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APPROACHING ULTIMATE LUMINOSITY AT THE SSC*

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ABSTRACT

The SSC is designed[1,2] to operate conservatively at a luminosity of 10^{33} cm^{-2} s^{-1} over essentially its entire energy range, up to the peak energy of 20 TeV per beam. This luminosity is dictated by the envisioned detector limitations. This note attempts to explore the possible scenarios to approach an ultimate SSC luminosity from the accelerator point of view. We find and reconfirm earlier studies[3,4] that the ultimate luminosity limit is much beyond the 10^{33} cm^{-2} s^{-1} level.

The nominal operation of the SSC, as presently conceived, requires two counter-rotating proton beams, each consisting of a train of about 17000 beam bunches. Each bunch contains 7×10^9 protons and adjacent bunches are spaced by 5 meters. To avoid spurious bunch collisions, the two beams cross at an angle, which is nominally 75 μrad, but can be varied in the range up to 150 μrad.

The design model assumes 4 interaction regions, 2 with high-luminosity interaction points (IP) and 2 with medium-luminosity IP's. For a typical detector that can handle 1 event per crossing, or an event rate of about 6×10^7 events per second, the corresponding luminosity is given by the event rate divided by the pp total cross section, which is about 60 mb. This reproduces the nominal SSC luminosity of 10^{33} cm^{-2} s^{-1}. In fact, the luminosity is

$$L = N^2 c\gamma / 4\pi \varepsilon_N \beta^* S \quad , \tag{1}$$

where N = number of protons per bunch, S = bunch spacing, β^* = beta-function at the high-luminosity IP, ε_N = normalized rms emittance. With $N=7 \times 10^9$, $\gamma = 21000$ (20 TeV), $\varepsilon_N = 1\ \pi$ mm-mrad, $\beta^* = 0.5$ m, S = 5 m, the luminosity is 10^{33} cm^{-2} s^{-1}.

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This nominal luminosity is dictated by the physics requirements for the SSC and by considerations of practical limitations to the event rates that can be handled by typical detectors expected to be employed at the SSC. For example, the speed of electronic devices prevents the bunch spacing to be much less than 5 meters, while the event resolution prevents the number of events per bunch crossing to be approximately less than 1. However, these limitations are process related and it is useful to explore the ultimate limits to the SSC luminosity as far as the accelerator—not the detector—is concerned. It is possible that specialized experiments can be designed to exploit higher luminosity when very rare, but distinctive processes are to be studied. Indeed, one finds that this ultimate luminosity limit is much beyond the 10^{33} cm^{-2} s^{-1} level, as we will discuss below.

The question is how to increase the luminosity, given in Eq. (1), by varying N, ε_N, β^*, or S without violating known limits of accelerator physics. Because of its very high energy, synchrotron radiation plays an important role in the performance of the SSC. At the highest energies, synchrotron radiation, which is absorbed on the vacuum chamber walls at liquid helium temperatures, will limit the total beam current and, hence, the luminosity. At lower energies, it is expected that the highly nonlinear fields of one beam acting on particles of the other beam will ultimately limit the luminosity—the beam-beam limit. These considerations are specified by three quantities: the synchrotron radiation power per unit length, P/C, the head-on beam-beam tune shift per IP, $\Delta\nu_{HO}$, and the long range beam-beam tune shift, $\Delta\nu_{LR}$:

$$P/C = Z_o N e^2 c^2 \gamma^4 / 3CS\rho \qquad (2)$$

$$\Delta\nu_{HO} = N r_p / 4\pi\varepsilon_N \qquad (3)$$

$$\Delta\nu_{LR} = N r_p L_{LR} / \pi\gamma\beta^*\alpha^2 S \ , \qquad (4)$$

where Z_o = 377 ohms, C = circumference, ρ = bending radius, r_p = classical proton radius = 1.535×10^{-18} m, α = crossing angle, L_{LR} = length over which two beams interact with long range beam-beam interaction. In this study, we ignore the collective instability limits, assuming they are taken care of by other means.

In the attempt to find the ultimate luminosity limit in the SSC, we fix the following quantities:

$$\beta^* = 0.35 \text{ m}, \alpha = 150\ \mu\text{rad}, L_{LR} = 170 \text{ m}, \rho = 10 \text{ km}, C = 85 \text{ km}, S = 5 \text{ m}.$$

The value of β^* assumes a higher peak IR triplet quadrupole gradient than that of the present design. The crossing angle has been opened up to the envisioned maximum. It is possible to consider variation of the bunch spacing S.[5] It turns out that, due to a scaling property, the same ultimate luminosity is obtained, although different combination of the other parameters will be used.

We consider a beam-beam limit imposed by the condition that the total tune shift induced by the beam-beam interactions be less than 0.02, which is about the value that can fit into a tune space without crossing low order resonances. In other words, we consider

$$\Delta\nu_{tot} = 4\,\Delta\nu_{HO} + 2\Delta\nu_{LR} < 0.02 \ . \tag{5}$$

The factors 4 and 2 in Eq. (5) follow from the fact that we assumed 2 high-luminosity-IP's and 2 medium-luminosity IP's, and the fact that $\Delta\nu_{HO}$ is the same for high- and medium-luminosity IP's, while $\Delta\nu_{LR}$ is significant only for high-luminosity IP's.

It turns out that, at low energies when condition (5) is dominating, the best luminosity is achieved when the head-on and the long-range components equally share the 0.02 allowance, i.e.,

$$4\,\Delta\nu_{HO} = 0.01 \tag{6a}$$

and

$$2\Delta\nu_{LR} = 0.01 \ . \tag{6b}$$

At high energies, we must consider the limit imposed by synchrotron radiation power per unit length

$$P/C < 0.4\ \mathrm{W/m} \ . \tag{7}$$

In this energy range, the beam-beam limit is mainly imposed by the head-on component (6a); the long-range component will stay below the limit (6b). The present SSC design allows 0.1 W/m synchrotron radiation power. By strengthening cryogenic pumping and introducing more pumping locations, a higher synchrotron radiation does of 0.4 W/m may be tolerable.

Figures 1(a)-(f) show the energy dependence of the various parameters (note bunch spacing has been assumed fixed at 5 m). The transition between low- and high-energy behaviors occurs at 17.8 TeV. Below and above the transition energy, we have

	Below	Above
N	$\sim E$	$\sim E^{-4}$
ε_N	$\sim E$	$\sim E^{-4}$
P/C	$\sim E^5$	$\sim$ const
$\Delta\nu_{HO}$	$\sim$ const	$\sim$ const
$\Delta\nu_{LR}$	$\sim$ const	$\sim E^{-5}$
L	$\sim E^2$	$\sim E^{-3}$

The peak luminosity occurs at the transition energy and has the value of $2.4 \times 10^{34}\ \mathrm{cm^{-2}\ s^{-1}}$. Luminosity at 20 TeV is $1.7 \times 10^{34}\ \mathrm{cm^{-2}\ s^{-1}}$ as compared with the nominal value of $10^{33}\ \mathrm{cm^{-2}\ s^{-1}}$.

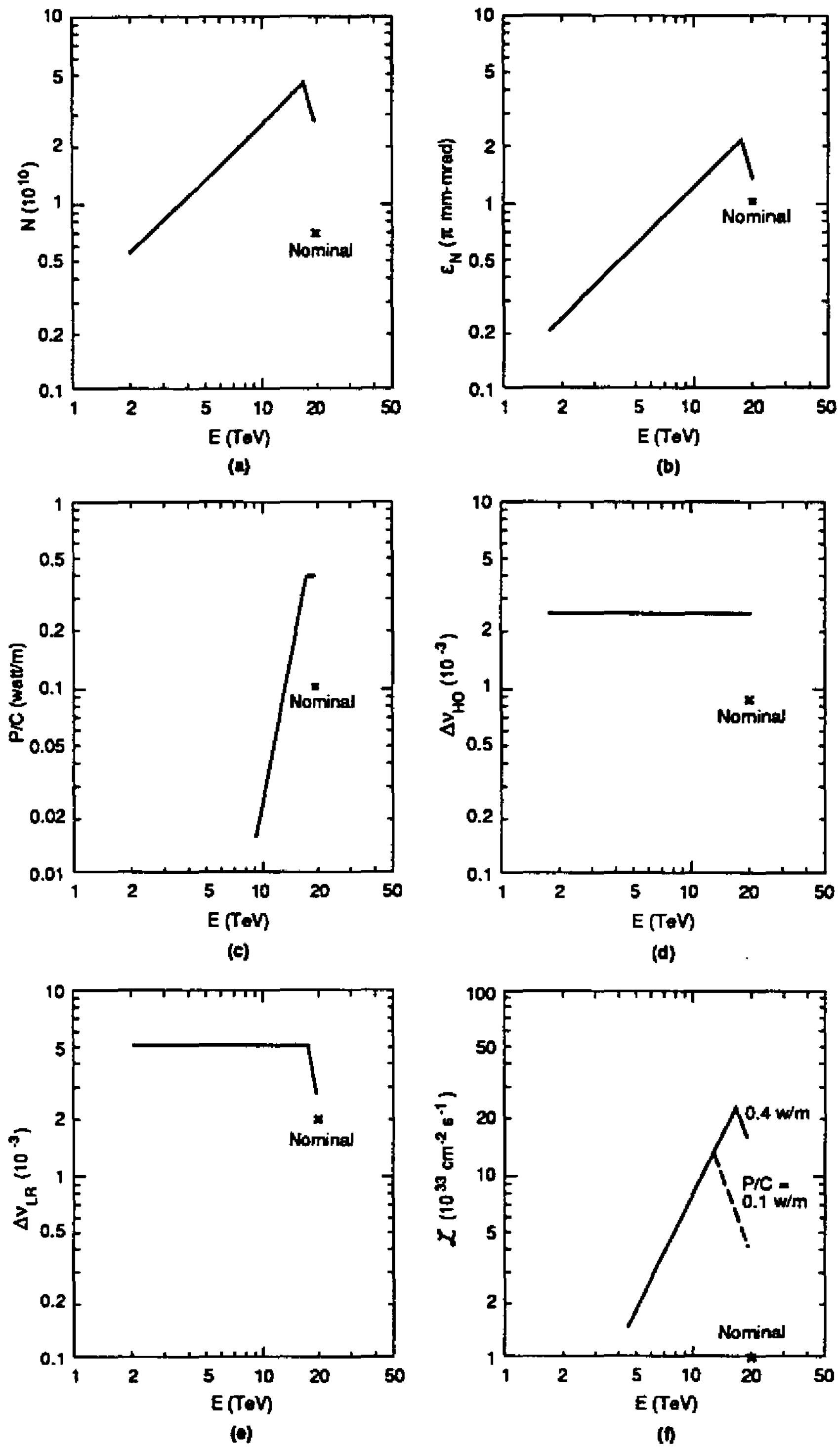

Figure 1. Energy dependence of various parameters. (a) number of protons per bunch, (b) normalized emittance, (c) synchrotron radiation power, (d) head-on tune shift, (e) long-range tune shift, and (f) luminosity. The nominal operation at 20 TeV are marked by crosses. In (f), a dotted curve representing 0.1 W/m limit has been added for reference.

It may be useful to mention a few additional considerations which seem to be potential for further increasing the ultimate luminosity of the SSC. One consideration concerns the beam-beam limit. Another concerns the crossing angle. Still one more concerns a different operating temperature of the superconducting magnets. These considerations are more speculative than the scenario discussed so far and have to be considered correspondingly.

It is conceivable that the beam-beam limit is less stringent than that assumed in Eq. (5). This is because the limit is likely to be imposed on the tune spread instead of the tune shift. In case of head-on collisions, the tune spread is equal to the tune shift, but in case of long-range collisions, tune spread is related to tune shift approximately by

$$\Delta\nu_{LR,\,spread} = \Delta\nu_{LR}\ (3/2)\,(\,n^2\,\varepsilon_N\,/\,\alpha^2\,\gamma\,\beta^*\,)\ . \tag{8}$$

Consider a particle in the 6-sigma tail in its betatron amplitude, n=6, the nominal SSC has $\Delta\nu_{LR,\,spread}$ smaller than $\Delta\nu_{LR}$ by about a factor of 4. If we consider the beam-beam limit to be Eq. (5) except for replacing $\Delta\nu_{LR}$ by $\Delta\nu_{LR,\,spread}$, the ultimate luminosity in the lower energy regime will increase.

It turns out that in this case, the optimal sharing of the tune spread between the head-on and the long-range components are different from that of Eq. (6). The optimum occurs when

$$4\,\Delta\nu_{HO} = 0.015 \tag{9a}$$

and

$$2\Delta\nu_{LR,\,spread} = 0.005\ . \tag{9b}$$

In this case, the luminosity in the low energy regime is about 50% higher than shown in Fig. 1(f). This possibility is shown in Fig. 2 as the dashed curve.

The ultimate luminosity depends sensitively on the crossing angle in the low energy regime due to the long range beam-beam effect. The 150 μrad crossing angle for the SSC comes from the long interaction region quadrupoles needed for a 20 TeV beam. If for some reason it becomes important to maximize the luminosity at a lower energy, it is possible to redesign the interaction region using shorter quadrupoles to allow a larger crossing angle. For example, doubling the crossing angle to 300 μrad would increase the ultimate luminosity in the low energy regime by a factor of 2 and 4, assuming the long-range limit due to $\Delta\nu_{LR}$ and $\Delta\nu_{LR,\,spread}$, respectively. The dot-dash curve in Fig. 2 shows an increase of a factor of 4 below 10 TeV.

It is presumably possible to use the cryogenic power, not to absorb the synchrotron radiation in a luminosity upgrade, but to lower the operating temperature of the superconducting magnets. This would significantly complicate the magnet design, but assuming the magnet issues are all resolved, one could imagine lowering the temperature from the nominal 4.35 to 3 degree Kelvin, which translates into a field increase from the nominal 6.6 to perhaps 7.7 Tesla, allowing an operation at 23 TeV per beam. The corresponding luminosity curve would look perhaps like that shown as the dotted curve in Fig. 2.

One should also note that the considerations below for further increasing the ultimate luminosity are not meant to be exhaustive. A vacuum pipe liner would substantially reduce the impact of synchrotron radiation. Alternating the beam crossings horizontally and vertically would reduce the long-range beam-beam effects. Allowing for fewer IP's will make the luminosity at each IP's higher. Crossing the beam with a much larger angle could be possible if one uses 2-in-1 design of interaction region quadrupoles[6] Use of pre-splitters that separate the beam would help long-range encounters.[7]

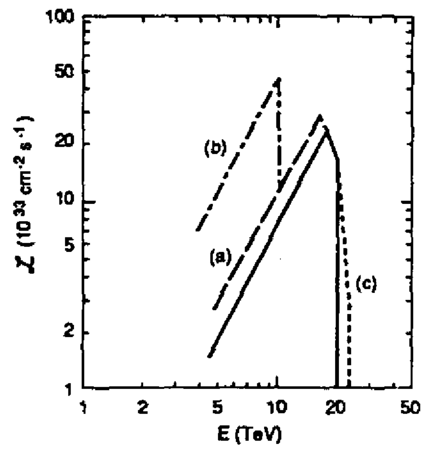

Figure 2. Three speculations that might lead to higher ultimate luminosities than shown in Figure 1(f), which is reproduced here as the solid curve. Curves (a): using $\Delta\nu_{LR,\ spread}$ instead of $\Delta\nu_{LR}$. Curve (b): with 300 μrad crossing angle below 10 TeV. Curve (c): operating the magnets at 3 degree Kelvin.

<u>References</u>

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