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WHY NOT RAISE THE SSC ENERGY INSTEAD?

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WHY NOT RAISE THE SSC ENERGY INSTEAD?*

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ABSTRACT

The SSC design provides for luminosity upgrades to at least a factor of ten above the design value, $10^{33}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$. Experimenters plan to take advantage of higher luminosity, in spite of the daunting challenge of dealing with even the design luminosity. Misstatements abound, but it is at least clear that only some fraction of this factor will appear as the multiplication factor for the number of events in a final histogram. In this note, we would like seriously to propose an alternative: Use the SSC design flexibility to raise the energy *instead*. Basically, the cryogenic capacity needed to obtain high luminosity is used to (a) absorb the extra synchrotron radiation from higher-energy protons, and (b) operate the magnets at a lower temperature in order to reach a higher field. The SSC could then operate at somewhat above $\sqrt{s} = 46$ TeV. The trade-off of energy for luminosity for physics processes is very dependent on the relevant mass scale, but for several high-mass processes the expected 17% energy increase is roughly equivalent to increasing the integrated luminosity by a factor of 2.2. Given the realities of high-luminosity operation, an energy upgrade might well be the better option.

1. Introduction

In late 1989, the Ad Hoc Committee on SSC Physics "reexamined the relationship between beam energy, machine luminosity, and physics capability"[1]. They concluded, in part, that "...the discovery reach is enhanced significantly by operating the SSC at the highest possible energy. The luminosity that may ultimately be reached...is approximately one order of magnitude above the present design value...We recommend that the planning of the SSC experiments take into account the possibility of such higher luminosities." The document successfully argued against reducing the design energy of the SSC, but also made a strong case for increasing the luminosity.

There is probably less to high luminosity than meets the eye. An increase by a factor of ten in peak luminosity results in a far smaller gain *in integrated luminosity, even though one must* deal with all the rate problems connected with the factor of ten. The detector almost certainly loses efficiency. The factor of ten might turn out to be a factor of two.

At $\mathcal{L} = 10^{33}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$, event rates will be between 200 and 500 times greater than any collider detector has yet experienced. Having heard the number for a few years but without having learned to deal with it, we now envisage rates an order of magnitude higher, with an average of 16 p-p collisions per crossing. The proponents have not claimed it will be easy.

In this note we propose an alternative: Use the refrigerator capacity needed to reach high luminosity to raise the energy instead. Take the Ad Hoc Committee's recommendations about the energy frontier seriously, and buy energy instead *of luminosity.*

2. Effective integrated luminosity

In the standard luminosity scenario, the luminosity increases to about $1.6 \times 10^{33}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ during the first 24 hours of operation, largely because of emittance damping due to synchrotron radiation. If an initial luminosity of $10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ *is obtained by increasing the current in each ring* by $\sqrt{10}$, the luminosity remains relatively constant for about 6 hours and then falls[2]. In an earlier study, D. Bintinger concluded on the basis of similar luminosity profiles that the integrated luminosity would be 5.5 times higher if the initial luminosity were increased by a factor of ten[3].

Even so, a detector cannot be expected to operate with the same efficiency at 10^9 interactions per second. Losses include:

1. The effects of decreased η coverage;

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2. Loss of electron efficiency through the effects of pileup on isolation requirements. For example, in reactions in which $ZZ \to 4\ell$ must be identified, even a modest decrease in single electron identification efficiency has a dramatic effect on the overall reconstruction efficiency;

3. Losses in pattern recognition efficiency due to pileup;

4. Losses because of increased deadtime.

A specific process and detector must be considered to quantify such effects, but the factor of 5.5 obviously needs further derating. As we shall see, the proposed energy increase is equivalent to a factor of at least two in luminosity, but the efficiency factors remain the same.

3. Attainable energy

Under standard conditions, about half of the design cooling capacity is used to remove the power synchrotron radiated by the 20 TeV beams. If the synchrotron losses were to treble (at three times the nominal beam current), then twice the total refrigeration capability would be needed. The SSCDR discusses two refrigerator upgrade options: An upgrade of the E-location refrigerator plants (allowing an increase of the heat-load factor by a factor of 1.4), and the addition of refrigeration at the F-locations (another factor of two)[2,4]. For purposes of this study, we assume that the total plant capacity will increase by just a factor of two.

At constant current (luminosity), what energy can then be reached? Two factors must be considered:

1. Synchrotron radiation scales as E^4 at constant bending radius. If half the nominal heat budget is to absorb the synchrotron radiation, then for beam energy E the necessary cryogenic power will scale by the factor

$$\frac{1}{2}\left[1+\left(\frac{E}{20\ \mathrm{TeV}}\right)^4\right] . \qquad (1)$$

2. Magnet temperature. We conservatively take the nominal magnet current as the maximum obtainable at the design temperature (6503 A at 4.15°K), and assume that further cooling will be required to reach higher energies. The temperature dependence of the SSC dipole DD0017 is shown in Fig. 1, together with a phenomenological fit[6]. Given the scatter of the data, it is sufficient to approximate this curve by a straight line. The dashed line in the figure has the same average slope as the solid curve, and is displaced to go through the design operating point at 4.35°K:

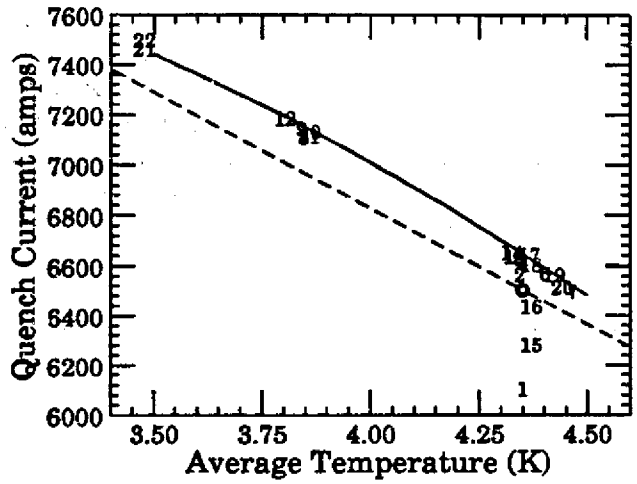

FIG. 1. Quench current of SSC dipole test magnet DD0017 as a function of temperature. Curve is short-sample prediction with $I_c(4.2°\mathrm{K}, 5\,\mathrm{T}) = 11.83$ kA; measured $I_c(4.2°\mathrm{K}, 5\,\mathrm{T}) = 12.85$ kA. The dashed line has the same mean slope and goes through the nominal operating point at 4.35°K (circle).

$$E = 32.4\ \mathrm{TeV} - (2.84\ \mathrm{TeV}/°\mathrm{K})T \qquad (2)$$

Although actual refrigerator efficiency is far below the Carnot efficiency, it is reasonably accurate to assume that the efficiency of a given refrigerator scales as the ratio of hot-bath and cold-bath temperatures[5]. In the present case this means that the power scales as the reciprocal of the magnet temperature, or, from Eq. 2, by the factor

$$\frac{4.35°\mathrm{K}}{T} = \frac{0.619}{1.619-(E/20\ \mathrm{TeV})} . \qquad (3)$$

Combining the factors given by Eqs. 1 and 3, we find that at energy E the cryogenic power requirement P is given by

$$P = \frac{P_0}{2}\left[1+\left(\frac{E}{20\ \mathrm{TeV}}\right)^4\right]\left[\frac{0.34}{1-0.66(E/20\ \mathrm{TeV})}\right], \qquad (4)$$

where P_0 is the nominal power. For $P = 2P_0$, $E/(20\,\text{TeV}) = 1.172$, or $\sqrt{s} = 46.9$ TeV. From Eq. (2) we obtain $T = 3.15°$. With a more careful analysis of dipole field strength *vs.* temperature and with both the refrigerator options discussed above, the SSCDR obtains 46.6 TeV at 3.0°K. It also states that 3°K may be attainable.

4. Other machine considerations

The above discussion is limited to cryogenic power considerations. It is also worthwhile to list other machine problems and design considerations which become relevant if the energy is increased by 17%:

1. Dipole and other magnet power supplies. Main bending and focussing elements operate in series or the equivalent. In Table 4.2.1.1-1 of the SSCDR (dipole magnet parameters), the dipole current is given as 6503 A. In Table 4.2.4.1-1 (power supply parameters) the maximum current in the main power supplies is given as 6600 A (7000 A during conditioning). It is unclear whether the difference is an allowance for headroom or an inconsistency. In any case, 6503 A × 1.17 = 7609 A. If the high energy option were to be part of the machine, then an additional 10% current capability should be specified.

2. Current range in smaller adjustable power supplies. A similar scrutiny of current range in the spool-piece power supplies, low-β^* quadrupole supplies and other power supplies is also necessary; we have not made such a survey. In this case the additional 17% allowance does not add much to the cost.

3. Low-β^* quadrupole design. This might be the most serious problem, since these quadrupoles have very high gradients. Even at 20 TeV the requirement for a 5-cm bore might already make necessary low-temperature and special materials, such as Nb_3Sn superconductor.

4. Magnetic stresses. Since magnetic stresses go as B^2, a field increase of 17% results in force increases of 37%. Short magnets have been taken to more than 7600 A, but we do not know the present design margins.

This list is not intended to be complete. The main point is that the entire design should be reviewed if any of these ideas are to be taken seriously. As with the cryogenics, the problem divides into provisions built into the initial machine, like the quadrupole designs, and things which can be added later as need and funding allow.

5. Physics capabilities

What is the tradeoff between luminosity and energy? We base our discussion on three examples from the Ad Hoc Committee's report[1]:

1. The production of a 10 TeV Z';
2. the production of a gluino with mass 2 TeV;
3. a search for quark compositeness at a mass scale of 30 TeV.

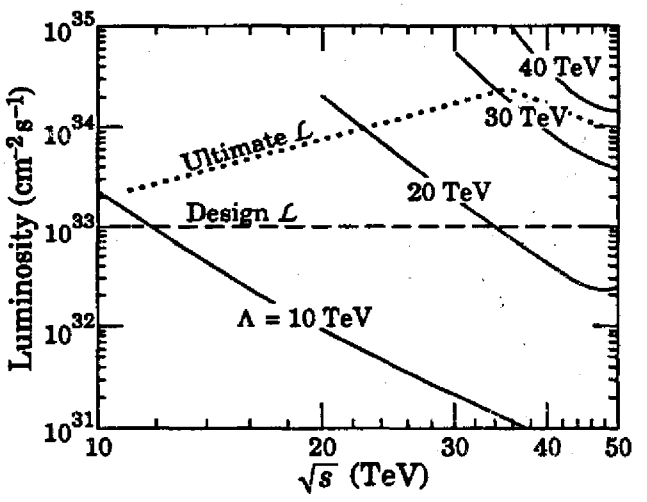

FIG. 2. Luminosity required to establish in one year quark compositeness scales of 10, 20, 30 and 40 TeV as a function of c.m. energy.

Most of the results are presented as "isophote" plots of luminosity *vs.* $\sqrt{s}$ for a fixed number of events. As an example, their Fig. 5 is redrawn as Fig. 2. The use of a log scale in $\sqrt{s}$ tends to "straighten" most of the curves; in other words, they are well-represented by power laws. (The kinks at the right end of the curves in Fig. 2 are artifacts.) For a fixed number of events at a given mass scale, we can write

$$\mathcal{L} \propto (\sqrt{s})^n \,. \tag{5}$$

The power n is given for the three processes listed above in Table 1. As can be seen, it varies from −4.0 to −5.4 for these relatively high-mass processes. For lower-mass processes such as 400 GeV Higgs production, the dependence on energy is considerably milder.

For $n \approx -5$ an energy increase by a factor of 1.17 is equivalent to an integrated luminosity increase of $(1.17)^5 = 2.2$. This is to be compared with a factor of 5.5 in the integrated luminosity to be gained if the initial luminosity were increased from $10^{33}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ to $10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$. But as emphasized in the introduction, this factor of 5.5 must be further derated for lost decay modes, event loss due to pileup, lost η coverage, deadtime losses, *etc.* It is not at all clear that increasing the luminosity is the best way to search for high-mass processes.

Table 1

Slope $d\ln\mathcal{L}/d\sqrt{s}|_{40\,\mathrm{TeV}} \equiv n$ for a fixed number of events in a given process.

Process	n
10 TeV Z' production	-5.4
2 TeV $\tilde{g}$ production	-4.0
Quark compositeness, $\Lambda = 30$ TeV	-5.1

There is also a negative conclusion: If the gains are only a factor of two in equivalent integrated luminosity in increasing either the luminosity or energy, then the mass reach of the SSC is less than anticipated. For example, if Z' discovery is defined as producing (observing?) 100 events in a year, then raising the energy to 46 TeV or increasing the effective integrated luminosity by a factor of two will extend the mass reach from 8 TeV to 9 TeV. An honest increase of the efficiency-weighted integrated luminosity by a factor of ten would extend the reach to about 11 TeV. Similar conclusions may be reached for the other high-mass processes.

For low-mass processes (say below 1 TeV) such as Higgs production, the logarithmic slopes are substantially smaller, and there is little point to raising the energy.

6. Conclusions

If the refrigeration capacity planned for an order of magnitude luminosity upgrade were used instead to increase the energy, the SSC could reach $\sqrt{s} = 46$ TeV. For high-mass processes, this energy increase is equivalent to increasing the product of integrated luminosity and detection efficiency by a factor of two. Given the experimental realities of 10^9 collisions s^{-1}, the energy increase might be the preferred alternative.

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