EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN-EP/98-03
CERN-SL 98-004 (AP)
CERN-TH/98-33

Options for Future Colliders at CERN

J. Ellis, E. Keil, G. Rolandi

Abstract

We discuss options for future colliders at CERN, after the LHC, which should address the burning problems of particle physics: mass, flavour and unification. We give and comment upon parameter lists for linear e^+e^- colliders, $\mu^+\mu^-$ colliders and future larger hadron colliders that are being studied in various places. We discuss how particle physics experiments can be carried out at these colliders. We make a number of observations how these colliders might be constructed on or near to the CERN site, and how the existing expertise and infra-structure might best be employed for their study. Finally, we formulate recommendations for action at CERN.

Geneva, Switzerland

January 23, 1998

Contents

1 INTRODUCTION

We have carried out a pilot study of possible future facilities which might be considered for construction at CERN after the LHC. We assess the feasibility, performance and physics potential of a number of possible facilities listed below, based largely on information already available or provided in written form by others. We have also consulted with available experts in relevant areas, such as the CLIC group. We do not carry out a conceptual design study of any such facility, nor of the associated experiments. We restrict our attention to major 'flagship' projects, and do not consider projects that would rely on novel schemes, such as plasma or wakefield acceleration.

Our list of facilities includes (i) linear e^+e^- colliders, (ii) $\mu^+\mu^-$ collider rings, including a 'Higgs factory' as a possible demonstrator machine, and (iii) circular pp colliders with centre-of-mass energies of 100 TeV or more [1]. In connection with the last option, we also bear in mind the possibility of an e^+e^- collider in the same tunnel, which could be a 'top factory', and the possibility of realising $e^\pm p$ collisions in the same tunnel.

For each possible facility, we quantify the discovery potential for ranges of performance parameters, i.e., energy, peak and average luminosity, and beam characteristics as needed. We also discuss briefly the interfaces with generic experiments, i.e., interaction region design, background, etc.. In each case, we review the utility of the infrastructure already available at CERN, including civil engineering and technical equipment. We also discuss principal aspects of new technical developments that would be required, highlighting areas where Research and Development effort might be targeted in the coming years. We also discuss how each such facility might be placed on or in the neighbourhood of the CERN site.

The remainder of this report is organised as follows. Chapter 2 discusses the principal physics issues that might be outstanding after the LHC comes into operation, and the possible world accelerator context [2]. Chapter 3 discusses the colliders included in our study. Chapter 4 presents their physics potential and detector issues. Observations specific to CERN are made in Chapter 5. Actions that we recommend to the CERN management are outlined in Chapter 6. The possibility of an $e^\pm p$ collider in the LEP/LHC tunnel, which we consider to be already part of the CERN programme, is considered for completeness in an Appendix.

[1] Our generic term for this type of collider is Future Larger Hadronic Collider, or FLHC.

[2] A HEPAP Subpanel on Planning for the Future of U.S. High Energy Physics, chaired by Fred Gilman, is scheduled to present its report by 27 February 1998.

2 POST-LHC SCENARIO

The discoveries for which future colliders such as the LHC will be remembered are probably not those which are anticipated. Nevertheless, the primary motivation for a large accelerator project must be the prospect it offers for major new discoveries. Therefore, we cannot avoid comparing the capabilities of new projects to address our present prejudices concerning the big issues in particle physics.

At the time of writing, these include, first and foremost, the **Problem of Mass**: is there an elementary Higgs boson, or is it replaced by some composite technicolour scenario, and is any Higgs boson accompanied by a protective bodyguard of supersymmetric particles? The current precision electroweak data tend to prefer a relatively light Higgs boson, which is quite difficult to reconcile with calculable composite scenarios. It is, however, compatible with the validity of the Standard Model all the way to the Planck scale, with no new physics required to stabilize the electroweak coupling or keep the Standard Model couplings finite. Nevertheless, such a low mass for the Higgs boson is a prediction of supersymmetry, and this theory also predicts successful relations between the gauge couplings and particle masses of the Standard Model. Thus we follow tradition and use supersymmetry as one of our benchmarks for future colliders. The **Problem of Flavour** includes the questions why there are just six quarks and six leptons, what is the origin of their mass ratios and the generalized Cabibbo mixing angles, and what is the origin of CP violation? One proposed answer to these questions is that quarks and leptons are in fact composite objects with substructure. The Standard Model predicts the presence of CP violation, but we do not yet have any quantitative tests of the Kobayashi-Maskawa mechanism: detailed studies may reveal its inadequacy. Finally, the **Problem of Unification** raises the possibility of neutrino masses and proton decay, that are not addressed by colliders. However, GUTs also predict many relations between couplings and masses that can be tested at colliders, e.g., relations between sparticle masses.

The primary task of the LHC, scheduled for first beams in 2005, is to make an initial exploration of the 1 TeV energy range. Top of the physics agenda for the LHC is the elucidation of the origin of particle masses, i.e., the mechanism of spontaneous electroweak symmetry breakdown. Within the Standard Model, this means looking for the Higgs boson, and detailed studies indicate that the major LHC detectors, ATLAS and CMS, should be able to accomplish this for any Higgs mass in the expected range up to about 1 TeV. If no Higgs boson is found in this energy range, the most likely scenario would be some very heavy and strongly-interacting replacement theory for which an accelerator with an effective centre-of-mass energy for hard collisions above 1 TeV would be mandatory.

It seems unlikely that the single Higgs boson of the Standard Model is the whole of the story, and the minimal supersymmetric extension of the Standard Model (MSSM) is often used as a reference for physics beyond the Standard

Model. It predicts that the lightest neutral Higgs boson should weigh less than about 120 GeV, which is quite consistent with the range indicated by precision electroweak measurements. The detection of the MSSM Higgs bosons at the LHC has also been studied intensively. Although it is known that there is a region of the MSSM parameter space which is difficult to cover, we presume that the LHC will establish the fate of this theory. In addition, the LHC has extensive mass reach in the search for supersymmetric particles, and should enable squarks and gluinos with masses between about 300 GeV and 2 TeV to be discovered. It has now also been realised that, in certain cases, their decay cascades may be reconstructed and some detailed spectroscopic measurements and tests of unified models made.

Other important parts of the LHC experimental programme include searches for the quark-gluon plasma and studies of CP violation and other aspects of flavour physics in hadrons containing bottom quarks. We do not consider further here the possible continuation of such programmes beyond the LHC, but limit ourselves to noting that they could be pursued using an FLHC facility.

We anticipate that a linear e^+e^- collider will start construction somewhere in the world within a few years time, and will come into operation during the exploitation of the LHC. These machines offer a very clean experimental environment and egalitarian production of new weakly-interacting particles. Moreover, polarizing the beam is easy and can yield interesting physics signatures, and $e\gamma$, $\gamma\gamma$ and e^-e^- collisions could also be arranged. Thus linear colliders have many features complementary to those of the LHC. It is likely that the first linear collider would have an initial centre-of-mass energy of a few hundred GeV, probably with the option of increasing the energy subsequently to about 1.5 TeV.

The range of Higgs masses preferred by the precision electroweak measurements gives hope that the Higgs boson may lie within the kinematic reach of such a first linear collider. Moreover, even if the Higgs discovery is first made elsewhere, a linear collider could tell us much more about its couplings and branching ratios. In the case of the MSSM, production and detection of the lightest MSSM Higgs is guaranteed, and the heavier Higgs bosons can also be observed if the beam energy is high enough. As for supersymmetry proper, if its beam energy is above threshold, a linear collider will produce cleanly electroweakly-interacting sparticles whose discovery may be problematic at the LHC, and any produced sparticle masses can be measured accurately. Moreover, the couplings and spin-parities of many sparticles can be measured. Thus a linear collider will certainly be able to add significantly to our knowledge of supersymmetry, even if the LHC discovers it first, and despite the large range of measurements possible at the LHC – provided the linear collider beam energy is large enough.

The scenario that emerges for the status of physics after the LHC is as follows. The LHC will have detected the Higgs boson and supersymmetry if they exist. It will also have made some detailed measurements, but not all supersymmetric questions will have been answered. The first linear collider will be able to complete these measurements if its energy is high enough, but this is not guaranteed. If the Higgs sector is instead strongly interacting, neither the LHC nor the first linear collider is likely to be able to answer all the questions.

The priorities that emerge are therefore: (i) an $\ell^+\ell^-$ collider with a centre-of-mass energy comparable to the physics reach of the LHC, which means above 2 TeV and preferably capable of 4 or 5 TeV, and (ii) a pp collider able to make a first exploration of the next energy range beyond the LHC, say up to 10 TeV in the effective hard-scattering centre of mass.

3 COLLIDERS

In this Chapter, we briefly describe the various collider projects we have studied for this report. We have tried to include in this list all the types of colliders which CERN might want to build after the LHC. In view of our uncertainties as to the precise issues in particle physics that will seem most urgent at that time, and as to what colliders might be built elsewhere in the meantime, we have tried to be inclusive rather than exclusive.

3.1 Linear e^+e^- Colliders

Linear e^+e^- colliders are being studied in several laboratories that have joined together in the Inter-Laboratory Collaboration for R&D on TeV-Scale Linear Colliders. The report of the International Linear Collider Technical Review Committee ILC-TRC [1] was the first attempt to gather in one document the current status of every major e^+e^- linear collider project in the world.

3.1.1 Linear e^+e^- Collider Parameters

Table 1 is a brief summary of typical parameters, taken from the WWW page of the ILC-TRC which was last updated in September 1997 [2]. We include only colliders which are currently being pursued actively, and leave out the S-band colliders and VLEPP. The listed parameters are for a nominal CoM energy of 500 GeV. The main linac technologies are quite different: TESLA is superconducting, the others are at room temperature, and the frequencies range from 1.3 to 30 GHz between TESLA and CLIC. The RF power sources are klystrons for all machines except CLIC, which uses a second beam. Accelerator parameters, e.g. emittance growth and alignment tolerances, have become quite similar [3], contrary to expectations from naive scaling laws. The parameters relevant to particle physics have also converged towards similar values over the last few years.

Energy upgrades are foreseen for all these projects. Table 2 shows their parameters at 1 TeV CoM energy, 0.8 TeV CoM energy in the case of TESLA. The JLC(X), NLC and CLIC designs are genuine 1 TeV CoM designs, scaled to

Table 1: Linear Colliders: Parameter lists for 500 GeV in the CoM

	TESLA	JLC (C)	JLC (X)	NLC	CLIC
RF frequency of main linac (GHz)	1.3	5.7	11.4	11.4	30
Nominal Luminosity $(\text{nbs})^{-1}$	3.69	5.02	5.18	3.5	4.4
Actual luminosity $(\text{nbs})^{-1}$	6	7.18	6.11	4.95	6.3
Linac repetition rate (Hz)	5	100	150	180	511
No. of particles/bunch at IP	3.63	1.11	.7	.75	.4
No. of bunches/pulse	1130	72	85	81	60
Bunch separation (ns)	708	2.8	1.4	2.8	1
Beam power/beam (MW)	8.2	3.07	3.57	4.4	4.9
Damping-ring energy (GeV)	3.2	1.98	1.98	2	2.15
Unloaded/loaded gradient (MV/m)	25/25	40/33	73/58.2	50/37	122/100
Total two-linac length (km)	30	18.8	10.5	15.6	7.3
Total beam-delivery length (km)	2.5	3.6	3.6	10.4	2.4
Emittances $\gamma\epsilon_x/\gamma\epsilon_y$ (μm)	14/.25	3.3/.05	3.3/.05	4/.09	1.9/.1
β functions at IP (mm)	25/.7	15/.2	10/.1	10/.15	10/.1
Beam radii (nm) at IP before pinch	845/19	260/3	260/3.1	294/6.3	206/5.4
Bunch length (μm)	700	200	90	125	50
Crossing Angle at IP (mrad)	0	8	8	20	20
Disruptions D_x/D_y	.28/17	.25/17.9	.106/8.8	.07/7.3	1/2.9
H_D	1.63	1.7	1.57	1.41	1.4
Υ_0	.02	.21	.319	.09	.07
$\Upsilon_{\text{effective}}$	.03	.144	.12		.17
δ_B (%)	2.5	4.1	3.4	3.2	3.5
n_γ/e	2.0	1.5	.9	1.1	0.7
N_{pairs}	31	15.8	6.0	7	
N_{hadrons}/crossing	.13	.1	.06	.05	
$N_{\text{jets}} \cdot 10^{-2}$	.3	.27	.14	.14	

0.5 TeV CoM energy for the purposes of the ILC-TRC report. Energy upgrades beyond 1 TeV CoM energy have been discussed: 1.5 TeV in the case of the NLC, 1.6 TeV in the case of TESLA.

Table 2: Linear Colliders: Parameters for 1 TeV in the CoM

	TESLA	JLC (C)	JLC (X)	NLC	CLIC
Initial energy (CoM) (TeV)	0.8	1	1	1	1
RF frequency of main linac (GHz)	1.3	5.7	11.4	11.4	30
Nominal Luminosity $(\text{nbs})^{-1}$	7.48	5.53	12.2	10.4	11.4
Actual luminosity $(\text{nbs})^{-1}$	11	7.65	16.7	14.5	15
Linac repetition rate (Hz)	3	50	150	120	700
No. of particles/bunch at IP	1.8	1.39	.7	1.1	.8
No. of bunches/pulse	2260	72	85	75	30
Bunch separation (ns)	283	2.8	1.4	1.4	1
Beam power/beam (MW)	7.8	4	7.15	7.9	13.5
Damping-ring energy (GeV)	3.2	1.98	1.98	2	2.15
Unloaded/loaded gradient (MV/m)	40/40	56/47.1	73/58.2	85/63	120/100
Total two-linac length (km)	30	26.6	21.8	18.7	15
Total beam-delivery length (km)	2.5	6	6	6.8	2.4
Emittances $\gamma\epsilon_x/\gamma\epsilon_y$ (μm)	12/.25	3.3/.05	3.3/.05	5/.05	4.6/.13
β-functions at IP (mm)	25/.5	30/.2	10/.1	25/.1	10/.15
Beam radii (nm) at IP before pinch	618/4	318/3.1	184/2.3	360/2.3	216/4.4
Bunch length (μm)	500	200	90	100	160
Crossing Angle at IP (mrad)	0	8	8	20	20
Disruptions D_x/D_y	.2/14	.16/15.9	.1/8.6	.05/7.6	.15/7.6
H_D	1.6	1.6	1.57	1.35	1.32
Υ_0	.053	.5	.95	.27	.17
$\Upsilon_{\text{effective}}$	.053	.29	.33	.27	.2
δ_B (%)	2.2	8.3	9.9	7.4	7.5
n_γ/e	1.2	1.73	1.43	1.1	1.38
N_{pairs}	7.3	13.8	7	3.4	
N_{hadrons}/crossing	.16	.55	.25	.13	
$N_{\text{jets}} \cdot 10^{-2}$	.66	5.3	2.3	.95	

Components of future linear e^+e^- colliders are being tested in several laboratories [2]. The Final Focus Test Beam FFTB at the end of the SLAC linac has achieved and measured spot sizes close to the design goal of 50 nm. The TESLA

Test Facility TTF at DESY has achieved acceleration through a module of eight super-conducting RF cavities to well above 125 MeV, corresponding to the TTF design gradient 15 MV/m. The Accelerator Test Facility ATF at KEK consists of an S-band injector linac, a damping ring and a bunch compressor. Its goal is demonstrating the small emittances and bunch lengths needed in the X-band linear collider designs. The Next Linear Collider Test Accelerator NLCTA at SLAC, a prototype high-gradient X-band linac, has accelerated a 120 ns pulse of 0.34 A through 6 structures to 305 MeV, corresponding to a loaded gradient of 34 MV/m. The first Compact Linear Collider Test Facility CTF1 at CERN initially decelerates an electron beam in a section of 30 GHz linac, and transfers the RF power up to 76 MW into a second section of 30 GHz linac that accelerates the same electron beam. It has achieved a peak decelerating gradient of 123 MV/m, and a peak accelerating gradient of 94 MV/m. Since then, it has been replaced by the second Compact Linear Collider Test Facility CTF2, a prototype 30 GHz two-beam linac.

3.1.2 Linear e^+e^- Collider Schedules

Conceptual design reports have been published for the NLC [4], TESLA [5] and JLC [6]. However, a conceptual design report for CLIC is not foreseen at the present time. At the VIIth International Workshop on Linear Colliders, the following schedule for TESLA was presented [7]: proposal including cost and schedule in 1998 to 2000, creation of an international project organization in 1998 to 2001, and project ready for a decision in 2001 to 2002. A schedule for a linear e^+e^- collider to be built by a KEK-SLAC collaboration was presented [8] at the 2nd meeting of the HEPAP Subpanel on Planning for the Future of U.S. High Energy Physics. A conceptual design could be completed in 2001. Construction could start in 2002 at the earliest and last six years. Upgrades to higher energies and operation would run in parallel. According to these optimistic schedules, a linear e^+e^- collider might be under construction before the LHC is completed. This appears to be technically realistic if the ongoing component tests yield the expected results.

3.1.3 Prospects for a Higher-Energy e^+e^- Collider

After a first linear e^+e^- collider with a CoM energy between 0.5 and 1 TeV, the next step could be a machine with a centre-of-mass energy of 2 TeV, the energy of the original CLIC proposal, or more. A collaboration between SLAC and the CLIC group at CERN has published a pilot design for a 5 TeV collider [9]. CERN and SLAC experts agree that higher frequencies are more favourable for energies above 2 TeV, because of the higher accelerating gradient, and the higher threshold gradient for dark-current capture. The CLIC group is making a significant contribution to the world-wide linear-collider effort, and is working successfully at the frontier of high frequencies and high energies. The drive-beam concept is currently in an evolving stage. The CLIC effort will undoubtedly be an essential aspect of any future high-frequency, high-energy machine.

Table 3: Parameters of a Very Large Lepton Collider

Beam energy E (GeV)	180
Circumference C (m)	531000
Luminosity L ((nbs)$^{-1}$)	0.915
Beam-beam tune shift ξ	0.03
Amplitude functions at IP $\beta_x^* : \beta_y^*$ (m)	1.0 : 0.05
Emittances ϵ_x/ϵ_y (nm)	32.5:1.7
Beam radii at IP $\sigma_x^* : \sigma_y^*$ (μm)	180 : 9.01
Bunch population N	8.04E+11
Total current/beam I_b (mA)	37.2
Number of bunches/beam k	512
Bending radius ρ (m)	72628
Dipole field $B_{\rm max} : B_{\rm min}$ (mT)	8.3 : 2.3
Phase advance $\mu/2\pi$	0.125
Cell length in arcs L_p (m)	249
Amplitude functions in arcs $\beta_{\rm max} : \beta_{\rm min}$ (m)	488 : 218
Beam radii $\sigma_x : \sigma_y$ (mm)	4.3 : 2.8
Aperture radii $A_x : A_y$ (mm) for 10σ	53 : 38
Synchrotron radiation loss U_s (MeV)	1376
Center of mass energy spread σ_E (GeV)	0.26
RF voltage $V_{\rm RF}$ (MV)	1616
Total generator power P_g (MW)	102

3.2 Circular e^+e^- Colliders

Circular e^+e^- colliders with energies beyond the LEP2 energy have been discussed in conjunction with Future Larger Hadron Collider (FLHC) projects [10, 11]. The same large-circumference tunnel might house at the same or different times a circular e^+e^- collider, typically a top factory, a pp collider, and an ep facility.

Table 3 shows a typical set of parameters for such a circular top factory [11] in the tunnel of an FLHC at low dipole field, similar to that in the first column of Table 5. The beam energy E in a circular e^+e^- collider scales typically like the square root of the radius R [12]. This makes it difficult to increase the beam energy much beyond the top mass, and/or to install a top factory in the tunnel of a high-field FLHC.

3.3 $\mu^+\mu^-$ Colliders

The possibility of muon colliders was introduced by Budker [13], Parkhomchuk and Skrinsky [14], and Neuffer [15]. It has been developed intensively over the past three years [16, 17, 18, 19, 20]. A feasibility study for a 4 TeV muon collider was presented at Snowmass [21], and a formal collaboration was set up recently.

Table 4: Example parameters for feasibility studies of $\mu^+\mu^-$ colliders of 4 TeV and 100 GeV CoM energy

CoM Energy (GeV)	4000	100	
Proton energy (GeV)	16	16	
Proton bunch population (10^{13})	2.5	5	
Proton beam power (MW)	4	4	
Repetition rate (Hz)	15	15	
No. of $\mu^\pm$ bunches/sign	2	1	
$\mu^\pm$ bunch population (10^{12})	2	4	
Collider circum. (m)	8000	260	
Free space ℓ^* at IP (m)	6.5	5	
RMS momentum spread $\Delta p/p$	0.12%	0.12%	0.003%
Normalized emittance ϵ_n (π mm mrad)	50	85	280
β^* at IP (cm)	0.3	4	13
Bunch lengthσ_z (cm)	0.3	4	13
RMS beam radius at IPσ_r (μm)	2.8	82	270
Beam-beam tune shift ξ	0.04	0.05	0.015
Luminosity $(\text{nbs})^{-1}$	100	0.12	0.01

3.3.1 $\mu^+\mu^-$ Collider Parameters

Table 4 shows a list of parameters for two machines, one operating at 4 TeV CoM energy and a Higgs factory operating at 100 GeV CoM energy [22]. The 100 GeV Higgs factory has a circumference smaller than the PS with $C = 628$ m, whereas the 4 TeV muon collider is slightly larger than the SPS with $C = 6912$ m. However, their shapes are more like racetracks than circles.

The critical issues of a $\mu^+\mu^-$ collider are best discussed by inspecting their luminosity $\bar{L}$ averaged over the muon lifetime. It can be written as follows, assuming that the cycle time is long compared to the muon lifetime:

$$\bar{L} = \left(\frac{\tau_0}{e\mu_0}\right) \dot{N}_\mu \left(\frac{\xi\gamma B}{\beta_\perp}\frac{2\pi\rho}{C}\right) \qquad (1)$$

The first bracket contains natural constants: the muon lifetime at rest τ_0, the muon charge e, and the permeability of free space μ_0. The rate $\dot{N}_\mu$ at which muons are stored describes the features of the muon source. The last bracket contains the parameters of the circular $\mu^+\mu^-$ collider beam-beam tune shift ξ, dipole field B, muon energy γ, and amplitude function at the interaction point $\beta_\perp$. The fraction containing the bending radius ρ and the circumference C is a filling factor < 1.

The muon source outlined in [22] consists of the following components.

- A proton synchrotron with a peak energy of 16 GeV, a cycling rate of 15 Hz, dumping the beam with a power of 4 MW onto a pion production target. These figures are extrapolations beyond the projected machines KAON [23] in Canada (30 GeV, 10 Hz, 3 MW), JHF [24] in Japan (50 GeV, 0.3 Hz, 0.5 MW), and the European Spallation Source [25] (1.334 GeV, 50 Hz, 5 MW), and are far beyond the present CERN PS (28 GeV, 0.4 Hz, 56 kW).
- A system, as yet untested, to capture and accelerate the pions and the muons resulting from their decay.
- An ionisation cooling channel, as yet untested, to reduce the six-dimensional phase space volume of the muon beam by a factor between 10^5 and 10^6. A proposal for an initial cooling experiment is being prepared.
- Rapid muon acceleration to the collision energy, e.g. in a cascade of recirculating linear accelerators similar to CEBAF.

The circular $\mu^+\mu^-$ collider ring itself consists of nearly-isochronous arcs with a high dipole field, and an insertion that uses techniques from the final-focus systems of linear e^+e^- colliders to achieve a lower value of $\beta_\perp$ at the interaction point, and a higher value of ξ than in hadron colliders at comparable energy. Muons can be recirculated and stored in circular machines at high bending field, and collided at a high value of ξ, since they produce much less synchrotron radiation and beamstrahlung than electrons of the same energy, because of their larger mass. Hence, $\mu^+\mu^-$ colliders are much more compact than linear e^+e^- colliders at the same energy.

3.3.2 $\mu^+\mu^-$ Collider Schedules

The following milestones for the development of $\mu^+\mu^-$ colliders were presented [26] at the 3rd meeting of the HEPAP Subpanel on Planning for the Future of U.S. High Energy Physics: a Higgs collider feasibility study in 1998, a Higgs collider technical study by 2002, and complete prototypes by 2007. This schedule is clearly subject to considerable uncertainties associated with some of the components of a $\mu^+\mu^-$ collider, in particular the capture and acceleration and the ionisation cooling sections. We therefore consider that it should be regarded as rather rough and possibly optimistic.

3.4 Future Larger Hadron Colliders "FLHC"

Future larger hadron colliders FLHC beyond the LHC and the discontinued SSC were discussed in 1996 at a mini-symposium during the APS meeting in Indianapolis, and at workshops on VLHC and RLHC studies at Snowmass [27] and on Eloisatron studies at Erice [28]. Exploratory studies continue in several laboratories [29, 30, 31].

3.4.1 Future Larger Hadron Collider Parameters

Table 5 shows a comparison of the LHC parameters with those of two machines at 50 TeV beam energy with 1.8 and 12.6 T dipoles and suitable circumference C, labelled Low B and High B, respectively, which were discussed at Snowmass, and one machine at 100 TeV beam energy with $C \approx 220$ km and 12 T dipoles, labelled E12T, which was discussed at Erice. This choice makes possible comparisons at two fields B and two energies E. The number of events in a collision $n_c = Ls\sigma_{\text{inel}}$ is calculated, assuming an inelastic non-diffractive cross section $\sigma_{\text{inel}} = 60$ mb in all four machines.

Table 5: Comparison of LHC and FLHC Parameters

	LHC	Low B	High B	E12T
Beam energy E (TeV)	7	50	50	100
Dipole field B (T)	8.4	1.8	12.6	12
Circumference C (km)	27	646	104	229
Bunch spacing s (ns)	25	16.7	16.7	37.5
Bunch population $N/10^{10}$	10	0.94	0.5	0.9
Beam radius $\sigma_x = \sigma_y$ (μm)	16	1.9	0.74	1.3
Bunch length σ_s (mm)	75	30	18	28
Beam-beam tune shift $\xi/10^{-3}$	3.4	1.2	4	3
Luminosity L ((nbs)$^{-1}$)	10	10	12	10
Events/collision n_c	19	10	12	23
Damping time τ_z (h)	26	$-$ve	2.6	1.5
Energy loss U_s (MeV)	0.0069	0.53	3.68	28
Radiation power P (MW)	0.0037	0.048	0.189	1.08
Stored energy G (t TNT)	0.07	2.07	0.19	0.63
Debris power D (kW)	0.8	4.8	5.8	9.6

Apart from their size and cost, the stored energy G per beam, the synchrotron radiation power P, and the power in the debris D of hard proton-proton collisions are critical issues in an FLHC. The synchrotron radiation loss per turn U_s scales like E^3B, and is intimately linked to the damping time τ_z for the transverse betatron oscillation. The synchrotron radiation power P scales like

$$(E^{3/2}L\beta_{\rm IP}\xi^{-1})\tau_z^{-1/2},$$

and the stored energy G per beam scales in proportion to

$$(E^{3/2}L\beta_{\rm IP}\xi^{-1})\tau_z^{1/2}.$$

Both P and G are proportional to the term in brackets, the product of $E^{3/2}L$ which contains the physically relevant performance parameters, multiplied by the ratio $\beta_{\rm IP}/\xi$ which cannot be chosen freely. The damping time τ_z scales with energy E and dipole field B in proportion to $E^{-1}B^{-2}$. A short damping time decouples the beam parameters at injection and in collision, and helps against diffusive phenomena with larger time scales, e.g. intra-beam scattering of the particles in a bunch on each other, or resonance streaming enhanced by ripple of the magnetic fields. Note that P and G vary with opposite powers of τ_z. For a given L performance, $\beta_{\rm IP}$ and ξ, small τ_z and small G occur at large P, and large τ_z and large G at small P. Both P and G pose engineering problems.

Table 5 also shows the power in the debris $D = L\sigma_{\rm inel}E$ of hard proton-proton collisions, falling on the components on one side of the interaction point. Some of this power ends up in the detector. The remainder hits the neutral particle dumps next to the beam-splitting dipoles, the collimators protecting the front faces of the low-β quadrupoles, and their super-conducting coils, in that order. Note that D is proportional to EL.

Simply scaling the tunnelling cost from LEP and/or SSC, and the cost of super-conducting magnets from SSC and/or LHC, would result in an exorbitant cost for an FLHC. Therefore R&D programmes, addressing these issues and aiming at significant reductions of the unit prices, have been launched at BNL and Fermilab.

3.4.2 Future Larger Hadron Collider Schedules

We believe that about a decade of R&D and a few years for a conceptual design study are needed before the construction of an FLHC can be envisaged. Construction could only start in the second decade of the third millenium. The construction time of the low-field version of an FLHC would be dominated by the tunnel. Hence, physics at such a machine could not start before 2020.

4 PHYSICS EXPERIMENTS

4.1 High-Energy $\ell^+\ell^-$ Collider Physics

Such a machine with a CoM energy of 2 TeV or more will be ideal for continuing the types of physics already undertaken with e^+e^- colliders such as LEP, namely electroweak physics in a clean environment with high precision. Specific examples might include the higher-mass Higgs bosons in the MSSM, or heavy strongly-interacting Higgs sectors in models of the technicolour type. Another example from the MSSM could be the detailed exploration of squarks, including their masses, decay modes and spins, if their masses are in the upper half of the LHC physics range, namely 1 to 2 TeV.

The luminosities of the $\ell^+\ell^-$ colliders given in the previous sections correspond to a rate of few events per hour for the reaction $\ell^+\ell^- \to \tau^+\tau^-$. Samples of few hundreds fb^{-1} integrated luminosity could be collected in a few years running time. With these integrated luminosities several thousand Higgs bosons would be produced in the Higgs-strahlung ($\ell^+\ell^- \to \mathrm{ZH}$) and WW/ZZ fusion ($\ell^+\ell^- \to \bar{\nu}\nu/\ell^+\ell^-\mathrm{H}$) processes allowing the determination of a large ensemble of Higgs couplings to other particles. If the supersymmetry mass scale is of order 1 TeV, LHC will discover it and will detect squarks and gluinos with masses up to about 2 TeV. In this scenario large –typically one thousand per flavour– samples of SUSY particles would be produced at an $\ell^+\ell^-$ collider with a high enough CoM energy. These samples can also provide complementary information on electroweak gauginos. Moreover, the properties of these new particles can be measured in the clean $\ell^+\ell^-$ environment. Since a discussion of the physics topics at a 0.5 TeV CoM $\mathrm{e^+e^-}$ collider can be found in [5] we do not go here in any further detail.

The general detector concepts and the details of a detector for a linear $\mathrm{e^+e^-}$ collider have also been studied in [5]. The conclusion of this study is that a detector which matches very well the requirements of the physics analyses could be built with today's technology.

4.2 $\mu^+\mu^-$ Collider Physics

A $\mu^+\mu^-$ collider possesses certain physics advantages compared with a linear $\mathrm{e^+e^-}$ collider and also some practical disadvantages. In the interests of increasing familiarity with $\mu^+\mu^-$ colliders, we discuss both here in more detail.

4.2.1 Particular Physics Features

With $\mu^+\mu^-$ colliders it is realistically possible to extend the CoM energy to 4 TeV or more. In addition, the beam energy spread may be significantly smaller than in a $\mathrm{e^+e^-}$ collider, thanks to the relative suppression of photon radiation such as beamstrahlung: spreads down to 0.01 % have been discussed in the literature [20]. Another possible advantage is provided by the violation of lepton universality expected in the couplings of Higgs bosons. In the Standard Model, the ratio of the Higgs boson couplings to $\mu^+\mu^-$ and $\mathrm{e^+e^-}$ is expected to be m_μ/m_e, so that the direct-channel production rate should be larger by a factor of 40,000. The same would be true for the lightest Higgs boson in the MSSM.

Since there are also many technical issues that need to be resolved before a multi-TeV $\mu^+\mu^-$ collider can be proposed, such as the accumulation of the $\mu^\pm$, their cooling, shielding the detectors and the surrounding populace from their decay radiation, etc., a Higgs factory could be a very interesting smaller-scale demonstrator project, much as the SLC demonstrates the linear-collider principle. Neglecting the energy spread, the $\mu^+\mu^-$ cross–section in the neighbourhood of the H peak is given by

$$\sigma_H(s) = \frac{4\pi\ \Gamma(\mathrm{H} \to \mu^+\mu^-)\ \Gamma(\mathrm{H} \to \mathrm{X})}{(s - m_H^2)^2 + m_H^2\Gamma_H^2}$$

where the natural width of a 100 GeV Higgs is expected to be about 3 MeV, whereas the beam energy spread $\Delta\sqrt{s}$ may be as low as 10 MeV. Such a Higgs factory would be able to measure Higgs decay branching ratios into channels such as $\bar{\mathrm{b}}\mathrm{b}$, $\tau^+\tau^-$, WW^* and ZZ^*. It could also draw a clear distinction between the Standard Model H and the MSSM h, could (at higher energies) separate the H and A of the MSSM, and also make detailed studies of their properties. Other possible applications of the narrow $\mu^+\mu^-$ spread in E_{cm} include the measurement of m_H with a precision $\sim$ 45 MeV, and improved precision in the values of m_t and m_W.

The high-intensity neutrino beam produced by the muon decays can be used for oscillation experiments in a range of mixing angles and Δm^2 not probed heretofore [34]. The proton source could also be used for high-statistics studies of rare K decays, and interesting physics could also be done with stopped muons.

4.2.2 Background and Detector issues

The main disadvantage of a $\mu^+\mu^-$ collider compared to an e^+e^- collider is the very high detector background, which creates a more difficult environment for the experiments. This has been studied in [20] for the 4 TeV $\mu^+\mu^-$ collider described in Table 4. In absence of the constraints induced by the background, the design of a detector for a $\mu^+\mu^-$ collider experiment would be similar to that of a linear e^+e^- collider.

In addition to the *standard* background due to beam-beam interactions, that is probably not overwhelming, there are two background sources specific to the $\mu^+\mu^-$ colliders.

- The muon halo , i.e., the 2 TeV muons that are lost from the beam and cannot be shielded due to their high penetration. Beam particles lost anywhere around the machine may propagate through the vacuum chamber walls, magnet yokes and other surrounding structures and eventually reach the detector and contribute to the background.
- The muon-decay-induced backgrounds. With 2×10^{12} muons per bunch there are about 2×10^5 muon decays per meter producing high energy electrons.

These electrons are very collimated ($1/\gamma_\mu \approx 5 \times 10^{-5}$) and have a momentum spectrum induced by the three-body decay kinematics. The electrons are bent outside the beam pipe by the magnetic elements of the final focus region and produce showers on magnet yokes or other structures.

Stray muons can be controlled only with magnetic fields. Predictions for the muon halo depend on a detailed knowledge of the beam profile and on a credible model for the beam profile and beam losses and have not yet been done.

The backgrounds induced by decay electrons can be mitigated by the design of the shieldings and of the final focus region. Toroids installed near the interaction point can be used to scrape the electro-magnetic debris and to deflect the muons produced upstream in the interactions of the decay electrons. The region near the detector requires tungsten plus additional shielding boxes to help to contain neutrons produced by photons in the electromagnetic showers.

The decay electrons can reach rather large distances from the beam axis resulting in substantial synchrotron radiation in the high field regions of the quadrupoles. One important background is caused by the Bethe-Heitler muon pairs that are generated near the electron impact point and penetrate the shieldings to reach the detector. Hundreds of muons cross the detector at each interaction producing spikes in the energy distribution in the calorimeters. Neutrons are produced by the low energy photons created by the decay electrons. A typical high energy electron hitting a collimator produces initially, on average, few hundred neutrons of few MeV kinetic energy. The fluence of neutrons near the detector is larger than at the LHC, but seems to be manageable.

The background at a 100 GeV CoM machine is probably similar. The number of decays per meter increases as $1/E_{beam}$ and the typical energy of the decay electrons decreases proportionally to E_{beam}. The straight sections are shorter, reducing the length of the region where the decay electrons produce secondaries that may cause background into the detector. The probability of producing Bethe-Heitler pairs of penetrating muons is substantially reduced due to the decrease of the cross section.

In these high-background conditions the design of the detector is strongly influenced by the machine-induced background. The outstanding need will be for an 'anti-hermetic' detector. The experience gained from the development of the LHC detectors will be important.

4.3 FLHC Physics

As already mentioned in Section 2, it is currently difficult to be precise about the physics issues that may require exploring higher energies in hadron-hadron collisions after the LHC. However, we expect the initial exploration of the mass-energy range up to 10 TeV to appear high on the agenda. Pilot studies indicate that an FLHC with 100 TeV in the centre-of-mass and a luminosity of 10 $\mathrm{nb}^{-1}\mathrm{s}^{-1}$

indeed has sufficient physics reach to produce heavy quarks, strongly-interacting sparticles or leptoquarks with masses up to 10 TeV.

The detector issues associated with an FLHC have been studied in [32, 33]. The most challenging tasks for this detector are to deal with the larger (compared to LHC) number of interactions per crossing and to keep the momentum resolutions of 10 TeV leptons in the few percent range. The conclusion of these preliminary studies is that – for a luminosity comparable to LHC luminosity – FLHC detectors seem feasible. There are, however, many challenges and new and/or old technologies would need to be pushed.

4.4 e^+e^- and $e^\pm p$ Physics in the FLHC Tunnel

As already mentioned, a circular e^+e^- machine with circumference comparable to that of the FLHC could be interesting as a top factory. The first linear e^+e^- collider to be built will very likely have this as one of its own primary physics goals, and it is difficult to foresee what issues in top physics might be outstanding after its operation. We do not imagine that a large-circumference tunnel would be constructed with a circular e^+e^- collider as its primary purpose. However, the possibility of including such a machine should be borne in mind if an FLHC is envisaged, with the additional aim of retaining as a possible side option an $e^\pm p$ collider in the FLHC tunnel. A brief survey does not indicate any particular problems with performing experiments with such a top factory. The design of an experiment for the $e^\pm p$ option would have to bear in mind the very forward nature of the interesting final states, provided by the asymmetry between the beam energies, which would be an order of magnitude larger than at HERA.

5 OBSERVATIONS

At the start of our study, we included three types of machines: linear e^+e^- colliders, $\mu^+\mu^-$ collider rings, and very large hadron collider rings. At this point, we have analyzed the physics potential and the feasibility of all three types, and we have not found particle physics or technical arguments to eliminate any one of them as a candidate for a future option at CERN.

A linear e^+e^- collider with about 3 TeV CoM energy and a total length of some 30 km can be constructed along the Jura in the neighbourhood of CERN, and entirely in molasse rock [35]. There is space for a $\mu^+\mu^-$ collider with about 4 TeV CoM energy to be constructed on or near the CERN site, even bearing in mind that the footprint of the recirculating linear accelerators is larger than that of the collider ring itself, which has roughly the size of the SPS. However, finding a site for even a high-field FLHC with about 100 TeV CoM energy and a circumference of some 120 km in the neighbourhood of the present CERN site is difficult.

The maturity of the concepts for these colliders in decreasing order, and correspondingly the amount of further R&D needed in increasing order, is: linear e^+e^- colliders, very large hadron colliders, $\mu^+\mu^-$ colliders. The variety of approaches to linear e^+e^- colliders, shown in Tables 1 and 2, with room temperature and super-conducting RF, four frequencies (1.3, 5.7, 11.4 and 30 GHz) and two RF power sources (klystrons and a second beam) has good and bad features. A good feature is that there might be a choice when the time comes to propose a machine. A bad feature is that the studies have not advanced to a point where the most promising concept is agreed upon, so that further work is needed to narrow down the choices. The studies of very large hadron colliders are at the stage where parameter searches are carried out at two extreme values of the dipole field, the need of engineering studies in tunnelling and magnet fabrication with the aim of reducing the unit prices significantly is recognized, and such studies have just been started. The concept of $\mu^+\mu^-$ colliders involves components that are at best extrapolations well beyond existing ones, or that do not exist at all. Considerable R&D will be needed to make it plausible that they can actually be built at an acceptable price and with the performance needed.

Table 6: Estimated resources appropriated here and elsewhere for future collider studies, in terms of full-time employees (FTE) and annual expenditure for 1997 (FY98 in US). The integrated cost over the period shown is also given, for the past by calendar years, for the future by number of years. The asterisk * marks cases in which the capital expenditure does not include personnel costs.

Lab	Collider	FTE 1997	Budget 1997	Cost	Period	Currency
CERN	CLIC	25	1.8*	21*	89−97	MCHF
DESY[36]	TESLA	83	16	48	94−97	MDEM
Fermilab[37]	VLHC	10	1	25[a]	5	MUSD
KEK[38]	JLC[b]	25−30	0.7*	5.9*	93−97	GJPY
SLAC[39]	NLC	50−60	8	75[c]	90−97	MUSD
USA[40]	$\mu^+\mu^-$	27	3[d]	32[e]	6	MUSD

[a] 65% are personnel costs

[b] Includes ATF, C- and X-band linac R&D, FFTB, etc.

[c] Includes FFTB, NLCTA, ASTA, ASSET, klystron R&D, structures, pulse compression, theory, ZDR

[d] Only personnel costs

[e] Initial cooling experiment only

Table 6 summarises the estimated resources in full-time employees and annual budget for 1997, appropriated for the ongoing studies of future colliders around the world, as well of the integrated cost of these studies over past and projected future calendar years. It provides part of the context in which the future allocation of manpower and funds for studies at CERN could be assessed.

There is a large knowledge base at CERN in accelerator physics and engineering that covers most of the topics needing attention. It is concentrated in the CLIC team of PS Division for linear e^+e^- colliders, in the SM Group of EST Division for super-conducting RF development [41], and in the LHC, PS and SL Divisions for circular colliders. It ought to be possible to tap this knowledge base for studies of future colliders, by permitting knowledgeable people to participate for a fraction of their time, despite their commitment to operating machines and the LHC project.

We note that forthcoming changes in the orientation of the CERN accelerator sector, away from LEP operation and LHC design towards LHC production, will require the reassignment of many staff members. This will provide the opportunity to explore the possibility that some may be able to participate in future collider R&D, while assuring the primary responsibility of CERN to operate the existing accelerators and to bring the LHC into operation in 2005.

The infra-structure at CERN which would be useful for future collider studies includes (i) for linear e^+e^- collider studies: LIL and EPA, the LEP Injection Linac and the Electron-Positron Accumulator, and CTF2, the second CLIC Test Facility, (ii) for $\mu^+\mu^-$ collider studies: the CERN PS as a proton source at low repetition rate and beam power, and (iii) for FLHC studies: the LHC magnet testing and measuring installations for the development of super-conducting FLHC magnets.

6 RECOMMENDATIONS

We are firmly of the opinion that there are exciting future options for major new particle accelerator projects at CERN after the LHC. We are also convinced that CERN, as the world's largest accelerator laboratory, has a particular responsibility to maintain the long-term vitality of this type of fundamental research. From this perspective, we make the following recommendations to the CERN management.

1. CERN should intensify and diversify its research and development effort on possible future accelerator options. This effort should be coordinated by the management, and periodically reviewed.
2. CERN should continue its current technical studies of linear e^+e^- colliders, centred on the CLIC programme, as planned. The central thrust of this programme should be a collider with a CoM energy of 2 TeV or more. Its scope and orientation after the currently approved programme should be reviewed soon.

3. CERN should launch technical studies of $\mu^+\mu^-$ colliders, notably in the areas of the source and beam cooling, and should explore the possibility of locating such machines on or in the neighbourhood of the CERN site.
4. CERN should also participate in studies of very large hadron collider rings. It could concentrate on finding likely parameters, and on the technological development of economic high-field magnets. Pilot site investigations with outside geological experts should also be initiated.
5. The detailed choice of the orientations of these new accelerator studies should be based on the expertise available at CERN, and perhaps not available elsewhere.
6. These studies should be carried out in collaborations with other laboratories, since most technical problems do not depend on the site. CERN's goal in these collaborations should be to contribute to the global pool of technologies for future collider options. It should confirm its reputation as a valuable and reliable partner in the international collaborations that will form to develop proposals for future collider projects.

APPENDIX: THE LHC $e^{\pm}p$ OPTION

We consider the LHC $e^{\pm}p$ option to be already part of the LHC programme, and not one of the flagship projects we have been requested to study.

The availability of $e^{\pm}p$ collisions at an energy roughly four times that provided currently by HERA would allow studies of quark structure down to a size of about 10^{-17} cm. The recent high-Q^2 from HERA data indicate the interest that such probing might generate. The discovery of the quark substructure could explain the Problem of Flavour, or one might discover leptoquarks or squarks as resonances in the direct channel.

Reviews of an $e^{\pm}p$ option for the LHC are published in the proceedings of workshops in La Thuile [42] and Aachen [43], and in a report describing a small study [44] of an $e^{\pm}p$ option for the LHC, undertaken between November 1994 and March 1995 at the request of the CERN Scientific Policy Committee (SPC). The synchrotron radiation background in an $e^{\pm}p$ experiment, caused by the dipole magnets separating the lepton and proton beams, has been studied [45]. Table 7 shows the current proton beam, lepton beam and collision point parameters of the LHC $e^{\pm}p$ option [44].

The physics interest of the LHC $e^{\pm}p$ option will be easier to assess after HERA has accumulated more data at higher luminosities, and after the initial runs of the LHC in pp mode.

Table 7: Compilation of Proton Beam (+) and Electron Beam (−) Parameters in the LHC $e^{\pm}p$ Option

	Protons	Electrons
Energy $E^{\pm}$ (GeV)	7000	67.3
Number of bunches k	508	508
Bunch population $N^{\pm}$	10^{11}	$6.4 \cdot 10^{10}$
Emittances $\epsilon_x^{\pm}\epsilon_y^{\pm}/$ (nm)	0.500.50	9.5/2.9
β-functions $\beta_x^{\pm}/\beta_y^{\pm}$ (m)	16.0/1.50	0.85/0.26
Beam-beam tune shifts $\xi_x^{\pm}/\xi_y^{\pm}$	0.0032/0.0010	0.027/0.027
Beam current $I^{\pm}$ (mA)	92	59
Polarisation time τ^{-} (h)		0.81
Radiation power W^{-} (MW)		34.5
Beam radii σ_x/σ_y (μm)	90/28	
Luminosity L ((nbs)$^{-1}$)	0.12	

References

[1] G.A. Loew and T. Weiland (eds.), *International Linear Collider Technical Review Committee ILC-TRC Report 1995*, SLAC-R-95-471 (1995).

[2] These parameters are taken from `http://www.slac.stanford.edu/xorg/ilc-trc/ilc-trchome.html`, September 1997.

[3] T. Raubenheimer et al., Scaling Laws for e^+e^- Linear Colliders, CERN-PS-97-51 (LP).

[4] NLC Design Group, *A Zeroth-Order Design Report for the Next Linear Collider*, SLAC-R-96-474 (1996).

[5] R. Brinkmann *et al.* (ed.), *Conceptual Design of a 500 GeV e^+e^- Linear Collider with Integrated X-Ray Laser Facility*, DESY 1997-048, ECFA 1997-182 (1997).

[6] N. Toge (ed.), *JLC Design Study*, KEK Report 97-1, April 1997.

[7] O. Napoly, *TESLA General Design Overview*, VII International Workshop on Linear Colliders (Zvenigorod, Russia, 29 Sep – 3 Oct 1997).

[8] D.L. Burke, *Status and Plans for the Next Linear Collider*, presented at the 2nd meeting of the HEPAP Subpanel on Planning for the Future of U.S. High Energy Physics, 24-26 June 1997.

[9] J.P. Delahaye *et al.*, *A 30 GHz 5-TeV Linear Collider*, CERN-PS-97-023-LP, Submitted to PAC 97, Vancouver.

[10] J. Norem and E. Keil, *A High Energy e^+e^- Collider in a "Really Large" Tunnel*, *Proc. New Directions for High Energy Physics* (Snowmass, 1996) 325.

[11] J. Norem *et al.*, *An e^+e^- Top Factory in a 50+50 TeV Hadron Collider Tunnel*, PAC 97, Vancouver.

[12] B. Richter, *Very high energy electron-positron colliding beams for the study of the weak interactions*, Nucl. Instrum. Methods **136** (1976) 47.

[13] G.I. Budker, *Accelerators and Colliding Beams*, *Proc. 7th Internat. Accelerator Conference* (Erevan, 1969) Vol. I, 33, Talk at the International High Energy Physics Conference (Kiev, 1970).

[14] V.V. Parkhomchuk and A. N. Skrinsky, *Ionization Cooling: Physics and Applications*, *Proc. 12th Int. Conf. on High Energy Accelerators*, F. T. Cole and R. Donaldson (Eds.) (1983) 485;
A. N. Skrinsky and V.V. Parkhomchuk, *Methods of Cooling Beams of Charged Particles*, Sov. J. Part. Nucl. **12** (1981) 223;
D. Cline, *Early Concepts for $\mu^+\mu^-$ Colliders and High Energy μ Storage Rings*, in *Physics Potential & Development of $\mu^+\mu^-$ Colliders - 2^{nd} Workshop*, Sausalito, California, D. Cline (Ed.), AIP Conf. Proc. **352** (1996) 3.

[15] D. Neuffer, *Design of Muon Storage Rings for Neutrino Oscillation Experiments*, IEEE Trans. **NS-28**, (1981) 2034.

[16] *Proc. of the Mini-Workshop on $\mu^+\mu^-$ Colliders: Particle Physics and Design*, Napa, California, Nucl Inst. and Meth. **A350** (1994) 24−56;
Proc. of the Muon Collider Workshop, February 22, 1993, Los Alamos National Laboratory Report LA- UR-93-866 (1993);
Physics Potential & Development of $\mu^+\mu^-$ Colliders 2^{nd} Workshop, Sausalito, California, D. Cline (Ed.), AIP Conf. Proc. **352** (1996).

[17] Transparencies at the 2 + 2 TeV $\mu^+\mu^-$ Collider Collaboration Meeting, Feb 6-8, 1995, BNL, compiled by Juan C. Gallardo;
`http://www.cap.bnl.gov/mumu/`
Transparencies at the 2 + 2 TeV $\mu^+\mu^-$ Collider Collaboration Meeting, July 11-13, 1995, Fermilab, compiled by Robert Noble;
Proc. of the 9th Advanced ICFA Beam Dynamics Workshop, Ed. J. C. Gallardo, AIP Conf. Proc. **372** (1996).

[18] D.V. Neuffer and R.B. Palmer, *A High-Energy High-Luminosity $\mu^+\mu^-$ Collider*, *Proc. European Particle Acc. Conf.* (London, 1994) 52;
M. Tigner, *Imperatives for Future High Energy Accelerators*, in *Advanced Accelerator Concepts*, Port Jefferson, New York, 1992, AIP Conf. Proc. **279** (1993) 1.

[19] R.B. Palmer *et al.*, *Monte Carlo Simulations of Muon Production*, in *Physics Potential & Development of $\mu^+\mu^-$ Colliders 2^{nd} Workshop*, Sausalito, California, Ed. D. Cline, AIP Conf. Proc. **352** (1996) 108;
R. B. Palmer *et al.*, *Muon Collider Design*, in *Proc. of the Symposium on Physics Potential & Development of $\mu^+\mu^-$ Colliders*, San Francisco CA, USA 13–15 December 1995, Nucl. Phys. B (Proc. Suppl.) **51A** (1996).

[20] *$\mu^+\mu^-$ Collider: A Feasibility Study*, BNL-52503, Fermilab-Conf-96/092, LBNL-38946 (1996).

[21] R.B. Palmer, A. Tollestrup and A. Sessler, *Status Report of a High Luminosity Muon Collider and Future Research and Development Plans*, in *Proc. New Directions for High-Energy Physics* (Snowmass, 1996) 203.

[22] The Muon Collider Collaboration, *Status of Muon Colliders and Future Research and Development Plans*, to be published in Nucl. Instrum. Methods.

[23] *KAON Factory Study – Accelerator Design Report*, TRIUMF, Vancouver B.C., Canada (1990).

[24] Y. Mori *et al.*, *Synchrotron Design Issues of the Japanese Hadron Project*, in *Proc. European Particle Accelerator Conf.* (Sitges, 1996) 569.

[25] H. Lengeler *et al.* (ed.), *The European Spallation Source, Vol.III, The ESS Technical Study*, ESS-96-53-M (1996).

[26] R.B. Palmer, Talk presented at the 3rd meeting of the HEPAP Subpanel on Planning for the Future of U.S. High Energy Physics, 12-14 August, 1997.

[27] G. Dugan, P. Limon, M. Syphers, *Really Large Hadron Collider Working Group Summary*, Cornell University CBN 96-18 (1996), also in *Proc. New Directions for High-Energy Physics* (Snowmass, 1996) 251.

[28] E. Keil, *Synchrotron Radiation Dominated Hadron Colliders*, CERN-SL-97-13 (AP) (1997).

[29] Updated information may be obtained from:
`http://www-ap.fnal.gov/VLHC`.

[30] S. Peggs, M. Harrison, F. Pilat, M. Syphers, *Flat Beams in a 50 TeV Hadron Collider*, submitted to PAC 97, Vancouver.

[31] E. Keil, *Synchrotron Radiation Dominated Hadron Colliders*, LHC Project Report 102, submitted to PAC 97, Vancouver.

[32] D. Denisov and S. Keller, *Summary of the Very Large Hadron Collider Physics and Detector Subgroup*, in *Proc. New Directions for High-Energy Physics* (Snowmass, 1996) 277.

[33] G. Anderson *et al.*, *Summary of the Very Large Hadron Collider Physics and Detector Workshop*, FERMILAB-CONF-97/318-T.

[34] R.N. Mohapatra, *Neutrino Physics in a Muon Collider*, hep-ph/9711444;
S. Geer, *Neutrino Beams from Muon Storage Rings: Characteristics and Physics Potential*, hep-ph/9712290.

[35] H. Laporte, Memorandum to G. Plass, and attachments (1989).

[36] *DESY Forschungs- und Entwicklungsprogramme* 1995/96 (1995) and 1997/98 (1997).

[37] E. Malamud, private communication (1998).

[38] K. Takata, private communication (1997).

[39] J.M. Paterson, private communication (1997).

[40] A.M. Sessler, private communication (1997).

[41] C. Benvenuti and P. Darriulat, Memorandum to K. Hübner and E. Keil, 20.1.1998.

[42] W. Bartel, *ep interaction regions*, CERN 87-07, Vol. I, 303 (1987).

[43] A. Verdier, *An e−p Insertion for LHC and LEP*, CERN 90-10, Vol. III, 820 (1990).

[44] E. Keil, *LHC e–p Option*, LHC Project Report 93 (1997).

[45] E. Wallén, *Synchrotron Radiation in the e–p Interaction Region of LHC and LEP*, LHC Note 227 (1993).