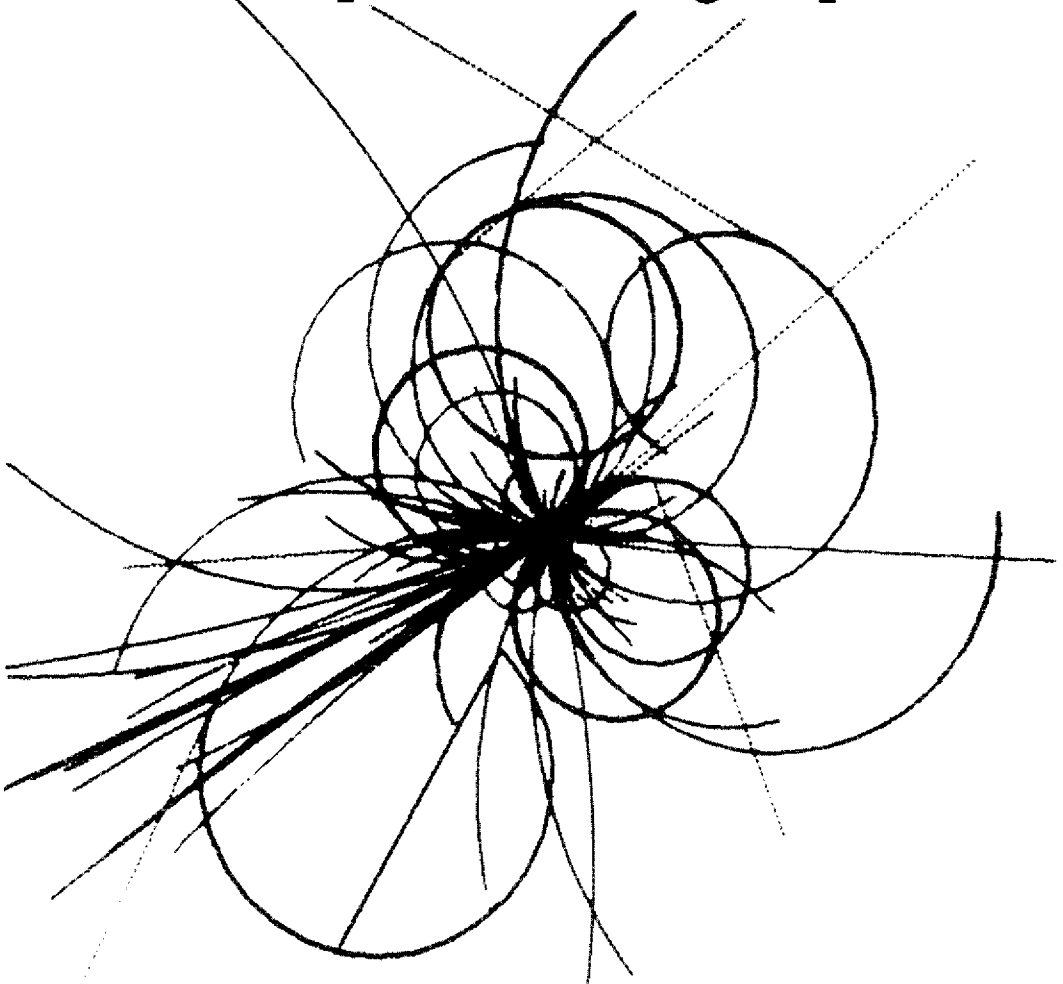
SSC-160

The Superconducting Super Collider



Luminosity Limitations

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January 1988

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*Operated by Universities Research Association for the U. S. Department of Energy

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ABSTRACT

This paper investigates the limitations to luminosity that are contained in the present SSC design. Increase in luminosity is considered by varying beam current, emittance, β^*, and the total number of beam bunches. Possible luminosity at different beam energies is also considered. The difference between initial luminosity and integrated luminosity is emphasized.

1. Introduction

Initial luminosity (L_o) is given by the formula

$$L_o = I_B^2 E_B C / 4\pi m_p c^3 e^2 \epsilon_N \beta^* M \qquad (1)$$

where

I_B = beam current in each ring
E_B = beam energy
C = ring circumference
m_p = proton mass
c = speed of light
e = electron charge
ϵ_N = normalized beam emittance
β^* = focusing parameter at the interaction point
M = number of proton bunches in each ring.

Increasing luminosity by varying each of the parameters I_B, ϵ_N, β^*, M and E_B is considered in this paper. The design limitations encountered are noted. The design [1] values for these parameters, giving an initial luminosity of $10^{33} cm^{-2} s^{-1}$, are

I_B = 73 mA
ϵ_N = 1×10^{-6} rad•m
β^* = 0.5 m
M = 17100
and E_B = 20 TeV.

The time evolution of luminosity involves a complex interplay between the number of protons in a bunch (N_B) and the emittance. A computer program is used to calculate luminosity as a function of time [2]. For the design values of the SSC, the calculated luminosity rises from the initial value, before eventually falling. Figure 1 shows this. The rise is due to emittance shrinkage caused by synchrotron radiation damping. This calculation is probably naive given the realities of an actual collider; however, it is based on our present best knowledge and provides a method for comparing integrated luminosity under various assumptions.

By knowing luminosity as a function of time and assuming a time to fill both rings (here, 2 hours), the time to maintain stored beams for physics that will maximize integrated luminosity can be calculated. Using this storage time, the maximized integrated luminosity for a given period is obtained. For one year (3.15×10^7 seconds) of continuous operation of the SSC at design parameters, the maximized integrated luminosity is $5.3 \times 10^{40} cm^{-2}$. This quantity will be recomputed as the various luminosity equation parameters are varied. It will be seen that increasing initial luminosity by a factor will in general increase integrated luminosity by a lesser factor.

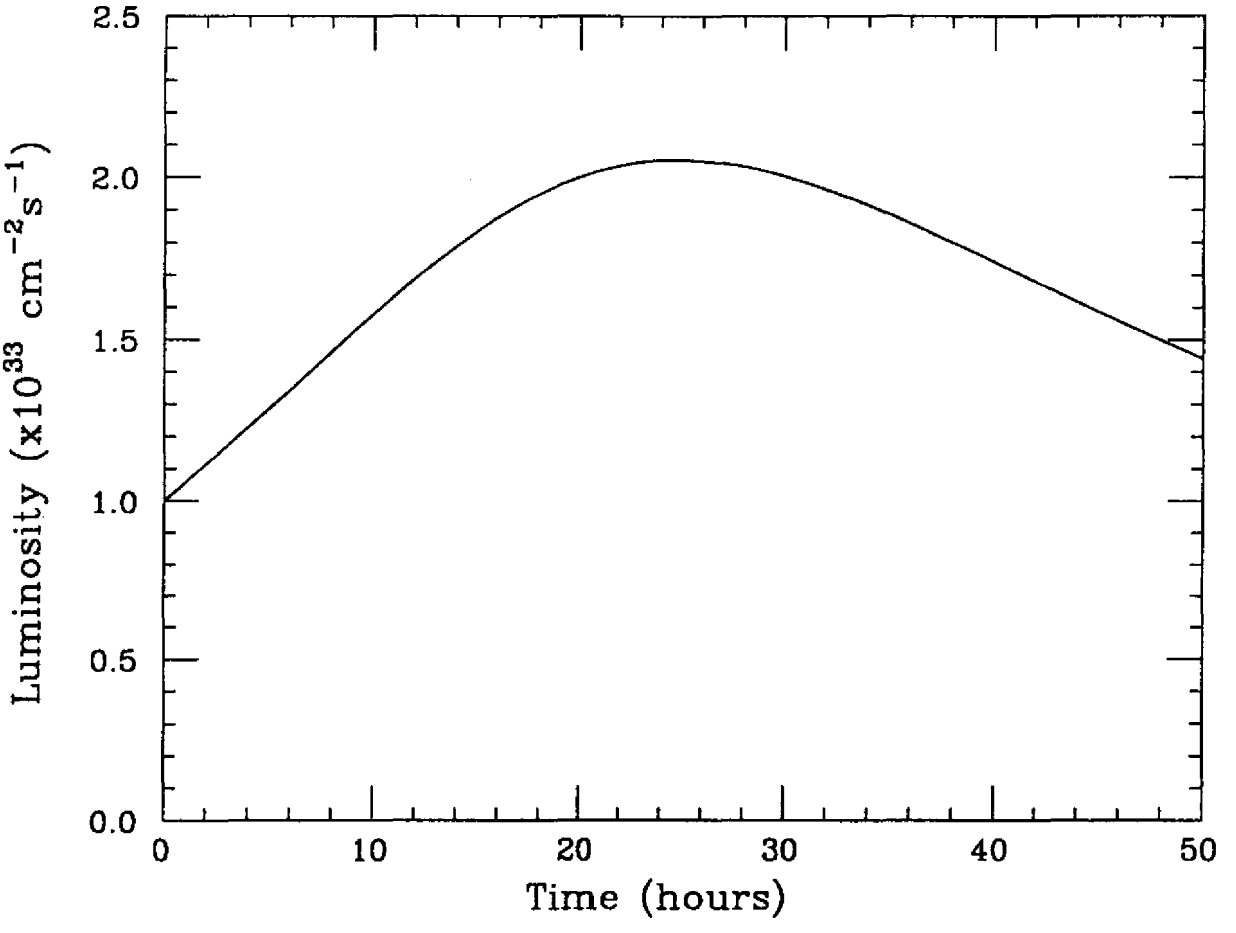

FIG. 1. Luminosity vs time for the design parameters.

The primary reason for this is that the number of protons is more quickly depleted at higher luminosities.

2. *Beam Current Variation*

In this section the effect of increasing the luminosity by increasing the beam current will be considered. All other parameters in Eq. (1) will be held constant. To be specific, an increase in initial luminosity of a factor of 10 will be considered, implying a beam current increase of $\sqrt{10}$. The number of protons in a bunch will be increased by this same $\sqrt{10}$ factor. The number of proton-proton interactions per bunch crossing increases proportionally to luminosity giving 14 interactions per crossing initially, versus 1.4 for design beam current and σ_{Inel} = 90 mb. Following the prescription to obtain integrated luminosity of the previous section, an increase in beam current by $\sqrt{10}$ results in an increase in integrated luminosity by a factor of 5.5, less than the initial luminosity increase of a factor of 10.

The remainder of this section will investigate the effects of beam current increased by $\sqrt{10}$ on the various subsystems of the SSC and on beam stability. The majority of the comments below are taken from a paper by R. Diebold [3].

a) Injector System. A limitation to the current injected into the Low Energy Booster (LEB) by the LINAC is given by the incoherent Laslett tune shift. This tune shift increases with beam current. Its current value is 0.09 [4] and it is desirable to keep it at or below this value. To do this for a beam current larger by $\sqrt{10}$ will require the energy of the LINAC to be increased from the design value of 600 MeV to 1600 MeV, as this tune shift is inversely proportional to $\beta\gamma^2$ of the LINAC. This increased energy will then cause premature stripping of the H^- ions in the transfer line bend between the LINAC and LEB. Either the bend will have to be eliminated or its radius increased. A larger beam current in the LEB will also require more turns to fill the LEB resulting in an increased emittance due to the beam passing through the H^- stripping foil. This increased emittance will decrease somewhat the luminosity gain from increased current.

b) Collider Stability. As noted above, the number of protons per bunch, N_B, is also increased. The single bunch stability limits are proportional to N_B^{-1}. The design limits have a factor of 6 safety margin; hence an increase in N_B by $\sqrt{10}$ is feasible.

The growth rates of the transverse and longitudinal dipole mode multi-bunch instabilities will increase by $\sqrt{10}$. A feedback system stronger than the present system will be required to damp these instabilities. More importantly, the quadrupole multi-bunch oscillation modes, for which no control is necessary at design beam current, become unstable. The preferred method at present for controlling this quadrupole instability is a fast feedback system. Such a system will require R&D to fabricate and apply to

the SSC. The problem of multi-bunch instability is a potentially serious one for increased beam current.

The beam-beam tune shift is a beam stability parameter that is directly proportional to beam current, and whose value must be kept below a limit. The beam-beam tune shift has two components, the head-on and the long-range. Both are related to the crossing of the beam at interaction points. An optimistic upper limit for the beam-beam tune shift is that the head-on portion should be less than 0.005 per interaction point; a pessimistic upper limit is that the sum of head-on and long-range should be less than 0.005. With design value parameters, the tune shifts are 0.0008 for head-on and 0.002 for long-range. A beam current increase by $\sqrt{10}$ will exceed the pessimistic limit but not the optimistic. Some of the long-range tune shift can be cancelled out by having interaction point crossing planes alternate between horizontal and vertical. It is felt that the beam-beam tune shift can be brought safely below limit for a beam current increased by $\sqrt{10}$.

c) Heating in IR Quadrupoles. The final focus quadrupoles in the Interaction Regions will absorb radiation from the interaction point at rates up to 2 W/m, or 0.2 mW/gm, at design luminosity. The amount of radiation scales with the luminosity, hence a $\sqrt{10}$ increase in beam current will cause radiation depositions of up to 2.0 mW/gm. The level at which quenches will occur, extrapolated from Tevatron data, is estimated as 10 mW/gm. This implies a safety margin of 5 at the increased luminosity; however, there are large uncertainties in the data extrapolation. Better measurements and calculations are necessary.

d) Tunnel and IR Radiation. Radiation in both the tunnel and interaction halls will increase as the square of the beam current. In the interaction hall this is because radiation is proportional to luminosity. In the tunnel this is due to the fact that increased beam current also gives increased synchrotron light which in turn causes increased gas desorption from beam tube walls. Electronics in both areas will thus have to survive or be shielded from ten times the radiation if beams current is increased by $\sqrt{10}$. As outlined in the Invitation for Site Proposals [5], a factor of $\sqrt{10}$ increase in beam current will not result in environmental radiation beyond proscribed limits.

e) Vacuum. As explained in the above paragraph, beam gas scattering will increase with the square of the beam current. Beam lifetime will then decrease. It is assumed that operation with increased current will occur far into the life of the SSC when present information suggests that the beam lifetime at design current will be about 1000 hours. Increasing beam current by $\sqrt{10}$ will then degrade the beam lifetime to approximately 300 hours. This is well within tolerable limits.

f) Total Beam Energy. At the design current of 73 mA the total energy in one 20 TeV beam is 405 megajoule. This energy, of course, will scale with beam current. Thus all systems sensitive to being damaged by significant beam loss will have their jeopardy increased proportionally.

g) Beam Dump System. The current beam dump system can safely handle up to $\sqrt{10}$ times the design beam current. The beam dump consists of graphite pellets whose boiling point is 4000°C. A beam current $\sqrt{10}$ larger than design will cause a temperature rise in the beam dump of 770°C.

h) Cryogenics. A study by Mike McAshan [6] indicates that an increase in beam current, and therefore synchrotron radiation heat, by $\sqrt{10}$ will increase refrigeration load by a factor of 2.1. (The refrigeration load will not directly scale as there is a significant static load.) For extended high current operation, then, refrigerator capacity will have to be increased by this factor. The diameter of the helium gas return line in the magnet cryostats will also have to be enlarged to carry increased flow. Other cryostat and magnet cold mass modification may also be necessary due to increased heat flow outward from the beam tube. Doubling the number of recoolers in the tunnel may also be necessary. The cryostat and cold mass design and the number of recoolers must be decided before initial construction. Refrigerator capacity, however, can be increased in stages with some components, namely heat exchangers, best installed at initial construction. An alternative solution to handling increased synchrotron heat is to install a beam tube liner that would intercept the synchrotron heat at higher temperature (~20 K). This would make refrigerator size largely independent of synchrotron radiation load. However, a beam tube liner would increase the magnet coil size, significantly increasing cost. Additionally, the effects of a liner on aperture and impedance would have to be examined closely.

(i) RF System. The amount of RF power required increases from 1.74 (1.50) MW for design current acceleration (storage) to 3.74 (2.98) MW for current times $\sqrt{10}$ acceleration (storage). Doubling the number of klystrons should provide for this increase.

Summarizing this section, there are three areas where limitations to increasing luminosity by increasing beam current by $\sqrt{10}$ appear in the present design. They are the injector system, multi-bunch stability, and cryogenics. In none of these areas are the problems insurmountable. Increasing luminosity by increasing beam current, then, is feasible with additional design work.

3. Emittance Variation

The design emittance of the SSC is considered to be achievable under optimum conditions. Decreasing it further is problematic; however, for purposes of this article we will investigate a factor of 2 decrease in emittance. This decrease will give a factor of two increase in initial luminosity and a factor of 1.6 increase in integrated luminosity. The number of interactions per bunch crossing will increase initially from 1.4 to 2.8. As previously, the remainder of this section will investigate the effects of emittance decreased by a factor of 2 on subsystems of the SSC.

a) Injector System. Almost the same comments that apply to the case of increased beam current apply here. The incoherent Laslett tune shift doubles with halved emittance. It is desirable to keep this tune shift at or below

its design value. An increase in LINAC energy can be used to offset the increase caused by decreased emittance. The problem of premature stripping of H^- in the transfer line bend between LINAC and LEB occurs again with the same cure of decreasing the curvature of or eliminating the bend.

b) Collider Stability. Neither single bunch nor multi-bunch stability is affected by decreased emittance. The head-on beam-beam tune shift increases with decreasing emittance, while the long-range beam-beam tune shift remains constant. A factor of 2 increase in head-on beam-beam tune shift is not serious.

c) Heating in IR Quadrupoles. The same comments for an increase in luminosity due to increased beam current apply here for an increase in luminosity due to decreased emittance. The IR quadrupoles will have to absorb more radiation. A factor of 2 more should produce no quenches.

d) IR Radiation. This also will increase proportionally with any increase in luminosity.

Summarizing this section, the main limitation to increasing luminosity by decreasing emittance is the ability to decrease emittance. As mentioned at the start of this section, a factor of 2 decrease is thinkable. If such a decrease is achieved, then the restrictions of the LINAC-LEB interface will be encountered.

4. β^* Variation

In this section the effects of increasing luminosity by decreasing β^* are investigated. The parameter β^* is directly related to the cross section of the beams at the interaction point and, hence, inversely proportional to luminosity. The design β^* is 0.5 m and the design free distance on either side of the interaction point is 20 m. (There also exist in the present design 2 medium luminosity interaction points with β^*s of 10 m and free distances of ±120 m. These will not be discussed.) A standard method of decreasing β^* in e^+e^- storage rings is to move the final focusing quadrupoles closer to the interaction point. This moves the points of maximum vertical and horizontal beam spread, referred to as β^{MAX}, closer to the interaction point to allow for tighter focusing. For the SSC, the final focusing quadrupole triplet is 55 m long, and β^{MAX} vertical and horizontal are 50 m and 80 m from the interaction point respectively. Even if the quadrupole triplet is moved the entire 20 m of free distance, not much of a fractional gain would be made in moving vertical or horizontal β^{MAX} closer to the interaction point. Additionally, to take advantage of moving β^{MAX} closer to the interaction point, either β^{MAX} must be increased or the gradient of the quadrupoles must be increased. At present β^{MAX} is approximately 8 Km which implies a beam cross section at β^{MAX} that is as large as is presently considered prudent in the aperture of the quadrupoles.

Increasing the gradient of the quadrupoles will decrease β^*. Achieving a gradient higher than the current design of 230 T/m is considered difficult. However, being optimistic concerning gradient, and simultaneously reducing free distance, a reduction in β^* by a factor of 2 is conceivable [7]. This reduction gives a factor of 2 in initial luminosity and, following the prescription outlined in the introduction, a factor of 1.5 in integrated luminosity. Again, as in previous sections, the number of interactions per bunch crossing will increase, here initially from 1.4 to 2.8.

There is a natural limit to increasing luminosity by decreasing β^* for a given proton bunch length. This occurs when the distance along the beam over which the beam is focussed becomes less than the proton bunch length. A measure of this is when the bunch length becomes order of the same length as β^*. The bunch length for the SSC is 7 cm. Hence a β^* of 0.5 m allows for a significant luminosity increase, although factors previously mentioned restrict this increase.

Other considerations for increasing luminosity by decreasing β^* are increased beam-beam long-range tune shift (head-on portion not affected), increased IR quadrupole heating, and increased IR radiation. The IR quadrupole heating will not necessarily be any worse due to quadrupoles in a reduced β^* configuration being closer to the interaction point. This is due to the fact that the point of highest radiation deposition, even with the 0.5 m β^*, is significantly away from the beginning of the closest quadrupole. The increase in radiation absorbed will come from the increased luminosity.

In summarizing increasing luminosity by decreasing β^*, the main point is that at present a factor of 2 decrease in β^* is the maximum practical. An auxiliary consideration is that free distance may be reduced to as little as 3 m. A concern related to β^* considerations is that IRs at the SSC come in pairs of matching β^*. With present β^*s this pairing is not a restriction. For example, one IR in a pair could have $\beta^* = 0.5$ m and its mate IR have $\beta^* = 10$ m. Whether this pairing becomes more restrictive if one β^* is less than 0.5 m is presently being investigated.

5. Number of Proton Bunches Variation

Keeping the current constant, the luminosity can be increased by decreasing the number of proton bunches. The number of protons in each bunch then increases. The luminosity increase is directly proportional to the decrease in number of bunches, M, as shown in Eq. (1). The number of interactions per bunch crossing, however, increases as the square of the decrease. For specificity a factor of 3 reduction in number of bunches will be considered. This gives a factor of 3 increase in initial luminosity, but only a factor of 1.7 increase in integrated luminosity. This method of increasing luminosity gives the poorest integrated luminosity return on increased initial luminosity of the methods studied in this paper.

Other systems or effects to be considered when reducing the number of bunches are the injector system, collider stability, and IR radiation. The injector system is again faced with the limitations imposed by the incoherent Laslett tune shift. However, the solution here is a new, lower frequency RF system for the LEB. For this case the more extensive injector modifications of sections 2 and 3 can be avoided. The single bunch stability limits will be lowered by a factor of 3 which still leaves a factor of 2 safety margin. Multi-bunch stability may be affected by resonances excited by the new bunch spacing; however, it should be possible to avoid these resonances by slightly altering machine tune. The head-on beam-beam tune shift will increase by a factor of 3. The long-range beam-beam tune shift will remain constant. The total beam-beam tune shift will stay below the limit of 0.005 given earlier. As for all the previous cases IR radiation will increase proportionally to luminosity.

In summary for this section, increasing luminosity by holding the current constant and decreasing the number of bunches has the major drawback that it gives the poorest return of integrated luminosity. It also increases the number of interactions per bunch crossing as the square of the initial luminosity increases.

6. Variation of Beam Current and Number of Bunches

The luminosity can be increased by adding more proton bunches to the beam. If the added bunches have the same number of protons as the original bunches, the current will increase proportionally to the increase in the number of bunches, and, according to Eq. (1), so will the initial luminosity. For this case the integrated luminosity will also increase proportionally. In this section we will consider a factor of three increase in the number of bunches and therefore in the beam current and initial and integrated luminosities. The number of interactions per bunch crossing will remain constant; however, the time between bunches and crossings will decrease from 16 ns to 5.3 ns.

The remainder of this section will investigate the effects of increasing beam current a factor of 3 by increasing the number of bunches. Most of these effects have been considered in the section on beam current variation, section 2, and those portions of section 2 will be referred to here.

a) Injector System. Again, as in section 2a, the incoherent Laslett tune shift limits increasing current in the LEB. Here, though, the limit is due to the tune shift being inversely proportional to bunch spacing. The solution to offsetting this limit is the same as in section 2a, namely to increase the LINAC energy and to decrease or eliminate the curvature in the LINAC-LEB transfer line. A consequence of decreasing the bunch spacing not encountered in section 2a is that the RF system frequency must be increased by a factor of 3 in all three booster rings. The emittance will increase in the LEB due to the increased current thus degrading the luminosity increase by a factor that is unknown at this time.

b) Collider Stability. Since the number of protons per bunch remains constant, there is no change to single bunch stability. However multi-bunch

stability encounters the same problems as outlined in section 2b. The solution is, as in section 2b, a fast feedback system to control this instability. The head-on beam-beam tune shift will not increase. The long-range beam-beam tune shift increases since it is inversely proportional to the bunch spacing. Again, some of the long-range tune shift can be cancelled out by having interaction point crossing planes alternate between horizontal and vertical. The beam-beam tune shift should not be a serious problem.

The effects on the following topics or systems are the same as those considered in section 2 and will not be repeated here. These effects result from beam current or luminosity increase, regardless of how the increase is achieved. The topics or systems along with the corresponding portion of section 2 are: Heating in IR Quadrupoles (2c), Tunnel and IR Radiation (2d), Vacuum (2e), Total Beam Energy (2f), Beam Dump System (2g), Cryogenics (2h), and RF System (2i). Concerning the RF system, it should be noted that in the present design every sixth bucket is filled, hence there is room for a factor of three increase in number of buckets.

Summarizing this section, the same three areas where limitations appear in section 2 for a factor of $\sqrt{10}$ beam current increase also appear here. These areas are the injector system, multi-bunch instabilities, and cryogenics. Again, in none of these areas are the problems insurmountable, and, as in section 2, the conclusion is that, with additional design work, increasing luminosity by increasing both beam current and number of bunches is feasible.

7. Variation of Beam Energy

Since synchrotron radiation power varies as E_B^4, decreasing beam energy will quickly lessen the cryogenic load due to synchrotron radiation. At a lower beam energy, then, the excess cryogenic capacity can be used to absorb the power from increased beam current. If this is done, beam current will scale as E_B^{-4}, and initial luminosity, as shown by Eq. (1), will scale as E_B^{-7}. For a beam energy decrease from 20 TeV to 15 TeV, the initial luminosity will increase from 1×10^{33} $cm^{-2}s^{-1}$ to 7.5×10^{33} $cm^{-2}s^{-1}$. Table I lists beam energy, initial luminosity, and integrated luminosity for beam current scaled to keep total synchrotron radiation power constant. The last entry is for the beam current scaled in the same manner if beam energy is raised. All the considerations of section 2 apply for increased beam current, except of course the need for increasing cryogenic capacity. Avoiding the expense of increasing cryogenic capacity is in fact the major reason for increasing luminosity by decreasing beam energy.

8. Summary

Table II lists the methods by parameter for increasing luminosity that have been considered in this paper. The table lists a variation for the parameter that is considered possible and the resulting initial luminosity

Table I. Luminosity vs. Beam Energy.
Scaled by Keeping Synchrotron Power Constant.

Beam Energy (TeV)	Initial Luminosity (cm^{-2} s^{-1})	Integrated Luminosity for 1 Year (cm^{-2})
15.0	7.5×10^{33}	2.6×10^{41}
17.5	2.5×10^{33}	9.7×10^{40}
20.0	1.0×10^{33}	5.3×10^{40}
22.5	4.4×10^{32}	3.2×10^{40}

Table II. Parameter Variation vs. Luminosity

Parameter	Variation	Initial Luminosity Increase	Integrated Luminosity Increase	Major Limitations
Beam Current	$\times\sqrt{10}$	x10	x5.5	Injector System Multi-bunch Stability Cryogenics
Emittance	x1/2	x2	x1.6	Emittance itself Injector System
β^*	x1/2	x2	x1.5	β^* itself IR Free Space
Number of Bunches	x1/3	x3	x1.7	Limited Integrated Luminosity
Beam Current and Number of Bunches	x3	x3	x3	Decreased Bunch Spacing Injector System Multi-bunch Stability Cryogenics
Beam Energy	x3/4	x7.5	x4.9	Cross Section Decrease Injector System Multi-bunch Stability

and integrated luminosity increases. Also listed are what are considered the major limitations to varying this particular parameter. It is seen from the table that significant luminosity increase is only achieved by increasing the beam current. However, as beam current is increased emittance may also increase lessening the gains.

9. Acknowledgements

This paper is an outgrowth of a group that studied luminosity limitations. The group consisted of Alex Chao, R. Diebold, Gil Gilchriese, Al Garren, Dave Johnson, Steve Peggs, Jack Peterson, W. Scandale, and the author. This paper would not have been possible without the contributions and criticism of the entire group.

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