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Future Accelerators

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An overview of the various schemes for electron-positron linear colliders is given and the status of the development of key components and the various test facilities is given. The present studies of muon-muon colliders and very large hadron colliders are summarized including the plans for component development and tests. Accelerator research and development to achieve highest gradients in linear accelerators is outlined.

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1 Introduction

This review covers the studies being conducted at present by various laboratories and collaborations in order to determine and to optimise the next generation of particle accelerators for physics at the high energy frontier beyond HERA[1], LEP[2], LHC[3], SLC[4] and the TEVATRON[5]. These studies cover linear e^+e^- colliders, $\mu^+\mu^-$ colliders and circular hadron colliders.

This review summarises the underlying principles and the key issues in accelerator physics and technology relevant for these studies. Special emphasis is given to the status and plans for the development of components and for the test facilities. The most important results of the tests are summarised.

The review concludes with an overview of advanced accelerator concepts which could be applied to linear colliders in the far future. Also there the emphasis is on experimental results and future plans.

2 Linear colliders

An International Collaboration explores different approaches with the individual laboratories, often with a large number of partners, taking the leadership in one or two technologies, resp. in operating test facilities. The interest concentrates on e^+e^- collisions however in nearly all designs an option exists for colliding $\gamma\gamma$ by backscattering laserlight just before the interaction point 6). The possibility for polarising one of the beams has been considered and the case for e^-e^- collisions has been made7, 8).

2.1 TESLA

The TESLA collaboration based at DESY plans for a linear collider with a CM energy of 0.5 – 1 TeV9) . The linear accelerators rely on 1.3 GHz superconducting, standing-wave superconducting rf cavities with an accelerating gradient of 25 MV/m. The design study10) indicated a luminosity of 0.7 x 10^{34} cm^{-2} s^{-1} at 0.5 TeV CM but left room for improved machine performance with somewhat less safety margin with regard to beam dynamics. The new parameter set is based on a shorter bunch length, a smaller effective spot size obtained by a stronger focusing in the interaction point and smaller emittances. The rf pulse has been lengthened to accommodate more bunches per train but the bunch charge has been reduced. All this results in a luminosity of 3 x 10^{34} cm^{-2} s^{-1} at 0.5 TeV.

The basic layout foresees the grouping of eight 9-cell standing-wave resonators in one cryogenic module. A new scheme with reduced spacing between four of the resonators has been adopted where they form a string fed from a single input coupler. This reduces the number of input couplers per module from eight to two. The klystron feeding four cryomodules has to provide 8.3 MW. The first multi-beam prototype klystron reached 10 MW with 65 % efficiency (70 % design value).

The new parameter set 9) is based on this reduced spacing between the cavities resulting in a higher fill-factor (66 to 76%) which can be used in turn for a reduction of the required gradient from 25 to 21.7 MV/m and will lead to an improved overall efficiency as the cavity quality factor consequently increases from 0.5 to 1.0 x 10^{10} . Fig. 1 shows the performance of all TESLA cavities indicating that either of these parameter sets is reasonably within reach.

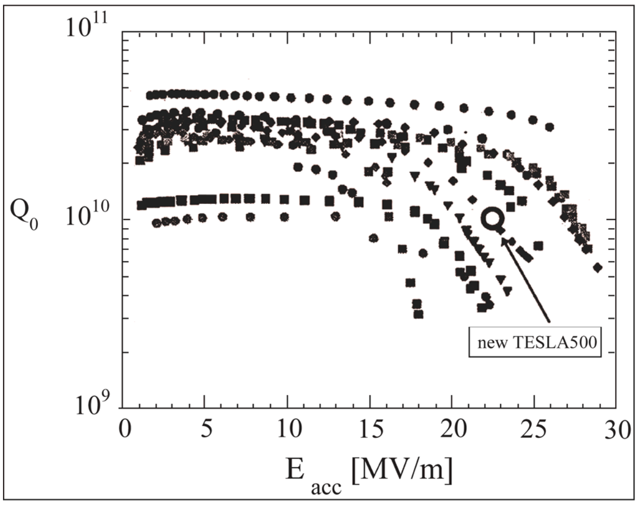

Fig. 1 Quality factor as a function of accelerating gradient of all TESLA cavities measured in cw mode in the vertical test stand. The circle shows the new nominal values for 0.5 TeV CM.

All subsystems have been laid out for 0.8 TeV CM, which would require 34 MV/m in the superconducting rf cavities. Since single-cell resonators have reached 40 MV/m, it is conceivable that eventually this gradient could be achieved in industrially produced 9-cell TESLA cavities. The number of klystrons will be doubled but the repetition frequency has to be reduced from 5 to 3 Hz in order not to exceed the available cooling power. A luminosity of 5 x 10^{34} cm^{-2} s^{-1} is expected and nearly twice as much if the cryogenic system is upgraded for 5 Hz operation.

A TESLA Test Facility (TTF) 11) is operating at DESY with one module containing eight 9-cell cavities where in beam tests 16 MV/m (goal 15 MV/m) have been achieved. Two more modules with cavities operating at 20 to 25 MV/m will complete this first phase with 500 MeV electron beam energy in 1999. The beam energy will gradually be raised in a second phase to 1 GeV by installing 5 more modules until 2001.

A Test facility for testing 3 GHz (S-band) components is also in operation in DESY but will be discontinued after 1998 as it is felt that TESLA no longer requires a fall-back solution. Two high-power (150 MW) klystrons have been developed providing a rf pulse of 3 µs; 230 MW have been reached with a shorter pulse. Two 6-m long travelling-wave accelerating section have been tested [9].

2.2 ILC and C-band developments

The International Linear Collider (ILC) Optimisation Study Group formed in early 1998 by KEK and SLAC pursues the study of a collider based on room-temperature copper accelerating structures operating in the travelling-wave mode [12, 13, 14] . This is a well-proven technology (e.g. SLAC) which however has to be transposed from the S-band (3 GHz) to X-band (11.4 GHz). Both Laboratories have previously published design reports for 0.5 TeV CM colliders called JLC [15] at KEK and NLC [16] at SLAC providing a luminosity of about 5 x 10^{33} cm^{-2} s^{-1}.

Both have made a significant progress in the development of key components. Klystrons have been developed providing 75 MW in 1.1 µs. Klystrons with the required pulse length of 1.5 µs with permanent magnet focusing are under development. The duration of the rf pulse must be compressed by a factor 6. This is proposed to be accomplished by a novel Delay-Line Distribution System (DLDS) invented in KEK and refined by SLAC. DLDS consists of a cluster of eight klystrons feeding twelve accelerating sections via a waveguide which transmits power in four modes. Each of the modes drives a group of three cavities. Some key components of this system have been produced and tested under full power.

Accelerating structures between 1 m to 1.8 m long have been produced consisting of individually machined cells brazed or bonded together at low temperature. In order to reduce the cross-talk via the wakefields between the bunches in a train, these structures are damped and/or detuned slightly, i.e. tuned such that the net effect of the offending dipole mode on the following bunches is strongly reduced whereas the fundamental accelerating mode is disturbed as little as possible. The accelerating field is 77 MV/m without beam (« unloaded ») and 57 MV/m with beam (« loaded »).

NLC and JLC have options for an energy upgrade to 1 TeV CM. The proposals include measures as doubling the number of klystrons and/or increasing their power, and increasing the length of the linac, i.e. in the first phase (0.5 TeV CM) only the two opposite extremes of the tunnel would contain a linac and the 0.25 TeV beams would be guided by transfer lines to the interaction point in the middle. For the upgrade, these transfer lines become replaced by linacs.

The NLC Test Accelerator (NLCTA) [17] at SLAC is the first X-band linear accelerator being a unique facility to test the X-band technology. It consists of 3 klystrons each powering two 1.8 m long accelerating sections ; a fourth klystron powers the injector. The rf pulse compression system is however still the former one, called SLED II based on resonant delay lines associated with each klystron. A test of the novel multi-moded DLDS rf compression and distribution system, a key component of the ILC design, is foreseen in NLCTA in the next two years. The facility in its present configuration has already demonstrated that the bunch energy variation over a bunch train can be adequately reduced by proper shaping of the rf pulse, which is a significant result.

Apart from this specific X-band test facility a number of other facilities exist at SLAC and KEK which have addressed or will address more general issues. At SLAC, the most notable facility is SLC[4] which is an extremely valuable prototype of a linear collider especially with regard to beam dynamics and beam control. The Final Focus Test Beam (FFTB) Collaboration demonstrated that the SLAC electron beam ($\gamma\varepsilon_y$ = 3 x 10^{-6}) can be de-magnified by a factor 350 leading to a vertical be rms beam size of 70 nm (Fig. 2) [18] .

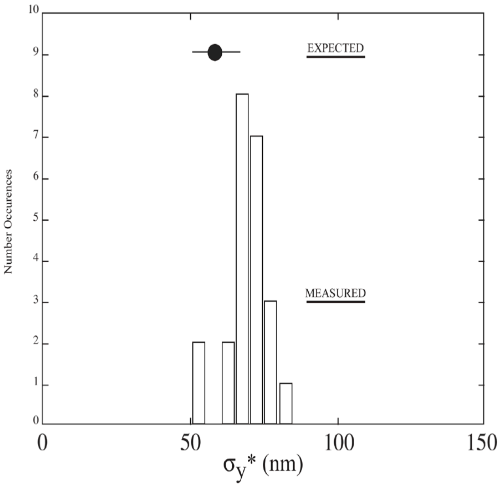

Fig. 2 Histogram of vertical beam sizes measured in the focus of FFTB at SLAC. The expected value is 58 ± 8 nm, the measured value is 70 nm ± 7 nm rms (after hour-glass and power imbalance corrections; run December 1997) [12]

The ASSET facility, being a part of the SLC linac, provides a unique possibility for testing the transverse wakefields of accelerating structures [19]. A first bunch excites the wakefields which are inferred from the deflection of the following probe bunch. By measuring this deflection as function of the delay between first and second bunch, the wakefield as a function of time can be reconstructed. At KEK, the Accelerator Test Facility (ATF) [13, 20] consists of an S-band linac and a prototype damping ring, which is another key element common to all linear collider designs. Linac and ring operate at 1.26 GeV (1.54 GeV design energy not yet reached for lack of funds). The most notable achievement in the linac tests was the compensation of the energy droop in a bunch train induced by beam loading. The damping ring operating since the beginning of 1997 with single bunches has reached the expected horizontal emittance but the vertical emittance is still a factor 10 larger than expected. Further progress is expected and multi-bunch operation is scheduled for 1999. Fig. 3 shows a plot of the achieved emittances in the SLC damping rings, at the end of SLC and in the ATF ring. The plot also gives the emittances required by the different schemes, indicating that it will be challenging to reach specifications especially in the high-energy versions of CLIC and TESLA. Note that the damping rings must produce an emittance somewhat smaller than used in the final focus leaving some margin for emittance blow-up between damping ring and final focus.

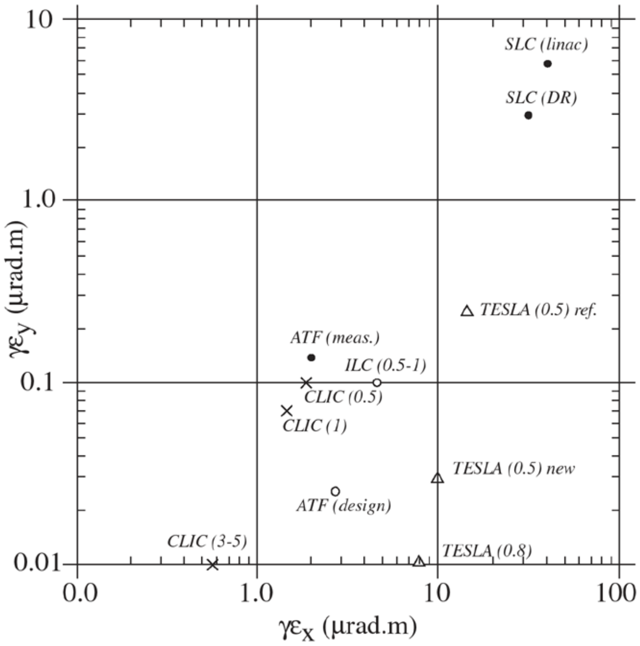

Fig. 3 Normalized vertical beam emittance as a function of normalized horizontal emittance. Full circles: measured values; open circle: design values of ATF damping ring; all other values: goals in final focus.

At KEK, a design study based on C-band (5.7 GHz) is being pursued on a modest scale in parallel with the X-band study [13, 21]. The first prototype klystron nearly reached the specified performance (50 MW, 2.5 μs), the rf compressor was cold tested and a 111 MW klystron modulator has been built and tested. The accelerating structure is being made from special choke-mode cells which let the offending higher order modes escape from the structure to absorbers (SiC) while the fundamental mode (36 MV/m) cannot couple to the absorbers. A 55 cm long S-band model of this structure accelerated beam with even 50 MV/m. It is planned to test one basic rf unit in the injector of the KEK B-Factory.

2.3 CLIC and Relativistic Klystron Development

The Compact Linear Collider (CLIC) Study Group based at CERN has as goal to develop a concept and the key components for a Linear Collider with a CM energy of 3 to 5 TeV, i.e. with a physics potential reaching beyond LHC[22]. In order to make the linac as compact as possible and to reduce the cost per unit length, a high rf frequency (30 GHz) is chosen in order to reach 150 to 200 MV/m with copper travelling-ware structures without breakdown and low dark current. The rf power source [23] for each of the two main linacs is a low-energy (1.2 GeV) drive beam which consists of a number of pulses (20 for 3 TeV CM) running in parallel to the main linac. Each of these pulses is decelerated one after the other by special travelling-ware structures feeding 400 MW/m of 30 GHz power to the accelerating structure (150 MV/ m) over 700 m before being dumped at 0.15 GeV (Fig. 4).

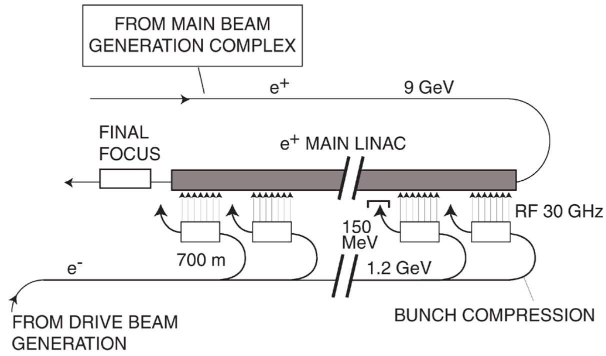

Fig. 4: Scheme for rf generation of CLIC. Only positron linac shown.

Each drive pulse consists of 2144 bunches spaced by 2 cm (2 λ_{rf}) with a bunch length of 2 mm being small compared to λ_{rf}; the bunch charge is 17.5 nC. Since this drive beam decelerator can be accommodated in the same tunnel as the main beam, a single tunnel is sufficient though with an enlargement for the 180° bend of each of the drive beam pulses. No second tunnel for klystrons and their modulators is required resulting in a cost-effective and easily extendable arrangement.

The drive beam is generated by a fully-loaded conventional 1.2 GeV linac operating at 0.94 GHz with a 0.1 ms long pulse, followed by a delay for every second bunch and two small combiner rings (86 m and 344 m circumference) which produce the required longitudinal time structure of the drive beam. The present design is optimized for 3 TeV CM but 5 TeV CM has also been investigated. Parameter studies for 0.5 TeV and 1 TeV CM have also been performed in order to allow comparison with other though low-energy schemes.

Accelerating structures suitable for single bunch operation have been built with 1 to 2 μm fabrication tolerances. A structure for multi-bunch operation has been designed consisting of 150 cells and a scaled prototype is in preparation for a test in ASSET.

A first CLIC Test Facility (CTF1) produced 76 MW of 30 GHz power for component testing and generated 125 MV/m on axis in an accelerating structures suitable for single-bunch operation. A new test facility (CTF 2) is at present being commissioned [24] . It contains 2 decelerating structures in the drive beam line, each feeds one accelerating structure. The number of structures will be doubled next spring. Two-beam acceleration has been demonstrated with 59 MV/m mean accelerating field in the accelerating structure with the transfer structures providing 27 MW from a drive beam with an initial energy of 62 MeV. Work continues to reach the respective CTF2 design values of 95 MV/m with 71 MW from the transfer structure.

A new test facility (CTF3) [22] is under study which would test all major parts of the CLIC rf power generation and acceleration scheme though not quite at the final level of rf power. To reduce costs, the drive linac uses the eight 3 GHz klystrons and modulators of the LEP Injector Linac (LIL) to provide a drive beam of 0.12 GeV which obtains the suitable longitudinal structure in one delay ring and a 5 x combiner ring. The drive beam is decelerated to 0.06 GeV in six 30 GHz transfer structures which provide rf power to twelve 30 GHz accelerating structures of 0.9 m length operating with an average gradient of 130 MV/m and accelerating the main beam to about 1.4 GeV.

A collaboration between LBNL and LLNL is working on an alternative rf powersource for a high-frequency linear collider, called Relativistic Klystron (RK) [25] . Each unit would provide up to 760 MW/m over 300 m for a 5 TeV CM collider. The design rf is 11.4 GHz but the scheme could be applied also for 30 GHz. Each unit consists of an injector producing a 2.5 MeV 1.2 kA electron beam, a chopper producing a longitudinal beam modulation, and an adiabatic bunch compressor also accelerating the beam to 10 MeV. This is followed by about 150 rf transfer structures decelerating the beam. They alternate with accelerating sections which keep the average beam energy at 10 MeV. The last transfer structure, the “after burner”, decelerates the beam to 2.5 MeV before the latter is dumped. All beam acceleration is performed by induction accelerator cells. A major technical challenge is the transport of the relatively low-energy beam through several hundred meters of narrow-aperture microwave transfer structures and induction accelerator cells. A test facility, called RTA, has been established a LBNL to verify the analysis used in the design by the construction of a prototype of about 26 m length operating with a 4 MeV electron beam.

2.4 Parameters for Linear Colliders

Each scheme has its merits: e.g. TESLA offers an impressive luminosity, ILC requires least extrapolation from known and well-tested technology (even more true for C-band), and CLIC is the only scheme which can eventually reach beyond LHC. On request of the collaboration, a Technical Review Committee chaired by G.A. Loew has attempted a first comparison of the merits and drawbacks of the different schemes [26]. For this purpose, detailed parameter lists for the 0.5 TeV and 1.0 TeV CM cases have been established which are regularly updated. Table 1 shows the most important parameters for the 0.5 TeV CM case giving an idea of the different schemes. VLEPP is a Linear Collider scheme proposed by our Russian colleagues. It is included in the table for completeness but since its study has been suspended it has not been described in detail.

Table 1, Principal parameters of linear colliders at 0.5 TeV CM

	TESLA	JLC(C)	ILC(X)	VLEPP	CLIC
f_{rf} (GHz)	1.3	5.7	11.4	14	30
Acc. Structure	sc	nc	nc	nc	nc
rf power source	klystrons	klystrons	klystrons	klystrons	Two-beam acc.
Luminosity (cm^{-2}-s^{-1})	3.0	0.7	0.7	12	0.5
Mean energy loss (%)	2.8	4.1	3.7	10	3.6
Photons / e	2.0	1.5	1.1	4.7	0.8
Bunches / pulse	2820	72	95	1	150
Bunch spacing (ns)	337	2.8	2.8	-	0.7
$\gamma\varepsilon_x/\gamma\varepsilon_y$ (10^{-8} rad.m)	1000/3	330/5	450/10		188/10
Beam size (H/V) (nm)	553/5	318/4	330/5	2000/4	196/4.5
Accel. gradient (MV/m) (loaded)	22	36	55	91	100
Two linac length	30	16	11	7	7.3
η (ac $\rightarrow$ beam)	23				14
P_{ac} (for rf in both linacs)	95	130	≈ 100		68

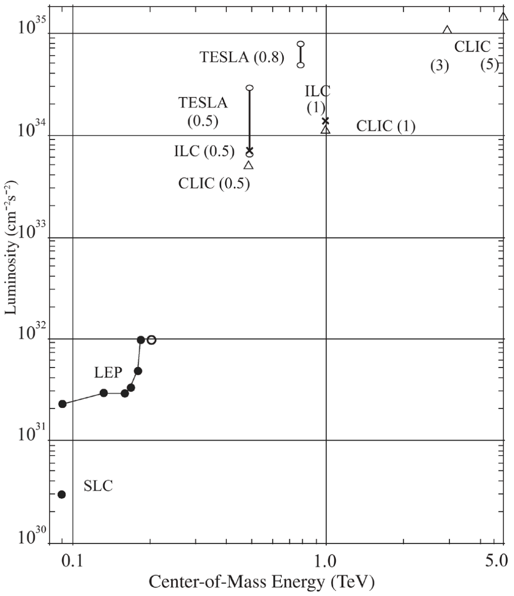

Fig. 5 Luminosity of e^+e^- colliders as a function of centre-of-mass energy. Full circles: colliders in operation; all others: under study.

Fig. 5 shows the published expected values of luminosity as a function of CM energy indicating the present situation. SLC and LEP data are added to provide a perspective. Obviously, all the parameters are under constant evolution and it will take a number of years until they will settle as the R&D is not yet terminated in any of the schemes.

3. Muon colliders

Muons emit relatively little synchrotron radiation and can therefore be accelerated and stored in rings up to at least the 5 TeV CM. The very low level of beamstrahlung is another advantage permitting very small energy spreads in collision. A large international collaboration is studying muon colliders with CM energies at 0.1 TeV, 0.5 TeV and 3-4 TeV [27, 28]. Especially, the 0.1 TeV collider has received a lot of attention as it would be very well suited as Higgs factory due to the large s-channel Higgs production being proportional to the mass squared of the primary particle. Such a Higgs factory would also serve as a valuable demonstration facility before proceeding to a collider at high energy.

In the following, a brief description of the baseline scheme is given without discussion of the variants which have been studied for nearly each subsystem [28].

3.1 Basic scheme of a muon collider

Fig. 6 shows schematically the main components of a muon collider. The first element is a 16 GeV proton synchrotron having as injector a 1 GeV linac and a 3 GeV booster in the baseline design. It provides 1 x 10^{14} protons/pulse in either two (for 0.1 TeV) or four bunches with a 15 Hz repetition frequency. Half of the bunches are used to make μ^+ and the others for μ^-.

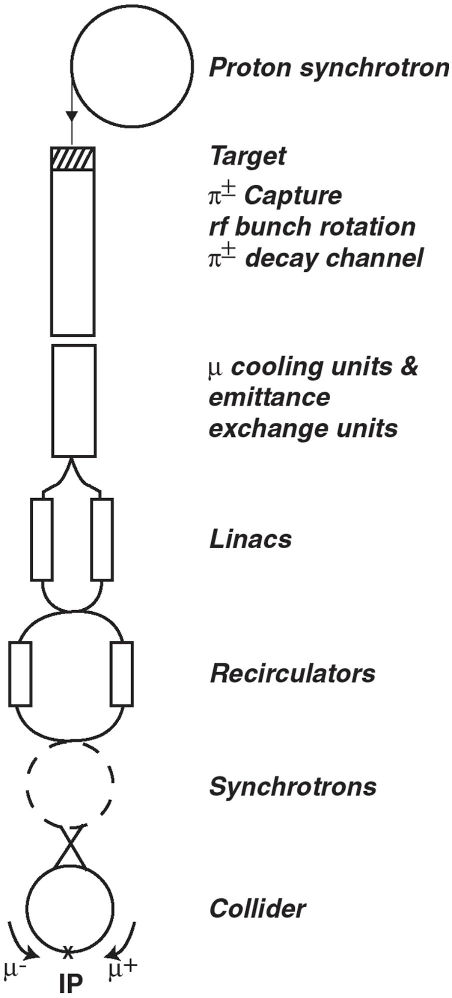

Fig. 6 Schematic layout of a $\mu^+ \mu^-$ collider.

The target 2 to 3 interaction lengths long is a very critical component due to the unprecedented beam power. It is immersed in a 20 T solenoid of 7.5 cm radius which captures all pions with transverse momenta less than 200 MeV/c so that 0.6 pions per primary proton enter the decay channel. In order to reduce the momentum spread, a linac is introduced along the decay channel which rotates the bunch in the longitudinal phase plane. The phasing of the linac is such that only the μ^+ originating from the odd proton bunches and the μ^- from the even proton bunch are rotated correctly. About 0.3 muons per proton are expected at the end of the decay channel which is about 100 m long.

The decay channel is followed by the device which increases the 6-dimensional phase space density of the muon bunches by about 10^5 to 10^6 using ionisation cooling, which is not a new concept but was never tested. The cooling is obtained in a number of stages, each stage consists of a transverse cooling section, which is composed of liquid hydrogen absorbers in strong solenoids (15 to 30 T) followed by accelerating cavities (36 MV/m), and sections which exchange transverse with longitudinal emittance so that the latter is also reduced. The total acceleration in the linacs is about 6 GeV. Approximately 60 % of the initial muons emerge from the cooling system with a momentum of about 0.2 GeV/c.

Since the lifetime of the muons is short, rapid acceleration is mandatory. This is accomplished by a number of accelerators in series. This chain of accelerators is still relatively simple for a Higgs factory: 2 linacs and 3 recirculators of a total length of 2 km based on warm magnets and Cu rf cavities. For the 3 TeV CM case, the system is quite complex: 1 linac, 4 recirculators and 2 synchrotrons in series, some of them requiring superconducting magnets and superconducting rf systems. The sum of the circumferences is 30 km.

After acceleration the μ^+ and μ^- bunches are injected in opposite directions into a collider storage ring. The bending field is as high as possible to maximise the number of bunch collisions before the muons decay. For example, a field of 8 T is used in the various lattices worked out for the collider of the Higgs Factory, which has a circumference of 350 m and where the muons make 450 turns. The ring has a racetrack shape with one long straight section for the low-beta insertion focusing the beams in the detector; the other long straight section is foreseen for injection and beam scraping. The detector must be shielded carefully from the off-energy electrons stemming from the muon decays and producing mainly electromagnetic showers which in turn create again very penetrating muons. High energy muons are also lost from the circulating beam bunches. All this strong background requires an elaborate detector shielding and a performing beam scraping system.

The neutrinos created in muon beam decays can create excessive radiation at large distances from the collider. Since the dose rate at the surface is proportional to E^3/d where E is the muon energy and d the depth of the collider, the dose rate is negligible for 0.1 TeV CM but its control requires a depth of 100 to 500 m for the 0.5 TeV collider and many km for the 3 TeV version provided other measures do not mitigate this problem.

Table 2 shows parameter lists to give an idea of the present thinking. Obviously, these parameters are also under constant evolution. Note the very low energy spread of the muon beam compared to the energy spread in a linear collider (cf. Table 1). The latter is brought about by the strong energy loss in collision due to beamstrahlung. A second parameter set is shown for the Higgs Factory providing a very low energy spread though at reduced luminosity, which might be interesting for high-resolution Higgs studies.

Table 2, Key parameters of $\mu^+ \mu^-$ colliders

	H-factory		$t\bar{t}$	Energy frontier
Collider				
Ecm (TeV)	0.1		0.4	3
<L> (cm-2 s-1)	10^{32}	10^{31}	10^{33}	7 x 10^{34}
<Δp/p> rms %	0.12	0.003	0.14	0.16
$\sigma_\perp$*(μm)	86	294	26	3.2
2πR (m)	350		1000	6000
B_{dipole} (T)	3		4.7	5.2
N_{turns}	450		700	785
Depth (m) [a)]	10		100	500
P_{ac} (MW)	81		120	204
Proton driver				
E_p (GeV)	16		30	
P_b (MW)	4		7	

[a)] for ≤ 1mSv/y US Fed. limit

Note that the proton beam power at target P_b is much larger in all cases than what is handled at present (e.g. 0.9 MW at PSI in Switzerland) but comparable with what is contemplated for spallation sources (5 MW for JAERI in Japan and the European Spallation Source). The challenge for the synchrotron design can be inferred from a comparison with the AGS at BNL having a beam power of 0.14 MW with 25 GeV protons.

The total length of all accelerators including the collider is 36 km for the 3 TeV CM version, which is about the same length as the CLIC version (35 km) for the same energy 22). However, the layout of the accelerators of the muon collider can be arranged that they all fit inside the last synchrotron in the chain of accelerators (2πR = 11 km), which is the largest accelerator, and, therefore, the muon collider may fit on an existing site.

3.2 *R&D for muon colliders*

Extensive computer simulations have been performed of the most critical parts of the scheme and it will take quite a while to complete them. A few experiments at existing accelerators provided some guidance but a substantial R&D programme [27, 28, 29] is still required. The most critical issues are the target and the ionisation cooling which will be addressed with priority by a number of tests.

The target absorbs about one tenth of the beam power. Hence, the existing static designs cannot be applied and a moving target is required. The options include an open liquid jet where the liquid is Hg (eddy current problems) or liquid insulators (PtO_2, Re_2O_3 or slurries), or a solid target of the "band saw" type. A proposal for test of targetry and π collection at BNL in 1999 has been made where AGS bunches with 1.5 x 10^{13} protons of 24 GeV will impinge on a liquid Ga-In jet. This jet will also be exposed to a 20 T magnetic field to study the effects of eddy currents in the same year. In order to test issues related to radiation resistance, a 20 T magnet plus 70 MHz rf cavities will be exposed to the secondary flux downstream of an AGS target in 2000/2001.

A proposal for a six-year R&D programme to demonstrate the feasibility of the muon ionisation cooling has been submitted to FNAL. It is suggested that critical sections of the cooling channel are designed and built. Single muons of 100 to 300 MeV/c will be used as probes.

4. Very Large Hadron Colliders

The next step after a linear e^+e^- collider or a muon collider could be a Very Large Hadron Collider (VLHC) as "discovery machine" [30] . At present, it is the only known route to the 10 TeV scale. Recently, the US effort [31, 32, 33, 34] in this field has been organized under the leadership of BNL, LBNL and Fermilab in order to study a superconducting proton-proton collider with approximately 100 TeV CM energy and 10^{34} cm^{-2} s^{-1} mean luminosity with the aim to produce 100 fb^{-1} per year. The luminosity is limited by the detector's ability to deal with the number of interaction per crossing. The study is focused on technology and cost reduction.

In order to illustrate the salient points, we consider the two approaches by Fermilab [29] and comment later on the complementary studies at BNL and LBNL. In both cases, it is assumed that the detectors can tackle 28 events per crossing. The bunch spacing is 19 ns in all versions.

The first approach uses low-field magnets with a low cost per unit length but leads to a fairly large circumference. In the second approach, high-field magnets requiring advanced technology are contemplated implying a ring of much reduced circumference.

The low-field magnets are 2 T superferric combined-function magnets made with NbTi coils operating at 7 K. Fig. 7 shows the cross-section of such a magnet proposed by G.W. Foster [32] .

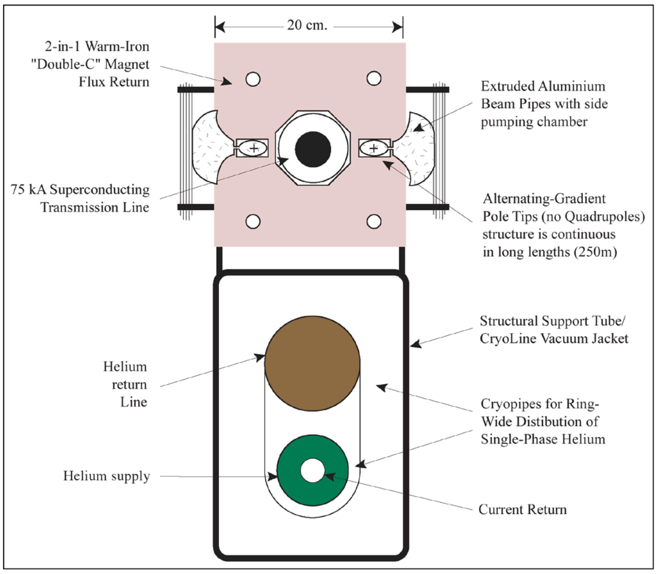

Fig. 7 Schematic cross-section of two-in-one low-field magnet for VLHC proposed by G.W. Foster [32].

The two warm vacuum chambers for the two counter-rotating proton beams are in the gaps on both sides of a 75 kA superconducting transmission line which powers the magnet. The magnet profiles in the gap are shaped to produce a combination of a dipole and a quadrupole field. Hence, no individual quadrupoles are required in the arcs of the ring. The He return line and below it the He supply line are inside the magnet support. The current return is embedded in the He supply line. The length of the magnet assembly is 250 m. The advantage of these magnets is the simple design leading to a very low cost per unit length which is especially imperative for the low-field ring as it has a circumference of 600 km.

In the other approach, the magnetic field would be in the 10 to 12 T range, somewhat higher than LHC which will operate at 8.4 T nominal field. In order to reach this magnetic field, Nb_3Sn at 4.5 K must be used which is more difficult to handle than the NbTi alloy. Drawback of this magnet type are the tighter tolerances for conductor positioning, the higher stored energy and the requirement for more elaborate cryogenics. However, the circumference would be only about 100 km, approximately three times the circumference of LEP/LHC.

Synchrotron radiation is stronger in the high-field version which exacerbates the heat-load problem in the cold vacuum chamber and requires a more powerful cryogenic system. However, synchrotron radiation damping is strong enough in the high-field version so that the average luminosity is significantly increased as illustrated by two examples (Fig. 8) given by C.S. Mishra [32] . In spite of a decrease in the number of particles due to scattering on the counter-rotating beam or the residual gas, the luminosity increases at the beginning of a run because the beam emittance shrinks due to synchrotron radiation (Fig. 8a), the damping time being smaller than the storage time.

The sensitivity of the luminosity averaged over 10 h to the initial beam emittance is shown in Fig. 8b. It can be seen that the high-field version is rather insensitive to the initial emittance. Obviously, synchrotron radiation in this version also helps quite effectively to damp instabilities and mitigates the adverse effects of ground motion and vibrations.

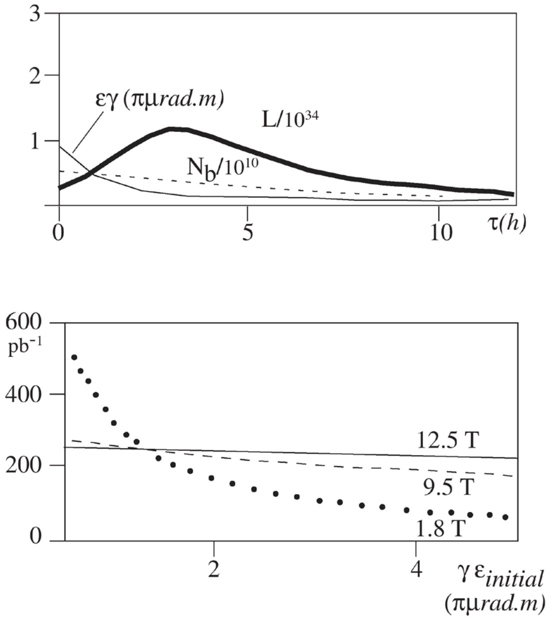

Fig. 8 a) Luminosity L, invariant emittance εγ, and number of protons per bunch N_b as a function of time in a high-field VLHC during a run;
b) luminosity integrated over 10h as a function of the initial emittance for different levels of magnetic field in the VLHC dipoles.

The 3 TeV rapid cycling synchrotron is the injector for the 50 TeV collider but would be also the ideal near-term demonstration project being built with the same technologies as the VLHC. It will provide a correct cost basis for the 16 times larger VLHC reducing therefore considerably the technical risks. Its circumference is 34 km if low-field magnets are used. Its injector in turn could be the new 120 GeV/c Main Injector of Fermilab.

The planned R&D focuses on magnet technology, accelerator physics and improvements of conventional construction techniques as tunnelling, maintenance by robots, etc.

A first 2 m model of a low-field magnet has been tested in 1997 at Fermilab with up to 43 kA in the superconductor (50 kA design value). A 50 m long prototype with 75 kA is under preparation. The short-term R&D comprises also high-field magnets. An initial one meter long Nb_3Sn prototype dipole with 11 T at 4.4 K will be constructed by a collaboration of Fermilab / KEK / LBL in 1999. Such field levels have been achieved in a LHC model magnet by a group from the University of Twente and surpassed by a LBNL group having reached 13 T. BNL studies High-Temperature Super-conductors (HTS) especially YBCO and a crude demonstration model is under construction. LBL is building a magnet with a simple pancake coil extending over both beam channels. A first low-field magnet will be tested this year.

In the long term, in order to advance the low-field version, NbTi and Nb_3AL conductors will be further developed and a 100 m long prototype could be ready in 2000 in Fermilab. For the high-field version (10-12 T), a three-year R&D programme is under discussion aiming at improving the NbTiTa and Nb_3Sn conductors, explore design options for coils with LBNL, and test one or more 11 T models in 2000/2001. No work will be done on the very high field option ($\geq$ 12 T) judged to be too difficult but a moderate effort will be made together with BNL, Cornell and LBNL to study the potential of High-Temperature-Superconductors (HTS). Power leads made from HTS have been successfully tested for the Tevatron (6 kA) and LHC (13 kA). However, many years of intensive R&D will be required before reliable cost estimates become available and a choice can be made between the low and high field route.

5. Advanced Accelerator Technologies

The strong growth in available CM energies for accelerator-based Particle Physics has been based in the past on conceptual breakthroughs (e.g. strong focusing and colliding beams) but also on technology developments as the invention of the klystron and the application of superconductivity. It is very likely that accelerator research could again lead to improvements which dramatically decrease costs and increase capabilities. The R&D at present concentrates on new acceleration methods providing higher gradients in electron linear accelerators. It is summarized in the following. The emphasis is on schemes based on lasers and plasmas 35) but investigations of normal conducting rf-driven accelerators at highest rf frequency are also mentioned36, 37) . Detailed references can be found in the recent Proceedings of the Accelerator Conferences and the Proceedings of the Advanced Accelerator Workshops which regularly take place in the US.

Pulsed lasers reach these days peak power densities of 10^{20} W/cm^2 in their focus corresponding to 30 TV/m. However, since the direction of the electric field is perpendicular to the light wave propagation, unfortunately the laser beam cannot be used directly for particle acceleration and more complex schemes have to be applied.

The Inverse Free-Electron Laser (IFEL) is one of these. It accelerates electrons interacting with the transverse electric field of a laser beam in a wiggler magnet. Acceleration has been observed at Yerevan, Columbia and the BNL Accelerator Test Facility (ATF) but the potential of this method is limited. The reason is the energy loss by synchrotron radiation suffered by the electrons in the wiggler. An experiment to accelerate electrons from 40 to 106 MeV is in preparation at BNL (38).

A test of a crossed laser beam accelerator (39) is in preparation at Stanford (36). Fig. 9 shows the principle. The incoming two laser beams, formed by splitting a single beam, cross at an angle. They are polarized in the crossing plane and phased such that the transverse field components interfere destructively and the longitudinal components add. Average gradients of almost 1 GV/m are expected. Since the bunch length is small compared to the laser wave length, the energy loss in the narrow slits may severely limit the maximum bunch charge.

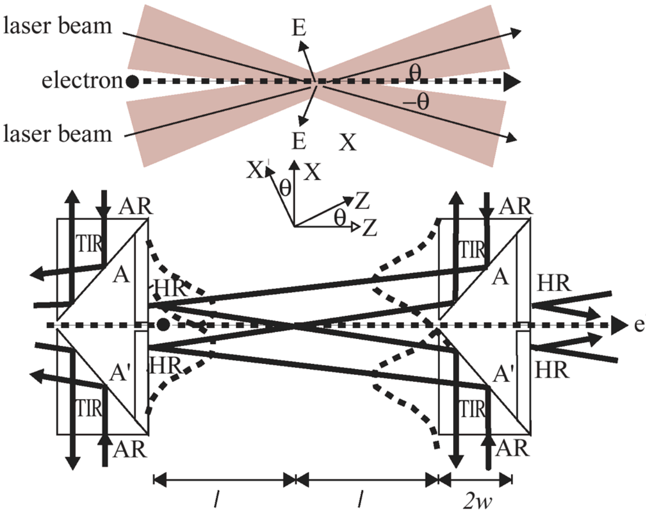

Fig. 9 a) Schematic layout for crossed-laser-beam accelerator. The electron traverses the focal zone at an angle θ with respect to each of the two beams. The two lasers are phased so that the longitudinal fields add and the transverse fields cancel;
b) reflection scheme of a single stage showing the surfaces with anti-reflection coating (AR), high reflectivity coating (HR) and total internal reflection (TIR). Acceleration takes place over length 2 l between slits (39).

In the Inverse Cerenkov Accelerator (ICA), a gas is used to slow down the phase velocity of the light and to match it to the particle velocity. Laser beam and particle velocity are not parallel but cross with the Cerenkov angle. The particle gets accelerated by the longitudinal component of the electric field. The transverse component is nearly cancelled by polarizing the laser radially and using a special lens for focusing. An accelerating gradient of 30 MV/m over 12 cm has been achieved in an experiment in ATF/BNL in agreement with simulations (40). A new experiment is planned in BNL using an IFEL as prebuncher and injector so that the electrons have a high enough energy to mitigate gas scattering in ICA. However, breakdowns in the gas may limit the laser power and, in turn, the achievable accelerating gradient.

A considerable effort has been made to understand the potential of electron acceleration by plasma oscillations where the electrons of the plasma oscillate relative to the static ions. The electron density oscillations create very strong fields which are easily sustained by the plasma as the latter has no electrical breakdown limit. The plasma oscillations can be excited by a laser or by a short particle bunch.

In the case of the Plasma Beat-Wave Accelerator (PBWA), the plasma frequency is tuned to the beat frequency of two incident laser beams by carefully choosing the plasma density which determines the plasma frequency. Gradients of 3 GV/m over 1 cm have been achieved by a UCLA group (41). Limitations are saturation of the plasma oscillation amplitude when the plasma electrons become relativistic and instabilities due to movement of the ions.

A single short (< 1 ps) laser pulse excites the plasma oscillations in the Laser Wake Field Accelerator (LWFA). Experimental demonstration of this effect had to wait for the development of high brightness lasers in the TW domain. Acceleration of electrons up to 250 MeV (42) and electric fields of 1.5 GV/m over 1 mm have been achieved (43).

In the beam-driven plasma accelerator, the plasma oscillations are generated by a short electron pulse. They in turn accelerate the main bunch following with some delay. A collaboration between LBNL, SLAC and UCLA plans an experiment at SLAC (E-157) whereby a single 30 GeV electron bunch excites oscillations in a 1 m long Li-plasma column. The oscillations are produced by the head of the bunch while being decelerated by the energy transfer to the plasma. Simulations show that the tail of the bunch should gain 0.75 GeV over the length of the plasma (36). A similar experiment is planned by INP/ Novosibirsk where an electron bunch of 0.8 GeV extracted from VEPP-2 M will excite oscillations in a plasma column immersed in external quadrupole focusing (44).

Acceleration in traditional, metallic travelling-wave structures operting at 90 GHz (middle of W-band) is under study (36, 37). The short-range goal is to achieve 1 GeV over 1 m. The advantage of the very high-frequency structures is that they support much higher electric fields without breakdown and generation of dark current. Since the rf surface currents are confined to a very small skin depth, surface heating by the rf pulses can lead to fatigue and failure of metals. A TE_{011} mode X-band pill-box cavity driven by a 20 MW, 1.5 μs rf pulse with a 60 Hz repetition frequency will be used to investigate the damage thresholds. A clamped cold model of a planar 7-cell $2\pi/3$ travelling wave structure has been measured. A 25-cell structure, diffusion bonded and equipped with waveguides, vacuum pumping and watercooling is in preparation.

While the quest for new accelerator technology providing highest accelerating gradients is becoming more vigorous, it should be kept in mind that other features are equally important for a high-energy linear collider. e.g. high energy transfer efficiency from wall-plug to beam power, main beam emittance preservation, capability of positron acceleration, stability, reliability and last but not least cost. It will certainly require a sustained and challenging R&D programme to bring these very interesting new ideas to full fruition and to advance the field significantly.

6. Conclusions

Scrutinizing the studies of future accelerators performed world-wide it can be seen that the development at linear colliders is well advanced. A number of concepts have been firmly established and the different technologies are being tested in a number of impressive large-scale test facilities. However, it will still take some time until all technological aspects are fully understood and the various proposals can be completed with cost estimates required for an ultimate comparison of the different schemes.

Although the muon collider is under vigorous study since a number of years, its technical development is only starting now and the results from the first experimental tests will not be available before some years. They will be needed to provide guidance for the future R&D for this challenging scheme which has a large variety of complex subsystems.

Concepts for a Very Large Hadron Collider have been worked out in particular by the leading Laboratories in the US which are now defining an R&D programme emphasizing the development of the magnets as key components. Also in this case, it will take many years until the results become available and a judgement between the options can be made.

A summary of the most promising new accelerating techniques has been given. Increasing support for this activity is required as new concepts must be developed to increase the capability of particle accelerators and to reduce their unit costs in order to make them affordable by the global physics community. Hence, a reasonable fraction of the operating budget foreseen for High Energy Physics should be invested world wide in proposal-driven, peer-reviewed long-range Accelerator Research and Development.

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