ENERGY AND LUMINOSITY LIMITS OF HADRON SUPERCOLLIDERS

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ABSTRACT:

Extending the frontiers of experimental high energy physics in a manner that maximizes discovery potential requires the building accelerators of ever higher particle energies and luminosities. Both hadron and e^+e^- colliders have been proposed for this role. Based on a self-consistent computational model, this paper explores the features of hadron supercolliders beyond the SSC. The application of the presently available accelerator technologies embodied in the designs of the LHC and SSC to an ELOISATRON operating at 100 TeV per beam would yield a collider with a luminosity of 10^{34} cm^{-2} s^{-1}. Even higher energies and luminosities are clearly possible. The paper concludes with an examination of the ultimate potential of synchrotron–based colliders to explore PeV energies.

I. GENERAL CONSIDERATIONS

The continuing search for understanding the nature of mass and the dynamical principles underlying the physical universe has led particle physicists to explore phenomena at the energy frontier particle interactions. The modern tools for the experimental explorations are colliders with ever higher beam energies and ever higher luminosities. Fig. 1 illustrates the performance trends for present and future hadron colliders. What are the energy dependences of the physics and technology that determine these trends?

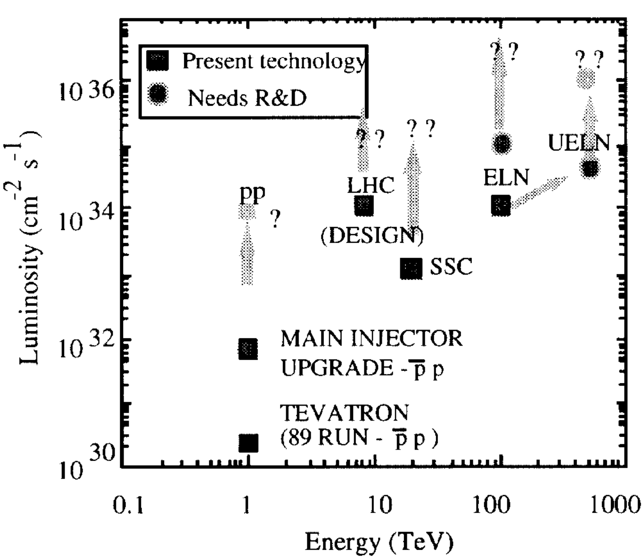

Figure 1. Luminosity goals of present and future hadron colliders

For simplicity, assume that both beams have bunches of equal population, N_B with a spacing S_B. In terms of the normalized emittance, ε_n, the relativistic factor γ and the β-function at the interaction point, β^*, the luminosity is

$$\mathcal{L} = \frac{N_B^2\, c\, \gamma}{4\pi\, \varepsilon_n\, \beta^*\, S_B} = \frac{1}{e\, r_p}\left(\frac{N_B\, r_p}{4\pi\, \varepsilon_n}\right)\left(\frac{\gamma\, I}{\beta^*}\right) \equiv \frac{1}{e\, r_p}\, \xi \left(\frac{\gamma\, I}{\beta^*}\right) \tag{1}$$

In eq. (1) I is the average current; r_p is the classical proton radius; ξ is the tune shift. The luminosity rises naturally with increasing beam energy at the "price" of increased practical difficulties in machine design. The difficulties of increasing the luminosity faster than linearly with energy are associated with increasing the beam current.

In analyzing the energy and luminosity limits of supercolliders one looks to choose N, S_B, β^*, and ε_n as a function of energy, E, subject to the following design constraints: 1) Detector limitations – electronics cycling and event resolution; 2) Beam physics – tune shifts, beam lifetimes, emittance growth; 3) Accelerator technology – magnets, fault modes handling of synchrotron radiation, beamline impedance, radiation damage of components.

II. SYNOPSIS OF SELECTED CONSTRAINTS

Constraints deriving from the interaction region reflect problems of event resolution and challenges of detector survival. For adequate event reconstruction, one ideally chooses the current per bunch and the bunch spacing so that the mean number of events per crossing, $\langle n \rangle$, is sufficiently low that the luminous region contains fewer than 1 event/cm. $\langle n \rangle$ depends on E via the inelastic cross-section, σ_{inel};

$$\langle n \rangle = \frac{\mathcal{L}\, \sigma_{inel}\, S_B}{c} \tag{2}$$

Furthermore, cycling of the data acquisition electronics requires ≥10 ns between crossings. In a general sense the difficulties of dealing with the radiation from the collision point are most simply expressed by the power in charged particle debris (per side); namely,

$$P_{debris} = 350\ \mathrm{W}\left(\frac{\mathcal{L}}{10^{33}}\right)\left(\frac{\sigma_{inel}}{90\ \mathrm{mb}}\right)\left(\frac{E}{20\ \mathrm{TeV}}\right). \tag{3}$$

The fundamental beam-beam effect that limits luminosity is the tune shift due to the space charge of the colliding beams. Although tune shifts as high as 0.06 have been measured in e^+e^- colliders, the experience with hadron beams at the CERN S$\bar{p}$pS and at the Tevatron indicates

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that the maximum total tune shift is 0.024 with several interaction points. This observation might suggest that the luminosity can be maximized with a single high luminosity interaction point. Unfortunately, the validity of such an extrapolation is unknown. A more conservative assumption is that the maximum value of ξ per interaction point is 0.01 and that $\xi_{tot} \leq 0.024$.

Supercolliders will have to cope with a phenomenon that has been previously unimportant to proton colliders, i.e., the production of intense synchrotron radiation in the vacuum UV to hard X-ray range. The radiation will heat the walls of the vacuum chamber and desorb gas from the chamber. The synchrotron radiation power generated per meter of bend, $\mathcal{P}_{sync}$, is proportional to the energy lost per turn, U_o, to the beam current, I, and is inversely proportional to the radius of curvature of the bends, ρ;

$$U_o = 6.03 \times 10^{-18} \text{ GeV/turn} \frac{\gamma^4}{\rho \text{ (meters)}} . \quad (4)$$

As the radiation is deposited onto the cold walls of the vacuum chamber, the heat must be removed with a efficiency that is limited by the Carnot efficiency of the compressors which supply the cryogenic coolant. To limit operating power to practical levels the SSC design limits $\mathcal{P}_{sync}$ to 0.13 W/m on the magnet bore (at 4.2 °K). The LHC design incorporates a radiation shield at 20 °K inside the vacuum chamber, permiting 1 W/m. For supercollider operation at the highest possible energy or luminosity, $\mathcal{P}_{sync}$ must be allowed to exceed 1 W/m. To limit the power consumed, one also must increase the temperature of the surface on which the radiation is deposited; e.g., one might operate the radiation shield to 70 °K. Unfortunately, raising T_{wall} leads to serious consequences for collider luminosity due to the transverse resistive wall instability.

Transverse displacements of the beam from the centerline of the beam chamber will grow due to the finite conductivity of the wall, σ_{wall}. The growth time [1] of the instability in a beam pipe of radius, b, is

$$\tau_{RW}^{-1} = \frac{N_B\, M\, r_p\, \beta_{ave}\, \omega_o\, c}{(2\,\pi\,\sigma_{wall}\;\omega_o\,\delta\nu)^{1/2}} \frac{\mathrm{Im}\left[(1+i)\,\zeta\right]}{2\,\pi\,\gamma\, b^3} . \quad (5)$$

M is the number of bunches, σ_{wall} is the conductivity of the inner layer of the beam tube, ω_o is the revolution frequency, $\delta\nu$ is the fractional tune, ν–n, (use 0.1), and ζ is a correction for the multiple metallic layers (equal to 2.87 + 2.87i for SSC). The residual resistivity ratio (R_w) for copper plated onto stainless steel varies as

$$\mathrm{Ln}(R_w) = 3.1 \left[1 + \frac{41.6\, T_{wall}^{-0.93} - 0.24\; T_{wall}^{0.93}}{41.6\, T_{wall}^{-0.93} + 0.24\; T_{wall}^{0.93}} \right] + 0.24 \quad (6)$$

where R_{wall} is normalized to its value at 300 °K, (1.6×10^{-6} ohm cm^{-1}).

As the resistive wall is an absolute instability, its growth cannot be Landau damped by spreading the betatron frequencies in the beam. Hence, controlling the instability will require the use of a digital, bunch-by-bunch feedback system. The limits of such a system have not been established. However, many experts consider $\tau_{RW} \approx 6\, T_o$ to represent the limits of available feedback electronics. Similar feedback electronics can also control emittance growth due to injection errors, coupled-bunch modes, and ground vibrations.

At energies >10 TeV, for which copious radiation is generated, maximizing the luminosity while keeping $\tau_{RW} >> T_o$ places an upper limit on the T_{wall} and a lower limit on the vertical aperture of the dipoles. Both T_{wall} and b are functions of B_{dipole}. The consequences of the constraints on T_{wall} and the beam pipe radius are both the operating costs of supplying power to the compressors and the capital cost of providing for a large magnetic field volume.

The most expensive sub-system of the supercollider is the magnetic transport. In evaluating the prospects for a 100 TeV ELN, the maximum value of B_{dipole} was taken to be 10 T. For the longer tern future values as high as 15 T were considered. In that a 13.5 T dipole is presently under development at LBL, the assumption for the long term is not just wishful thinking.

III. PARAMETER STUDIES

Self-consistent characteristics of supercolliders at the highest energies and luminosities are explored most easily with a simple computer code for performing parameter searches. ELOSCALE is a spreadsheet–format design code based on the scaling relations described ref. [2]. The input variables are the injection and maximum beam energies, the normalized emittance and the bunch spacing. A critical characteristic is the maximum permissible tune shift per interaction point – taken to be 0.01. The inputs describing the storage rings are as follows: the maximum dipole field, and dipole fraction, and the vertical dipole aperture, the radiation power on the walls and the temperature of the beam tube, the number of interaction points, the crossing angle, the distance from the collision point to the septum, the scale value of β^* at 20 TeV, and the rf-system frequency. The injection chain consists of a linac and four intermediate boosters. All other characteristics of the collider and the injector chain are computed in the code.

Table 4. Possible sets of characteristics of ELOISATRON

	ELN34	ELN35	2ELN
Circumference (km)	355	355	355
B_{dipole} (T)	7.7	7.7	13
Maximum energy (TeV)	100	100	170
Beam current (mA)	100	400	50
Mains power (GW)	2	0.33	0.33
$\langle P_{sync} \rangle$ (W/m)	5	20	20
Crossing angle (μrad)	70	120	70
Interaction regions (IR)	2	2	2
Tune shift per IR	0.003	0.01	0.006
Events/cm/crossing	1.2	9	2.4
Luminosity (cm^{-2} s^{-1})	10^{34}	10^{35}	10^{34}

A parameter exploration with ELOSCALE indicates an approach to construct a 100 TeV proton supercollider (ELN-34) with a luminosity $>10^{34}$ cm^{-2} s^{-1} at $\mathcal{P}_{sync}$ =5 W/m by using the same technologies that are being realized for the LHC. Raising $\mathcal{P}_{sync}$ to 20 W/m yields 10^{35} cm^{-2}s^{-1} (ELN-35). Parameters for both of these cases are given in Table 4. The variation of the luminosity of ELN with $\mathcal{P}_{sync}$ and operating energy are shown in Fig. 2. Fig. 3 displays two examples of cost and operational sensitivities such as those dependent on B_{dipole}.

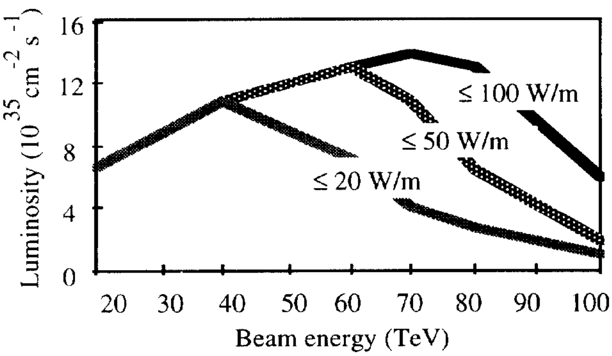

Figure 2. The luminosity ELN as a function of beam energy for radiation loads from 20 – 100 W/m.

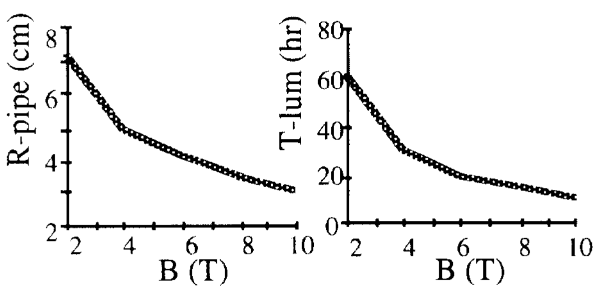

Figure 3. Variation of dipole aperture and luminosity lifetime with B_{dipole} for ELN35.

IV. ULTIMATE SUPERCOLLIDER

For the long term, ELOSCALE studies suggest the ultimate potential of conventional storage ring technology in the exploration of the high energy frontier of elementary particle physics. If the vacuum chamber of the storage ring operates at room temperature, then one could construct a hadron collider with a center of mass energy of 1 PeV and a luminosity > 10^{36} cm^{-2} s^{-1}. With a circumference twenty times SSC's and consuming ≈ 2 GW of mains power, this proton synchrotron may well be the ultimate supercollider.

As the survival of detector components is doubtful at such a high luminosity, a more probable scenario for UELN is to keep the luminosity at 10^{34} cm^{-2} s^{-1}. In that case all of the technical sub-systems are much closer to the present state of technology. In particular the vacuum sub-system should be fairly close in character to that of the ELN. The walls could be kept at 150 °K to limit the power to the compressors to 500 MW. Table 5 compares the high and "low" luminosity options.

Table 5. Two possible sets of characteristics of an Ultimate ELOISATRON (UELN)

Center of mass energy	1 PeV	
Circumference (km)	1500	1015
B_{dipole} (T)	8	13.5
Beam energy	500 TeV	
Beam current (mA)	800	10
Mains power (GW)	2	0.5
$\langle P_{sync} \rangle$ (W/m)	1400	55
Interaction regions (IR)	2	2
Limiting technology	IR survival	Management
Tune shift per IR	0.01	0.006
Luminosity (cm^{-2} s^{-1})	$\approx 10^{36}$	10^{34}

V. CONCLUSIONS

A systematic parameter search with the ELOSCALE code shows that conventional proton synchrotrons are a suitable technology for hadron supercolliders with an energy and luminosity much higher than those of the SSC. In particular, an ELOISATRON operating at 100 TeV per beam with a luminosity $>10^{34}$ cm^{-2}s^{-1} (ELN-34) could be constructed by using technologies now available. Assuming moderate advances in accelerator technology during its design cycle, one could expect to operate ELN at luminosities $\approx 10^{35}$ cm^{-2}s^{-1} at 100 TeV/beam (ELN-35). Such a hadron supercollider based on conventional technology would have the physics reach and discovery potential at least as great as a 10 TeV e^+-e^- linear collider, for which no reasonable design concept now exists. With further advances in a few key technologies, a PeV collider based upon conventional proton synchrotron approaches would be technologically possible.

If existing technologies are extended into new regimes (e.g., given practical, high T_c superconductors suitable for magnet windings), one could extend the luminosity at 100 TeV/beam to $\sim 10^{36}$ cm^{-2} s^{-1}. Such a supercollider would contain ≈500,000 bunches with associated beam crossing rates approaching 1 GHz yielding several tens of collisions per crossing. As detectors are unlikely to accommodate or even survive extremely high luminosities, a more fruitful upgrade of a 100 TeV class collider would be a 70% energy increase in the existing tunnel (ELN-Up in Table 4).

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