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A Review of Possible Future High-Energy Colliders for the Post-LHC Era

J.-P. Delahaye

Abstract

A review of the studies being conducted by various laboratories and collaborations in order to determine and optimise the next generation of particle accelerators for physics at the high-energy frontier beyond HERA at DESY, LEP and LHC at CERN, SLC at SLAC and the TEVATRON at FNAL is presented. The relative advantages of the Very Large Hadron Colliders, Electron Positron Colliders and Muon Colliders are compared pointing out their main challenges and key issues both in beam dynamics and technology. The present status and future plans of the various studies are summarised outlining the research and development of key components and their tests in ambitious test facilities. Finally, the schedules presently assumed and the possible scenarios for the post-LHC-era around 2010 are presented.

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A review of possible future high-energy colliders for the post-LHC era

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A review of the studies being conducted by various laboratories and collaborations in order to determine and optimise the next generation of particle accelerators for physics at the high-energy frontier beyond HERA[1] at DESY, LEP[2] and LHC[3] at CERN, SLC[4] at SLAC and the TEVATRON[5] at FNAL is presented. The relative advantages of the Very Large Hadron Colliders, Electron Positron Colliders and Muon Colliders are compared pointing out their main challenges and key issues both in beam dynamics and technology. The present status and future plans of the studies are summarised outlining the research and development of key components and their tests in ambitious test facilities. Finally, the schedules presently assumed and the possible scenarios for the post-LHC-era around 2010 are presented.

1. Introduction

In the quest for higher and higher colliding beam energies and because of the necessarily increasing size (and cost) of the new facilities at the high-energy frontier, an anticipation of the physics needs is necessary well in advance to leave time for:

- R&D on new technologies,
- long term tests of components and optimisation in test facilities,
- performance and cost optimisation of the designs,
- prototyping and technology transfer to industry,
- political decision process and eventual site selection,
- construction and running-in time.

The overall procedure lasted about 16 years for LEP (from 1973 to 1989), 20 years for LHC (from 1985 to 2005). It will take at least 25 years for the next facility at the high-energy frontier. This is why the reflection and the studies of various possible options have already started several years ago, in preparation for the post LHC era around 2010. They are based on a projection in the future of the possible High Energy Physics (HEP) landscape and corresponding HEP requests (recalled in Chapter 2) in order to determine the various possible candidates for the best suited collider namely:

- Very Large Hadron Colliders (Chapter 3),
- Electron-Positron Linear Colliders (Chapter 4),
- Muon Colliders (Chapter 5).

Possible conclusions are summarised in Chapter 6.

Very complete reviews of these studies have already been published[6,7]. The goal of the present paper is to update their status with the main results already achieved and their schedule and future plans which are all rapidly evolving. With the permission of the author, parts of the text of Ref. 6, where still valid, are included in this report for completeness.

2. The High Energy Physics landscape in 2010

The history of accelerator complexes at the high-energy frontier clearly points out (Fig. 1) a very parallel evolution of the lepton and hadron colliders centre-of-mass (c.m.) energy at the level of the constituents with an excellent complementarity for HEP. The hadron colliders are known to be very efficient for exploratory measurements and possible discovery of new particles, whereas the lepton colliders are better adapted to precise measurements of the properties of the particles, once discovered.

As a consequence, a hadron collider is usually built first for the exploration of a new energy range. A lepton collider then follows with performances (energy and luminosity) well adapted and optimised for the physics of the new particles (Fig. 2). A typical example at CERN is the antiproton programme of the $S\bar{p}pS$, which discovered the Z and W bosons. The properties of these two particles have then been precisely measured with LEP.

Following an analysis[8] by the US High Energy Physics Advisory Panel (HEPAP) and by an exploratory study[9)] of possible colliders at CERN after LHC, physics experiments over the past 30 years have conclusively determined that the elementary particles and their interactions are well described by the so-called Standard Model. According to the Standard Model, the fundamental constituents of matter consist of three families of quarks and leptons. Quarks and leptons interact through the electro-weak force while quarks alone feel the strong force or Quantum Chromo-Dynamics (QCD). All forces are mediated by the exchange of particles known as gauge bosons namely the gluons for QCD and photons, and W and Z for the electro-weak interaction. Together with gravity, the interactions they mediate ultimately govern all of matter and energy. The interactions between quarks, leptons and gauge bosons have been measured very accurately with protons-antiprotons at the S$\bar{p}$pS and the Tevatron and with electron-positrons at SLC and LEP. They agree within a tremendous accuracy with the predictions of the Standard Model.

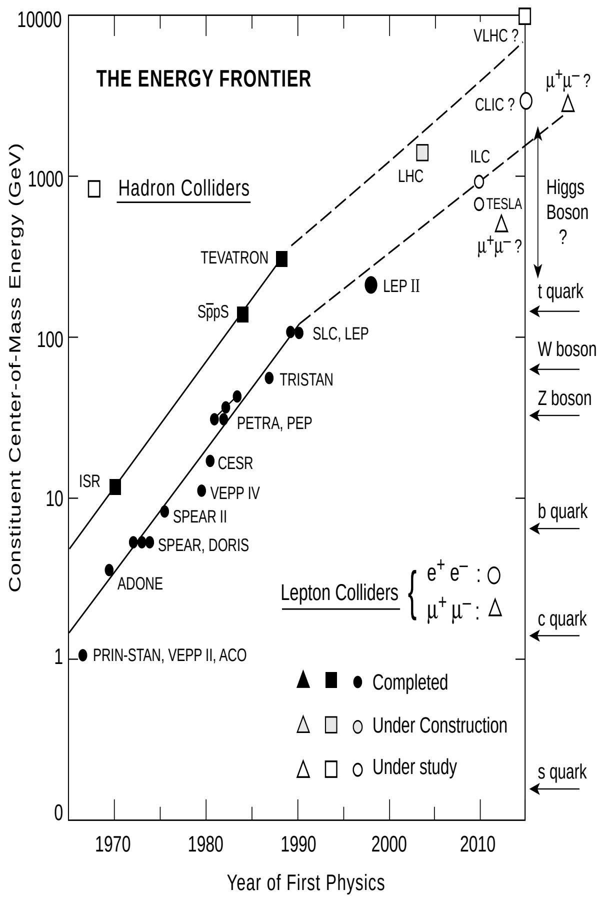

Fig. 1: Evolution of the particle physics energy frontier.

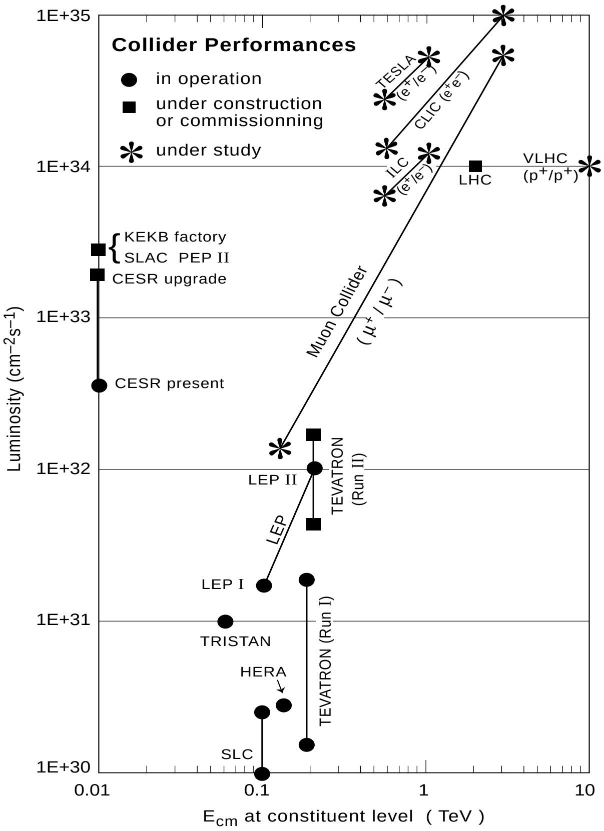

Fig. 2: Energy and luminosity reach of colliders.

Nevertheless, a number of questions still remain open that are not answered by the Standard Model:

- What is the origin of the mass of the force carriers and can particle masses be predicted by the supersymmetry model (which requires each kind of particle to be associated with a super-particle and supposes the existence of a new force carrier, the so-called Higgs boson)?
- Why are there just six quarks and six leptons? Are they composite objects with substructure? What is the origin of their mass ratio and mixing angles?
- Why is there apparently more matter than antimatter in the universe although they are created in equal quantities during annihilation? Can this be explained by Charge and Parity (CP) combined symmetry violation?
- Can the multiplicity of particles, forces and masses be unified at high energy in a Grand Unification Theory (GUT) and at what energy threshold does it break?

Answers to these questions require physics beyond that of the Standard Model. The next decade will undoubtedly provide exciting campaigns of measurements which will concentrate on tighter and tighter tests of the Standard Model and on a search for non Standard Model behaviour in the following areas:

- Fixed target facilities, B factories and the Tevatron about the quark-mixing matrix explanation of CP violation,
- Underground detectors on neutrino oscillations to understand the atmospheric neutrino flux anomaly and the deficit in solar neutrinos,
- Signs of electro-weak symmetry breaking could possibly show-up at LEP2 or at the Tevatron with a possible discovery of the light Higgs boson ,
- The main "raison d'être" of the LHC is the search for electro-weak symmetry breaking and associated particles (Standard Model and/or Super-Symmetry particles) in the TeV range. Indeed, because the 14 TeV colliding beam energy of the LHC is distributed among all constituents of the hadron (quarks and gluons), only 1/7 to 1/10 of the energy or about 1.5 TeV is available at the level of the constituents.

Nevertheless, the LHC as a hadron collider is much better adapted to the exploration of a new energy range and the discovery of possible particles than for a precise measurement of their properties. This is why a number of questions will certainly still remain unanswered after the LHC and will require:

- a precise parameterization of these particles (if found) by an accurate collider in the same energy range for which a Lepton Collider (Electrons/ Positrons or Muons+/ Muons-) with a 0.5 to 1.5 TeV c.m. energy is an ideal candidate,
- an exploration in a higher energy domain (>1.5 TeV) at the constituent level for which a lepton collider with a c.m. >2 TeV or a hadron collider in the 100 TeV energy range (about 10 TeV at the level of the constituents) is better adapted.

Assuming that an electron/positron collider in the 0.5 to 1.0 TeV energy range could have been built in the meantime, the possible options for a future collider after LHC have been analysed by an exploratory study[9)] at CERN which concluded that the priorities that would most probably emerge are:

i) a $lepton^+/lepton^-$ with a c.m. energy comparable with physics reach at LHC, which means above 2 TeV and preferably capable of 4 to 5 TeV,
ii) a proton/proton 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 c.m.

As shown in Fig. 2, the performances (luminosity and energy available at the level of the constituents) of possible future lepton colliders (e^+/e^- or μ^+/μ^-) have been chosen to cover the range between the lepton colliders presently in operation and the LHC, while the performance of a possible future Very Large Hadron Collider (VLHC) has been adjusted to extend the energy range well above the LHC reach.

3. Very Large Hadron Colliders

A Very Large Hadron Collider (VLHC) as a "discovery tool"[11)] (similar to LHC but extending its exploratory range) is presently the only known route to the 10 TeV scale. Recently, the US effort[12)] in this field has been organised under the leadership of BNL, Cornell, FNAL and LBNL in order to study a super-conducting proton-proton collider with approximately 100 TeV c.m. energy and 10^{34} cm^{-2} s^{-1} mean luminosity with the aim of producing 100 fb^{-1} per year. The study is mainly located in the U.S. where FNAL will lose its present leadership in energy reach with the Tevatron once LHC starts in 2005.

Such a collider could be built with today´s technology derived from HERA, LHC, RHIC, or the SSC but would be unaffordable[13)]. Its construction could only be envisaged if the cost/TeV, presently around 120 MEuro (or M$) for the LHC, is reduced by about a factor ten. Because, at this energy scale, the collider is mainly constituted by bending magnets in a tunnel with a large circumference, the main cost drivers are the magnets including the associated cryogenics and the tunnel. The cost can be minimised for an optimum magnetic field in the bending magnets as shown in Fig. 3.

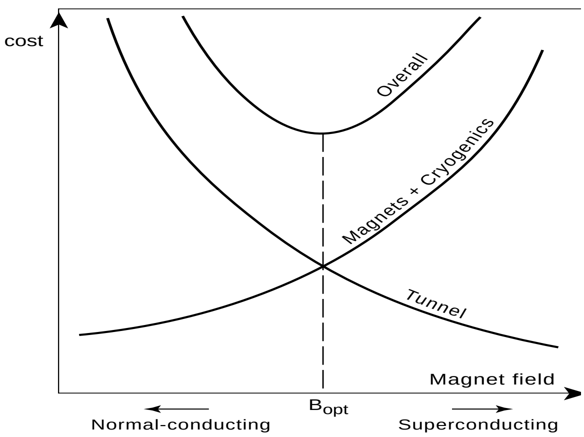

Fig. 3: Cost optimisation of the VLHC.

Indeed, with higher fields, the relative cost due to magnets and cryogenics increases because of the magnet complexity whereas the tunnel cost is reduced due to the smaller circumference. The optimum magnetic field depends on the relative cost of magnets and cryogenics per Tesla-meter of integrated field and on the cost per meter of tunnel.

In order to explore the whole technology range, various approaches at different magnetic fields are compared, namely:

- low-field (2 T) and fairly large circumference (600 km),
- high-field (11 to 15 T) and more reasonable but still large circumference (100 km).

The choice of the bending magnet strength is essential as it drives not only the ring circumference and the magnet technology but also many accelerator issues and, in particular, the amount of emitted synchrotron radiation. The latter is negligible at low field but considerable at high field with important consequences on the accelerator components and on beam dynamics. Therefore, R&D focuses not only on magnet cost reduction but also on accelerator physics and improvements of conventional construction techniques such as tunnelling, maintenance by robots, etc…

3.1. Low-field option

The low-field option as studied at FNAL is based on a "two-in-one", 2 T, super-ferric, combined-function magnet[14)] made with a "double C" iron yoke at normal temperature which is driven by a 75 kA superconducting transmission line built with standard NbTi coils (Fig. 4). The low current density and low-field allow an operation of the coils at a temperature as high as 7^{o}K which results in a simple cryogenics system. The two vacuum chambers for the two counter-rotating proton beams are in the gaps of the yoke on both sides of the transmission line which powers the magnet. The gap profile is shaped to produce a combination of dipole and quadrupole fields. Crenellated laminations (material missing in every 10^{th} lamination) are used to reach a field of 2 T without saturation quadrupole and sextupole fields. Hence, no individual quadrupoles are required in the arcs of the ring. The Helium supply and return lines are both inside the magnet support. The current return is embedded in the Helium supply line. A 1m-long proto type has already been built and tested with a drive current up to 43 kA. A 13m-long prototype magnet at full current and a 50m-long string is planned for the year 2000.

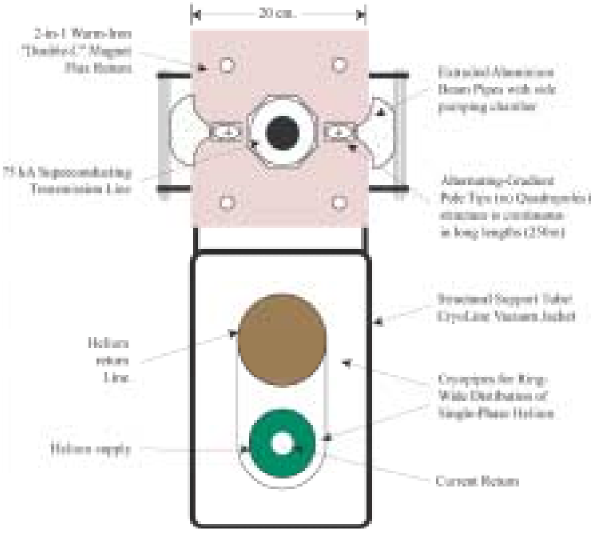

Fig. 4: Schematic cross-section of a two-in-one super-ferric magnet[14)].

This very attractive magnet design presents three main advantages:

i) a good field quality defined by the shape of the iron poles independently of the position of the superconducting coils and without significant persistent fields,
ii) a reduced amount of synchrotron radiation allowing a vacuum system similar to a low-energy electron ring with ante-chamber and distributed pumping system,
iii) a simple design leading to a low cost per unit length which is especially imperative for the low-field ring because of its 600 km-long circumference. Due to its advanced state of development, a relatively reliable cost as low as 540 $/Tm has been estimated.

In addition to the large circumference of 600 km, the main drawback of this approach concerns the beam emittance control because of the absence of damping by synchrotron radiation and of the sensitivity to low resonant frequencies at which ground motions and vibrations are known to be larger. On the other hand, the availability of a large circumference tunnel makes possible the implementation of an extra high-energy electron ring in the same tunnel for electron-positron and proton-electron collisions. With the same emitted synchrotron radiation per turn as in LEP and in spite of the 4^{th} power dependence with energy, the electron energy could be raised to about 450 GeV.

Such a technology is envisaged for the 3 TeV fast cycling injector of the VLHC. It would constitute an excellent demonstration project with a 34 km circumference and would provide a reliable cost basis for the 16 times larger VLHC, reducing therefore considerably the technical risks.

3.2. High-field option

In the high-field alternative approach, R&D focuses on super-conducting conductors and magnet technologies to reach magnetic fields in the 11 to 15 T range, significantly higher than LHC which will operate at 8.4 T nominal field. Drawbacks of this magnet type are the tighter tolerances for conductor positioning, the higher stored energy, the stronger emission of synchrotron radiation and the requirement for more elaborate cryogenics. However, the circumference would be only about 100 km, approximately three times the circumference of LEP/LHC.

3.2.1. Superconducting conductors

Two classes of conductors are being studied[13)]:

i) the first is A15 compound low-temperature superconductors, NB3Sn or NB3Al, operating at 4.5°K and studied by FNAL, LBL and Texas A&M University (TAMU). They allow higher critical current density (2000-3000 A/mm^2) than the usual NbTi used in LHC but are less strain tolerant, have a small filament diameter (<20 μm) and are more difficult to make,
ii) the second includes copper oxide High Temperature Superconductors (HTS) such as BSCCO or YBCO operating in the 20 to 30°K range and studied by BNL. They would considerably reduce the cryogenics requirements due to the higher operating temperature but fabrication of reliable small filament diameter has still to be developed.

3.2.2. Magnet design and prototyping

In order to explore all various possible technologies and compare their performances and cost, four major high-field magnet R&D programmes are underway:
FNAL is designing a 40 mm bore dipole[15)] in the 11 T range with NB_3Sn two-shell coils and conventional cosΘ shape technology (Fig. 5) as derived from the SSC and LHC. A first prototype is expected in summer 2000.

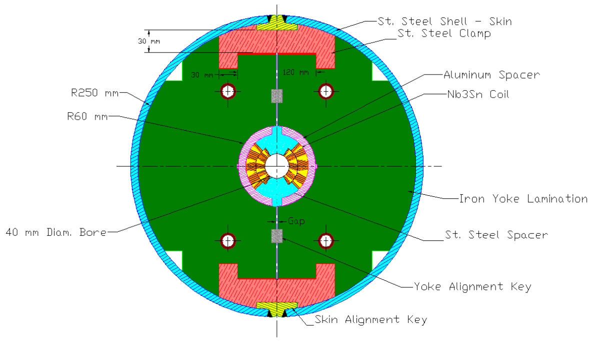

Fig. 5: Fermilab Nb3Sn High-Field dipole Model[15)].

FNAL and LBL are collaborating on the development of a common-coil block magnet[16)] with flat race-track coils in Nb_3Sn, simpler, more robust, more compact and easier to fabricate than with cosΘ dipoles (Fig. 6). Because of the simplicity of the design, tooling and labour costs tend to be moderate and a low-cost magnet may be expected. A 1m-long prototype with ITER conductor has been built and reached 6 T. Subsequent magnets will use improved conductors with an ultimate field magnet of 15 T.

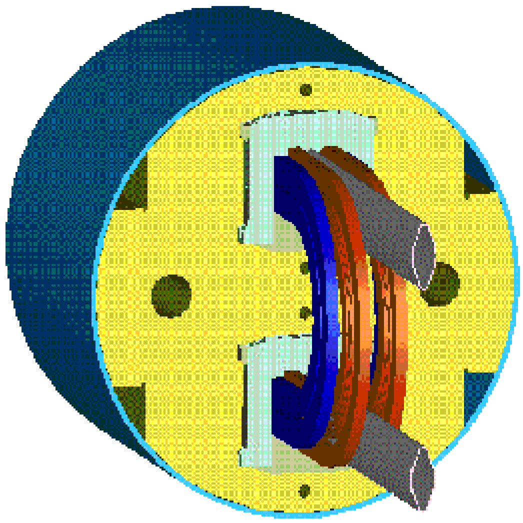

Fig. 6: Common Flat Coil for 2-in-1 High-Field Magnet[16)].

BNL is building a 1m-long, 4 cm bore, modular, common-coil bloc, hybrid magnet[17)] with NbTi background field coils and BSSCO inserts operating at 20°K in order to gain experience with High Temperature Superconducting (HTS) tape conductors. This will eventually lead to an all HTS magnet.

TAMU is trying to push the segmented block coil design[18] with Nb3Sn coils to 16 T range and emphasises stress management techniques using laminar inconel springs to intercept stress and mica sheets to prevent friction at the coil Nb interface.

3.2.3. Beam dynamics

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 that the average luminosity is significantly increased as illustrated in Fig. 7 taken from [12]. 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 damping by synchrotron radiation (Fig. 7a).

The luminosity averaged over 10 h is shown in Fig. 7b to be rather insensitive to the initial beam emittance in the high-field version. Synchrotron radiation also helps quite effectively to damp instabilities and mitigates the adverse effects of ground motion and vibrations.

3.3. Civil engineering

Both variants of the VLHC would benefit from minimum-possible-cost tunnels, but this is particularly important for the low-field VLHC because of the extremely large circumference.

For tunnels excavated with present-day technology of tunnel boring machines (TBM), the minimum cost tunnel has been found[19] to be a bore diameter in the range of 2.5 to 3 m and is estimated around 4000 $/m. This cost may be reduced with continued R&D and tunnelling technology improvements in the future.

3.4. Future plans

The planned R&D focuses on magnet technology, accelerator physics and improvements of conventional construction techniques with the aim of cost reduction and to be ready for the post LHC era. Several 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.

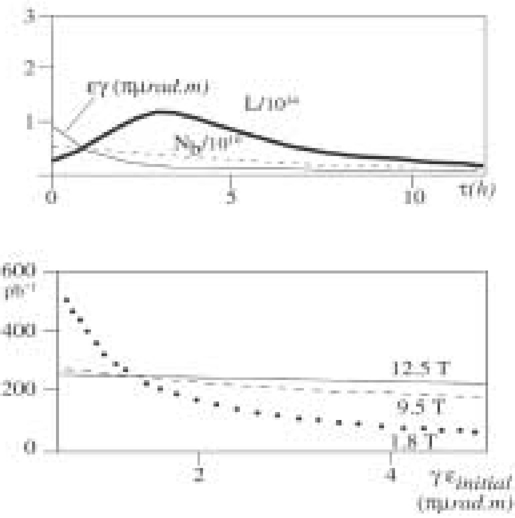

Fig. 7: Effect of synchrotron radiation on VLHC beam. parameters and luminosity:

a) Luminosity L, emittance $\varepsilon\gamma$, and number of protons per bunch N_b as a function of time in a high-field VLHC;
b) Integrated luminosity as a function of the initial emittance for different magnetic fields in the dipoles.

4. Linear Colliders

Electron-positron colliders benefit from a number of advantages over proton colliders:

- the overall colliding beam energy is totally available at the level of the constituents as compared with only 1/7th to 1/10th with the protons, the so-called energy advantage,
- the particle production process is well defined with clean experimental conditions,
- they are well suited to precision measurements,
- polarisation of at least one kind of particle if not both is possible,
- HEP with e^+/e^- collisions comes for free,
- they can be adapted to HEP with $e\gamma$ or $\gamma\gamma$ collisions by creating γ from back-scattering laser light just before the interaction point (IP),
- they are the natural extension of LEP2 limited to 200 GeV c.m. by synchrotron radiation emission,
- they ideally complement the LHC limited to 14 TeV/10 ≈ 1.5 TeV c.m. by the magnetic field in the super-conducting bending magnets.

On the other hand, they suffer from the emission of synchrotron radiation in bends which limits the possible energy reach in rings. The usual technology of lepton colliding beams in storage rings reaches its natural economical limit with LEP2 at ~200 GeV c.m.

Synchrotron losses scaling with the 4^{th} power of the beam energy makes a circular collider prohibitively expensive in the TeV range. Instead the linear collider technology with a cost increasing linearly with the beam energy is well adapted to extend the lepton energy frontier. The first and only linear collider built so far, the SLC[4)] at SLAC successfully demonstrates their feasibility and operation at a remarkable level of performance. Nevertheless, the cost of the accelerator system has to be significantly reduced with respect to present standards which correspond to about 7 MEuro/GeV.

Because of the size of the complex and the large extrapolation in performance with respect to the SLC (one order of magnitude in energy and three orders of magnitude in luminosity as shown in Fig. 2), a wide range of technical options is being explored before technology and design parameters are chosen. New concepts of beam acceleration based on lasers, plasmas or wakefields have been envisaged[6)] but it does not look as if any of these exotic schemes would present the required performance and energy conversion efficiency for such a high-energy collider.

An international collaboration for R&D on TeV Linear Colliders (TLC), joining the efforts of 24 laboratories from all over the world was created at EPAC94. A Technical Review Committee (TRC) was nominated with a precise mandate, i.e. "examine accelerator designs and technologies suitable for a collider that will initially have c.m. energy of 500 GeV and luminosity in excess of 10^{33} cm^{-2} s^{-1} and be built so that it can be expanded in energy and luminosity to reach 1 TeV c.m. with luminosity of 10^{34} cm^{-2} s^{-1}." International workshops are regularly organised to monitor the progress of the studies, compare possible performances with physics requests and favour exchanges between experts in the field. The TRC described the status of the various options and is continuously updating their performances[20)]. After a large exploration of the various options, three lines of R&D are intensively pursued which mainly differ by the technology and the frequency of the main linac accelerating structures covering a wide range of frequency from 1.3 to 30 GHz and based on:

- superconducting technology (SC) in TESLA,
- high-frequency klystrons and normal conducting structures (NC) in JLC and NLC,
- Two Beam Acceleration (TBA) in CLIC and TBNLC.

Their respective parameters are compared in Table 1.

4.1. Linear Colliders design

The luminosity of a linear collider depends on a small number of parameters[23)] (see Table 1 for definition of parameters):

$$L = \frac{H_D N_b N_e^2 f_{rep}}{4\pi\sigma_x\sigma_y} \propto H_{Dy} \frac{\delta_B^{1/2} P_b}{U_b \varepsilon_y^{*1/2}}$$

The enhancement factor, H_D, takes into account the modification of the beam sizes by disruption during collision at the I.P. The so-called pinch effect helps to increase the integrated luminosity by mutual focusing of the bunches when colliding electrons and positrons. However, this effect has to be limited as it generates synchrotron radiation by beamstrahlung which is responsible for an average beam energy loss, δ_B, broadening of the luminosity spectrum and background, all detrimental to good physics conditions. A flat beam at the IP ($\sigma_y \ll \sigma_x$) makes a high luminosity possible and at the same time a reasonable δ_B. Acceptable average energy loss, typically of the order of a few %, limits the achievable enhancement factor. As a consequence, the luminosity at a given beam energy U_b and a specified δ_B only depends on the beam power and its normalised vertical emittance.

In order to reach the specified luminosities, a future TLC will have to collide beams with several MW of power and extremely small emittances strongly focused to vertical sizes of a few nanometres at the IP (Table 1). The values of beam sizes and emittances specified in the various studies are compared respectively in Figs. 8 and 9 with the operational values obtained in the SLC and with the performances achieved in test facilities. The feasibility of a few 10^{-8} rad m vertical emittance has already been demonstrated by an international collaboration in the Accelerator Test Facility (ATF)[21)] at KEK (Fig. 8). rms beam dimensions down to 45 nm with a demagnification factor of 350 as required by linear collider designs have been achieved by another international collaboration in the Final Focus Test Beam (FFTB) experiment[22)] at SLAC (Fig. 9). A beam size reduction by one order of magnitude in the vertical plane has still to be demonstrated.

In order to reduce the beam power and therefore the wall plug power consumption, the average energy loss by beamstrahlung is allowed to rise in high-energy designs and ultimately limits the possible colliding beam energy in linear colliders (Table 1).

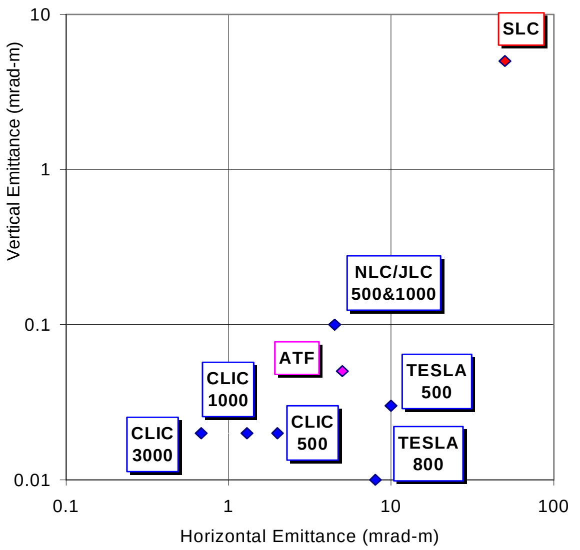

Fig. 8: Emittances at collision in linear colliders and comparison with performances in SLC and ATF.

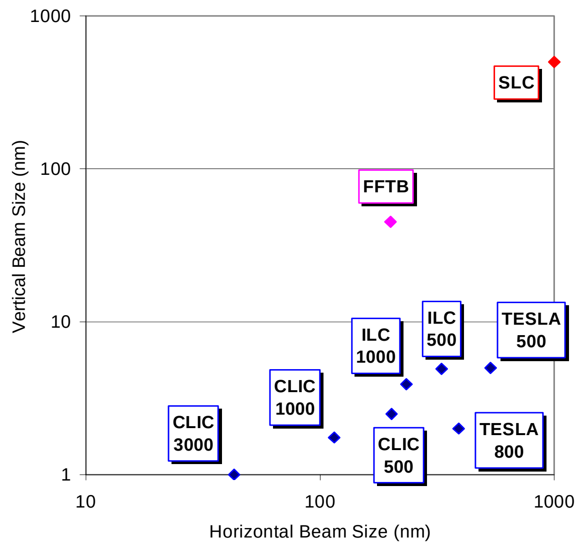

Fig. 9: Beam sizes at collision in linear colliders and comparison with performances in SLC and FFTB.

Finally, the main R&D effort focuses on the various possible approaches of the beam acceleration technology in the main linac.

4.2. TESLA

The TESLA collaboration located at DESY plans for a linear collider with a c.m. energy of 0.5 TeV[24]. The linacs rely on 1.3 GHz standing-wave superconducting rf cavities with an accelerating gradient of 21.8 MV/m, possibly improved to 34 MV/m to reach an energy of 0.8 TeV with the same overall extension of 32 km as shown in Fig. 10.

There are three main motivations for using superconducting structures for beam acceleration in the linac:

- their low rf losses due to a high quality factor ($Q \approx 10^{10}$) provides an excellent rf to beam transfer efficiency of 23%.
- the wakefields generated by the particles in the structures, which possibly deteriorate the beam quality, are small because of the low frequency of 1.3 GHz and the large internal dimensions of the structures. As a consequence, the beam emittances are well preserved during acceleration in the long linacs leading to a very high luminosity of $3\ 10^{34} cm^{-2}s^{-1}$ at 500 GeV.
- because of the small losses in the superconducting structures, a large interval between bunches (330 ns or 100 m) can be accommodated which makes head-on collisions at the IP possible and simplifies the detector working in single-bunch mode.

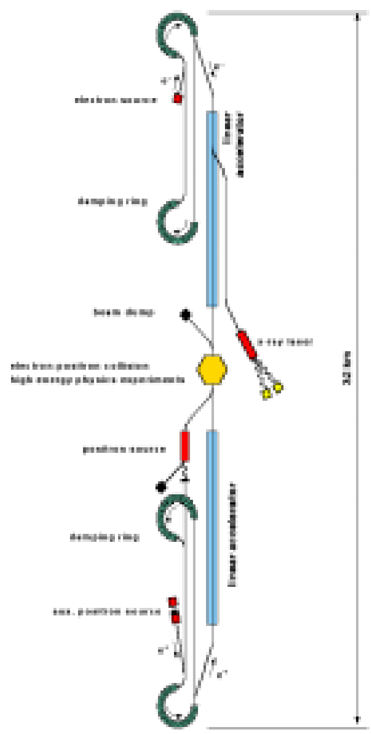

Fig. 10: TESLA schematic layout.

The two main challenges of the superconducting technology development are:

- an improvement of the accelerating fields, well above the present standards of 6 to 7 MV/m achieved in CEBAF or LEP2, in order to limit the overall size of the facility,
- a reduction of the cost by about a factor of 20 per MV with a goal of 2 kEuro/MV as compared with the present standards of about 40 KEuro/MV. The objective is to achieve this goal by an increase of the accelerating field by a factor 3 to 4 (at 500 GeV) and a reduction of the cost per meter by a factor 5 to 7.

A strong R&D programme has been initiated by the TESLA collaboration in order to improve the performances of superconducting cavities and reduce their cost.

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 and results in a filling factor of accelerating structures along the linac as high as 78%. The klystron feeding four cryomodules has to provide 8.3 MW. The first multi-beam prototype klystron reached 10 MW with 65 % efficiency (close to the design value of 70 %). A compact arrangement in a 5 m-diameter tunnel is shown in Fig. 11.

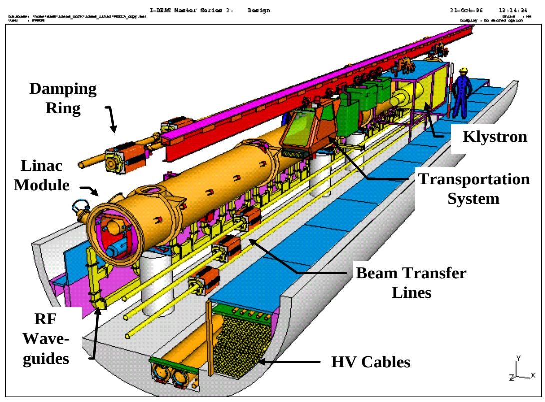

Fig. 11: Schematic view of TESLA tunnel installation.

Excellent progress has already been achieved in both accelerating fields and quality factor as shown in Fig. 12, which compares the TESLA specifications with the measured values in the various cavities built so far. Moreover, the mean value of the accelerating field and especially the best test values obtained after conditioning, continuously improve with time together with a progressive reduction of the spread of performance as displayed in Fig. 13, demonstrating that the main criteria of fabrication are now better understood and controlled.

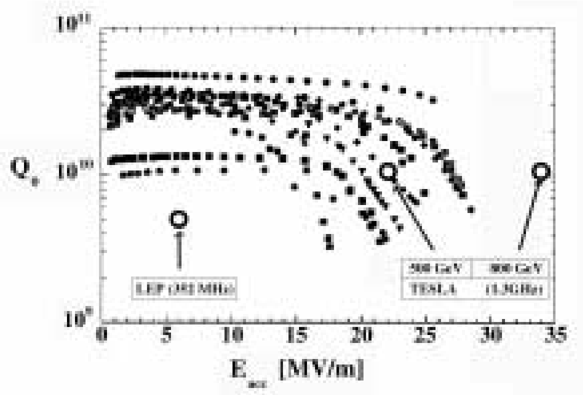

Fig. 12: Quality factor and accelerating gradient of the TESLA cavities and comparison with the specified values at 500 and 800 GeV.

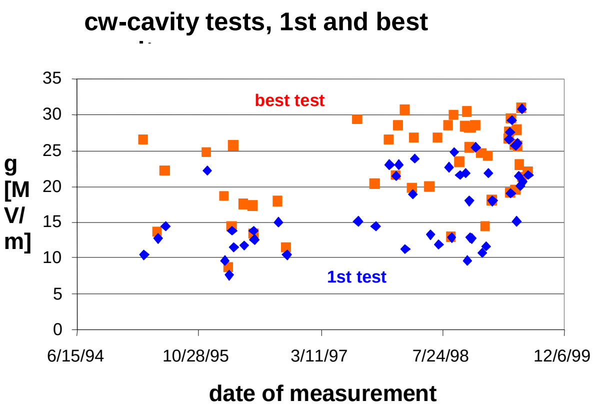

Fig. 13: Evolution with time of the performances of all TESLA cavities built to date.

A TESLA Test Facility (TTF)[25] is operating at DESY with one module containing eight 9-cell cavities where, in beam tests, 16 MV/m have been achieved. Two more modules with cavities operating at 20 to 25 MV/m have been installed and demonstrated an overall beam acceleration of 400 MeV at the end of 1998. The installation of an undulator for testing the Self Amplified Spontaneous Emission (SASE) Free Electron Laser (FEL) at a 40 nm wavelength before the end of 1999 will complete this first phase. A second phase of the facility, TTF2, is under preparation with the construction of another 5 modules to gradually raise the beam energy above 1 GeV until 2001. TTF2 could then be used as a VUV Laser facility based on the SASE principle (if demonstrated) from 2002.

A conceptual design report of a linear collider based on the TESLA technology was published[24)] in 1997. A design report including the cost and schedule is foreseen in 2000 for a possible decision in 2003 and a construction in 6 to 7 years leading to a possible beam commissioning at the earliest in 2010. The first part of the electron linac is proposed to feed a 30 to 50 GeV beam to an X Ray facility[26)] based on the SASE principle and providing an excellent average brilliance up to a few 10^{26} photons/(s.mrad^2.0.1% bandwidth) in the 10 keV energy range.

Nevertheless, further R&D is still needed, mainly:

- accelerating field improvements towards 34 to 40 MV/m,
- superconducting technology cost reduction,
- superstructure development with 1 coupler feeding 4 cavities for better filling and lower cost,
- multi-beam klystron with high-power (10 MW), long rf pulse (1.3 ms) and high efficiency (70%),
- wiggler dominated damping ring with dog-bone shape and 17 km long circumference generating very small equilibrium emittances,
- positron production with γ generated by the high-energy beam in an undulator just before the IP.

4.3. NLC + JLC = ILC

An International Linear Collider (ILC) Optimisation Study Group was created early 1998 by KEK and SLAC and was extended recently to FNAL, LBL and LLNL. It pursues the study of a collider[27, 28)] based on the well proven technology of the SLC (room-temperature travelling-wave copper accelerating structures powered by pulsed klystrons operating at an rf frequency of 2.86 GHz and accelerating fields of 17 MV/m) but at a 4 times higher rf frequency of 11.4 GHz in the X-band range. Indeed, as shown in Fig. 14, all linear collider studies (except TESLA because of the specificity of the superconducting technology) intend to increase the rf frequency of their accelerating structures in line with the one of the SLC, in order to benefit from higher accelerating fields and therefore to limit the overall extension of the complex. KEK and SLAC have chosen a 11.4 GHz frequency as

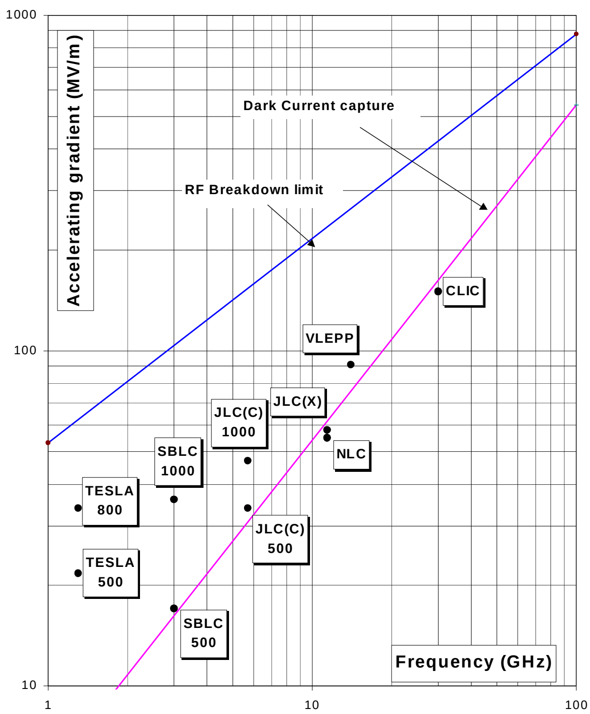

Fig. 14: Accelerating fields in linear collider studies.

the highest frequency at which high-power klystrons are still feasible. Such a frequency allows accelerating fields of 55 MV/m which makes linear colliders in the 1 TeV range possible.

The main challenges of this technology consist of:

- the development of all accelerator components at an unusual frequency,
- the development of efficient, high-frequency rf power sources including modulators, klystrons and rf pulse compression system,
- a multi-bunch emittance preservation in a strong wakefield environment which scale with the second power of the frequency in the longitudinal plane and with the third power in the transverse plane.

Both laboratories have published Zero Design Reports (ZDR) called JLC [29)] at KEK and NLC [30)] at SLAC providing a luminosity of about 5 x 10^{33} cm^{-2} s^{-1} at 500 GeV with possible upgrade up to 1 TeV with a luminosity of 1 x 10^{34} cm^{-2} s^{-1} by doubling the length of the linacs. Each 500 GeV linac is built with 414 standard and repetitive modules (Fig. 15). Each module comprises 4 modulators powering 8 klystrons, 2 by 2, and providing rf power which is distributed in time by a Delay Line Distribution System (DLDS) to efficiently feed 4 groups of 3 accelerating structures. A 1 TeV

ILC therefore requires the large number of 3312 modulators, 6624 klystrons, 828 DLDS and 9936 accelerating structures. Strong R&D is engaged in developing and optimising each of these key components in terms of performance, cost, efficiency and reliability.

Modulators, based on the conventional technology of power storage in a Pulse Forming Network, are compared with induction modulators where the power to feed the klystrons is provided by 500 power supplies (5 kV/2kA) inductively coupled with metglass. Such a technology, derived from the induction linacs and recently proposed by LNLL, is potentially more efficient.

Excellent progress has been made in the development of klystrons in the X-band range where the conventional technology of solenoid focusing is being replaced by Periodic Permanent Magnets (PPM) in order to reduce the power consumption (Fig. 16). The performance achieved with klystrons with both methods of focusing are compared in Fig. 17 with the specifications in the two planned modes of operation with 1.5 or 2.5 µs pulse length. Klystrons with solenoid focusing meet all specifications except the efficiency whereas klystrons with PPM focusing demonstrate a better efficiency but only reach the power requirements in the long pulse mode so far.

In order to meet the rf power requirements of the accelerating stuctures (200 MW during 380 ns), the rf power provided by the klystrons is multiplied and compressed in time by a factor of 4 or 6 respectively in the short and long pulse klystron operation. This is accomplished by a novel Delay-Line Distribution System (DLDS) invented[31)] in KEK and refined by SLAC.

The rf power after summation from 8 klystrons in single or multi-modes is distributed in four modes to the accelerating sections via an over-moded waveguide. Each of the modes drives a group of three cavities (Fig. 15). The DLDS provides a pulse compression with a transmission efficiency which is potentially very efficient (85%). However, it requires an excellent efficiency of each individual component and the absence of trapped modes in the overall system operating with a power up to 600 MW.

Accelerating structures between 1 m and 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

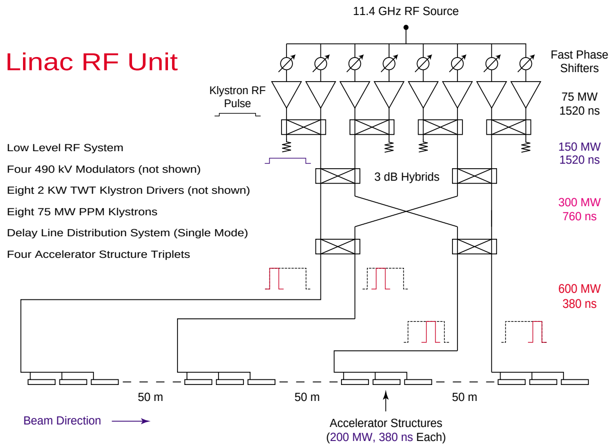

Fig. 15: Schematic layout of one rf module of the NLC Linac.

Fig. 16: Photograph of the 50 MW, X-Band, PPM focussed, Klystron developed at SLAC.

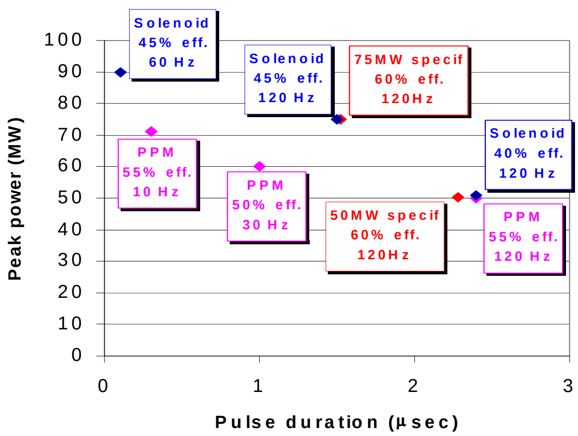

Fig 17: NLC Klystron performances.

wakefields between the bunches in a train, the cells are damped and detuned 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. Reduction of the wakefields by two orders of magnitude have been obtained with excellent agreement between measured and expected values (Fig. 18).

The NLC Test Accelerator (NLCTA)[32] at SLAC is the first X-band linear accelerator and is a unique facility for testing 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. The facility in its present configuration demonstrated a beam acceleration of 200 MeV with an energy variation over a bunch train adequately reduced (beam loading compensation) by proper shaping of the rf pulse. A string test constituted by a complete ILC module based on the new multi-moded DLDS system is under construction for test with beam in the NLCTA from October 2001.

At SLAC, a great effort has been put into developing modern management tools for costs, resource loaded schedules and risk analysis. The overall cost of an ILC has been estimated to be 7.9 G$ at 500 GeV and 10.3 G$ at 1 TeV (including salaries as well as 25% contingency and 20% escalation till the period of construction). A DOE review recently recommended the preparation of a conceptual design report (CDR) and the corresponding necessary R&D to continue improving the performances of an ILC and to reduce its cost. The road map towards an ILC foresees the submission for approval of the CDR in summer 2002 and a construction starting in Autumn 2003 for a commissioning with beam from Autumn 2010.

At KEK, a design study[33] based on C-band (5.7 GHz) is being pursued on a modest scale in parallel with the X-band study. 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 50 MV/m. It is

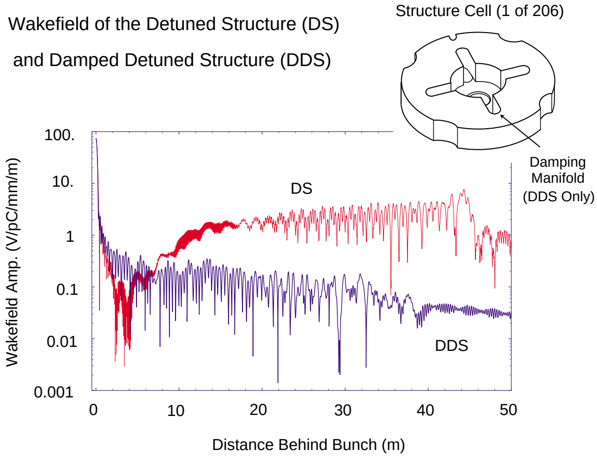

Fig 18: Wakefield reduction in the NLC detuned structure (DS) and damped - detuned structure (DDS.

planned to test one basic rf unit in the injector of the KEK B-Factory.

4.4. Compact Linear Collider (CLIC)

The Compact Linear Collider (CLIC) Study[34] located at CERN is developing the concept and the technology for a linear collider in the multi-TeV range with physics potential comparable and beyond LHC. It is optimised for a 3 TeV $e^{\pm}$ colliding beam energy and high luminosity (10^{35} cm^{-2} s^{-1}) to meet post-LHC physics requirements[9]. It is planned to be built in stages without major modifications and covers a c.m. energy range for $e^{\pm}$ collisions of 0.5 up to 5 TeV. An overall layout of the complex is shown in Fig. 19.

The rf frequency of the linac accelerating structures is chosen as high as possible in order to increase the accelerating field and therefore limit the overall length and the cost of the linacs. An rf frequency of 30 GHz has been selected as it is considered to be close to the limit beyond which standard technology for the fabrication of structures can no longer be used and allows 150 MV/m accelerating fields with copper travelling-wave structures without breakdown and low dark current (Fig. 14).

The rf power pulse of 400 MW/m during 130 ns, necessary to feed the 50 cm-long accelerating structures and generate fields of 150 MV/m, cannot be provided by klystrons especially at this high frequency of 30 GHz. The rf system is based on a Two-Beam Accelerator (TBA) method the principle of which was

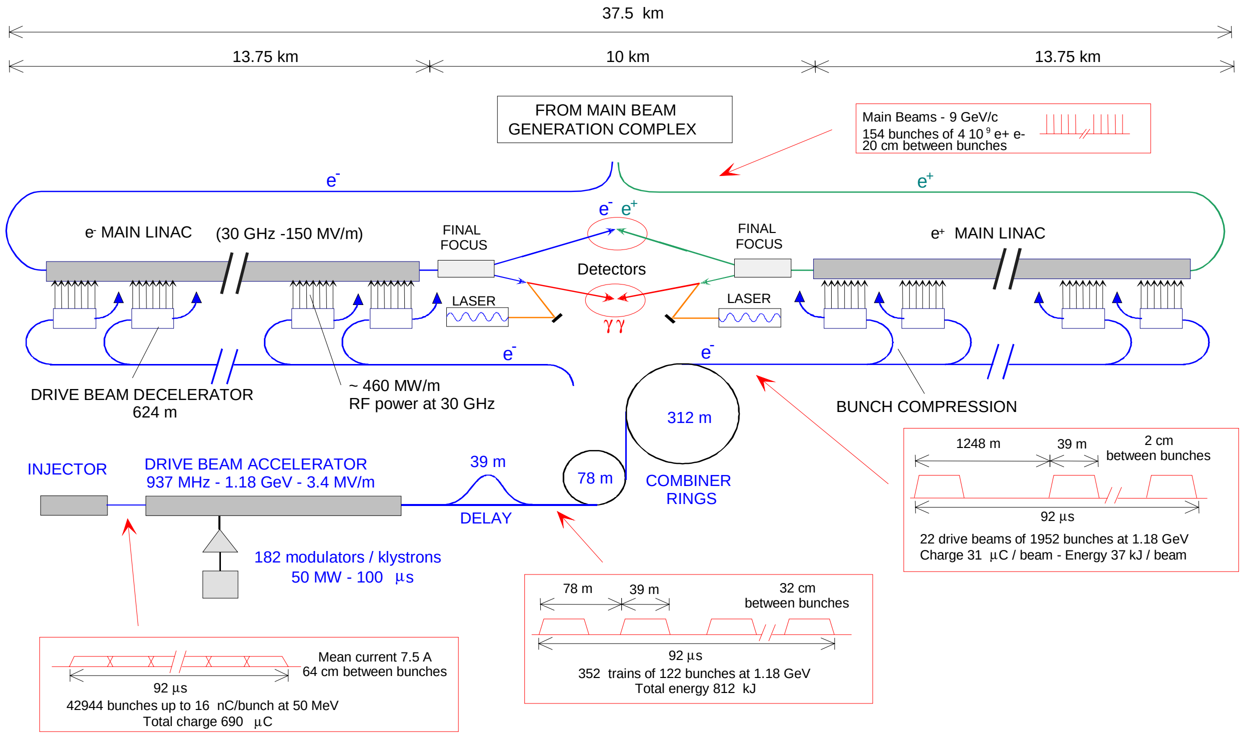

Fig 19: Overall layout of the CLIC complex at 3 TeV c.m.

initially proposed by A. Sessler[35], adapted to linear colliders by W. Schnell[36] and further developed in a novel, efficient and promising scheme by the CLIC study team[37]. The rf power is extracted by decelerating structures from a so-called drive beam running parallel to the main beam and transferred to the accelerating structures of the main linac (Fig. 20). One drive beam for each linac at 3 TeV c.m. is constituted by a series of 22 drive beam pulses with a high-intensity (240 A) and low-energy (1.2 GeV). By sending this drive beam train towards the on-coming main beam, different time slices of the pulse can be used to power separate sections of the main linac. Each of these pulses is used one after the other to provide rf power to a 624 m-long section of the main linac, after which it is dumped when its beam energy is reduced to 120 MeV. A single tunnel, housing both accelerating and decelerating linacs as well as the various beam transfer lines without any modulators or klystrons, results in a very simple, cost effective and easily extendable arrangement (Fig. 21).

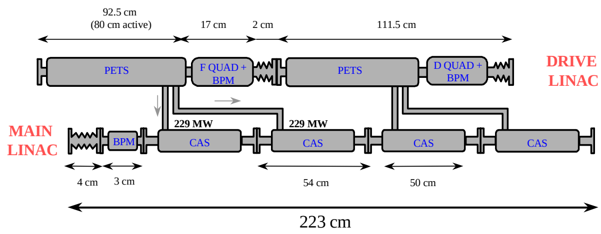

Fig. 20: One CLIC main beam and drive beam module.

The 22 pulses of each drive beam, spaced at intervals of 1.25 km, are produced as one long pulse by one of the two drive-beam generators. All the bunches are first generated and accelerated with a spacing of 64 cm as one long continuous train (92 µs) in a normal-conducting fully-loaded 937 MHz linac with an rf beam efficiency ≈ 97%. After acceleration the continuous train is split up into successive trains in a delay line. These trains are then merged in a combiner ring by interleaving four successive bunch trains over

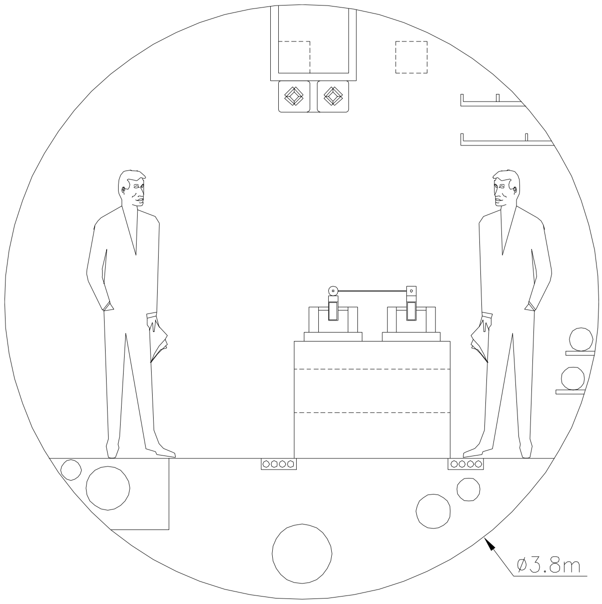

Fig. 21: Tunnel cross-section.

four turns in two successive stages of combiner rings to obtain a distance between bunches of 2 cm. A power compression and frequency multiplication by a factor 32 with an excellent efficiency is therefore obtained by simple beam manipulations. Such a power generation method[37)], which transforms the long pulse at low frequency and low power provided by efficient Multi-Beam Klystrons (MBK) to high-field linac requirements with short pulse of high-power at high frequency is valid for any frequency. It is easily upgradable to the higher energy of the main linac by a simple extension of the modulator pulse of the drive beam accelerator.

The main challenges of the CLIC scheme are very similar to those of the ILC but reinforced because of the higher frequency. This is especially true for the wakefields because of their strong dependence on the frequency. Taking advantage of the enormous effort invested in the design of linear colliders over one decade of frequency range during the last ten years, general scaling laws have been established[38)]. They clearly demonstrate that beam and linac parameters can be chosen such that the effects of the wakefields can be made independent of the frequency of the accelerating structures. The highest wakefields at high frequency are compensated by:

- a lower charge per bunch,
- a stronger transverse focusing made possible by the reduced size of the components,
- shorter rf structures for optimum rf to beam efficiency,
- better alignment made possible by the smaller size of the components.

As a consequence, high-frequency linear colliders are not more difficult to operate than lower frequency ones and benefit from higher accelerating fields. Nevertheless, components at the unusual frequency of 30 GHz have to be developed and the novel Two-Beam Acceleration scheme has to be demonstrated.

Accelerating structures suitable for single bunch operation have been built with 1 to 2 μm fabrication tolerances. A Tapered Damped Structure (TDS) for multi-bunch operation consisting of 150 cells has been designed[39)]. For the sake of beam stability, each cell is damped by its own set of four radial waveguides giving a Q of 16 for the lowest dipole mode (Fig. 22). A simple linear taper of the iris dimension provides a slight detuning frequency spread of 2 GHz (5.4%) and a quasi constant unloaded accelerating field. Transverse wakefield calculations in this structure with non-perfect loads show a short-range level of about 1000 V/(pC·mm·m) decreasing to less than 1% at the second bunch and a long time level below 0.1%. A 15 GHz scaled prototype has been built and the strong damping behaviour confirmed by measurements in ASSET at SLAC.

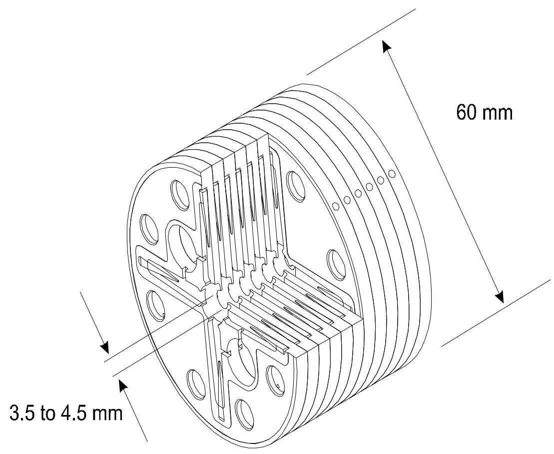

Fig 22: Cut-away of a Tapered Damped Structure (TDS).

The first CLIC Test Facility (CTF1) operated from 1990 to 1995 and demonstrated the feasibility of two-beam power generation. It produced 76 MW of 30 GHz rf power and generated on-axis gradients in the 30 GHz structures of 125 MV/m. A new test facility (CTF2)[40)], equipped with four 30 GHz modules made with rf components as similar as possible to the one envisaged for CLIC and including a few-micron-precision active alignment system, is now complete and is presently being commissioned. The drive beam generation is based on a laser driven rf photo-injector, providing a train of bunches which are accelerated with a 3 GHz TW accelerating structure specially designed for high-charge operation and compressed in length by a magnetic chicane. Accelerating gradients of 70 MV/m have been achieved so far resulting in a 55 MeV energy gain of the 0.7 nC probe beam.

A new facility (CTF3) is under study (Fig. 23), which will test all major parts of the CLIC rf power scheme[41]. To reduce costs, it is based on the use of the ten 3 GHz 40 MW klystrons and modulators from the LEP injector Linac. The drive beam is generated by one thermionic gun and is accelerated to 180 MeV by 20 short fully loaded structures operating at 7.4 MV/m with an rf to beam efficiency of 96%. The beam pulse is 1.4 µs long with a current of 3.5 A. The bunches are initially spaced by 20 cm (two 3 GHz buckets) but after two stages of frequency multiplication they have a final spacing of 2 cm. This bunch train is then decelerated by four power-extracting structures in the drive-beam decelerator. Each structure provides 460 MW. The main beam is accelerated to 0.5 GeV by eight 30 GHz accelerating structures operating at a gradient of 150 MV/m. This facility is foreseen to be built as soon as LEP stops at the end of 1999 and will extend over 5 years up to 2004. It could then be upgraded to the so-called CLIC 1 complex, able to power and test one section of the linac with one complete drive beam pulse at full energy and full current and to accelerate one main beam up to 68 GeV. Such a complex would be very close to the rf power source of one CLIC beam. Only the modulator pulse length would have to be extended. This would accurately test all long-range effects and high-power beam management. It would constitute an excellent demonstration project and would provide a reliable cost basis for the 44 times larger CLIC, reducing therefore considerably the technical risks. A decision could then be made for the construction of a linear collider based on CLIC technology at the earliest in 2009 and a commissioning facility with beam in 2015.

A collaboration between LBNL and LLNL is working on an alternative rf power source for a high-frequency linear collider, called Relativistic Klystron (RK)[42]. Each unit would provide up to 760 MW/m over 300 m. The design rf is 11.4 GHz but the scheme could also be applied for 30 GHz. Each unit consists of an injector producing a 2.5 MeV, 1.2 kA electron

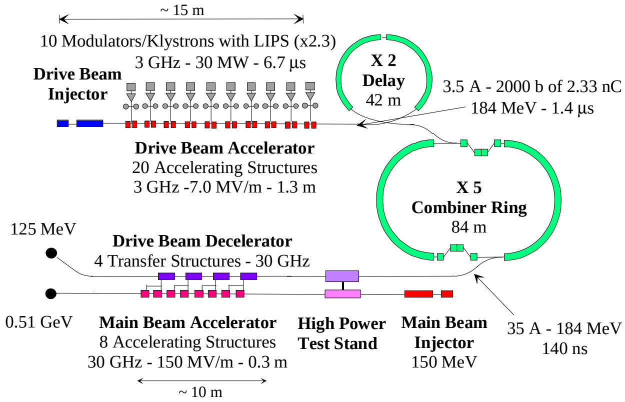

Fig 23: Schematic layout of the CTF3.

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 test facility, called RTA, has been established at LBNL to verify the analysis used in the design. A prototype of about 26 m length operating with a 4 MeV electron beam will be tested.

4.5 Parameters for Linear Colliders

After a broad exploration of the various technologies of linear colliders, three schemes are now considered that are highly complementary:

TESLA offers an impressive luminosity but is limited in colliding beam energy.

ILC and JLC_c requires least extrapolation from known and well-tested technology but require a large number of klystrons and high power components,

CLIC is the only scheme which can eventually reach the multi-TeV energy range beyond LHC but the novel Two-Beam Acceleration scheme has to be demonstrated.

A selection of the main parameters of these studies at their nominal energy is given in Table 1 below.

Technology			TESLA	JLC_C	ILC	CLIC
			S.C.	KLYSTRONS		TBA
Beam parameters at I.P.						
Centre-of-mass energy	[TeV]	$2U_b$	0.5	0.5	1.0	3.0
Luminosity	$10^{33}cm^{-2}s^{-1}$	L	30	7.2	13	100
Average energy loss	[%]	δ_B	2.8	4.1	10.3	31
Linac repetition rate	[Hz]	f_{rep}	5	100	120	100
Number of particles/bunch	$[10^{10}e^{\pm}]$	N_e	2	1.1	0.95	0.4
Number of bunches/pulse	[-]	N_b	2820	72	95	154
Bunch spacing	[nsec]	Δ_b	337	2.8	2.8	0.67
Transverse emittances .(H/V)	10^{-8} radm	$\gamma\varepsilon_{x,y}$	1000/3	330/5	450/10	68/2
RMS beam width .(H/V)	[nm]	$\sigma_{x,y}$	553/5	318/4.3	234/3.9	43/1
Bunch length	[µm]	σ_z	400	200	120	30
Beam power per beam	[MW]	P_b	11.3	3.1	8.7	14.8
Main Linac						
rf frequency of main linac	[GHz]	$\omega/2\pi$	1.3	5.7	11.4	30
Accelerating field (loaded)	[MV/m]	G	21.7	36	55	150
Total two linacs length	[km]	l_T	30	16	20.9	27.5
Klystron peak power	[MWatts]	P_k	8	50	75	50
Klystron pulse length	[µsec]	Δ_k	1330	2.4	1.55	92
rf pulse compression ratio	[-]	-	-	5	4	32*22
Number of klystrons	[-]	N_k	616	3560	6624	364
AC to beam efficiency	[%]	η_b^{AC}	23	4.6	8.6	9.8
AC power for rf generation	[MW]	P_{AC}	95	130	200	300

Table 1: Main parameters of linear collider designs at various colliding beam energies taken from[20].

5. Muon colliders

The main limitations of electron-positron colliders, due to the emission of synchrotron radiation in bends, can be removed if muons are used instead of electrons. This makes the emission of synchrotron radiation negligible, which scales with the – 4th power of the particle mass. As a consequence, muon colliders benefit from all the advantages of lepton colliders over hadron colliders (Chapter 4) without suffering from the drawbacks:

- Because of the absence of synchrotron radiation, muons can be accelerated and collide in a circular ring similar to LEP. As the same cavities are re-used at each turn, acceleration in a ring is, in principle, less expensive and more efficient than in a linac.
- The luminosity is increased with the number of circulating turns such that the beam sizes at collision can be much larger, in the micron rather than in the nanometre range.
- Because of a lower Initial State Radiation (ISR) and of the absence of beamstrahlung radiation during collisions, the induced beam momentum spread is very narrow which provides precise energy determination.
- The light Higgs boson (if it exists) is produced at low-energy, in the 130 GeV range, profiting from a direct s-channel and with a good luminosity because of the cross-section scaling with the square of the mass of the primary particle.

Muon colliders are therefore very attractive but no experience is presently available. Their technology has to be totally invented and developed with two main challenges:

- Muons are produced with a very low density in phase space leading to large transverse emittances and momentum spread which requires an efficient particle production and a strong cooling in the six dimensional phase space.
- Their lifetime is limited to 2 μs at rest (or 600 m travelling distance) and increases linearly with the particle energy. Therefore, muons have to be accelerated rapidly before they decay into neutrinos. Disintegration of muons generates large background in the detector and limits the colliding beam energy due to the so-called neutrino hazard. On the other hand, the decay of muons into neutrinos can be profitably used to provide a high flux neutrino source.

There is a proposal to build a muon collider in three successive and complementary steps:

1. **A neutrino factory** where the neutrinos are produced from the decay of muons circulating in a storage ring at an energy of 30 to 50 GeV. It would improve the performance of present neutrino sources by several orders of magnitude in short and long base line facilities and would constitute the “ultimate weapon” for Neutrino Oscillations measurements.
2. **A high-precision muon collider** in the 100 to 500 GeV range for precision measurements of resonance widths taking advantage of the very narrow beam momentum spread during collisions. At 100 GeV, it would constitute an Higgs factory with a good luminosity by direct Higgs production in the s-channel. It could then be upgraded in the 350 to 500 GeV for an excellent Top factory and would constitute the ideal tool for Higgs and Top physics.
3. **A high-energy muon collider in the TeV range** for exploration of the high-energy frontier. Because of the acceleration and collisions in rings, the overall size of a muon complex is still reasonable and well adapted to existing HEP laboratories. The maximum beam energy is limited to around 3 to 4 TeV by the neutrino hazard for maximum allowed public radiation.

The concept of muon colliders was first introduced in 1969 by G.I Budker[43)] but only became of interest with the proposal of ionisation cooling by N. Skrinsky[44)] in 1981. Cooling opened the way to decent luminosities which were improved further by D. Neuffer and R. Palmer[45)]. A large international Muon Collider Collaboration (MCC)[46)] is now studying muon colliders with representatives from many different laboratories and R. Palmer as the spokesman. In the USA, the HEPAP subpanel in 1998 recommended an “expanded program of R&D to be carried out on a muon collider including both simulations and experiments”. This recommendation is now followed by a collaboration between BNL, FNAL, LBNL Princeton, and UCLA. In Europe, a prospective study[47)] has recently been initiated at CERN following a recommendation by the ECFA. A collaboration between the CEA Saclay, CERN and Rutherford is presently envisaged.

After a number of iterations and optimisation by the Muon Collider Collaboration, the reference scheme of a muon collider[48)] is presented below with a schematic description in Fig. 24. Basic parameters at various energies are summarised in Table 2.

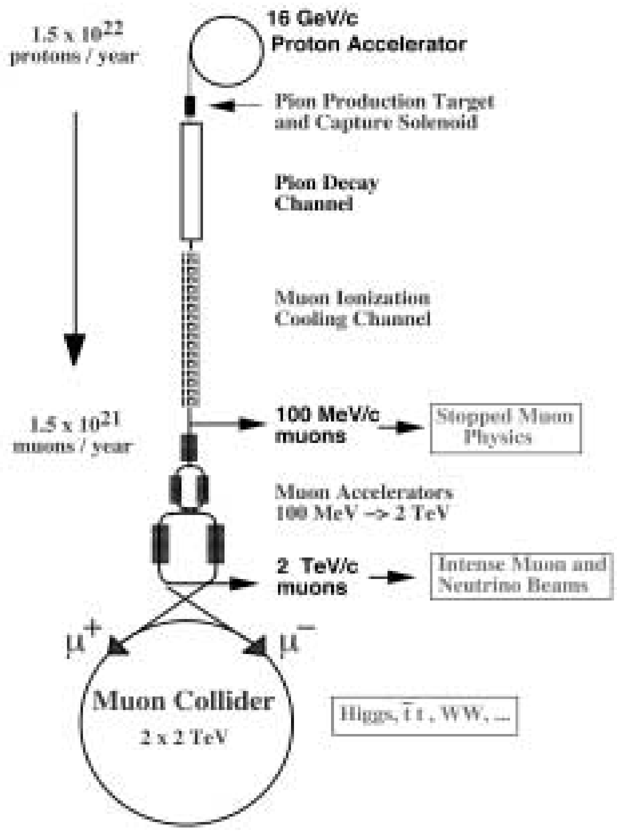

Fig. 24: Schematic layout of a $\mu^+ \mu^-$ collider.

5.1. Basic scheme of a muon collider

The first element is a 16 GeV proton synchrotron with a 1 GeV linac injector and a 3 GeV booster in the baseline design. It provides 1 x 1014 protons/pulse in four bunches with a 15 Hz repetition frequency, which

	Higgs-factory	Top factory	Energy frontier
Collider:			
*E*cm (TeV)	0.1	0.4	3
<L> (cm-2 s-1)	1.2 10^{32} 10^{31}	10^{33}	7 x 10^{34}
<$\Delta p/p$> rms %	0.12 0.003	0.14	0.16
$\sigma_{\perp}$*(μm)	86 294	26	3.2
$2\pi R$ (m)	350	1000	6000
B dipole (T)	3	4.7	5.2
N turns	450	700	785
Depth (m)	10	100	500
P_{ac} (MW)	81	120	204
Proton driver:			
E_p (GeV)	16	16	16
P_b (MW)	4	4	4

Table 2. Key parameters of μ^+ μ^- colliders.

corresponds to a beam power of 4 MW. Half of the bunches are used to make μ^+ and the others for μ^- . 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 (Figure 25).

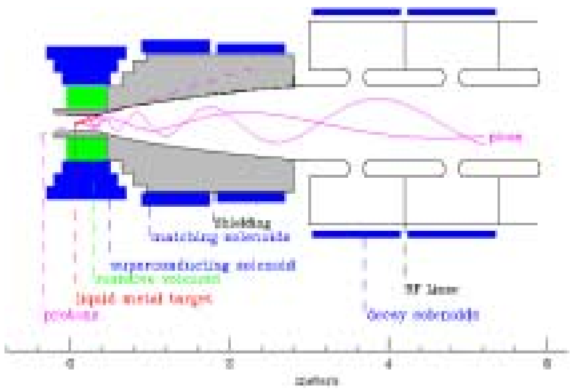

Fig. 25: Schematic view of pion production in a target followed by pion capture and phase rotation.

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 0.1 muons per proton are expected at the end of the decay channel which is about 600 m long.

The decay channel is followed by the cooling section which increases the 6-dimensional phase-space density of the muon bunches by a factor 10^6 using ionisation cooling. The cooling is obtained in about 20 stages, each one providing a cooling by a factor 2 in the six dimensional phase space. 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. The overall power consumption of the pion decay channel and of the ionisation cooling channel is a concern.

Fast acceleration of muons is accomplished by 1 linac and 2 recirculators in series in the CEBAF fashion, preferably equipped with super-conducting rf systems. 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 that focuses 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 very penetrating muons. High-energy muons are also lost from the circulating beam bunches. All this strong background requires an elaborate detector shielding and an effective 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 c.m. but its control requires a depth of 100 m for the 0.5 TeV collider and at least 500 m for the 3 TeV version.

Table 2 shows possible parameter lists for Higgs and Top factories and for a collider at the high-energy frontier. Note the very low-energy spread of the muon beam compared to the energy spread in a linear collider. The energy spread can be further reduced though at the expense of lower luminosity, as shown in a second parameter set for a Higgs factory. The total length of all accelerators, including the collider is 36 km for the 3 TeV c.m. version, which is about the same length as the CLIC version (37.5 km) for the same energy[36)]. However, the layout of the accelerators of the muon collider can be arranged so that they all fit inside the last synchrotron which is the largest accelerator and, therefore, the muon collider may fit on an existing site.

The main novelty of the scheme designed at CERN[47)] is the proton driver which is based on a 2 GeV superconducting linac using the 352 MHz LEP cavities rather than the 16 GeV synchrotron inspired by an improved version of the FNAL or AGS rings. Note that, the proton beam power of 4 MW on target is much larger in all cases than is handled at present. The PSI case is not really comparable (e.g. a few kW of pulsed power at ISIS, Rutherford, U.K.) but comparable with what is contemplated for spallation sources (5 MW for JAERI in Japan and the European Spallation Source). Fig. 26 compares the proton driver specifications with the performance of facilities presently in operation or under study. 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.

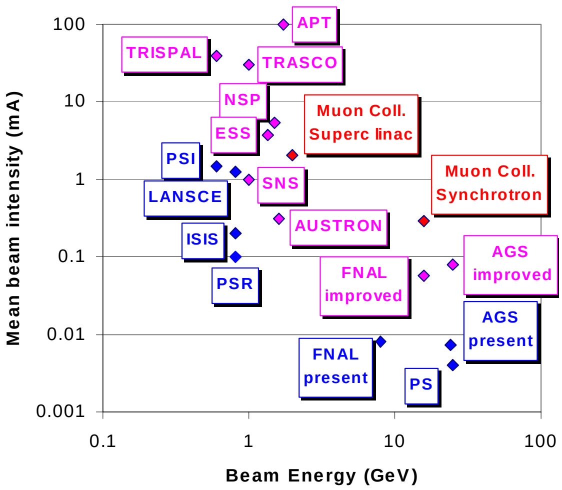

Fig. 26: Performances of proton linacs presently in operation or under study compared with specifi-cations of a muon collider proton driver

5.2. A neutrino factory as a first step

A neutrino factory constitutes a natural first step towards the construction of a muon collider. A schematic representation of such a facility is shown in Fig. 27 as defined in a recent workshop dedicated to this subject.

A neutrino factory requires a front-end very similar to the one of a muon collider with an equivalent proton driver, targetry and pion capture but a simplified cooling system (a factor 40 only) and limited to the transverse planes instead of a factor 10^6 in the 6^{th} dimensional phase space in a muon collider. That would provide 8 10^{13} muons per second in 0.005 radm normalized transverse emittances. After beam acceleration by recirculating linacs, as in a muon collider, but limited to 50 GeV, 4.7 10^{13} muons per second are obtained and circulate in a storage ring with a much simpler design than a muon collider ring.

The muons decay into neutrinos with a flux of 1.6 10^{13}/s or 1.6 10^{20}/year with a 10^7 s/year operation which would serve as neutrino source for short or long base line experiments. Because of the high-beam energy, the distance between experiments can be large with the neutrino factory in one country and the detectors in other parts of the world (Fig. 28) this stimulating fruitful worldwide collaborations.

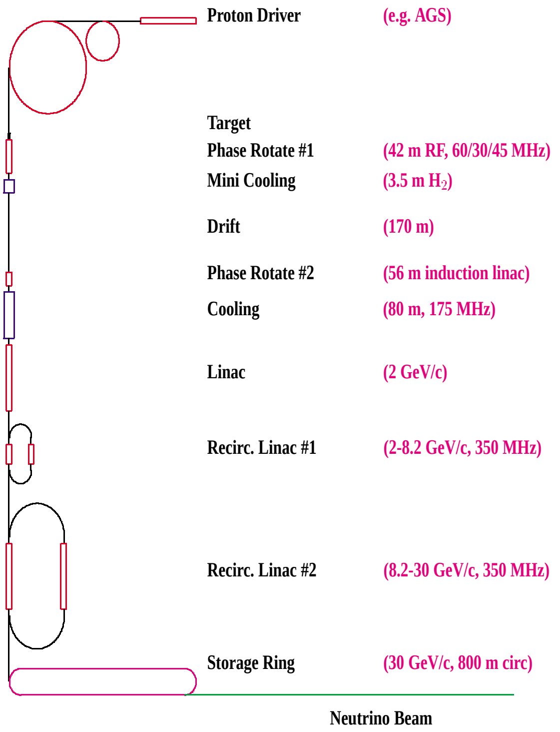

Fig 27: Schematic layout of a neutrino factory.

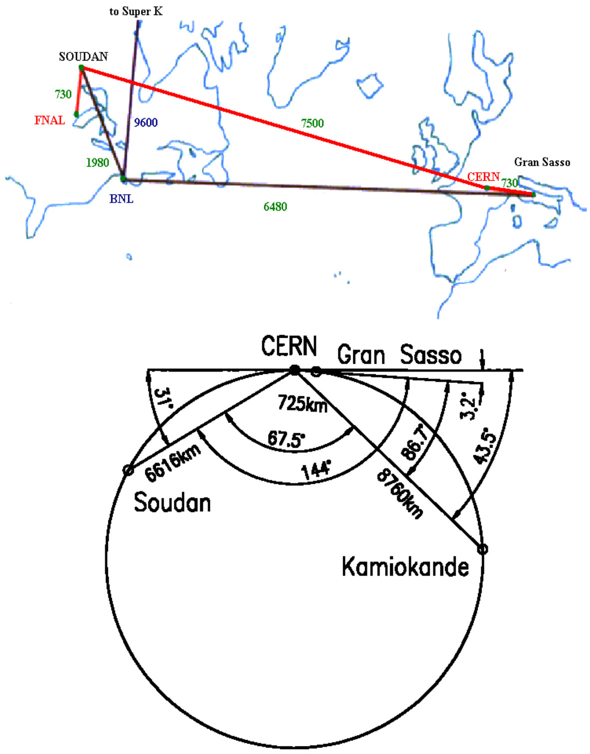

Fig 28: Possible Long Base Line neutrino experiments.

5.3. *R&D for muon colliders*

Extensive computer simulations of the most critical parts of the scheme are presently being performed. The main subjects of R&D are[49]:

- The 4 MW proton driver.
- A target able to handle such a high beam power.
- The production of pions and capture of μ after pions decay with large transverse emittances (200 πradm) and momentum spread (± 150 MeV around 250 MeV).
- The transverse and momentum ionisation cooling for which no experience presently exists.
- The fast acceleration by recirculation linacs or in fixed field synchrotrons.
- The collider ring design.
- The detector in a heavy background environment.

The most critical issues are the target and the ionisation cooling which are addressed with priority: 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 (raising eddy current problems) or liquid insulators (PtO_2,Re_2O_3 or slurries), or a solid target of the "band saw" type possibly in Carbon. A test of targetry and pions collection is being prepared at BNL[50] where AGS bunches with 1.5 x 10^{13} protons of 24 GeV will impinge on a liquid Ga-In jet (Fig. 29). This jet will also be exposed to a 20 T magnetic field to study the effects of eddy currents at the same time. 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 2001.

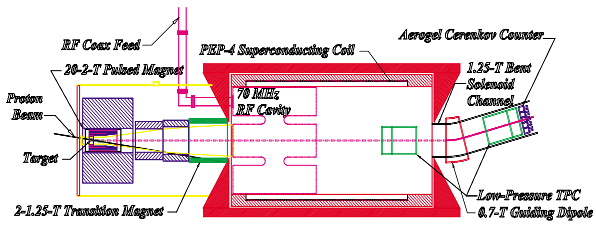

Fig 29: Targetry experiment as prepared at BNL.

A proposal for a six-year R&D programme to build one full stage of transverse and longitudinal ionisation cooling to measure its performance and demonstrate its feasibility is under consideration at FNAL (Fig. 30). Cooling by a factor 2 to 3 in the six dimensional phase space of single muons, with energies of 100 to 300 MeV/c used as probes, are expected.

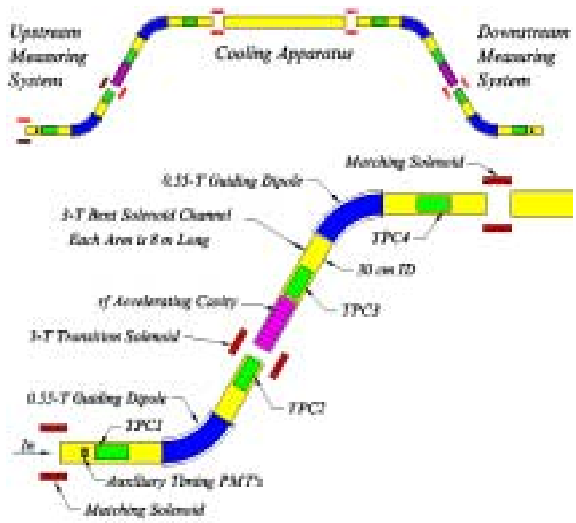

Fig. 30: Cooling experiment as proposed at FNAL.

Complementary tests in line with the linac based proton diver and avoiding duplication from FNAL or BNL tests are envisaged at CERN mainly:

- Measurement in the PS East Hall of pion and kaon production by 2 to 16 GeV protons at low intensity for a quantitative design of pion capture and phase rotation; extension to hadron production by pions for reliable calculation of the atmospheric neutrino flux,
- Measurement of large-angle scattering of muons with momentum of a few hundred MeV/c in various materials including liquid hydrogen for theoretical estimation of ionisation cooling.
- Development of high power targets and tests with beam in the ISOLDE facility at 1.4 GeV.
- High gradient cavities behaviour when exposed to high radiation fields with or without magnetic fields in the antiproton target area of the AD complex.
- Pulsed superconducting cavities for possible higher accelerating gradients.

6. Conclusion

The Tevatron at FNAL, presently at the high-energy frontier, and the LHC at CERN, who will take over from 2005, are excellent discovery tools such that particle physicists are looking forward to a decade of passionating measurements. But the Tevatron and LHC, both proton colliders, are not well suited for precise measurements of particles. Therefore, HEP will certainly require after LHC operating in the TeV range, a high-energy lepton collider much better adapted to precise measurements of particles (if found in the meantime) in the same energy range or/and a proton collider with a higher energy reach in order to extend the exploration range.

Because of the time needed to develop the technology and optimise such facilities with increasing size and cost, a very large R&D effort is presently being pursued by various laboratories all over the world. Very fruitful worldwide collaborations have developed not only to explore all the possible options before selecting the optimum technology but also because duplication of colliders at the high-energy frontier, necessitating investment of several GEuros, is not possible in the future.

Among the various possibilities for colliders, the development at electron-positron linear colliders is certainly the most advanced. A number of concepts have been firmly established and the different technologies are being tested in impressive large-scale test facilities. It will take some time until all technology aspects are fully optimised and the various proposals can be completed with cost estimates as required for an ultimate comparison. Nevertheless, TESLA or ILC technologies could become mature enough in the next few years to make possible a linear collider in the 500 GeV energy range with a possible upgrade in energy. The CLIC scheme is the only technology that can extend the linear collider energy range into the multi-TeV regime. It needs further R&D but could become a realistic candidate in 2010.

Muon colliders are very promising as they benefit from all the advantages of electron-positron colliders without suffering from the linear collider drawbacks. Moreover, they have the potential of a very narrow momentum spread at collision, which is especially appreciated for accurate measurements. The three-step scenario presently envisaged with a neutrino factory evolving into a muon collider to be used as a Higgs and Top factory possibly upgradable in energy up to a few TeV for high-energy exploration is especially attractive. Nevertheless, they require a very challenging R&D programme on a large variety of complex systems which is only starting now. The results from the first experimental tests will not be available for several years. Nevertheless, the technology for a neutrino factory could possibly become available for the post LHC era if a strong enough R&D is started soon. A neutrino factory would constitute an excellent demonstration project and would provide a reliable cost basis for a much larger muon collider thus reducing the technical risks considerably. An "aggressive" schedule has recently been envisaged at FNAL[52)] making the best use of and upgrading the present facilities. It foresees the possible start-up of a neutrino factory in about 7 years, which would be followed by a Higgs factory in another 5 years and a high-energy muon collider in another 5 years.

Concepts for a Very Large Hadron Collider have been worked out, mainly by the leading Laboratories in the US, which are now defining an R&D programme emphasising the development of the magnets as key components. Nevertheless, it will take several years until the results become available and a reasonable choice between the options can be made.

In a conclusion, it is generally accepted that an electron-positron linear collider based on TESLA or ILC technologies is the only scheme that could be mature enough for a collider in the 500 GeV range in the next few years (if the corresponding budgets can be made available). A vigorous worldwide R&D is already launched and ambitious facilities planned to develop the various options. Several collider designs at the high-energy frontier could be ready for an optimum choice around 2010 when the physics needs will be better known after analysis of the results from the Tevatron and the LHC. This will only be possible if, in the meantime, a reasonable fraction of the budget foreseen for HEP is invested worldwide in proposal-driven, peer-reviewed, long-range accelerator research and development.

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