FUTURE COLLIDERS

R.B. Palmer and J.C. Gallardo

Brookhaven National Laboratory
Upton, New York, 11973, U.S.A.

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R. B. PALMER and J. C. GALLARDO

Brookhaven National Laboratory, Upton, NY 11973-5000, USA

The high energy physics advantages, disadvantages and luminosity requirements of hadron (pp, $p\bar{p}$), of lepton (e^+e^-, $\mu^+\mu^-$) and photon-photon colliders are considered. Technical arguments for increased energy in each type of machine are presented. Their relative size, and the implications of size on cost are discussed.

1 Physics Considerations

1.1 General

Hadron-hadron colliders (pp or $p\bar{p}$) generate interactions between the many constituents of the hadrons (gluons, quarks and antiquarks); the initial states are not defined and most interactions occur at relatively low energy generating a very large background of uninteresting events. The rate of the highest energy events is higher for antiproton-proton machines, but this is a small effect for colliders above a few TeV. In either case the effective individual interaction energies are a relatively small fraction of the total center of mass energy. Nevertheless, because high energy hadron machines have been relatively easier and cheaper to build, and because all final states are accessible, many initial discoveries in Elementary Particle Physics have been made with these machines.

In contrast, lepton-antilepton and photon-photon colliders generate interactions between the fundamental point-like constituents in their beams, the reactions generated are relatively simple to understand and there is no background of low energy events. If the center of mass energy is set equal to the mass of a suitable state of interest, then there can be a large cross section in the s-channel, in which a single state is generated by the interaction. In this case, the mass and quantum numbers of the state are constrained by the initial beams. If the energy spread of the beams is sufficiently narrow, then precision determination of masses and widths are possible.

A gamma-gamma collider also has well defined initial states, complementing those attainable with lepton colliders.

For most purposes (technical considerations aside) e^+e^- and $\mu^+\mu^-$ colliders would be equivalent. But in the particular case of s-channel Higgs boson production, the cross section, being propor-

tional to the mass squared, is more than 40,000 times greater for muons than electrons. When technical considerations are included, the situation is more complicated. Muon beams are harder to polarize and muon colliders will have much higher backgrounds from decay products of the muons. On the other hand muon collider interactions will require less radiative correction and will have less energy spread from beamstrahlung.

Each type of collider has its own advantages and disadvantages for High Energy Physics: they are complementary.

1.2 Required Luminosity for Lepton Colliders

In lepton machines the full center of mass of the leptons is available for the final state of interest and the *effective energy* is equal to the total center of mass energy.

$$E_{\text{eff}} = E_{\text{c of m}} \qquad (1)$$

Since fundamental cross sections fall as the square of the center of mass energies involved, so, for a given rate of events, the luminosity of a collider must rise as the square of its energy. A reasonable target luminosity is one that would give 10,000 events per unit of R per year:

$$\mathcal{L}_{\text{req.}} \approx 10^{34} \ (\text{cm}^{-2}\text{s}^{-1}) \left(\frac{E_{\text{eff}}}{1 \ (\text{TeV})} \right)^2 \qquad (2)$$

Fig. 1 shows this required luminosity, together with crosses at the approximate achieved luminosities of some lepton colliders. Target luminosities of possible future colliders are also given as circles.

1.3 The Effective Energies of Hadron Colliders

Hadrons, being composite, have their energy divided between their several constituents. A typical
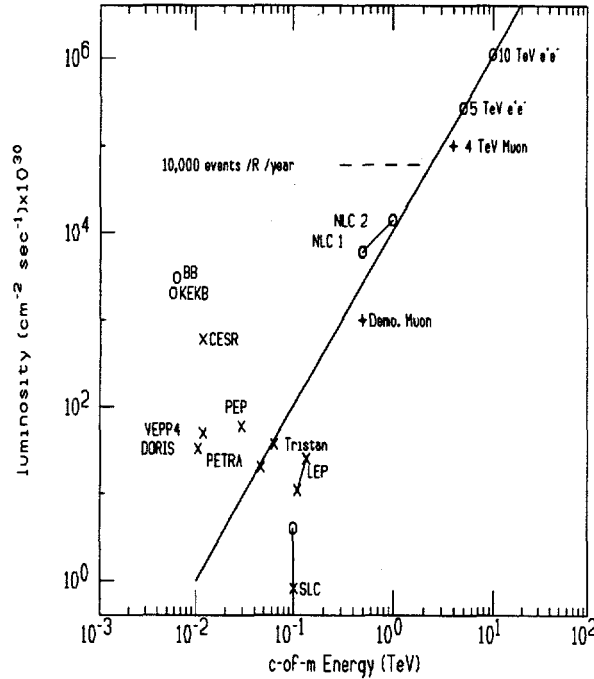
Figure 1: Luminosity of lepton colliders as a function of energy

collision of constituents will thus have significantly less energy than that of the initial hadrons. Studies done in Snowmass 82 and 96 suggest that given the required luminosity (as defined in Eq. 2) the hadron machine's *effective energy* is about 1/10 th of its total:

$$E_{\text{eff}}(\mathcal{L} = \mathcal{L}_{\text{req.}}) \approx \frac{E_{\text{c of m}}}{10}$$

The same studies have also concluded that a factor of 10 in luminosity is worth about a factor of 2 in effective energy, this being approximately equivalent to:

$$E_{\text{eff}}(\mathcal{L}) \propto (\mathcal{L}/\mathcal{L}_{\text{req.}})^{0.3}$$

From which, with Eq. 2, one obtains:

$$E_{\text{eff}}(TeV) \approx \left(\frac{E_{\text{c of m}}}{10(TeV)}\right)^{0.6} \left(\frac{\mathcal{L}}{10^{34}(\text{cm}^{-2}\text{s}^{-1})}\right)^{0.2} \quad (3)$$

2 Technical Considerations

2.1 Hadron-Hadron Machines

An antiproton-proton collider requires only one ring, compared with the two needed for a proton-proton machine, but the luminosity of an antiproton-proton collider is limited by the constraints in antiprotons production. Luminosities of 10^{33} cm^{-2}s^{-1} may be achievable at FNAL with antiproton-proton, but LHC, a proton-proton machine, is planned to have a luminosity of 10^{34} cm^{-2}s^{-1}, and might [1] be upgradable to 10^{35} cm^{-2}s^{-1}. Radiation damage to a detector would, however, then be a severe problem. The 60 TeV Really Large Hadron Colliders (RLHC high and low fields) discussed at Snowmass are being designed as proton-proton machines with luminosities of 10^{34} cm^{-2}s^{-1}.

The size of hadron-hadron machines is limited by the field of the magnets used in their arcs. A cost minimum is obtained when a balance is achieved between costs that are linear in length, and those that rise with magnetic field. The optimum field will depend on the technologies used both for the the linear components (tunnel, access, distribution, survey, position monitors, mountings, magnet ends, etc) and those of the magnets themselves, including the type of superconductor used.

The first hadron collider, the 60 GeV ISR at CERN, used conventional iron pole magnets at a field less than 2 T. The only current hadron collider, the 2 TeV TeVatron, at FNAL, uses NbTi superconducting magnets at approximately $4\,^{\circ}K$. The 14 TeV Large Hadron Collider (LHC), under construction at CERN, plans to use the same material at $1.8\,^{\circ}K$.

Future colliders may use new materials allowing higher magnetic fields. Fig.2 shows the critical current densities of various superconductors as a function of magnetic field. The numbers in parenthesis refer to the temperatures in $^{\circ}$ K. *Good* and *bad* refer to the best and worst performance according to the orientation in degree of the tape with respect to the direction of the magnetic field. Model magnets have been made with Nb$_3$Sn, and studies are underway on the use of high T_c superconductor. Bi$_2$Sr$_2$Ca$_1$Cu$_2$O$_8$ (BSCCO) material is currently available in useful lengths as powder-in-Ag tube processed tape. It has a higher critical temperature and field than conventional superconductors, but, even at $4\,^{\circ}K$, its current density is less than Nb$_3$Sn at all fields below 15 T. It is thus unsuitable for high field accelerator magnets. In contrast YBa$_2$Cu$_3$O$_7$ (YBCO) material has a current density above that for Nb$_3$Sn ($4\,^{\circ}K$), at
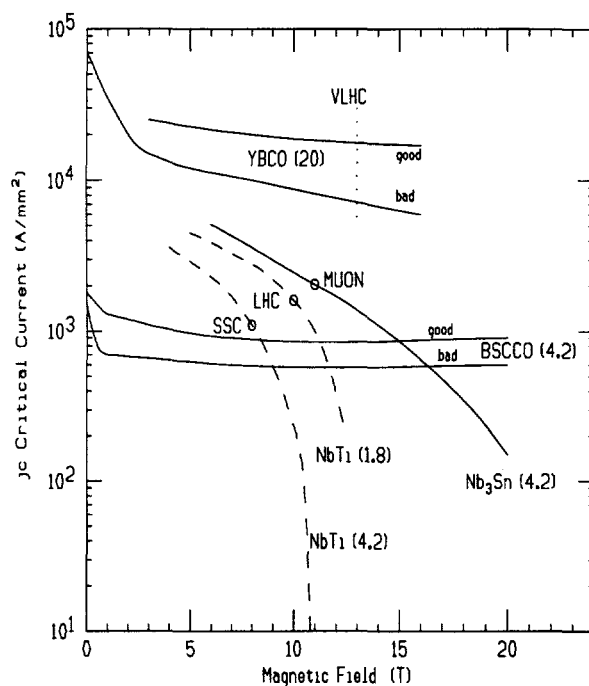
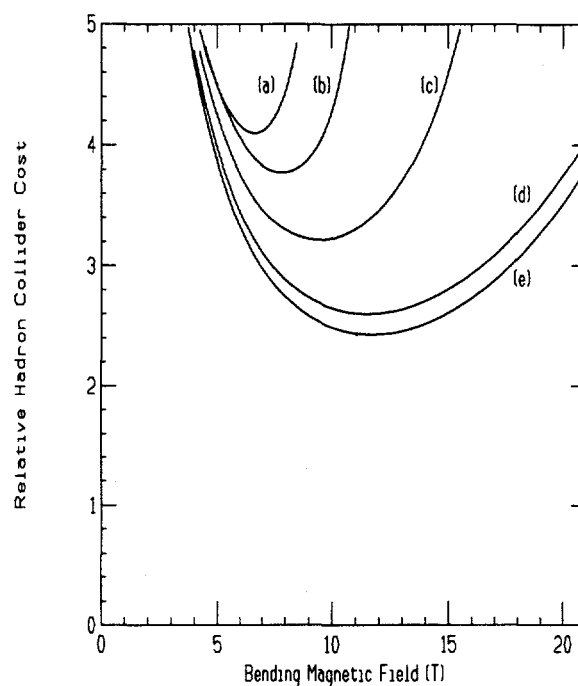Figure 2: Critical current densities of superconductors as a function of magnetic field.

Figure 3: Relative costs of a collider as a function of its bending magnetic field, for different superconductors and operating temperatures

all fields and temperatures below $20\,^\circ K$. But this material must be deposited on specially treated metallic substrates and is not yet available in lengths greater than 1 m. It is reasonable to assume, however, that it will be available in useful lengths in the not too distant future.

A parametric study[2] was undertaken to learn what the use of such materials might do for the cost of colliders. 2-in-1 cosine theta superconducting magnet cross sections were calculated using fixed criteria for margin, packing fraction, quench protection, support and field return. Material costs were taken to be linear in the weights of superconductor, copper stabilizer, aluminum collars, iron yoke and stainless steel support tube. The cryogenic costs were taken to be inversely proportional to the operating temperature, and linear in the outer surface area of the cold mass.

The values of the cost dependencies were scaled from LHC estimates. Results are shown in Fig. 3. Costs were calculated assuming NbTi at (a) $4\,^\circ K$, and (b) $1.8\,^\circ K$, (c) $Nb_3 Sn$ at $4.3\,^\circ K$, and (d) and (e) YBCO High T_c at $20\,^\circ K$. NbTi and $Nb_3 Sn$ costs per unit weight were taken to be the same; YBCO was taken to be either equal to

NbTi (in (d)), or 4 times NbTi (in (e)).

It is seen that the optimum field moves from about 6 T for NbTi at $4\,^\circ K$ to about 12 T for YBCO at $20\,^\circ K$; while the total cost falls by almost a factor of 2; i.e., the optimized cost per unit length remains approximately constant. This might have been expected: at the cost minimum, the cost of linear and field dependent terms are matched, and the total remains about twice that of the linear terms.

It must be noted that the above study assumes a particular type of magnet and may not be indicative of the optimization for radically different designs. A group at FNAL[3] is considering an iron dominated, alternating gradient, continuous, single turn collider magnet design (Low field RLHC). Its field would be only 2 T and circumference very large (350 km for 60 TeV), but with its simplicity and with tunneling innovations it is hoped to make its cost lower than the smaller high field designs. There are however greater problems in achieving high luminosity with such a machine than with the higher field designs.

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2.2 Circular Electron-Positron Machines

Although the luminosities of most circular electron-positron colliders has been between 10^{31} and 10^{32} cm^{-2}s^{-1} (see Fig.1), CESR is fast approaching 10^{33} cm^{-2}s^{-1} and machines are now being constructed with even high values. Thus, at least in principle, luminosity does not seem to be a limitation, although it may be noted that the 0.2 TeV electron-positron collider LEP has a luminosity below the above requirement.

At energies below 100 MeV, using a chosen reasonable bending field, the size and cost of a circular electron machine is approximately proportional to its energy. But at higher energies, if the bending field B is maintained, the energy lost ΔV_{turn} to synchrotron radiation rises rapidly

$$\Delta V_{\text{turn}} \propto \frac{E^4}{R\, m^4} \propto \frac{E^3\, B}{m^4} \qquad (4)$$

and soon becomes excessive (R is the radius of the ring). A cost minimum is then obtained when the cost of the ring is balanced by the cost of the rf needed to replace the synchrotron energy loss. If the ring cost is proportional to its circumference, and the rf is proportional to its voltage then the size and cost of an optimized machine rises as the square of its energy. This relationship is well demonstrated by the parameters of actual machines (see Fig. 8).

The highest e^+e^- collider is the LEP at CERN which has a circumference of 27 km, and will achieve a maximum center of mass energy of about 0.2 TeV. Using the predicted scaling, a 0.5 TeV circular collider would have to have a 170 km circumference, and would be very expensive.

2.3 Electron-Positron Linear Colliders

So, for energies much above that 0.2 TeV it is impractical to build a circular electron collider. The only possibility is to build two electron linacs facing one another. Interactions occur at the center, and the electrons, after they have interacted, must be discarded.

If the linacs are conventional, non-superconducting, structures, then there may again be a cost trade off; this time between the cost of rf to obtain accelerating gradient, and the linear costs of the structure, tunnel, etc. If the optimized gradient is less than its technical maximum, then
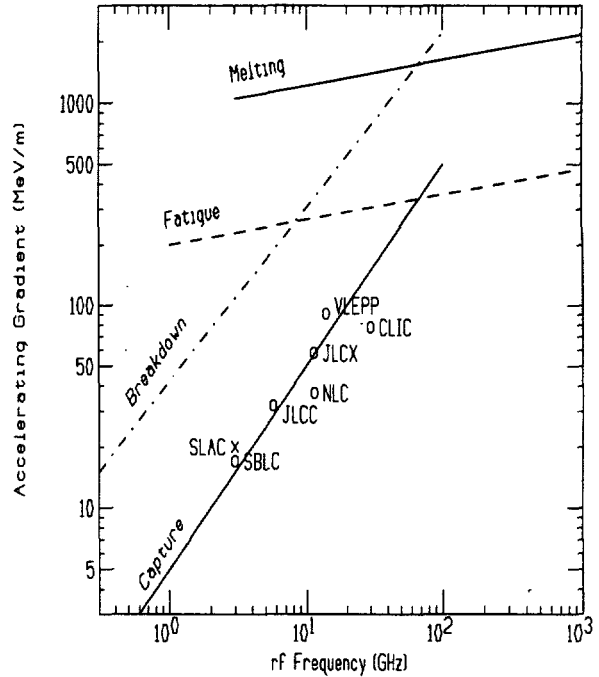

Figure 4: Gradient values and limits in linear collider electron linacs

the cost per unit length of an optimized machine should again be about twice the linear costs. But this time the *linear costs* include the linac itself, and these will be dependent on technology and rf frequency.

If, however, the rf costs can be constrained, for instance when superconducting cavities are used, then there will be no trade off and higher gradients should be expected to lower the length and cost. The gradients achievable in Niobium superconducting cavities is theoretically limited to about 40 MV/m and practically to 15-25 MV/m. Nb$_3$Sn and high Tc materials may allow higher field gradients in the future with no loss of luminosity.

The gradients for conventional structures have limits that are frequency dependent. Fig. 4 shows the gradient limits from breakdown, fatigue and dark current capture plotted against the operating rf frequency. Operating gradients and frequencies of several linear collider designs [4] are also indicated. One sees that the use of high frequencies allows higher accelerating gradients, less overall length and thus, hopefully, less cost. There are however counterbalancing considerations from the

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requirements of luminosity.

The luminosity $\mathcal{L}$ of a linear collider can be written:

$$\mathcal{L} = \frac{1}{4\pi E} \; \frac{N}{\sigma_x} \; \frac{P_{\text{beam}}}{\sigma_y} \; n_{\text{collisions}} \qquad (5)$$

where, in this case, $n_{\text{collisions}} = 1$; σ_x and σ_y are average beam spot sizes including any pinch effects: σ_x being greater than σ_y; E is the beam energy and P_{beam} is the total beam power. This can also be expressed as,

$$\mathcal{L} = \frac{1}{4\pi E} \; \frac{n_\gamma}{2 r_0 \alpha} \; \frac{P_{\text{beam}}}{\sigma_y} \qquad (6)$$

where r_o is the classical electromagnetic radius, α is the electromagnetic constant, and n_γ the number of photons emitted by one bunch as it passes through the other. If n_γ is too large then the beamstrahlung background of electron pairs and other products becomes unacceptable. So, for a fixed criterion for background, we have:

$$\mathcal{L} \propto \frac{1}{E} \; \frac{P_{\text{beam}}}{\sigma_y}$$

which may be compared to the required luminosity that increases as the square of energy, giving the requirement:

$$\frac{P_{\text{beam}}}{\sigma_y} \propto E^3. \qquad (7)$$

It is this requirement that makes it hard to design very high energy linear colliders. The 0.1 TeV SLC, with a relatively low energy, is still almost an order of magnitude below its design luminosity, and nearly four orders of magnitude less than that specified for the various designs for 0.5 TeV linear colliders[4].

Fig.5, using parameters from the linear collider proposals[4], plots some relevant parameters against the rf frequency. One sees that as the frequencies rise,

- the machine lengths fall as higher gradients become possible,

- greater alignment precision is required. For instance, in the resolution of beam position monitors; and

- despite these better alignments, the calculated emittance growth during acceleration is greater; and

- the wall-power to beam-power efficiencies are less.

Thus while length and cost considerations may favor high frequencies, yet luminosity considerations demand lower frequencies.

At higher energies (as expected from Eq. 7), obtaining the required luminosity gets harder. Fig.6 shows the dependency of some example machine parameters with energy. SLC is taken as the example at 0.1 TeV, NLC parameters at 0.5 and 1 TeV, and 5 and 10 TeV examples are taken from a review paper by one of the authors[5]. One sees that:

- the assumed beam power rises approximately as E^2;

- the vertical spot sizes fall approximately as E^{-2};

- the vertical normalized emittances fall even faster than E^{-2}; and

- the momentum spread due to beamstrahlung has been allowed to rise approximately linearly with E.

These trends are independent of the acceleration method, frequency, etc, and indicate that as the energy and required luminosity rise, so the required beam powers, efficiencies, emittances and tolerances will all get harder to achieve. The use of higher frequencies or exotic technologies that would allow the gradient to rise, will, in general, make the achievement of the required luminosity even more difficult. It may well prove impractical to construct linear electron-positron colliders, with adequate luminosity, at energies above a few TeV.

2.4 Photon-Photon Colliders

A gamma-gamma collider[6] would use opposing electron linacs, as in a linear electron collider, but just prior to the collision point, laser beams would be backscattered off the electrons to generate photon beams that would collide at the IP instead of the electrons. If suitable geometries are used, the mean photon-photon energy could be 80% or more of that of the electrons, with a luminosity about 1/10th.

If the electron beams, after they have Compton backscattered the photons, are deflected, then
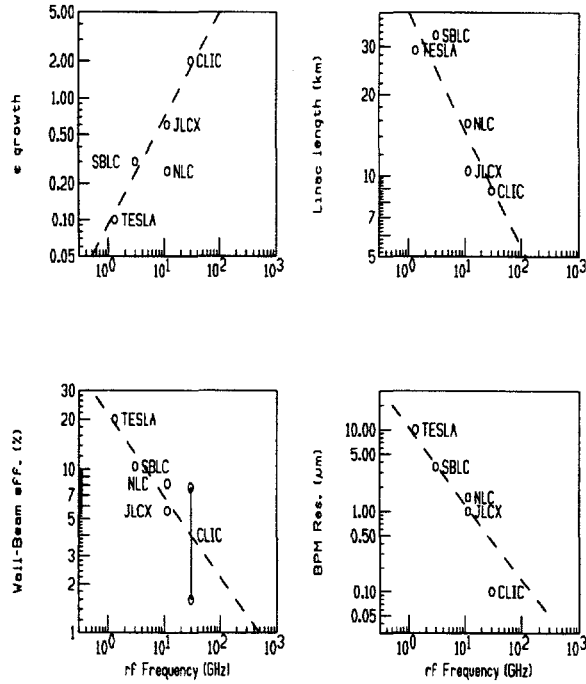
Figure 5: Dependence of some sensitive parameters as a function of linear collider rf frequency.
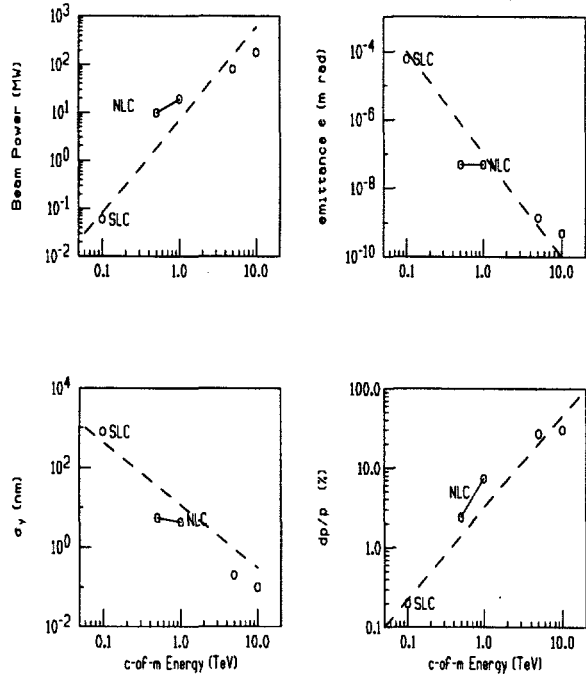

Figure 6: Dependence of some sensitive parameters on linear collider energy.

backgrounds from beamstrahlung can be eliminated. The constraint on N/σ_x in Eq.5 is thus removed and one might hope that higher luminosities would now be possible by raising N and lowering σ_x. Unfortunately, to do this, one needs sources of larger number of electron bunches with smaller emittances, and one must find ways to accelerate and focus such beams without excessive emittance growth. Conventional damping rings will have difficulty doing this.[8]. Exotic electron sources might be needed.

Thus, although gamma-gamma collisions can and should be made available at any future electron-positron linear collider, to add physics capability, they may not give higher luminosity for a given beam power.

2.5 Muon-Muon Colliders

There are two advantages of muons, as opposed to electrons, for a lepton collider.

- The synchrotron radiation, that forces high energy electron colliders to be linear, is (see Eq. 4) inversely proportional to the fourth power of mass: It is negligible in muon colliders with energy less than 10 TeV. Thus a muon collider, up to such energy, can be circular. In practice this means in can be smaller. The linacs for a 0.5 TeV NLC would be 20 km long. The ring for a muon collider of the same energy would be only about 1.2 km circumference.

- The luminosity of a muon collider is given by the same formula as in Eq. 5 as given above for an electron positron collider, but there are two significant changes: 1) The classical radius r_o is now that for the muon and is 200 times smaller; and 2) the number of collisions a bunch can make $n_{collisions}$ is no longer 1, but is now related to the average bending field in the muon collider ring, with

$$n_{collisions} \approx 150\, B_{ave}$$

With an average field of 6 Tesla, $n_{collisions} \approx$ 900. Thus these two effects give muons an *in principle* luminosity advantage of more than 10^5.

The problems with the use of muons are:

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- Muons can be best obtained from the decay of pions, made by higher energy protons impinging on a target. A high intensity proton source is thus required and very efficient capture and decay of these pions is essential.

- Because the muons are made with very large emittance, they must be cooled and this must be done very rapidly because of their short lifetime. Conventional synchrotron, electron, or stochastic cooling is too slow. Ionization cooling is the only clear possibility, but does not cool to very low emittances.

- Because of their short lifetime, conventional synchrotron acceleration would be too slow. Recirculating accelerators or pulsed synchrotrons must be used.

- Because they decay while stored in the collider, muons radiate the ring and detector with their decay products. Shielding is essential and backgrounds will certainly be significant.

Muon colliders were first considered more than 20 years ago, many papers have been written and many workshops held [9]. A collaboration, lead by BNL, FNAL and LBNL, with contributions from 18 institutions has been studying a 4 TeV, high luminosity scenario and presented a Feasibility Study [7] to the 1996 Snowmass Workshop.

The basic parameters of this collider are shown schematically in Fig.7 and given in Tb.1 together with those for a 0.5 TeV demonstration machine based on the AGS as an injector. It is assumed that a demonstration version based on upgrades of the FERMILAB, or CERN machines would also be possible.

The main components are:

- A proton source with KAON like parameters (30 GeV, 10^{14} protons per pulse, at 15 Hz).

- A liquid metal target surrounded by a 20 T hybrid or high T_c superconducting solenoid to make and capture pions.

- A 5 T solenoidal channel within a sequence of rf cavities is used to allow the pions to decay into muons and, at the same time, decelerate the fast ones that come first, while accelerating the lower momentum ones that
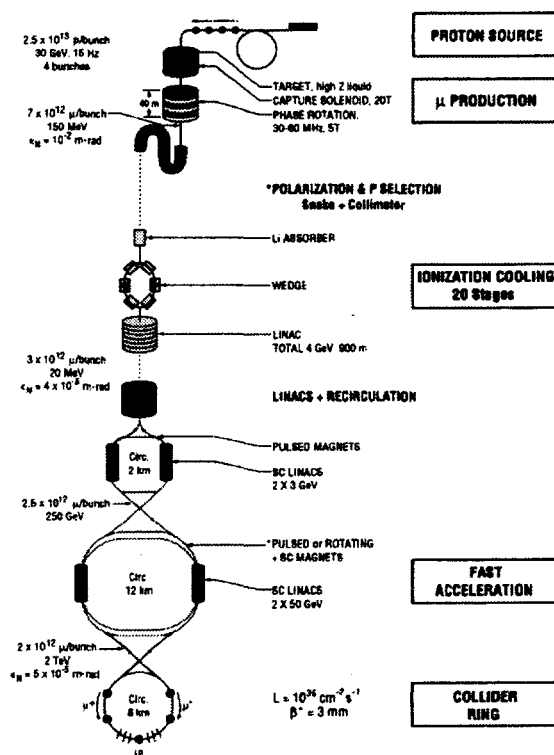

Figure 7: Overview of a 4 TeV Muon Collider

Table 1: Parameters of Collider Rings

c-of-m Energy	TeV	4	.5
Beam energy	TeV	2	.25
Beam γ	10^3	19	2.4
Repetition rate	Hz	15	2.5
Muons per bunch	10^{12}	2	4
Bunches of each sign		2	1
Norm. rms emit. ϵ_N	π m rad	$5 10^{-5}$	$9 10^{-5}$
Bending Field	T	9	9
Circumference	Km	7	1.2
Ave. ring field B	T	6	5
Effective turns	10^2	9	8
β^* at intersection	mm	3	8
rms I.P. beam size	μm	2.8	17
Luminosity	$cm^{-2}s^{-1}$	10^{35}	10^{33}

come later. Muons from pions in the 100-500 MeV range emerge in a 6 m long bunch at 150 ± 30 MeV bunch.

- A solenoidal snake and collimator to select the momentum, and thus polarization, of the

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muons.

- A sequence of 20 ionization cooling stages, each consisting of a) lithium energy loss rod in a strong focusing environment for transverse cooling, b) linac reacceleration and c) lithium wedges in a dispersive environment for cooling in momentum space.

- A linac, and/or recirculating linac, pre accelerator, followed by a sequence of pulsed field synchrotron accelerators using superconducting linacs for rf.

- An isochronous collider ring with locally corrected low beta ($\beta=3$ mm) insertion.

For a low energy muon collider, there would be a relatively large fixed cost for the muon source, but for a high energy machine the cost would still be dominated by that of the final circular accelerator and collider rings. Estimates suggest that the cost of these might be as much as a factor 3 higher than that for a hadron machine of the same beam energy, but, because of the advantage in colliding point like leptons, a factor of 3 or more less than a hadron machine of the same *effective energy*.

2.6 Comparison of Machines

In Fig. 8, the effective energies (as defined by Eq. 3) of representative machines are plotted against their total tunnel lengths. We note:

- Hadrons Colliders: It is seen that the energies of machines rise with their size, but that this rise is faster than linear ($E_{\text{eff}} \propto L^{1.3}$). This slope is a reflection in the steady rise in bending magnetic fields used as technologies and materials have become available.

- Circular Electron-Positron Colliders: The energies of these machines rise approximately as the square root of their size, as expected from the cost optimization discussed above.

- Linear Electron-Positron Colliders: The SLC is the only existing machine of this type and only one example of a proposed machine (the NLC) is plotted. The line drawn has the same slope as for the hadron machines and implies a similar rise in accelerating gradient, as technologies advance.
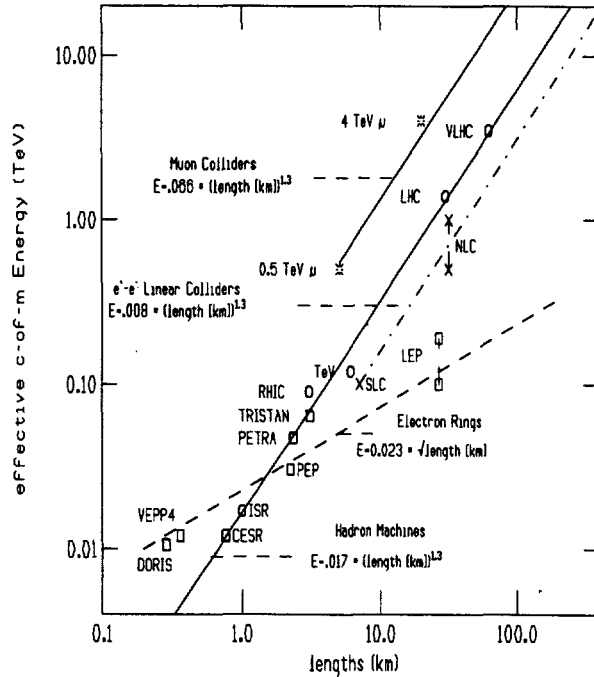

Figure 8: Effective energies of colliders as a function of their total length.

- Muon-Muon Colliders: Only the 4 TeV collider, discussed above, and the 0.5 TeV *demonstration machine* have been plotted. The line drawn has the same slope as for the hadron machines.

It is noted that the muon collider offers the greatest energy per unit length. This is also apparent in Fig. 9, in which the footprints of a number of proposed machines are given on the same scale. But does this mean it will give the greatest energy per unit of cost ? Fig. 10 plots the cost of a sample of machines against their size. Before examining this plot, be warned: the numbers you will see will not be the ones you are familiar with. The published numbers for different projects use different accounting procedures and include different items in their costs. Not very exact corrections and escalation have been made to obtain estimates of the costs under fixed criteria: 1996 \$'s, US accounting, no detectors or halls. The resulting numbers, as plotted, must be considered to have errors of at least ± 20%.

The costs are seen to be surprisingly well represented by a straight line. Circular electron machines, as expected, lie significantly below this
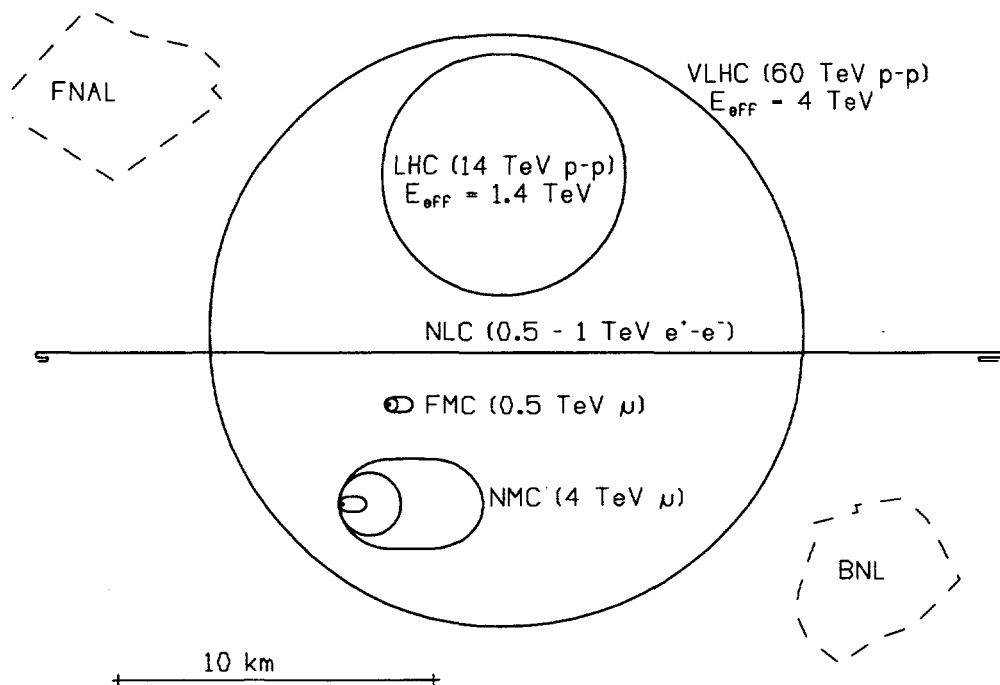
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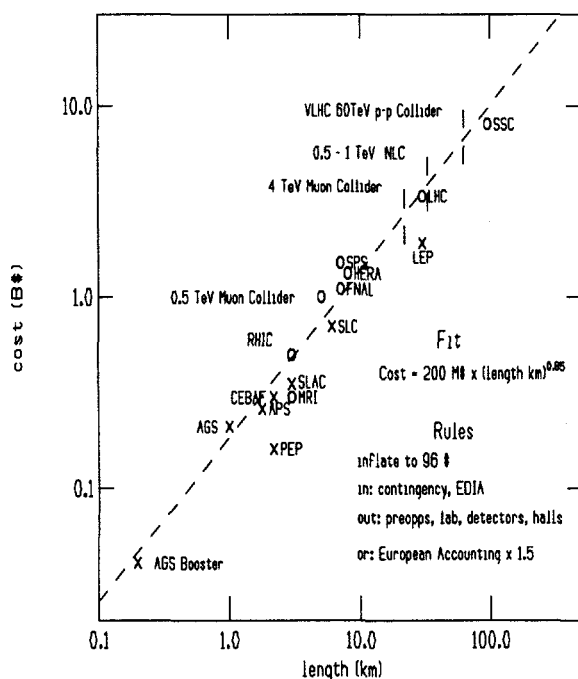Figure 9: Approximate sizes of some possible future colliders.

Figure 10: Costs of some machines as a function of their total lengths.

line. The only plotted muon collider (the 0.5 TeV demonstration machine's very preliminary cost estimate) lies above the line. But the clear indication is that length is, or at least has been, a good estimator of approximate cost. It is interesting to note that the fitted line indicates costs rising, not linearly, but as the 0.85 th power of length. This can be taken as a measure of economies of scale.

3 Conclusion

Our conclusions, with the caveat that they are indeed only our opinions, are:

- The LHC is a well optimized and appropriate next step towards high *effective* energy.

- A Very Large Hadron Collider with energy greater than the SSC (e.g. 60 TeV c-of-m) and cost somewhat less than the SSC, may well be possible with the use of high T_c superconductors that may soon be available.

- A "Next Linear Collider" is the only clean way to complement the LHC with a lepton machine, and the only way to do so soon. But it appears that even a 0.5 TeV collider

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will be more expensive than the LHC, and it will be technically challenging: obtaining the design luminosity may not be easy.

- Extrapolating conventional rf e^+e^- linear colliders to energies above 1 or 2 TeV will be very difficult. Raising the rf frequency can reduce length and probably cost for a given energy, but obtaining luminosity increasing as the square of energy, as required, may not be feasible.

- Laser driven accelerators are becoming more realistic and can be expected to have a significantly lower cost per TeV. But the ratio of luminosity to wall power and the ability to preserve very small emittances, is likely to be significantly worse than for conventional rf driven machines. Colliders using such technologies are thus unlikely to achieve very high luminosities and thus unsuitable for higher (above 2 TeV) energy physics research.

- A higher gradient superconducting Linac collider using Nb$_3$Sn or high T$_c$ materials, if it becomes technically possible, could be the only way to attain the required luminosities in a higher energy e^+e^- collider.

- Gamma-gamma collisions can and should be obtained at any future electron-positron linear collider. They would add physics capability to such a machine, but, despite their freedom from the beamstrahlung constraint, are unlikely to achieve higher luminosity.

- A muon Collider, being circular, could be far smaller than a conventional electron-positron collider of the same energy. Very preliminary estimates suggest that it would also be significantly cheaper. The ratio of luminosity to wall power for such machines, above 2 TeV, appears to be better than that for electron positron machines, and extrapolation to a center of mass energy of 4 TeV or above does not seem unreasonable. If research and development can show that it is practical, then a 0.5-1 TeV muon collider could be a useful complement to e^+e^- colliders, and, at higher energies (e.g. 4 TeV), could be a viable alternative.

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