LBL-34684
UC-414

Lawrence Berkeley Laboratory

UNIVERSITY OF CALIFORNIA

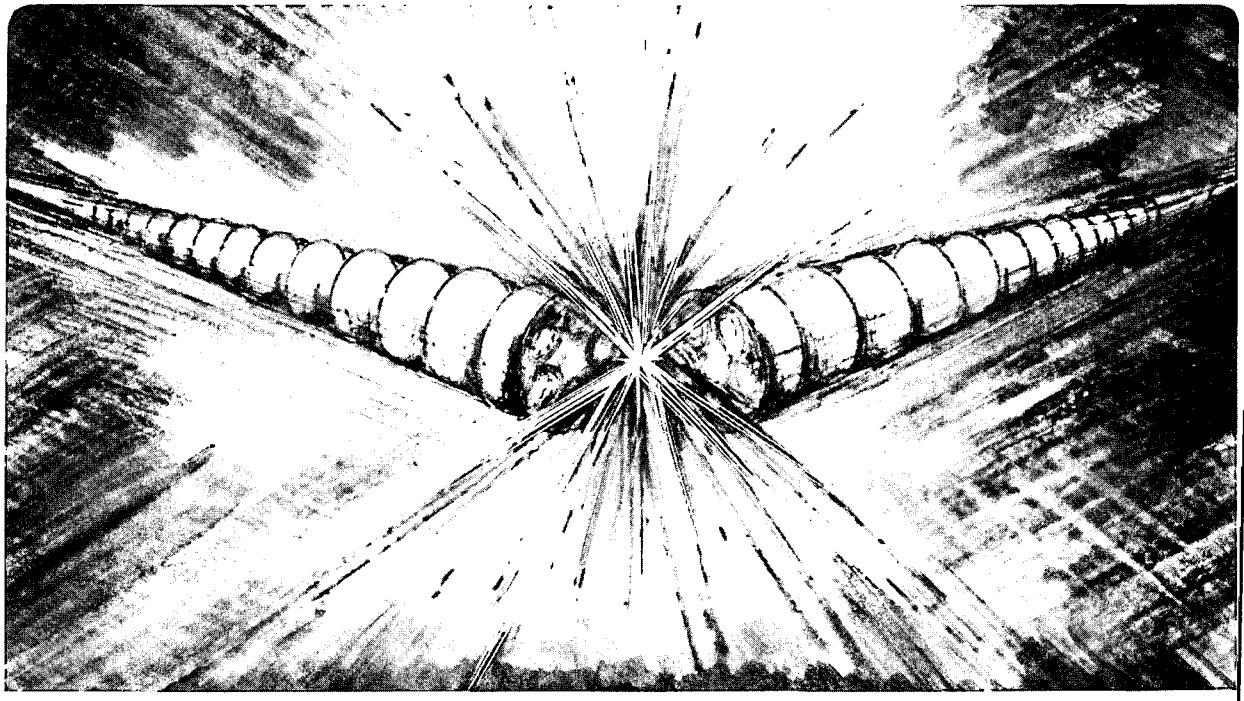
Accelerator & Fusion Research Division

To be published as a chapter in The Science and Culture Series,
World Scientific Publishing Company, Singapore, August, 1994

The Design of Hadron Supercolliders of 200 TeV or More

W.A. Barletta

October 1993



LOAN COPY
Circulates
for 4 weeks
Bldg. 50 Library.
LBL-34684
Copy 2

Prepared for the U.S. Department of Energy under Contract Number DE-AC03-76SF00098

DISCLAIMER

This document was prepared as an account of work sponsored by the United States Government. While this document is believed to contain correct information, neither the United States Government nor any agency thereof, nor the Regents of the University of California, nor any of their employees, makes any warranty, express or implied, or assumes any legal responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by its trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof, or the Regents of the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof or the Regents of the University of California.

LBL-34684
UC - 414

THE DESIGN OF HADRON SUPERCOLLIDERS OF 200 TeV OR MORE

William A. Barletta

Accelerator and Fusion Research Division
Lawrence Berkeley Laboratory
University of California
Berkeley, CA 94720

and

Dept of Physics, University of California
Los Angeles, California

October 1, 1993

This work was supported by the Director, Office of Energy Research, Office of High Energy Physics, U.S. Dept. of Energy under Contract No. DE-AC03-76SF00098.

THE DESIGN OF HADRON SUPERCOLLIDERS OF 200 TeV OR MORE

William A. Barletta

Lawrence Berkeley Laboratory
and
Dept. of Physics, University of California at Los Angeles

ABSTRACT

The extension of the frontiers of experimental high energy physics in a manner that maximizes discovery potential has been accomplished through the building of accelerators of ever higher particle energies and luminosities. This paper describes the features of a hadron supercollider well beyond the capabilities proposed for the Superconducting Super Collider (SSC) or the Large Hadron Collider (LHC). 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 proton synchrotron–based colliders to explore PeV energies.

I. GENERAL CONSIDERATIONS

The modern tools for the experimental exploration of the nature of mass and the dynamical principles underlying the physical universe are colliders with ever higher beam energies and ever higher luminosities. Presently the Tevatron $p\bar{p}$ collider at Fermilab provides beams with the highest available energy. Two projects aimed at exploring the Higgs mechanism as well as supersymmetry are the SSC at 20 TeV per beam and the LHC at 8 TeV per beam. To provide adequate (and roughly equivalent) discovery potential for a low mass Higgs, the machines designers must provide a luminosity significantly greater than that now available at the Tevatron. Assuring a discovery potential well beyond that the of SSC or LHC would require an even greater step in the energy available in the quark-quark center of mass and in the luminosity of the collider.

While e^+e^- linear colliders of 5 TeV per beam are sometimes discussed in this context, no credible design concept for such accelerators exists. In contrast, proton synchrotrons based on presently available technology should be able to provide beams in excess of 100 TeV per beam. Proton synchrotrons of even higher energy are possible without undue sacrifice of collider luminosity or without unrealistic extrapolation of present technology. The most notable example of such a supercollider is the ELOISATRON (ELN), proposed by A. Zichichi[1]. An earlier study[2] of the ELN design has concluded that an initial operating luminosity of 10^{34} $cm^{-2}s^{-1}$ is practical for ELN using present technology. Figure 1 compares the performance goals for the ELN and a potential upgrade with those of other present

and future hadron colliders. This paper presents the basic design characteristics of the ELN in the context of a discussion of the physics and the technology that determine the trends in energy and luminosity illustrated in Fig. 1.

The fundamental characteristics of a collider may be considered to be beam energy, current, emittance, bunch structure, and optics at the interaction point. The most general figure-of-merit of the performance of the collider is the time integrated luminosity. For simplicity of analysis, one may assume that both beams in the collider consist of bunches of equal population, N_B, separated by a spacing S_B. In terms of the normalized emittance, ε_n, the relativistic factor γ (beam energy divided by the particle rest mass) and the depth of field of the optics (β function) at the interaction point, β^*, the instantaneous luminosity is

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

In eq. (1) I is the average current; r_p is the classical radius of the proton; ξ is the tune shift, which is assumed to be equal in both transverse planes. The luminosity of a collider, therefore, rises naturally with increasing beam energy at the "price" of increased practical difficulties in machine design. The challenge of increasing the luminosity faster than linearly with energy are associated with increasing the beam current. Fortunately for hadron supercolliders it does not appear necessary to increase luminosity with the square of the beam energy as is the case for e^+e^- colliders; nonetheless achieving the highest practical luminosity is important to minimizing the running time of experiments.

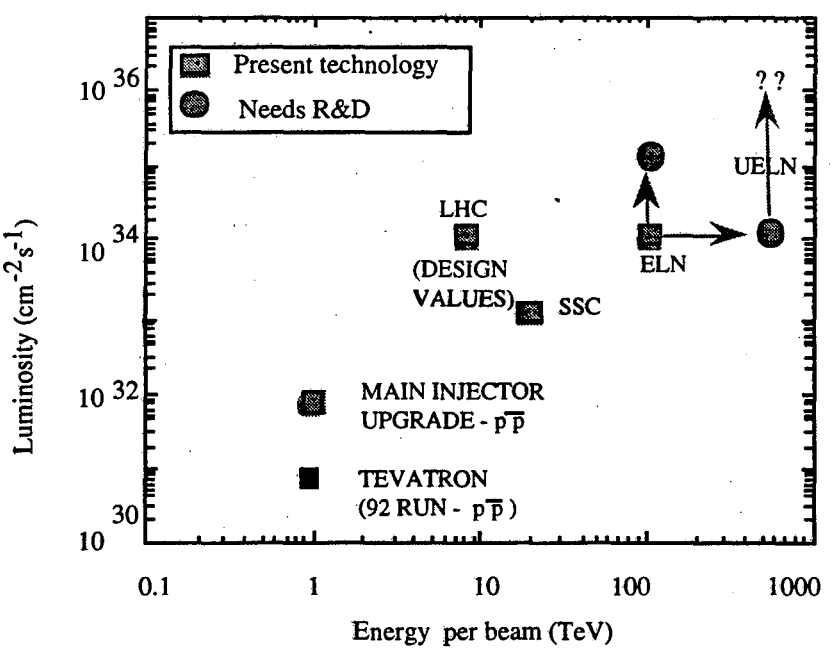


Figure 1. The luminosity and energy goals of present and future hadron colliders

In analyzing the energy and luminosity limits of hadron 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; and 3) Accelerator technology – magnets, fault modes handling of synchrotron radiation, beamline impedance, radiation damage of components.

II. SYNOPSIS OF SELECTED CONSTRAINTS ON COLLIDER DESIGN

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. The value of $\langle n \rangle$ depends upon the energy of the beam via the inelastic cross section, σ_{inel};

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

Clearly, $\langle n \rangle$ can be made sufficiently small by decreasing the time between bunches, S_B/c, to a few nanoseconds or less. Unfortunately, cycling the data acquisition electronics requires at least 10 ns between crossings. Moreover, small bunch spacing requires the use of a higher frequency rf-system than may be compatible with a low impedance. To reduce the number of events per crossing at a fixed luminosity one should lower the normalized emittance, which reduces the beam radius at the interaction point, and reduce the bunch spacing. A example of this interdependence for a 200 TeV collider is illustrated in Figure 2. In the design of the ELN, as in the design of LHC and SSC, a compromise among all these considerations leads to choosing a range of 15 - 25 ns between bunch crossings.

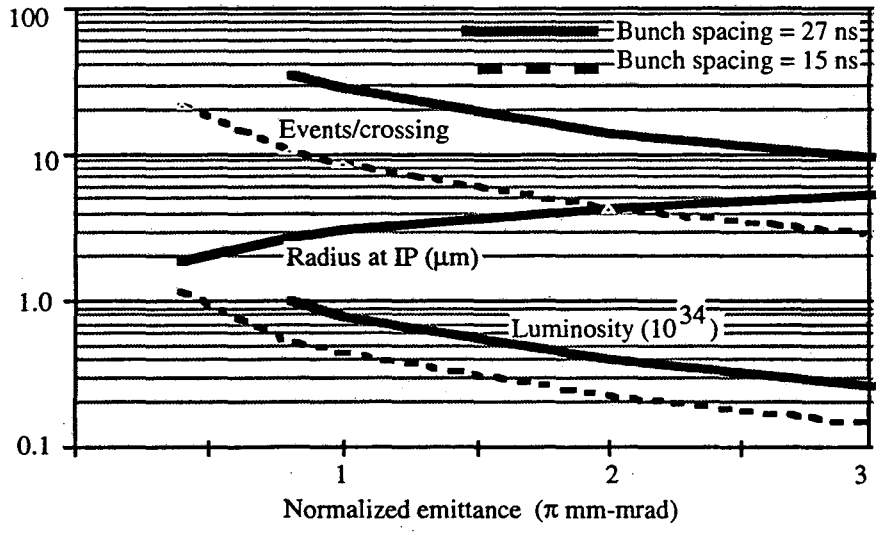


Figure 2. The interdependence of beam emittance, bunch spacing and luminosity for a 200 TeV proton supercollider as calculated with the design code ELOSCALE.

Another collider characteristic that can affect the number of events per crossing and the design of the detector is the angle at which the two beams cross. For small angles the major effect is to vary the length of the luminous region. Although detector considerations argue for choosing the crossing angle as small as possible, small angles lead to a large number of parasitic long-range interactions between the beams. A reasonable compromise is at a crossing angle of 70 to 120 μradians.

In a general sense that is applicable both to accelerator protection and to the survival of the innermost detector components, the difficulties of dealing with the radiation from the collision point are most simply expressed in terms of the power (per side) in the charged particle debris; namely,

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

A recent examination of detector lifetime at high luminosity by participants of the 25th ELOISATRON Workshop concluded that the power levels implied by eq. (3) probably preclude detector components within 1 m of the interaction point for a luminosity of 10^{35} $cm^{-2}s^{-1}$. In other words, inner tracking would be ruled out. Consequently, the design philosophy that has been adopted for ELN is to allow adequate margin in the choice of initial operating characteristics at 100 TeV per beam (such as the strength of the superconducting dipoles) so that a substantial energy upgrade (by a factor of 2 or 3) is allowed without major conventional construction. The approach of maximizing discovery potential of ELN via energy upgrades would not, however, preclude a luminosity upgrade of the ELN at 100 TeV per beam, if that approach were decided to be preferable for some experiments.

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 (PEP and Adone) with a single interaction point, the experience with hadron beams both at the CERN $S\bar{p}pS$ and at the Tevatron with several interaction points indicates that the maximum total tune shift allowable is 0.024. This observation might suggest that the luminosity can be maximized by designing the collider 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 $\xi_{tot} \leq 0.024$.

Proton supercolliders will have to cope with a phenomenon that has been insignificant in previous hadron colliders, that is, the production of intense synchrotron radiation with a critical energy in the vacuum UV to hard X-ray range. The synchrotron radiation will heat the walls of the vacuum chamber and desorb gas from the chamber. As critical energy increases beyond 5 keV, the radiation can penetrate into the superconducting magnet windings and can cause quenches.

The synchrotron radiation power generated per meter of dipole arc, P_{sync}, is proportional to the energy lost per turn, U_0, to the beam current, I, and is inversely proportional to the radius of curvature of the bends, ρ;

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

The rate at which the power is deposited on the walls of the chamber varies longitudinally along the accelerator and depends upon the details of the lattice. In a large collider, such as the ELOISATRON, the packing fraction of dipoles can be ≈ 80%. Hence the variation in power density along the collider walls is not very significant. One can, however, expect that radiation will be deposited within the region of the quadrupoles as well as the dipoles.

As the synchrotron 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 the required operating power to practical levels, the SSC design limits P_{sync} to 0.13 W/m on the magnet bore (at 4.2 K). The LHC magnets operate at 1.8 K; hence, the LHC design incorporates a radiation shield (liner) at 20 K inside the vacuum chamber, thereby permitting 1 W/m. For the ELN and its upgrades to operate at the highest possible energy or luminosity, P_{sync} must be allowed to exceed 1 W/m. An examination[4] of the utility of such a liner for the SSC indicates that the case is technically compelling for a 20 TeV collider even though the liner has not yet been incorporated into the SSC design. For the ELN, the liner will be essential.

To limit the power consumed by the compressors, one also must increase the temperature of the surface on which the radiation is deposited; e.g., one might operate the radiation shield (liner) at 70 K. Unfortunately, raising T_{wall} can lead 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[5] of the transverse resistive wall instability in a beam pipe of radius b, is

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

In eq. (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, $\nu - n$, (use 0.1), and ζ is a correction for the multiple metallic layers that constitute the liner (equal to 2.87 + 2.87i for SSC). The residual resistivity ratio (R_w) for copper plated onto stainless steel varies as

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

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 passively by spreading the betatron frequencies in the beam. Hence,

controlling the instability will require the use of a digital, bunch-by-bunch feedback system. Such a system is presently under development and test at the Advanced Light Source at LBL. 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, b. In this sense both T_{wall} and b depend upon the choice of B_{dipole}. The consequences of these 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.

A problem unique to hadron colliders, which do not have the rapid radiation damping typical of electron storage rings, is that vibrations of the magnets, injection errors, or electronic noise in the feedback system itself can lead coherent motions of the beam. These motions must be controlled to limit a) position errors between the beams at the interaction point and b) "decoherence" of the motion. The decoherence manifests itself as emittance dilution at a rate which is substantially faster than the radiation damping rate. In the Tevatron, which has no feedback systems to control emittance dilution, the normalized emittance is found to grow at a rate $\geq 3\pi$ mm-mrad/hr. Such a growth rate would be completely unacceptable in ELN or SSC or LHC where the normalized emittance must be kept to $\leq 1\pi$ mm-mrad. The consequence of emittance dilution would be a rapid loss of luminosity once the beams are brought into collision.

A recent examination[6] of the design of feedback systems for proton supercolliders has indicated that care in the design of the feedback electronics system can keep emittance growth to tolerable proportions. The most difficult system for an accelerator beyond SSC appears to be the transverse dampers of injection oscillations. Already for SSC such a system will require $\approx$ 400 kW. As the top energy of the collider is increased, the energy at injection must also be increased. However, the spacing between the closed orbit of the stored beam and the injection trajectory in the Lambertson magnets is likely to remain constant. The beam size at injection will be smaller because the geometric emittance will be smaller at the higher energy. Hence, the tolerance on the injection errors will shrink. The upshot is that a correction system for ELN would have to operate with a power $\approx$ 5 MW.

The most expensive sub-system of the supercollider is the magnetic transport. In evaluating the prospects for a 200 TeV ELN, the maximum value of B_{dipole} was taken to be 10 T, consistent with presently demonstrated technology. For the longer tern future, values as high as 15 T for an energy doubler and 20 T for an energy tripler were considered. In that a 1- long 13.5 T dipole is presently under development at LBL, this assumption for the long term is not just wishful thinking. One should also note that the development of superconducting cables with artificial pinning centers by LBL-industrial collaboration should reduce the cable costs by 30 - 50% depending on magnet design. Consequently one can expect the cost per

meter of ELOISATRON magnets to be substantially below the projected costs for the SSC and LHC dipoles.

III. PARAMETER STUDIES AND MACHINE CHARACTERISTICS

Self-consistent characteristics of supercolliders at the highest energies and luminosities are explored most easily with a simple computer code that has been specifically designed for performing parameter searches. ELOSCALE is a spreadsheet–format design code based on the scaling relations described in Ref. 2. The input variables specifiying the beam are the injection energy, the maximum beam energy, the normalized emittance, and the bunch-to-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.

As a starting point of the design, one should specify the lattice and the interaction point optics. For a very large storage ring such as the ELN, the SSC lattice is an appropriate design for scaling purposes with the dipole fraction in the range of 0.6 – 0.8. In the following designs the dipole fraction was taken to be 0.8. For the reference design (ELN-34) at a luminosity of 10^{34} cm^{-2}s^{-1}, the average values of the beta function and dispersion are ≈490 m and 5.6 m, respectively.

The scaling of the interaction region optics should be based on considerations of damage to the innermost quadrupole, Q1, due to the hadronic debris. The dose at 100 TeV and at a luminosity of 10^{34}cm^{-2}s^{-1} that is deposited by the hadronic debris in Q1 corresponds to ≈ 4.5 W/kg. For a superconducting Q1 without a collimator removing this power would require ≈ 2 kW/kg of compressor power. Similarly, one finds that were the first quadrupole a permanent magnet (SmCo), Q1 would have a lifetime of ≈ 3 months. In contrast, a normal conducting, iron Q1 with polyanimid insulation of the winding would have a lifetime of ≈ 30 months. Suitable shielding and collimation can attenuate the dose absorbed by the sensitive components by a factor of 10 – 100 depending on the energy of the beam and the details of the design. An additional reduction of the dose can be provided by increasing β^* by an amount that depends on the maximum design luminosity; a reasonable suggestion from a recent study[7] is to scale β^* according to

$$\beta^* \geq 0.3\,\mathrm{m}\left(\frac{\gamma}{10^4}\right)^{1/2} \mathrm{Max}\left[1, \mathrm{Log}_{10}\left(\frac{\mathcal{L}}{10^{33}}\right)\right]. \qquad (6)$$

A parameter exploration with ELOSCALE indicates that the reference design of ELN at 100 TeV can be realized at P_{sync} =5 W/m by using the same technologies

that are being realized for the LHC. Raising P_{sync} to 20 W/m yields 10^{35} cm^{-2} s^{-1} (ELN-35). Parameters for both cases are given in Table 4. For all the designs of Table 4 the rf-system operates at 412 MHz employing superconducting cavities. Note that the power demanded from the electric power mains is commensurate with the power level generally considered necessary for a 1 TeV e^+e^- linear collider - a machine with vastly smaller energy reach than ELN-34.

Table 4. Possible sets of characteristics of ELOISATRON and upgrades

	ELN34	ELN35	2ELN	3ELN
Circumference (km)	355	355	355	355
B_{dipole} (T)	7.7	7.7	13	20
Maximum energy (TeV)	100	100	170	260
Beam current (mA)	100	400	50	10
Mains power (GW)	0.2	0.33	0.33	0.39
$\langle P_{sync} \rangle$ (W/m)	5	20	20	25
Crossing angle (μrad)	70	120	70	70
Interaction regions (IR)	2	2	2	2
Tune shift per IR	0.003	0.01	0.006	0.003
Events/cm/crossing	1.2	9	2.4	0.5
Luminosity half-life (hr)	50	21	20	37
Damping time (hr)	1.8	1.8	0.3	0.1
Luminosity (cm^{-2} s^{-1})	10^{34}	10^{35}	10^{34}	10^{34}

Also presented in Table 4 are characteristics of a energy doubler and energy tripler upgrade option. In these cases the required normalized emittance is 0.2 and 0.12, respectively. While the H^- source constructed at LBL for the SSC can meet this goal, emittance growth in the injector chain will require that the beams be accelerated to full energy and be allowed to coast for two damping times to reduce the emittance to the desired level. Note that for both energy upgrades, the damping time is a small fraction of the luminosity lifetime. With respect to the luminosity upgrade option, the variation of the luminosity of ELN-35 with P_{sync} and with operating energy is shown in Fig. 3.

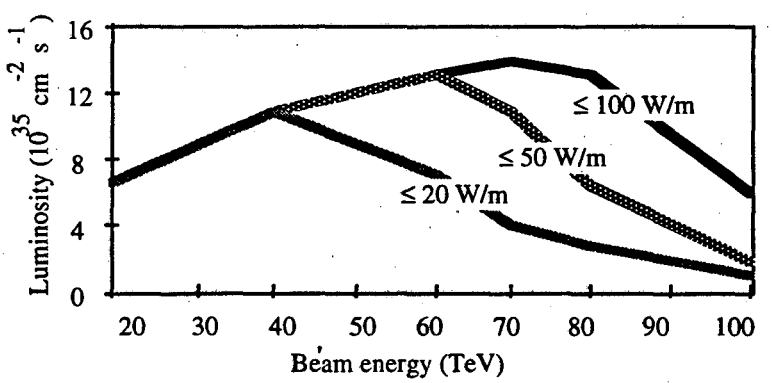


Figure 3. The luminosity ELN as a function of beam energy for radiation loads from 20 – 100 W/m.

A very important design issue is the choice of the dipole field. Fig. 4 displays two examples of cost and operational sensitivities that are dependent on B_{dipole}. As the dipole cost will be strongly effected by the magnet aperture, a field in excess of ≈ 6 T is highly desirable. As the luminosity should be ≈20 hr, for high time average luminosity, a field more than 8 T is undesirable. If ELN-34 is sized for 6 to 8 T, then it is quite reasonable to expect that a energy doubling (or even tripling) scenario will become practical.

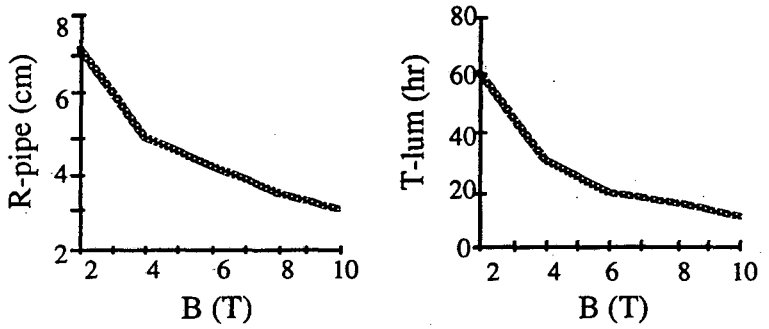


Figure 4. The variation of the dipole aperture and the luminosity lifetime with B_{dipole} for ELN35. For ELN34 the aperture (as determined by resistive wall instability considerations only) could be 20% smaller.

One challenging difference between the ELN and the SSC or LHC is that the critical energy, E_c, of the synchrotron radiation will be well in excess of 5 keV. As a consequence, the liner cannot be thin. It must be able to absorb nearly all of the the energy of the X-rays, else the synchrotron radiation power will be absorbed on the cold wall (at 2 – 4 °K) behind the liner. For the 3ELN upgrade option of Table 4, $E_c \approx 150$ keV. Fortunately, the angle of incidence of the radiation on the wall is << 1 mrad. Hence most of the energy should be absorbed in a liner that is a few mm thick. Detailed radiation transport calculations are needed to quantifiy this point further.

IV. THE ULTIMATE ELOISATRON

For the far future, studies with ELOSCALE 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 far more probable scenario for UELN is to keep the luminosity at $10^{34}\,cm^{-2}\,s^{-1}$. In that case the requirements on all of the technical sub-systems would be 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 for the UELN.

Table 5. Two 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}

As Ref. 2 argues, there seems to be no energy at which a linear proton-proton collider can match the performance of a proton synchrotron.

V. CONCLUSIONS

A systematic parameter search with the ELOSCALE design 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 the ELN at an enhanced luminosity of $\approx 10^{35}$ $cm^{-2}s^{-1}$ 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. If existing technologies are extended into new regimes (e.g., given practical, high T_c superconductors suitable for magnet windings), one might even extend the luminosity at 100 TeV/beam to $\sim 10^{36}$ $cm^{-2} s^{-1}$. Such a supercollider would contain $\approx$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 such extremely high luminosities, a much more fruitful upgrade of the ELOISATRON would be a 70 – 260% energy increase in the existing tunnel (2ELN and 3ELN in Table 4). The key to an energy upgrade would be the succesful development of long, superconducting dipoles wit a field of 15 - 20 T. With further advances in a few key technologies, a PeV collider based upon conventional proton synchrotron approaches would be technologically possible.

While the beams provided by the ELN and its upgrades would be far from the Grand Unification scale, they would be a large step beyond the capabilities of SSC, LHC, or any of the proposed e^+e^- colliders.

ACKNOWLEDGMENTS

The author thanks Prof. A. Zichichi for his kind hospitality at the Ettore Majorana Centre for Scientific Culture on several occasions during the period of these design studies. The author's participation in the 19th and 25th ELOISATRON Workshops provided a broad source of the physics embodied in ELOSCALE. This work was supported by the Director, Office of Energy Research, Office of High Energy Physics, U.S. Dept. of Energy under Contract No. DE-AC03-76SF00098.

REFERENCES

1. A. Zichichi, ELN reference
2. W. A. Barletta, "Maximizing The Luminosity Of Hadron Supercolliders At 10-100 TeV", in *Supercolliders and Superdetectors*, W. Barletta and H. Leutz, ed., World Scientific, 1993
3. See articles by Leutz, Schönbacher, and Contin in Supercolliders and Superdetectors, W. Barletta and H. Leutz, ed. World Scientific, 1993
4. W. C. Turner, "Dynamic Vacuum in the Beam Tube of the SSCL Collider – Cold Beam Tube and Liner Options", SSC, 1993
5. SSC Site-Specific Conceptual Design Report, 1990
6. Feedback references in *Supercolliders and Superdetectors*
7. Report of IR Working Group, in *Supercolliders and Superdetectors*, W. Barletta and H. Leutz, ed.

LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA
TECHNICAL INFORMATION DEPARTMENT
BERKELEY, CALIFORNIA 94720

AAT100
LBL Libraries