. Alternatively, the detector can be assembled directly in the collision hall; the "build-in-place" option. In this case the assembly hall is eliminated. Is this necessary for the very large 4π detectors? In the case of the L3' detector, as conceived, it is necessary to build it in place. For the other very large detectors (Model A, Model B, Iron Muon Spectrometer, and D1) it is possible to arrange the detector so that the central core of the detector can be rolled out of the beam line, although not quickly - see the discussion by the 4π detector group in these proceedings. Although it is possible to remove the central cores of these detectors, they are still massive, considerably larger than existing detectors. In the build-in-place option, routine maintenance could be done during weekly or bi-weekly machine down times but major repairs or upgrades could only be done during long shutdowns. The machine and detector schedules are therefore closely coupled. The build-in-place scenario also requires a tight coupling of the machine and detector construction schedules to allow a detector to be operational at turn on. This makes scheduling more complex, but likely raises the priority of funds for the detectors to be built in place. The decision to build-in-place or to construct assembly halls must be made on technical grounds (what is the cost of moving such large objects) and funding decisions for each detector or detector type.

For both cases, a simple algorithm (using a spreadsheet) has been developed to use the dimensions given in Table 1 to determine the size of the halls under the two options above. To determine the size of the collision hall in the case when there is both a collision and an assembly hall, the procedure is relatively simple. To the dimensions in Table 1 one must add clearance around the detector outline for the detector in an open configuration. Although the clearance dimension will likely vary slightly from detector to detector, representative values are given below.

- o crane (100 ton?) space (includes crane) - central detector - 5m
- o crane (10 ton?) space - forward region - 3m
- o lower supports - central - 2m (this may appear to be large, but working space for muon chambers and electronics may be needed beneath the detector in addition to supports
- o lower supports - forward - 1m
- o side space central (left and right) - 4m
- o side space forward - left - 3m
- o side space forward - right - 6m
- o end space central - 4m
- o end space forward - 6m

Adding these to the dimensions given in Table 1, we obtain the collision hall dimensions in Table 2.

TABLE 2. Collision hall dimensions in meters, and volume in m^3 for 4π detectors

Detector	Central Length	Central Height	Central Width	z-hall Forward	Forward Length	Forward Height	Forward Width	Total Volume
Model A	48	26	27	24	13	13	18	36426
Model B	48	26	27	24	13	13	18	36426
Iron Muon	48	26	27	24	14	13	18	36636
L3'	44	29	32					40832
D1	44	22	23	22	13	12	17	24630
CDF'	33	19	20	16.5	11	13	18	14850
D0'	41	20	21					17220
UA1'	28	20	21					11760

The clearance space transverse to the beam in the forward directions is asymmetric to allow removal of detector elements, space for detector support systems (gas, cooling, etc.) and passage into the tunnel region. For the CDF' (upgraded CDF), D0' (upgraded D0) and UA1' (upgraded UA1) detectors the dimensions in Table 2 are probably slight overestimates of the actual requirements. In particular, the crane capacity and the supports beneath the detector are likely to be smaller, which would reduce the height by about 2m. Also the dimensions assume that the central cores of the detectors (except L3') will roll out of the beam.

Of course, underground halls of the size in question do not have box-like dimensions, so the values given in Table 2 outline the useful rectangular volume rather than the true shape. The collision hall (and assembly hall) shapes are more quasi-cylindrical. For the large detectors, the axis of the cylinder should run parallel to the beam direction to reduce the required unobstructed span to a minimum. For the Model A or Model B 4π detectors, a cross-section view of a somewhat more realistic outline is shown in Fig.2. If the hall is mostly constructed in a circular cross section and then filled in, there is substantial extra space at the top and sides of the hall. Some of this space can be used for air ducts, cable-ways, etc. For comparison, a similar view of the L3 detector at LEP is shown in Fig. 3. In our model there is considerably more "empty" space surrounding the detector outline for the SSC than there is for L3 (or other) LEP detectors. This would seem prudent, at present, to allow for future expansion of the SSC detectors and uncertainties in the actual dimensions.

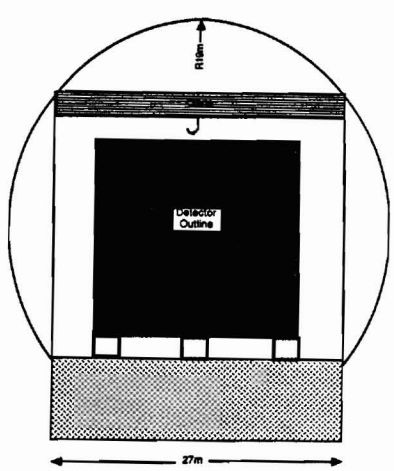

Fig. 2 A beams-eye view of the collision hall for large 4π detectors.

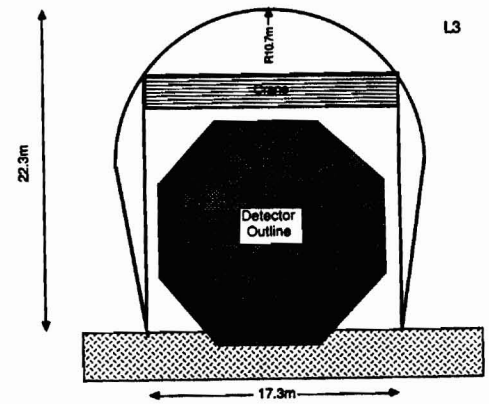

Fig. 3 A beams-eye view of the collision hall for the L3 detector at LEP.

The dimensions of the assembly hall can also be determined from Table 1 plus added space. Reasonable values for the additions are

- o crane (100 ton) height - 5m
- o space for removable shielding-wall thickness between the collision hall and the assembly hall - 7m
- o clearance around the central component of the detector to allow passage through the access door - 1m
- o space for assembly/disassembly

The dimensions of the assembly hall may be calculated from the numbers above and from Table 1 as given below

Hall length = 2 x core length (from Table 1) + 2 x forward length (from Table 1)

Hall width = 2 x core width (Table 1) + forward width (Table 1) + shielding thickness

Hall height = core height (Table 1) + clearance + crane height

Door height = core height (Table 1) + clearance

Door length = core length (Table 1) + 2 x clearance

This yields the assembly hall dimensions given in Table 3. The L3' (similar to the L3 detector at LEP) is assumed to be built in place and does not require an assembly hall (but does require access shafts). A plan view of the collision and assembly halls for the Model A or Model B detector is shown in Fig. 4. Again these dimensions are for the useful volume and do not include extra space from excavation.

TABLE 3. Assembly hall dimensions for 4π detectors

Detector	Door Length	Door Height	Hall Length	Hall Width	Hall Height	Total Volume
Model A	16	14	50	40	19	38000
Model B	15	14	48	40	19	38480
Iron Muon	14	11	48	34	16	26112
L3'			- none required -			
D1	17	10	52	31	15	24180
CDF'	13	14	40	40	19	30400
D0'	14	10	24	23	15	8280
UA1'	13	11	22	25	11	8800

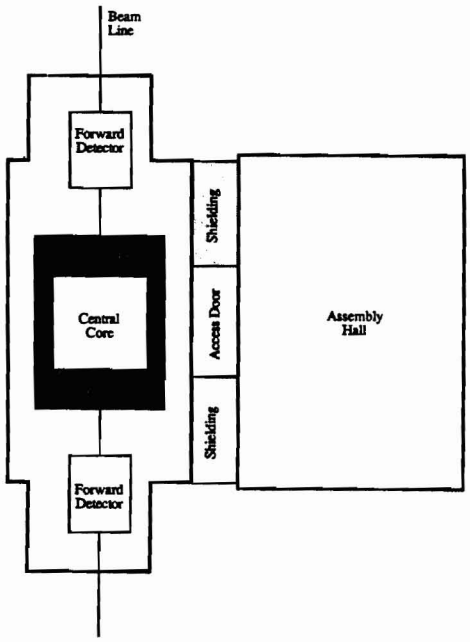

Fig. 4 Plan view of the collision and assembly halls for the Model A or Model B detector. The drawing is to scale.

For the option without an assembly hall (or possibly the L3' detector), the collision hall size must expand. Space for access shafts must also be included. Again an algorithm may be developed using the dimensions in Table 1. The formulae are similar to that for the assembly hall space and are given below

Hall length = retracted length(Table 1) + 2 x forward length (Table 1) + 4x6m(or 2x6m without forward detector)

Hall width - same as Table 2

Hall height - same as Table 2 - lower support distance

The resulting dimensions of the collisions halls are shown in Table 4. For reference a plan view for the Model A or B detector is shown in Fig. 5. Note the placement of the access shafts. It may be advantageous to have an access shaft over the collision hall rather than to the side for the larger detectors, if possible. In this design the additional space in the collision hall is added along the beam direction to keep the unobstructed span of the excavated hall to a minimum. It may be useful to increase this span somewhat, even if support pillars are needed, to allow more room for sideways expansion of the detectors (more iron for muon measurements).

TABLE 4. Collision hall dimensions for the build-in-place option

Detector	Hall Length	Hall Width	Hall Height	Total Volume
Model A	86	27	24	55728
Model B	86	27	24	55728
Iron Muon	88	27	24	57024
L3'	48	32	29	40832
D1	82	23	20	37720
CDF'	67	20	17	22780
D0'	45	21	18	17010
UA1'	32	21	18	12096

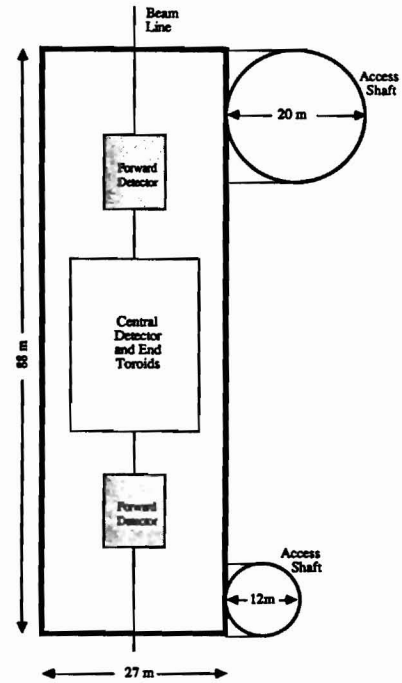

Fig. 5 Collision hall for Model A or Model B detector. No assembly hall.

A similar exercise has been done for the forward detectors. The approximate dimensions of these detectors are given in Table 5.

TABLE 5. Dimensions of special purpose forward detectors.

Detector	z front	Length	Height	Width
SSC-SR-1023	5	105	6	6
TASTER	≈1	20	14.5	14.5
Quadrupole spect.	10	1000-2000	1-3	1-3

The transverse dimensions of the quadrupole spectrometer detector elements are uncertain and will likely vary strongly with the distance from the IP. Again the collision hall dimensions may be obtained by adding the appropriate clearance space. In this case, however, the required space depends strongly on which forward detector is considered. The components of the very long quadrupole spectrometer are smaller in transverse dimension than the more conventional shorter spectrometers. We therefore give two values for the required space; the first for the conventional magnetic spectrometers and the second a range for the quadrupole spectrometer in parentheses

- o crane [20 ton(10 ton)] - 4m(3m)
- o support space beneath the detector - 1m(1m)
- o crane [20 ton(10 ton)] - 4m(3m)
- o support space beneath the detector - 1m(1m)
- o left side space - 3m(1-2m)
- o right side space - 6m(2-4m)
- o space where the forward collision hall begins to merge with the tunnel - 3m

The resulting collision hall dimensions are given in Table 6.

TABLE 6. Collision hall dimensions for special purpose forward detectors.

Detector	Half-length	Height	Width	Volume
SSC-SR-1023	108	11	15	17820
TASTER	23	19.5	23.5	10540
Quadrupole. Spectrometer	1000-2000	5-7	4-9	(20000-126000)x2(?)

Note that the half-length means the distance from the interaction point to the wall of the collision hall. Since these detectors may only be on one side of the IP, the collision halls would be very asymmetric. It is not clear if the quadrupole spectrometer can easily be implemented on one side only, hence the factor of 2 in Table 6. For comparison to the volume of the quadrupole spectrometer, the volume of the tunnel is about 7000 m^3 per kilometer. The dimensions of the remainder of the hall opposite to the forward detector cannot easily be specified. An example, however, would combine an upgraded detector (eg. CDF) with either of the short detectors. The resulting hall sizes would then be the appropriate combination of dimensions in Table 2 and Table 6.

For these detectors, assembly in place is not a likely possiblity, except by using the bypass option (see discussion later). Compared to the large 4π detectors, the sizes of the the components of the forward detectors are relatively modest. Also, unlike the 4π detectors, there is no central component which can be profitably rolled out of the beam. For forward detectors, much of the assembly work could be done away from the IR and a modest staging area would suffice.

Magnetic spectrometers at 90° have been described at Snowmass '84[7,8] and at the Fermilab Trigger Workshop.[9] Such spectrometers cover a small rapidity range near y = 0 on one side of the beamline. The length of such spectrometers may vary strongly, depending upon the particle momentum or jet energy range of interest. VanDalen and Hauptmann[7] in '84, and Theodosiou and Bensinger and Giokaris last year[9] describe spectrometers 12-15m in length, transverse to the beamline, and ±8m along the beam. Giokaris and Majewski[8], however, describe one 70 m long. The latter clearly requires a collision hall of unusual shape. The short 90° spectrometers might be accommodated into a 4π collision hall of the build-in-place variety. They would be tight or impossible matches to a collision hall with assembly hall unless the shielding between the halls were permanently moved. It is likely that jet or particle spectrometers at 90° would operate in conjuction with other detector elements, either a forward spectrometer or a modest calorimetric central detector. This experimental package has not been described in sufficient detail to determine realistic dimensions for collision halls or assembly halls. More work is needed to define such detectors.

Lattice and IR optics

Two experimental configurations for the SSC lattice have been discussed in which β^* may be very large[10]:

a) elastic scattering and very low p_T physics

b) high rapidity coverage, beyond the $|y| = 5\text{-}6$ covered by other experiments but not including elastic scattering

Exploratory studies were made of possible IR designs for each of these types of experiments.

The elastic scattering and very low P_T experiments require an IP with large β^*, variable between 400 and 4000m, and a suitable detector location whose betatron phase, ψ, from the IP is such that $\sin\psi$ is reasonably high. Such an IR has been designed by A. Garren and D. E. Johnson by modifying the low-β IR design of the CDR - see Fig.6. The modifications involve use of shorter quadrupoles and the addition of vertical dipole magnets six meters from the IP. The dipole magnets are necessary because large crossing angles are needed for large β^* as discussed later. The dipoles bend the beam parallel to the horizontal direction, enabling beam to pass through the quadrupole triplets with displacements of about 5mm or less. The detectors for elastic scattering are placed at spool piece locations next to a quadrupole, seven half-cells from either end of the straight section. At this location, the vertical β function is about 310 m, close to its maximum value. The betatron phase between a detector and the collision point is close to an odd multiple of 90°. Over the β^* range of 400-4000m, the range of $\sin\psi$ is -1.0 to -.91.

High rapidity experiments may require long drift lengths from the collision point for detectors. Fig. 7 shows a long straight section designed by A. Garren, made by combining the two "future IRs" of the CDR layout into a single long IR. By doing this, a free space between quadrupoles of about 1500 meters may be obtained. The beams could be made to cross twice, at either end of this space or elsewhere if desired. If there is a beam crossing near the middle of the free space, a larger β^* range would be possible.

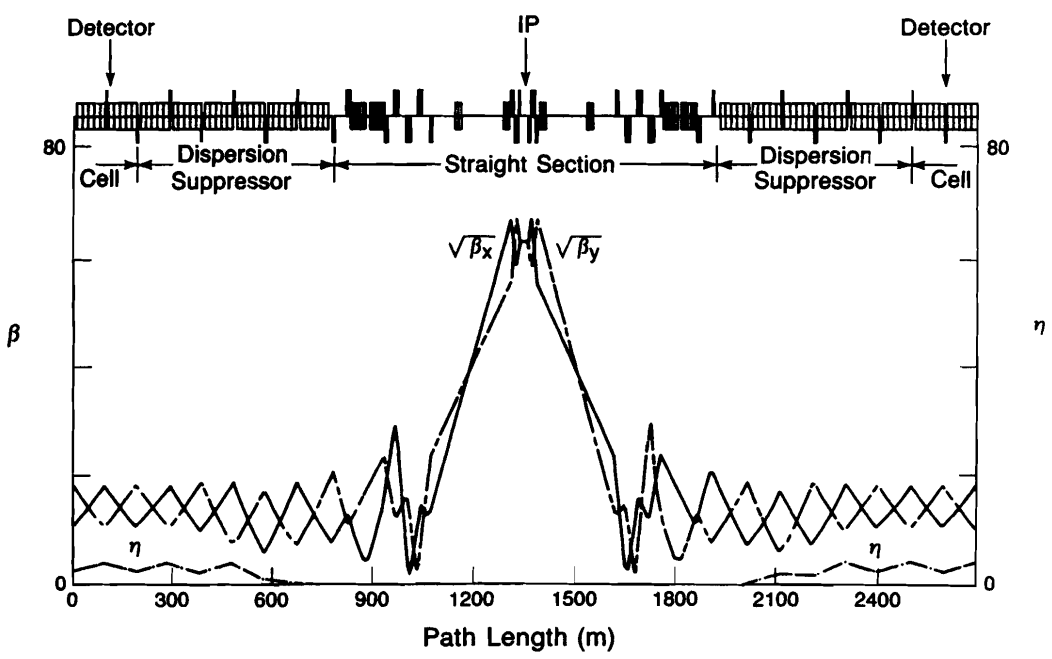

Fig. 6 Module containing interaction point with high β^* for elastic scattering and low p_T physics.

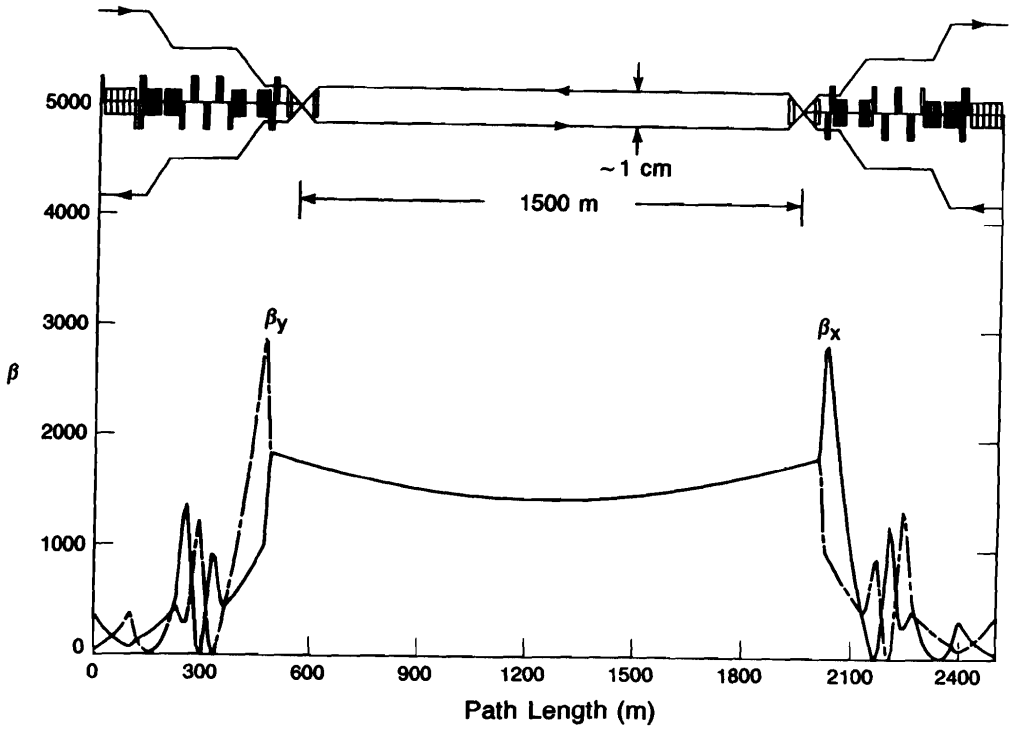

Fig. 7 Very long interaction region for high-rapidity experiment, made by coalescing the two "future" IRs.

For elastic scattering, the scattering angle must be large compared to the intrinsic spread due to the beam emittance. This implies $\beta^* \geq 4000$m. The free space (L^*) for the elastic scattering experiments can be modest and will likely be determined by crossing angle requirements as discussed below. However, the free space for high rapidity coverage must be very long, ≈ 1-2 km. The corresponding requirements for β^* are not as well defined, except that β^* must be large enough to reduce the luminosity to a manageable value. For our example we take $\beta^* = 500$ m and $L^* = 1000$ m.

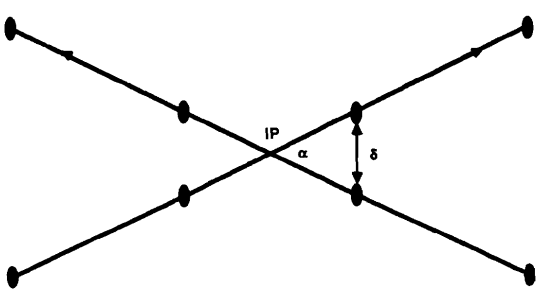

Fig. 8 A schematic diagram of beam crossing region.

Because of the larger β^*, the transverse bunch size at the collision point will be much larger than in low β^*, high luminosity, IRs. The transverse bunch sizes for the two cases under consideration are 430μ and 150μ for β^* of 4000m and 500m, respectively. Because the bunch sizes are larger, the beam crossing angle must be increased to prevent (a) regions of satellite luminosity, and (b) disruption via the beam-beam interaction. The beams must be separated by some minimum distance each time they cross as shown in Fig. 8. At the first crossing, δ/σ=m, must be some minimum value, determined by either the absence of satellite interactions or by beam-beam disruption limits. The precise requirement for the latter is uncertain but we use the value given in the CDR of m = 7. For this value, satellite luminosity is negligible. Given this criterion, the minimum opening angle, α, vs β^* can be determined as shown in Fig. 9.

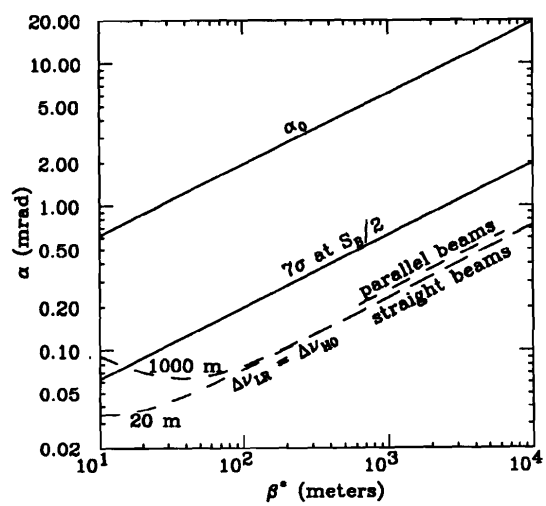

Fig. 9 Crossing angle constraints for different β^*. See text for more explanation.

An upper limit on the crossing angle results from considering headtail interactions of the intersecting bunches which excite synchrotron and betatron oscillations.[11] This limit is also shown in Fig. 9.

The other possible limitation on the crossing angle comes from long-range interactions between the bunches which cause a spread in tune shift. This limitation varies slightly if the beams are kept parallel for a substantial fraction of the free space by using dipoles or if the beams are undeflected - see Fig. 9. The minimum crossing angle requirement to avoid disruption is more severe.

In order to change β^*, one would like to operate roughly in the middle of the allowed range: a few milliradians for the elastic scattering experiment and perhaps a milliradian for the high rapidity experiment, to allow tuning over a range of β^*. If the beams are not deflected by dipoles between the collision point and the first focusing quad, they will be separated by a distance αL^* at the first quad. For example, if L^* is 1000 m and α is 1 mrad, then the separation will be 1m, clearly requiring separate IR quadrupoles. If there are dipoles before the quadrupoles, this can be reduced. However, this separation ignores the effects of quadrupoles, as part of a spectrometer, before the IR quadrupoles. For the elastic experiment, α might be, say, 4 mrad so the separation at 20 m will be 8 cm, too large for a single quadrupole but too small for separate quadrupoles. The solution is to either increase the free space, to at least 100m, or to add dipoles before the quadrupoles.

The nominal space between IR quadrupoles in a high luminosity intersection region is ±20m. Although it is probably possible to fit experimental apparatus for large detectors into this space, it will be a tight fit near the beam line in the forward/backward directions.[3] The trade-off between luminosity and free space has been discussed in detail by D. E. Johnson in an SSC Internal note and contribution to this conference.[12] Assuming that the IR quadrupoles have a gradient of 230 T/m as described in the CDR, the luminosity vs free space (L^*) is shown in Fig. 10. Increasing the free space by ±3m reduces the luminosity by about 10%. This amount of extra space may be very useful. If the field gradient in the quadrupoles can be raised by a modest amount, by operation at lower temperature for example, the full luminosity can be retained while increasing the free space by a few meters.

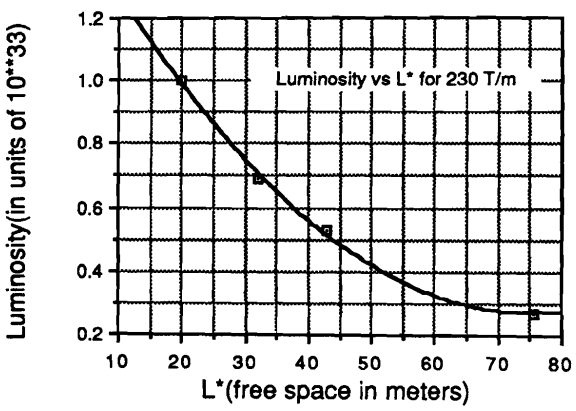

Fig. 10 Luminosity vs free space in high luminosity IR.

Experimental Magnet Compensation

Compensation of experimental magnets is discussed in detail in the contribution of S. Peggs to these Proceedings.[13] Solenoid magnets will not require any compensation. For the cases of dipole experimental magnets considered it is possible to devise compensation schemes, although there will be a limit on the allowed $\int Bdl$ to avoid large crossing angles. The bend direction of the experimental dipole should be perpendicular to the natural separation plane of the beams. At the cost of sacrificing luminosity from larger crossing angles, large dipole bends could be accommodated.

Backgrounds and Radioactivity in the Intersection Regions

The large luminosity at the SSC means that radiation levels from the primary pp collisions, and from secondary interactions of these particles with material could be high. Radiation damage to detector elements resulting from minimum ionizing particles produced directly in the pp collisions has been discussed before.[14] Damage to machine elements is discussed in the Conceptual Design Report.[15]

There are other background related problems which could be significant. These are

- o beam gas losses
- o non-linear beam loss mechanisms
- o neutron production
- o induced radioactivity

Beam losses from residual gas in the beam pipe are discussed in the CDR.[15] The loss rate due to beam gas collisions will be 1.7 protons-$cm^{-1}s^{-1}$ for a pressure of 10^{-9} Torr. In a high luminosity IR, collisions in the 160m between vertical bend magnets will produce a background rate of 27KHz. Since the pp interaction rate at full luminosity is 100 MHz, the beam gas rate is negligible. This background will only be significant for longer straight sections and lower luminosity experiments.

A much more serious problem is likely to be beam loss from unknown or partially understood reasons. In particular, the so-called nonlinear beam losses discussed by Jacques Gareyte[16] at this meeting could be significant. The belief is that intrabeam scattering replenishes the tails of the beam distribution and particles in these tails are quickly lost, within minutes, due to beam-beam interactions. It is believed that such processes are responsible for occasional large backgrounds observed by experiments in the SppS collider. These backgrounds occur despite careful scraping far from the detectors, and are alleviated by skillful tuning of the machine. The severity of this problem for the SSC is not yet known, but the large currents in the SSC mean that only a small fraction of the beam particles need to be lost for this to be a background. The severity of this background depends on its rate relative to the interaction rate of 10^8Hz. Clearly, collimators and scrapers judiciously and generously placed around the rings, must be included in the SSC design. If possible, more calculations of beam loss rates from these mechanisms should done for the SSC.

Estimates of neutron production from proton losses around the ring and from the interaction of the particles produced in the pp collisions with IR quadrupoles, collimators, or calorimeters have just begun. Estimates of neutron fluences (neutrons/cm^2) in the SSC tunnel are based on measurements at the Tevatron, and an extrapolation in energy using hadron cascade simulations. In the tunnel, the fluence (at the tunnel wall) in one SSC year (10^7 sec) is estimated to be in the range of 2-8 x $10^{10}cm^{-2}$, although there are substantial uncertainties in such estimates - the rate could well be higher.

The situation in experimental areas is much more complex.[17] Neutrons are produced predominantly by interactions of particles produced in the primary collision with IR quadrupoles and any calorimeters or collimators in front of the quadrupoles. Compared to the rate in the tunnel, the effective neutron production rate from interactions in the quadrupoles may be 100-200 times greater - a very serious problem. However, the quadrupoles near the interaction point either are shielded by experimental apparatus, or could be shielded rather easily. An accurate quantitative estimate of the effects of such shielding, using neutron transport codes, has not yet been made.

However, a crude estimate of the such shielding effects can be made. Measurements of the neutron energy spectrum produced at the Tevatron (800 GeV coasting beams) are shown in Fig. 11.[18] Roughly the same shape is obtained at 150 GeV, so we will assume that the neutron spectrum is similar in shape at the SSC. (Of course the number of neutrons will be much higher at the SSC, since more energy is available in each beam particle. The spectral shape should remain about the same since the neutrons primarily come from the end products of a hadronic cascade in the ring magnets.) The spectrum peaks at roughly 200KeV and most of the neutrons have energies between 10KeV and a few MeV. For 4π detectors, there will be a substantial amount of iron (muon toroids) surrounding part of the IR quadrupoles close to the intersection point and toroids shielding electronics on the end walls of the central detector. The neutron total cross section on iron in the energy region of interest is shown in Fig. 12.[19] There is substantial resonant structure in the cross section. This means that the iron will act as an energy selective filter.

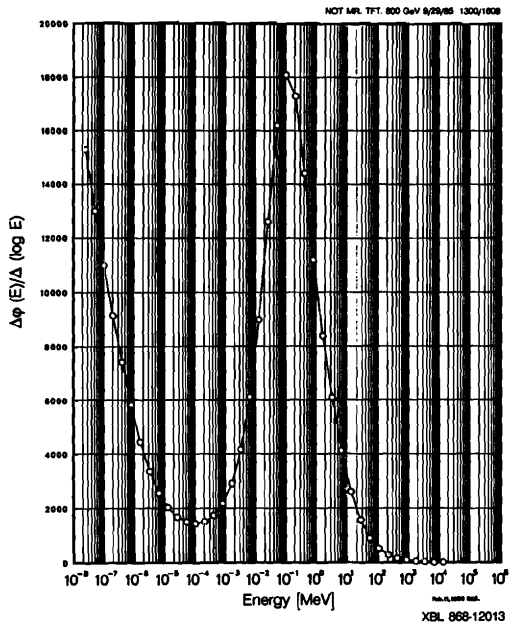

Fig. 11 Neutron energy spectrum measured at the Tevatron.

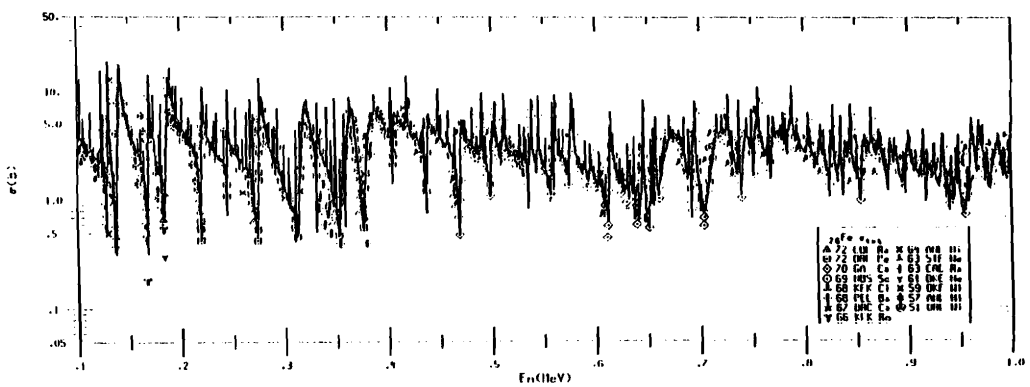

Fig. 12 Neutron cross-section on iron.

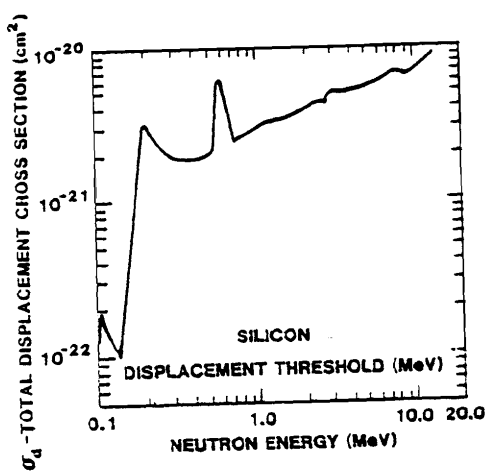

Fig. 13 Displacement cross-section in silicon vs. neutron energy.

Crudely, the cross-section average is about 5 barns in the relevant energy region. This implies an "interaction length" of about 2.5 cm in iron. At these low energies the neutrons do not lose much energy in a collision with an iron nucleus, and they are scattered isotropically. In a collision with a nucleus of atomic number A, a neutron with energy E has an average final energy, E, given by[20]

$$E = E_o \frac{1+r}{2} \quad \text{where } r = \frac{(A-1)^2}{(A+1)^2}$$

For iron A=56 and $\mu = (1+r)/2 = 0.966$. After n collisions, the energy is $E_o \mu^n$.

The number of collisions to go from E_o to E_f is given by

$$n = [\ln(E_o) - \ln(E_f)]/[-\ln\mu]$$

As an example, take E_o = 2MeV and E_f = 0.150 MeV and A = 56 (iron), then $-\ln\mu = 0.035$, and n = 74 collisions. Below energies of about 150KeV, damage to silicon (in electronics components) drops rapidly (see Fig. 13). Since the scattering is isotropic, the distance the neutron goes is about $\sqrt{74}\,\lambda = 21.5$ cm, assuming 5 barns as the cross section. If the cross section were 0.5 b, which is possible because of its resonant structure, the distance would be about 215 cm. Note that a modest amount of iron will even "thermalize" most of the neutrons, ie. reduce them to energies of about 0.025 eV. Again taking 5 b as the cross section (an underestimate below 1KeV) yields a length of 57 cm. This simple calculation suggests that electronics in 4π detectors might be effectively shielded from neutrons by iron and other material in the detector itself.

The study of radioactivation of detector or machine components in the IR region has also just begun. The components near the IR which might become significantly radioactive from activation by particle interactions are calorimeters near the beam, collimators in front of the IR quadrupoles and the quadrupoles themselves. Very preliminary estimates of radioactivation have been made assuming that iron is the material of interest.[21] For an iron target the principal sources of radioactivity induced by interactions are isotopes of manganese, mostly Mn^{54}, which has a half-life of 312 days. Modeling a quadrupole as an iron cylinder with a 13.8cm outer radius and a 1.7cm inner radius, the activity level at the the outside surface of the cryostat (44cm from the beamline) is estimated to be 140 mrem/hr. For comparison, the activity at the surface of uranium plates used in the D0 calorimeter, neglecting the contribution from α particles which are easily stopped, is about 200 mrem/hr.[22] Modest shielding, 1/4 inch of acrylic, for example, drops this to 5-10 mrem/hr.[22] Activation of collimators and calorimeters close to the beam will also occur although the magnitude of the activation depends on the material composition. Collimators for example are very unlikely to be iron. Calorimeters could be uranium, tungsten, lead or iron. Activation resulting in 100 or so mrem/hr will be a safety problem, but one which could be handled by placing temporary shielding over the activated material when access is required. Detector elements should be designed to minimize the need for access near areas that will become activated. Detector readout elements - wire chambers, for example - which are close to the activated components must be shielded by material which will not be activated.

Bypass Options - Lattice and Machine Considerations

It is possible to configure the lattice of the machine to allow the construction of a bypass of either clustered IR region. The details of the lattice are discussed in the paper by D. E. Johnson, contributed to this conference.[23] In the lattice described in the CDR, magnets are very closely packed to minimize the circumference. In order to create the potential for two separate beam channels, without removing magnets, additional magnetic elements and hence space must be added. In the design described by Johnson, six normal cells, each half filled with normal dipoles, are added to the end of each arc. Special splitting dipoles can be placed in the free regions in these cells to deflect the beam into the bypass when desired. To keep the total bend constant in the machine, six cells in each arc have been removed. The configuration for a bypass of the east IR cluster is shown in Fig. 14. A bypass for the west cluster would be similar.

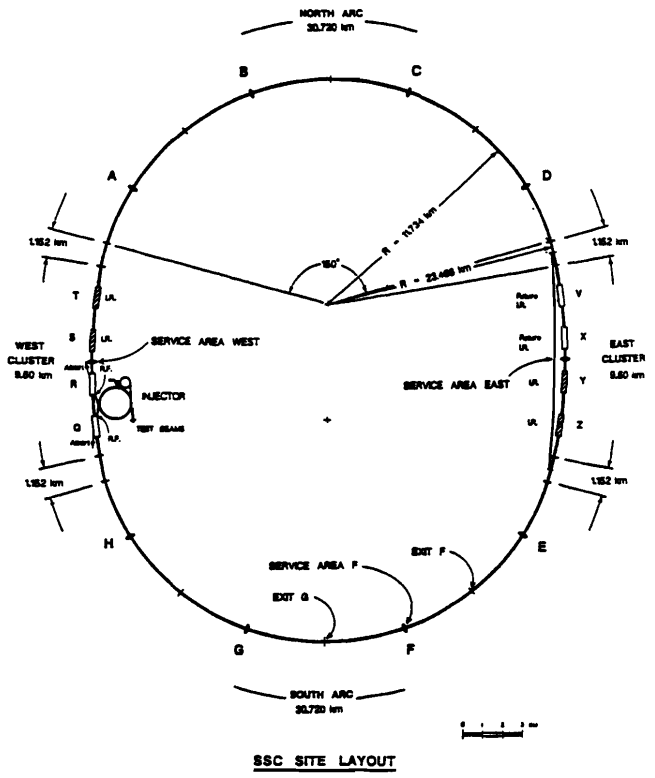

Fig. 14 SSC layout showing a bypass of the East experimental cluster.

The implementation of a bypass described by Johnson will increase the circumference of the machine, add the length of the bypass to the total tunnel length, and increase the number of magnets required. These increases are summarized in Table 7. In Table 7, we have assumed that four IRs are to be bypassed on either side, substantially increasing the circumference of the ring for a west bypass. If this condition were removed, the number of IRs in the main ring reduced, the length of the bypass could be shortened. For example, the number of straight sections in a cluster might be reduced to three or even two. In the latter case, only two experiments could be operational at any one time, the remaining two straight sections being used for injection. These two options have not been studied in detail.

TABLE 7. A summary of the CDR and bypass options.

	CDR	East Bypass	West Bypass
No. of potential IRs	6	6+4	4+4
Circumference (km)	82.9	85.3	89.9
Total tunnel length (km)	82.9	97.2	101.8
No. of dipoles	7680	8308	8308
No. of quadrupoles	1520	1724	1736

Bypass Options - Impact on Experimental Facilities

The machine requirements for implementing one or more bypass sections of the main SSC ring have been discussed in the previous section of this report. In this section, we discuss the impact of such a bypass or bypasses on collision/assembly halls and on construction and operation of experiments.

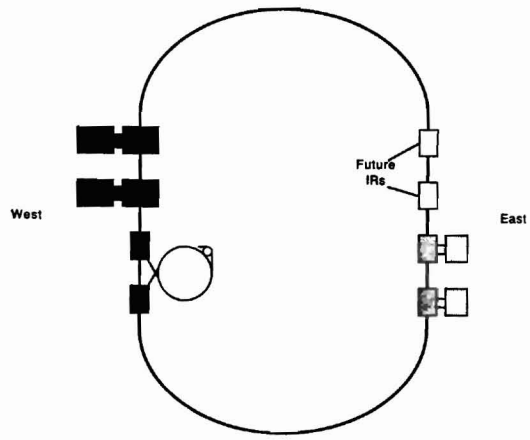

Fig. 15 A representation of the layout of experimental facilities as described in the Conceptual Design Report.

To provide a basis for discussion of the bypass options, we first briefly describe the experimental facilities outlined in the SSC Conceptual Design Report. There are two experimental regions on the same side of ring as the injector (the West side) and four on the other side (the East side) - see Fig. 15. Four of the IRs would be operational at turn-on of the machine, two on each side. At each of these IRs there would be a collision hall and an assembly hall. Although most of the experimental (and other) support facilities would reside on the West side, it is likely there would be need for considerable support facilities on the East Side as well.[24] Compared to the bypass options described below the advantages of this scheme are

- o minimum tunnel length
- o minimum number of magnets and amount of associated systems

The disadvantages are

- o inefficient utilization of underground space. With only a few exceptions, assembly halls have seldom been used after the initial construction of a large detector. Collision halls also tend to be undersized, without room for detector upgrades. Construction of the large access portal between the collision and assembly halls is difficult. Rolling many-thousand ton detectors requires massive supports beneath the detectors and strong floors into the assembly hall. To some extent these problems could be overcome by building detectors in place, independent of the bypass option. A bypass, however, gives more flexibility as described below.
- o the collision/assembly halls are on the critical path (this is a disadvantage from the machine point of view, not from an experimental viewpoint). The large underground caverns for the halls require the longest lead time of the underground work.
- o some of the detector components are on the critical path. Even with assembly halls, it is very likely that major parts of the large detectors (eg. iron muon spectrometers) must be built in place. These may need to be lowered through the roof of the collision hall, putting them on the critical path
- o construction of halls at the two IRs not in the initial complement requires shutting down the machine for a year or more.

There are two types of bypass options to be considered: bypass the East IR cluster, or bypass the West IR cluster.[25] Implicit in our discussion is the assumption that the bypass or the original ring can be functionally identical for experiments. First we discuss bypassing the East cluster of interaction regions as shown in Fig. 16a. With respect to collision and assembly halls, it is possible to have: no assembly halls (Fig. 16a); assembly halls common to both the original ring and the bypass (Fig. 16b); assembly halls for each of the eight IRs; or some mix of these. If there is an assembly hall shared by both legs of the machine major detector components can be shared. For example, one might begin initial operation with an upgraded central detector (eg. CDF', D0'.....) in one leg, while constructing a forward spectrometer in the other leg. Upon completion of the forward spectrometer, the proven central detector could be moved through the shared assembly hall into the leg with the spectrometer. Of course, having shared assembly halls adds to the cost and difficulty of underground excavation. Also the common assembly halls could not be used while beams are in the bypass because of radiation safety.

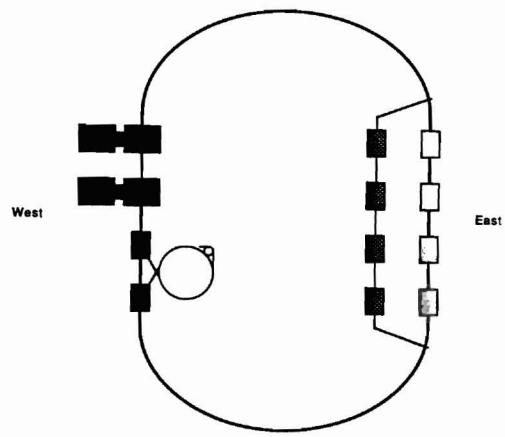

Fig. 16a Experimental layout with an East bypass. Experiments on the East would be built in place.

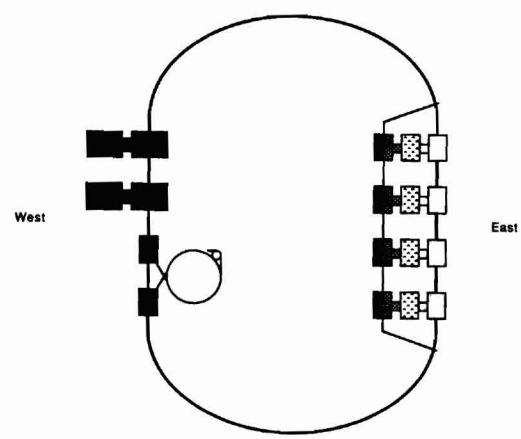

Fig. 16b Experimental layout with East bypass. In this option, there would be an assembly hall shared by all experiments.

The advantages of bypassing the East cluster are

- o the East IRs, for initial machine operation, no longer are on the critical path. A simple bypass to provide beam transport but no experiments would suffice. This assumes that halls for experiments on the East could be completed after commissioning the machine and start of operation of the detectors on the West Side. Of course for an experimentalist with an East-side detector this is not an advantage. It is not

clear if all of the bypass tunnel and experimental halls can be constructed while the machine is operating. Radiation safety and vibrations from the construction are a potential problem. This needs additional study.

- o there are more potential IRs and hence experiments. Even if they share the beam, experiment down time would be minimized.

- o if no assembly halls are built, the useful underground space is maximized on the East side, although the total volume may eventually be about the same, since the number of collision halls doubled. Complications associated with moving detectors would be eliminated.

- o assuming that the large detectors are on the West side, their productivity would be enhanced, since the beam could be switched around the East side experiments within days or less. At the start of the experimental program this would be particularly useful to allow staging and debugging of experiments on the East side would be bypassed, so scheduling problems would not be completely eliminated.

- o the construction of long IRs, including coalescing 4 to 2 IRs in the bypass is made easier

The disadvantages of building a bypass for the East cluster are

- o the circumference of the ring must increase by about 3% (see Table 7)

- o the bypass tunnel must be constructed which adds about 14% to the total tunnel length required

- o more magnets and associated systems are required (see Table 7)

- o although the bypass and the main leg are almost the same length, switching from one to the other might be done in as little time as one shift. Until experience has be attained, switching will inevitably require time to optimally tune the machine for the experiments

- o experiments on the East side probably would not be operational at turn-on to save money

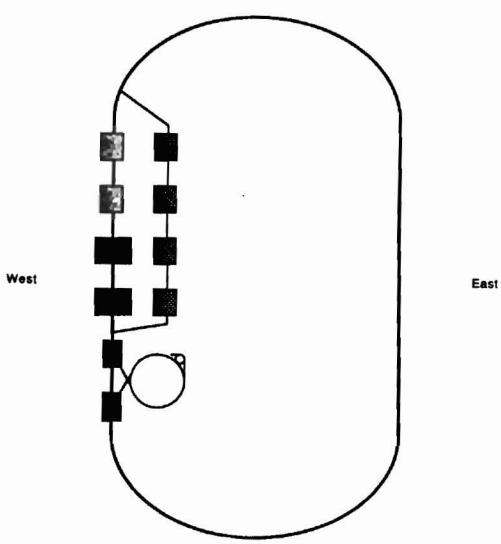

Fig. 17 The experimental layout with a West bypass. In this picture, all experiments would be built in place.

Construction of a bypass on the West Side is more complicated because of injection into the main ring. Injection requires two straight sections. We assume that the bypass contains four possible IRs, and an equal number in the main leg as shown in Fig. 17. In this scheme there would be minimal facilities on the East side. All of the experiments would be relatively close to the main laboratory area and facilities. Some of the advantages of a bypass on the West side are

- o siting constraints are less. Since only one side will be developed, the location of the ring is probably easier. Tilting the ring to put the West side closer to the surface is easier. Finding the appropriate geological conditions at one site is more likely than two.

- o assuming that the initial complement of experiments can be accommodated in four IRs, the construction of experiments and commissioning of the machine could be completely decoupled. Experiments could be assembled, in place, in the bypass while the machine is first operated. Of course, the machine elements in the bypass would have to be installed to get beams to the experiments, but initial (and probably lengthy) operation of the machine would be independent of the experiments. From an experimental point of view this is not completely desirable, since completing the bypass could take a long time after machine turn-on. The benefits to experiments after construction of the bypass and its successful operation are more clear. Initially this would also allow beam to be sent to experiments for short periods of time (days) for debugging. Experiment construction could also be profitably staged in time, ie. take data with a partial detector and then switch the beam to the other leg while completing assembly.

- o useful underground space is maximized if assembly halls are eliminated

- o utility distribution to the East side is substantially reduced, a cost savings

- o major support facilities (the East campus) would be eliminated

The disadvantages of a bypass on the West side are

- o the circumference of the machine is substantially increased, by about 8% over the design in the CDR

- o the bypass tunnel is needed. The total increase is therefore about 23%.

- o more magnets are required

- o initial operation of experiments, if they are in the bypass, could be substantially delayed unless the bypass construction and magnet installation is in phase with the completion of the main machine.

Either bypass option would allow more flexibility in staging the experimental program. As an example consider bypassing the East cluster. At turn-on of the machine the initial experimental complement might look like Fig. 18a, assuming that all detectors are built in-place. After an initial period of operation, the bypass has been completed, and the beams are switched to experiments in the bypass as in Fig. 18b. Again after a substantial period of machine operation, new experiments or upgrades have been constructed in the original leg of the machine and the beams are switched back as shown in Fig. 18c. This scenario and the choice of experiments is, of course, arbitrary; many other possibilities exist.

Assuming that either of the bypass options is technically feasible and will produce a working machine, the decision to bypass or not to bypass must be made on examination of funding requirements, up to and beyond the commissioning period of the machine and the desirability of increased flexibility in the experimental program.

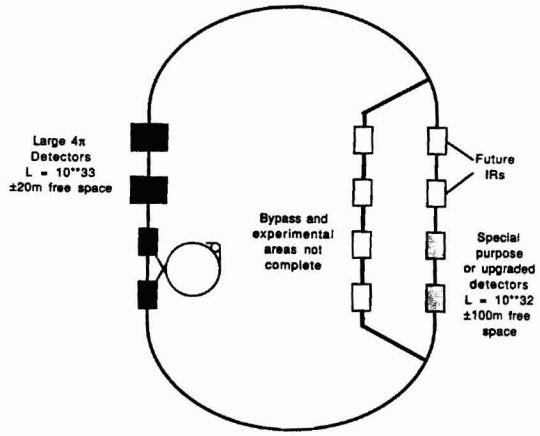

Fig. 18a An example of a possible initial complement of experiments. This would be Stage 1 in the experimental program.

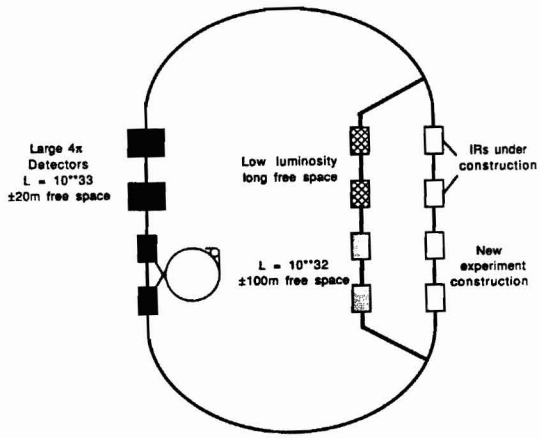

Fig. 18b An example of a possible Stage 2 of the experimental program. Experiments are in place in the bypass. Construction underway in the main leg.

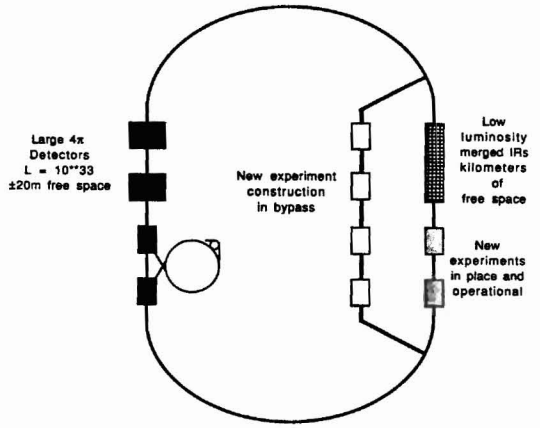

Fig. 18c An example of a possible Stage 3 in the experimental program. New experiments are underway in the main leg again. Two IRs have been coalesced to form very long straight sections.

Recommendations

Our most important recommendation is that the ramifications of the various bypass options should be the subject of a concentrated study by the Central Design Group and consultants as soon as possible. The desirablility of a bypass must be weighed against the cost.

Somewhat coupled to the above, are decisions about the existence of assembly halls and the size of collision halls. A cost comparison between building in-place and the customary collision/assembly hall situation must be made.

Various quantitative studies of neutron backgrounds, radioactivation and other backgrounds in the IR halls should be initiated.

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