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Energy Frontier Lepton and Photon Colliders

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31.1 Executive Summary

The Snowmass Community Summer Study 2013 was initiated by the Division of Particles and Fields of the American Physical Society to assess the long-term physics aspirations of the US high energy physics community. This report summarizes future capabilities of lepton and photon colliders to support Energy Frontier research, highlighting the research and development required and areas of US contribution. The content of this report has been developed in a series of workshops during spring and summer 2013 and is supported by white papers submitted by members of the community.

In its first three years of data taking the Large Hadron Collider (LHC) has begun to explore the energy region up to, and beyond, 1 TeV. The LHC experiments have discovered a Higgs boson which, within current experimental precision, is consistent with that of the Standard Model and have measured its mass to about 126 GeV. The discovery of the Higgs boson has energized high energy physicists to evaluate in depth the experiments that could be performed with a future lepton and photon collider. In response to the discovery of the Higgs boson, a number of machine concepts have been proposed to enable detailed study of the properties of this novel particle. These concepts include e^+e^- linear colliders, using superconducting or normal conducting RF cavity technology, a large circumference e^+e^- ring, a compact muon collider ring, a photon collider, either as a complement to an e^+e^- linear collider or as a standalone Higgs factory, and e^+e^- linear colliders based on wakefield acceleration techniques. These concepts span a broad range of technical readiness, from requiring demonstration of feasibility to having a detailed conceptual design, and timescales upon which a machine could be constructed. They also have varying energy reach from the 100's of GeV scale to the multi-TeV regime. As described in the report of the Snowmass Energy Frontier Study Group, a future lepton or photon collider would provide a factory for measurements of the properties of the Higgs boson with ultimate precision. It would also provide opportunities to probe for and study new physics, both through the production of new particles predicted by models of physics beyond the Standard Model and through the study of indirect effects of new physics on the W and Z bosons, the top quark, and other systems. A future lepton collider would allow searches for new particles that complement searches at the LHC.

In June 2013 the Global Design Effort (GDE) published a technical design report (TDR) of the International Linear Collider (ILC), an accelerator that will give these capabilities. The ILC is a superconducting linear e^+e^- collider with a center-of-mass collision energy tunable between 200 and 500 GeV with a luminosity exceeding 10^{34} cm^{-2}s^{-1} at 500 GeV roughly scaling in proportion to the collision energy. The ILC is upgradeable in luminosity by a factor of two and in energy to at least 1 TeV. The Japanese high energy physics community has named the ILC as its first priority. Discussions are taking place in Japan at high political level.

Our study welcomes the initiative for ILC in Japan. An experienced cadre of U.S. accelerator physicists and engineers is capable and ready to work on this project as part of a balanced portfolio of high energy physics.

The key characteristics of the ILC accelerator are the relatively long interval between collisions of bunches, beam energy spread of a few percent, beam position and energy stability, and the ability to polarize both electrons and positrons. The design and technical details of the ILC have been developed over more than 20 years and incorporate extensive US leadership contributions in beam dynamics, damping ring design, electron and positron sources, superconducting RF technology, and beam delivery system design. As described in the TDR, the ILC represents an extensive collection of challenging technologies that are largely ready to proceed to construction. The 1.2 GeV VUV Free-Electron-Laser "FLASH" at DESY has provided a critical integrated system test experience. FLASH technology is quite similar to ILC and ILC operational parameters are within the range of FLASH hardware. Tests at FLASH were done with the ILC bunch number, bunch repetition rate, bunch charge and peak beam current. These tests were successful and no fundamental technology issues with operating a superconducting linac at the ILC design parameters were encountered. The R&D has successfully demonstrated a gradient of 31.5 MV/m in installed cryomodules with beam loading, using niobium cavities with no more than two surface-preparation processing cycles. With the specified accelerating gradient, the total length of the 500 GeV ILC is 31 km. The R&D for the positron target has to be completed.

Industrial and institutional partners of the GDE advised a strong industrialization program from the outset. A key ingredient was the development, within the GDE, of a project governance and value-based cost-estimating strategy that was balanced regionally and took advantage of the intrinsic modularity and relative maturity of the Superconducting Radio Frequency (SCRF) technology. The most costly and time-consuming part of industrialization is the construction and commissioning of heavy infrastructure, notably institutional test facilities. Fabrication of superconducting cavities to the ILC design specifications has been industrialized, with qualified vendors in Europe, North America, and Asia. During the R&D phase, US labs and industry contributed substantially to cavity performance, cryomodule design, high-level RF (HLRF) performance, beam dynamics demonstrations and specific components and systems. For the construction of ILC, it is reasonable to assume the US contributions would reflect this effort. Specifically, the contribution of the greatest economic value to the project would be construction and testing of completed cryomodules. The US community would also provide detailed accelerator design development effort as an intellectual contribution. It is expected that the US would also contribute to design and construction of one or more linear collider subsystems. Given that the TDR estimates the required labor effort to be 13,000 person years, participation by America's highly experienced accelerator scientists and engineers would be crucial.

Extension of the ILC to 1 TeV is conceptually straightforward. It requires lengthened linac tunnels and additional cryomodules, but would use the original ILC sources, damping rings, final focus and interaction regions and beam dumps. No new technological breakthroughs would be required, although R&D to develop higher gradient cavities would permit shorter tunnel extensions and thus cost savings.

Alternative approaches to the ILC – albeit on a longer times scale– include approaches with potential to reach multi-TeV energies. One approach, the Compact Linear Collider (CLIC) two-beam accelerator, is based on X-band, warm linac technology and would stretch for 50 km at a colliding beam energy of 3 TeV. A Conceptual Design Report (CDR) addressing its feasibility has been published in 2012. For CLIC stages at 350 GeV, 1.5 TeV, and 3 TeV are currently being studied. The first and second stage use only a single drive-beam generation complex to feed both linacs, while in stage 3 each linac is fed by a separate complex. The CLIC design is based on three key technologies, which have been addressed experimentally: The normal-conducting accelerating structures in the main linac have a gradient of 100 MV/m, to limit the length of the machine. The RF frequency of ∼12 GHz and detailed parameters of the structure have been derived from an overall cost optimization at 3 TeV. Experiments at KEK, SLAC and CERN have verified the structure design and established its gradient and breakdown rate. Work is on-going to optimize power requirements for the energy stages, one of the key issues for CLIC. The drive beams run parallel to the colliding beams through a sequence of power extraction and transfer structures, where they produce short, high-power RF pulses that are transferred into the accelerating structures. These drive beams are generated in a central complex. The drive-beam generation and power extraction has been demonstrated in a dedicated test facility (CTF3) at CERN.

Wakefields in plasma-based accelerators can potentially provide a 1000-fold or more increase in acceleration gradient over standard technologies. Two primary approaches are being investigated: beam-driven wakefields (PWFA) and laser driven wakefields (LPA). Experiments at SLAC, LBNL and at European laboratories have shown that plasmas can accelerate and focus high energy beams at an accelerating gradient in excess of 50 GeV/m. At present two large R&D facilities are driving this research in the U.S., FACET at SLAC (PWFA) and BELLA at LBNL (LPA). Smaller efforts are being pursued at university laboratories. For any variant of wakefield accelerator to be practical as a linear collider, several feasibility issues must be resolved in the context of an integrated system test. Most importantly, wakefield accelerators must be capable of being staged in a series of phase locked segments just as standard accelerator modules are. Both approaches must demonstrate simultaneous positron acceleration and focusing in plasma densities consistent with preserving beam quality. They must demonstrate timing, pointing, and focusing control consistent with high luminosities required in a lepton collider. Finally, they must demonstrate that multi-bunch plasma instabilities, such as zero-frequency, convective hose instability, can be overcome with operation at the tens of kHz rep rate required for high luminosity. Beyond the feasibility issues are questions of practicality related to overall cost, efficiency and reliability. These issues may be more demanding for laser driven concepts as cost and efficiency limitations of drive beam sources are better known.

US is a world leader in these physics programs with high intellectual content. All variants of wakefield accelerators require an integrated proof-of-priciple test.

A circular collider has been advocated to offer an interesting potential alternative to the linear collider, with potentially higher luminosity. It can benefit from three characteristics of lower energy circular machines: 1) high luminosity and reliability, 2) the availability of several interaction points, 3) outstanding beam energy accuracy and the precise energy calibration by resonant depolarization. Based on the experience at LEP, beam polarization should be readily available for energy calibration up to the W pair threshold. A design study has begun for the TLEP storage ring, a machine with a circumference of 80 km and dissipated synchrotron radiation power set at 100 MW. In particular TLEP offers a very large luminosity per IP of $6{\times}10^{35}$ cm^{2}s^{-1} at the Z peak, $5{\times}10^{34}$ cm^{2}s^{-1} per IP at the ZH cross-section maximum around 240 GeV, and $1.3{\times}10^{34}$ cm^{2}s^{-1} per IP at the top pair threshold. Very high currents over 1 A are required to reach maximal luminosity at the Z peak and their effects need detailed studies.

For a given RF power, the luminosity of a storage ring collider rises more than linearly with its circumference, since the dispersion and transverse emittance naturally decrease and the filling factor increases with larger circumference. For a given tunnel size, and assuming the machine operates at the beam-beam limit, luminosity rises linearly with the total dissipated synchrotron radiation (SR) power, which is approximately proportional to the total available power. Therefore, the analysis can be scaled to different machine circumferences. The energy reach consistent with sufficient luminosity for Higgs studies depends strongly on the machine circumference; a machine of 27 km circumference can reach 240 GeV, the limit is about

350 GeV for a machine of 80 km circumference. At a given circumference the energy reach and dissipated synchrotron radiation power, the luminosity scales as $1/E^3$. Details of the design matter greatly.

TLEP is a proposed storage ring with ∼1 km of superconducting RF and low β^* insertions, operating at fixed field and fed by an accelerator situated in the same tunnel for continuous top-up injection. Multi-bunch operations are necessary for high luminosity below the top energy, thus separated beam pipes are foreseen for electron and positron beams. The design parameters benefit from the LEP2 experience and a strong demonstrator of the high luminosity scheme will be the superKEKb B-factory planned to begin operation in 2015 at KEK. Beamstrahlung from the collision process lead to short luminosity lifetime due to energy losses of individual electrons beyond the energy acceptance of the ring and to a large instantaneous energy spread in the beam of the order of several percent. Control of beam losses, even in a lattice of very large dynamic aperture has been simulated. It was shown that it can be mitigated by the combination of several factors: i) the ratio of vertical to horizontal emittances ratios should be reduced as much as possible – a ratio of 0.2% has been assumed, which roughly is the same as has been achieved at light sources; ii) the dynamic momentum acceptance, driven by the low beta optics and the RF has to be in excess of 2.5%; iii) the top-off rate has to be faster than a few times per minute. The above mentioned luminosity can be achieved if these requirements are satisfied.

The TLEP project is still young and its anticipated performance is based on parametric studies. It rests on the scaling of well-known technologies and beam physics being pushed to their limits. A circular e^+e^- collider in a large tunnel might be proposed in conjunction with a high energy pp collider (VHE-LHC). TLEP and the VHE-LHC would share the tunnel and cryogenics, as well as parts of the detectors and, possibly, some of the magnets and injector ring components. A thorough design study of a circular e^+e^- collider will show the potential as a Higgs factory and for the precision measurement of the top quark, W and Z, bosons.

Should a linear collider not be built over the next decade and should the renewed interest in a very large circumference hadron collider be sustained, the possibility of a circular Higgs factory deserves careful consideration.

On a longer time scale, the muon collider, if proven feasible, would fit a 6 TeV collider onto the present Fermilab site. Due to the strong reduction of synchrotron radiation by the muon mass, muon colliders could extend the lepton colliding beam energy up to 10 TeV with an excellent luminosity spectrum not being deteriorated by beamstrahlung. Moreover, the muon approach has a very large overlap with capabilities needed for intensity frontier accelerators. Yet another approach to accelerate electrons to higher energies would use wakefields driven either by beams or lasers to achieve accelerating fields of 10 to 100 GeV per meter with high wall plug to beam efficiency. Thus the technology has potential for significant cost and power consumption savings; many feasibility and practicality issues remain in these programs.

Muon accelerators have the potential to provide world-leading experimental capabilities for physics at center-of-mass energies from the Higgs boson at 126 GeV up to the multi-TeV scale. A circular muon collider can potentially reach the higher energy range because the larger mass of the muon means they produce far less synchrotron radiation; however, muons have an at-rest lifetime of $\sim 1\mu s$ and therefore decay in flight. The unstable nature of the muon demands that the process of beam creation, manipulation and acceleration be done rapidly; high gradient acceleration is essential. Therefore, an energy frontier muon collider would necessarily be relatively compact. Even a 6 TeV collider would fit on the Fermilab site. R&D crucial to the performance of a muon collider includes: 1) Development of a high power target station including a high field (20 T) capture solenoid that is ultimately capable of handling more than 4 MW of power. 2) Muon cooling by $\sim 10^6$ is required to achieve the beam parameters for the muon collider designs. 3) Control of collective effects in the high intensity beams at the low energy end of the production, capture and acceleration process.

4) Development of very large aperture, superconducting dipole magnets with heavy inserts to protect the superconductors from the decay products of the stored muons in the collider. Once items 1) and 3) are resolved, a muon accelerator would provide an outstanding high flux source of well characterized neutrinos for a range of intensity frontier experiments. Development of a muon collider capability would be closely connected with intensity frontier accelerators such as intense neutrino sources.

A vigorous, integrated R&D program toward demonstrating feasibility of a muon collider is highly desirable.

In a Higgs factory photon collider, two electron beams are accelerated to 80 GeV and converted to 64 GeV photon beams by colliding with low energy (3.5 eV) high intensity (5 J per pulse) lasers via the Inverse Compton Scattering (ICS) process. The two high energy photon beams then collide and generate Higgs particles through the s-channel resonance. Among various options for a Higgs factory, a photon collider has the distinct advantage that the 80 GeV energy required for the electron beam is lower than for other colliders (except muon collider). Photon colliders have been discussed as options to accompany proposed linear colliders or as a stand- alone facility.

Since the overall acceleration efficiency of any facility is the product of the individual efficiencies of each of the systems involved in the transfer of power from the wall plug to the beam, each of the systems has to be as efficient as possible. Innovative R&D on efficient RF generation and lasers would be extremely beneficial to all lepton collider designs. It should be strongly supported as a key technology to reduce the operating costs of future facilities for both the energy and intensity frontiers.

This report begins with a brief review the physics landscape relevant to future lepton and photon colliders in Section 31.2. The International Linear Collider (ILC) is a linear e^+e^- collider is the most mature project among the lepton colliders and is discussed in Section 31.3. The Compact Linear Collider (CLIC) is a technology aimed at extending the energy frontier for e^+e^- linear colliders to multi-TeV. CLIC has produced a Conceptual Design Report (CDR) [10]. It is discussed in Section 31.4 along with other novel technologies with higher energy reach. Circular e^+e^- colliders are limited to a maximum center-of-mass energy by power radiated in synchrotron and beamstrahlung radiation. They are discussed in Section 31.5. Muon colliders can potentially reach higher energy and are discussed in Section 31.6 along with the many R&D challenges to be addressed. Photon colliders provide an alternative route to a Higgs factory and a complementary physics program, whether as an option for e^+e^- colliders or as stand-alone machine. They are discussed in Section 31.7. The proposed collider projects face the challenges of generating and handling very large beam power. A discussion of acceleration efficiency and R&D is given in Section 31.8. We conclude this report with a summary of recommendations in Section 31.9.

31.2 Physics Landscape

The observation of the Higgs boson by the ATLAS and CMS experiments [2, 3] is a triumph of the Standard Model (SM) and has opened a new era in particle physics. Within the current uncertainties the newly found particle is consistent with the SM expectations. However, the SM is not able to explain dark matter, the matter-antimatter asymmetry, or neutrino masses. The absence of signals for physics beyond the SM up to at least 1 TeV makes the precise measurement of Higgs boson properties a key challenge of the field in the coming decades.

The LHC program and its future upgrade to large luminosities are essential components in this endeavor. The next LHC run at increased center-of-mass energy might lead to a discovery of beyond the SM physics, dramatically changing the landscape in particle physics. At the LHC Higgs couplings are measured as deviations from the SM expectation. The LHC will be able to probe Higgs couplings with a precision of 2-5% and measure its mass to 50 MeV. However, hadron collider experiments cannot directly measure a narrow Higgs width, so they cannot simultaneously constrain the couplings and new contributions to the total width. In addition, the Higgs decay to charm quarks, important because it contributes to the total width at the percent level, will likely remain unaccessible at the LHC. At electron-positron collider the situation is very different. The total width can be inferred from a combination of measurements. This is mainly due to the measurement of the inclusive ZH cross section based on a system recoiling against a Z boson decay. The measurement of couplings naturally divides according to the production of process. At relatively low $\sqrt{s}$ of 250 GeV, the Higgs-strahlung process dominates tagging the Z allows for a model-independent separation of the recoil Higgs decays. Above $\sqrt{s}$ of 500 GeV, the W-fusion mode $e^+e^- \to \nu_e\bar{\nu}_e H$ dominates and grows with $\sqrt{s}$ allowing for better precision of the WW coupling and higher statistics for other decay modes, including rare decays. These higher energies also provide access to the top quark Yukawa coupling through $e^+e^- \to t\bar{t}H$ and the Higgs trilinear self-coupling via double-Higgs production, $e^+e- \to ZHH$ and $\nu_e\bar{\nu}_e HH$. A muon collider can produce Higgs bosons via s-channel production and allows for the precision measurement of the Higgs boson mass and total width. A photon collider allows below per-cent level precision measurements of the partial width to photons which test contributions of new physics. Using linear polarization of the colliding photons give sensitivity to Higgs CP properties. A detailed and more complete discussion of future Higgs boson measurements can be found in [4].

Another way to test the existence of new physics beyond what could be observed directly at the LHC, is to sharpen considerably the precision tests of the Electroweak Theory, i.e. the W and Z masses, the top quark mass, and Z peak observables such as the Z width, the polarization and charge asymmetries, the b partial width, etc. Lepton collider are ideal instruments for such measurements due to the precise knowledge of the collision kinematics, the ability to polarize the colliding particle, and the clean environment of the recorded collisions. Lepton collider at large center-of-mass energy (multiple TeV) have discovery potential that is complementary and in some circumstances superior to a 100 TeV pp collider. For example, within SUSY models, the direct discovery limits for new particles such as scalar leptons, charginos and neutralinos are generally better at such a lepton collider than for a 100 TeV pp collider. The details of the crossover energy depends on the channel, the backgrounds and the relative attainable luminosities.

31.3 International Linear Collider

The International Linear Collider (ILC) is intended to satisfy these physics requirements, as established by ICFA in 2003 [5], for the next phase of collider-based High Energy Physics after the LHC. The center-of-mass collision energy range should be tunable between 200 and 500 GeV and the luminosity should exceed 10^{34} $\mathrm{cm}^{-2}\mathrm{s}^{-1}$ at 500 GeV, roughly scaling in proportion to the collision energy. The key characteristics of the ILC accelerator are the relatively long interval between collisions of bunches, narrow beam energy spread, beam position and energy stability, and the ability to polarize both electrons and positrons. Figure 31-1 shows a schematic layout of the ILC.

The ILC Technical Design Report (TDR) design [6] is based on a broad and globally-based R&D program [7]. The Technical Design meets the specifications set forth by ICFA. The technical readiness of the ILC project was assessed in late 2012 [8]. Three general technical categories comprise the readiness assessment

- SCRF technology,
- beam-based demonstrations using integrated systems,

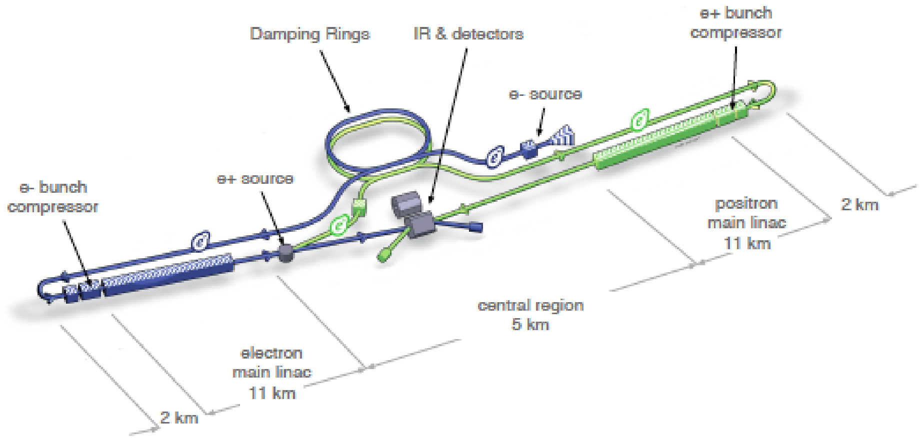

Figure 31-1. *Schematic layout of the ILC.*

- specific component and system design and performance.

The maturity of the ILC project cost estimate was reviewed in early 2013 and this review serves as an independent indicator of project readiness. The cost estimate for the 500 GeV ILC was produced using a value estimate methodology. This is the norm for large-scale internationally funded projects that are constructed using in-kind contributions. The value estimate for the construction of the ILC is 7.8 billion ILC Units together with 23 million person hours (approximately 13,000 person years) of additional labor, (one ILC Unit is equivalent to one 2012 USD) [9]. The estimate covers all construction costs for the accelerator complex. It does not include contingency and escalation, commissioning with beam or operations costs. It also does not include costs for project engineering, site acquisition and preparation costs, costs of R&D prior to construction start, and the cost of the detectors.

31.3.1 Technical Readiness Assessment – SCRF

R&D on superconducting linac technology has focused on four critical topics:

- production of SCRF cavities capable of reproducibly achieving at least 35 MV/m,
- assembly of a cryomodule consisting of eight or more cavities operating at a gradient of 31.5 MV/m,
- a linac string-test (or integration test) of more than one cryomodule,
- development of industrial SCRF production capability.

The latter includes industrial cavity production and cost-model analysis.

The R&D has successfully demonstrated the goal of 35 MV/m accelerating gradients in test stands and 31.5 MV/m in installed cryomodules with beam loading, using niobium cavities with no more than two surface-preparation processing cycles. Cavity fabrication to these specifications has been industrialized, with qualified vendors in Europe, North America, and Asia. With this accelerating gradient, the total length of the 500 GeV ILC is 31 km.

Superconducting RF techniques have wide applicability in other science facilities. The technical development for the ILC is already applied in X-ray light sources and spallation neutron sources, and it has enabled the design of energy recovery linacs. SCRF technology has also attracted considerable interest for military and homeland security systems. Remaining SCRF-related R&D, to be qualified in integration tests, serves to address supporting technologies such as high-level RF generation and distribution and cavity resonance control. An important aspect is the development of modular, plug-compatible component interfaces that allow independent development programs.

Production of SCRF cavities
The successful development of industrial capacity in each of the three regions resulted in multiple vendors capable of producing high-performance ILC cavities. In the USA, these were tested at Fermilab, Argonne National Laboratory and Jefferson Lab; in Japan at KEK; and in Europe at DESY, where development has been driven by the design and construction of the European X-ray free-electron laser (XFEL). The 17.5 GeV SCRF linac of the European XFEL represents the largest deployment of the technology to date. In many ways it provides an excellent large-scale prototype for the ILC.

The performance of superconducting cavities is primarily limited by two effects: field emission and quench-causing surface defects. Improvements in surface treatments have essentially mitigated the onset of field emission at gradients below 35 MV/m. The invention and deployment of tools to identify and repair quench-causing defects at low cavity gradient has led to the establishment of a baseline set of procedures for cavity fabrication and surface preparation which minimize surface defects. These techniques were fully implemented during the final phase of the R&D program and showed a two-pass production yield of 94% for cavities satisfying 35 MV/m $\pm$ 20%, with an average gradient of 37.1 MV/m. These results exceed the 2006 R&D goal of 90% yield and an average gradient of 35 MV/m.

Cryomodule with operating gradient
In addition to the above, an average field gradient of 32 MV/m has been achieved in a prototype cryomodule for the European XFEL program. The international cryomodule construction program S1-global successfully demonstrated design modularity, (also known as plug compatibility), by building one cryomodule from cavities and couplers supplied from several different national laboratories. The cryomodule power system was also assembled using a modular scheme. The ability to incorporate and test several different component designs within a single integrated test setup is the critical aspect of the S1-global program and provided input to baseline technology decisions for the TDR. Testing of the first US-built high gradient ILC cryomodule CM-2 was not completed in time for the TDR and is expected to be done during 2013.

Integrated system tests
The 1.2 GeV VUV Free-Electron-Laser “FLASH” at DESY has provided critical system test experience. FLASH technology is quite similar to ILC and ILC operational parameters are within the range of FLASH hardware. Tests at FLASH were done with the ILC bunch number, bunch repetition rate, bunch charge and peak beam current. These tests were successful and no fundamental technology issues with operating a superconducting linac at the ILC design parameters were encountered. As noted, the 17.5 GeV XFEL under construction at DESY and scheduled for completion in late 2015 is an excellent integrated system test. The XFEL linac consists of 100 8-cavity cryomodules and will be able to operate with beam parameters very close to ILC.

Industrialization
Industrial and institutional GDE partners advised a strong industrialization program for ILC from the outset. A key ingredient was the development, within the GDE, of a project governance and Value cost-estimating strategy that was well-balanced regionally and took advantage of the intrinsic modularity and relative maturity of the SCRF technology. The most costly and time-consuming part of the process is the construction and commissioning of heavy infrastructure, notably institutional test facilities. Long lead

time high-power high-tech industrial equipment such as vacuum distillation and heat-treatment furnaces and electron-beam welders are also critically important. A well-supported and realistic cost-estimate is the output of this process and will be a strong point in the project proposal going forward. Industrial studies for ILC included 1) vendor visits, 2) component development contracts, 3) satellite meetings with industrial partners at major conferences and, 4) industrial production study contracts. Roughly 15 companies from the three regions participated. Each interested party was requested to provide information and make cost comparisons between construction models with 20%, 50% or 100% of full-scale production in either a 3 or 6 year schedule.

31.3.2 Technical Readiness Assessment – Beam Dynamics Demonstrations

Two sets of beam dynamics and beam manipulation tests were done in addition to the beam-based SCRF integrated systems tests. First, the effects of the electron cloud in the positron damping ring have been experimentally studied in a comprehensive fashion, leading to the proven techniques included in the TDR design for its mitigation. Second, the ability to achieve and maintain a small final focus spot size is under study in a test facility that is intended to be a scaled-down copy of the ILC beam delivery system. Preliminary results give confidence that the goal of several nanometer vertical spot sizes will be achieved. Results of the latter are expected to be integrated into the final focus design.

31.3.3 Technical Readiness Assessment – Specific Components and Systems

Examples of specialized components are the polarized electron gun, positron target systems including the undulator, target wheel, proximity capture lens and capture RF accelerating section, and fast kicker deflectors needed to inject and extract the beam from the damping ring. Each of these has been studied and, with the exception of the positron target wheel, has yielded satisfactory prototypes. A prototype target wheel was constructed and its motion control system tested successfully but an adequate demonstration of the surrounding vacuum technology was not completed in time for the TDR.

A detailed Conventional Facilities design was completed in two regions, Asia (Japan) and Americas (US). The design includes a full set of layout drawings and initial plan for the civil construction, detailed mechanical and electrical design reports, and cost analysis. The design includes the final focus and interaction region detector push-pull system needed to allow two detectors to take data sequentially.

31.3.4 Technical Readiness – Summary

The US Department of Energy Office of Management, Budget and Evaluation (DoE-OMBE) have defined a series of five critical decisions (CD-0 to CD-4) to formally determine specific points in a project life cycle. Each CD involves assessment of topics ranging from project planning, cost and schedule, technical readiness to siting. Although the ILC will be a thoroughly international project and will therefore have very different constraints than those foreseen by DoE-OMBE for typical projects it is nevertheless useful to apply the CD assessment questions to ILC in the appropriate context and comment on them.

The ILC TDR, Project Implementation Planning document, and cost estimate documentation serve to meet several of the key elements of CD-1, namely, the Conceptual Design Report, Acquisition Strategy, Project Execution Plan, Funding Estimate, and baseline ranges.

The TDR design and the R&D results have been judged sufficient to begin the detailed, site specific design and construction stage once international negotiations for starting the project have been concluded. Remaining work includes beam tests in multi-cryomodule facilities now under construction to assess such topics as beam stability, low level RF controls and field emission behavior; as well as further industrialization of SCRF cavity and cryomodule components, value engineering, and detailed site-specific engineering design.

31.3.5 Areas for US contribution

During the R&D phase, US labs and industry contributed substantially to cavity performance, cryomodule design, high-level RF (HLRF) performance, beam dynamics demonstrations and specific components and systems. For the construction of ILC, it is reasonable to assume the US contributions would reflect this effort. Specifically, the contribution of the greatest economic value to the project will be construction and testing of completed cryomodules. This effort will use the test and processing infrastructure at Fermilab (cavities and cryomodules), Argonne (cavities), SLAC (couplers and HLRF) and Jefferson Lab (cavities) as well as the recently developed industrial expertise. The US community will also provide detailed accelerator design development effort as an intellectual contribution. For specific systems, it is expected the US will contribute to the final focus region design and construction.

31.3.6 Extending ILC performance

In a staged approach starting with 250 GeV e^+e^- operation for the Higgs boson study, it should be possible to accumulate sufficient statistics for the Higgs studies within about five years of operation, including an initial ramp up to full luminosity. Raising the energy to 500 GeV will allow precision measurements of the top quark mass and its properties well beyond those possible at the LHC and Tevatron. Measurements of the top coupling to the Higgs and the Higgs self-coupling would begin at 500 GeV. The $\gamma\gamma$ option can be installed in the ILC as designed with the addition of the required high power lasers to induce Compton backscattered photons of about 80% of the incoming electron/positron beam energies. The ILC could be operated as an e^+e^- collider if there is a physics need. The possibility of increasing the luminosity for the ILC at $\sqrt{s}$ =350 GeV by increasing the beam power can be considered. An approximately constant luminosity can be achieved across the center of mass energy range (250–500 GeV) without exceeding the installed AC power for 500 GeV operation. Overall a factor of four in luminosity over the published baseline could be achieved at 250 and 350 GeV resulting in 3×10^{34} $\mathrm{cm}^{-2}\mathrm{s}^{-1}$. Table 31-1 summarizes the expected performance and options in this energy range and luminosity in case physics will require an even larger dataset at these energies. Although the ILC TDR design has been optimized for collisions at 500 GeV, the option of upgrading the energy to 1 TeV has always been maintained and is discussed in the TDR. It is clear that before such an upgrade would be approved and constructed, the current progress in increasing the gradient of superconducting cavities would result in a significant improvement in the average gradient assumed for the additional 500 GeV construction.

Extension of the ILC to 1 TeV requires lengthening the linac tunnels to provide a cryomodules for an additional 250 GeV per beam. The design of the original ILC sources, damping rings, final focus and interaction regions, and beam dumps includes this option so these need not be changed. No new technological

Table 31-1. *Summary of performance in the range 250 to 500 GeV. Further options indicate scenarios which go beyond the parameters discussed in the TDR, but are still within the technical scope of the TDR.*

Ecm	GeV	250	350	500	upgrade 500	250	350
Rep. rate	Hz	5	5	5	5	10	8
Bunches / pulse		1312	1312	1312	2625	2625	2625
Total beam power	MW	5.3	7.4	10.5	21.0	21.0	23.5
Luminosity	10^{34} cm^{-2}s^{-1}	0.75	1.0	1.8	3.2	3.0	3.2

Table 31-2. *Cost and power consumption scaling as function of center-of-mass energy.*

Center-of-mass energy	% of TDR cost	Power consumption (MW)
250 GeV "Higgs factory"	70%	120
500 GeV	100%	163
1 TeV upgrade	150%	240
1.5 TeV upgrade	200%	320

breakthroughs would be required, although R&D to develop higher gradient cavities would permit shorter tunnel extensions and thus cost savings.

The cost of various options have been estimated using scaling rules and are listed here in terms of a percentage of the cost of the TDR machine and listed in Table 31-2; upgrade costs are total costs including the initial stage. Approximate power requirements are also listed, scaled from the TDR power requirement of 163MW for the baseline 500 GeV ILC. It is assumed that cavities capable of 45 MV/m accelerating gradient would be available for the upgraded ILC.

Indeed, it might well be expected that given the great interest in this technology world-wide, new technologies and materials, including e.g. thin-film coating, might result in very significant increases in achievable gradient with an acceptable cavity-quality factor, perhaps beyond 50 MV/m. On these assumptions, the civil construction necessary for a 1 TeV ILC and the overall cost increment would be significantly reduced. The new construction would begin at the ends furthest from the operating linacs in order to minimize downtime. The central campus concept for ILC minimizes the equipment that needs to be moved for a 1 TeV extension. Nevertheless, a downtime of around 1 year is likely to be necessary before operation at 1 TeV could begin. A further important option to be explored is the maximum energy that can be attained with a linear collider using superconducting technology. There is no technical factor that in principle limits this energy other than cost. With reasonable extrapolations of the achievable gradient for the cavities, the construction of a 1.5 TeV ILC seems technically feasible and probably at the limit of what could be proposed to the world's funding authorities both in terms of capital outlay and annual running costs. Should the physics landscape demand exploration of such an energy range, the design of the ILC could be readily optimized to achieve it.

31.3.7 Opportunity to site ILC in Japan

Japanese activity in support of ILC has four focal points

- consensus building within the scientific community,

- technological development of SCRF-related components built by industry and consideration of broad application of SCRF,
- political promotion of ILC as a center for scientific and technological innovation.

In early 2012, before the announcement of the Higgs boson discovery at LHC, the Japanese HEP community issued a very important, positive statement in support of ILC construction in Japan. Through the National High Energy Accelerator Laboratory, (KEK), the community commissioned a set of studies on two candidate sites including collider alignment, geotechnical, and urban studies. The latter is intended to provide understanding of the transportation and urban-living infrastructure that would be required to situate the ILC in these two somewhat rural candidate site areas. The reports are critical input to the community-based site recommendation process that is set to conclude in July or August 2013.

Japanese involvement in the specifics of the ILC design broadened significantly with the founding of the Association for Advanced Accelerators (AAA) in June 2008. This industry-academia-government group provided the GDE with siting and geotechnical analysis that has allowed the site-specific aspects of the design to move forward during the TDR phase. The group provided a civil construction and layout analysis (carried out by top Japanese general contracting firms) and an environmental impact analysis (also prepared by firms with equivalent experience). These reports and associated reviews provided the GDE with enough mountain-region (rural surrounding) siting information so that an appropriate cost estimate and initial schedule could be prepared.

The AAA also provided a venue for ILC technology transfer to Japanese industry. This activity, especially, has raised awareness of possible applications of SCRF to issues of social importance and high technology. Japanese companies working through KEK and AAA have in turn demonstrated their interest and built prototype ILC cavities with very good performance.

Also in 2008, Japanese parliament (Diet) members founded an intra-partisan group for the promotion of ILC. The group, together with the AAA, have arranged and hosted a series of meetings in Tokyo intended to facilitate communication between politicians, industry leaders, and scientists working on ILC. ILC was mentioned twice in the December 2012 Liberal Democratic Party (LDP) platform document as an example international scientific innovation center, to be supported and promoted. The LDP won the parliamentary election in December 2012 and the new Prime Minister, Shinzou Abe, met with ILC Linear Collider Collaboration Director Lyn Evans in late March 2013. For their part, the Japanese academic and industrial community would like reconfirmation of international interest in constructing and using a Japan-hosted ILC.

31.4 Multi-TeV e^+e^- Linear Colliders

While the ILC is the most mature technology in the TeV energy range, there are a number of novel technologies being explored that could possibly extend the energy frontier for e^+e^- linear colliders into multi-TeV given sufficient physics justification. To provide a collider with high luminosity, these novel technologies have to be able to accelerate several MW of beam power with: high accelerating gradients to limit the size and cost of the facility high wall plug to beam power transfer efficiency to reduce the power consumption and operating cost preservation of beam quality and ultra-low beam emittances during acceleration to allow collisions with small beam sizes in the nm range. The four technologies under study are based on novel methods of beam acceleration over a broad parameter space: CLIC, Plasma Wake-Field Accelerator (PWFA), Laser Plasma Accelerators (LPA) and Dielectric Laser Accelerators (DLA). The facilities described below attempt to answer the basic questions raised by the CSS2013 WG2 on Lepton Colliders. The technologies are not in the same stage of development. CLIC has completed a feasibility demonstration and published a detailed conceptual design while the other technologies are pursuing R&D to demonstrate feasibility. For each technology, the major highlights and technical challenges are described along with the required R&D and a possible schedule. We also list possible applications of these technologies outside of HEP. The main parameters for multi-TeV are summarized in Table 1, and parameters for a possible first stage in the TeV range around the HIGGS energy are presented in Table 2. The luminosity, wall plug power, figure of merit of luminosity per unit power and wall plug to beam power transfer efficiency are compared with other potential technologies in Fig. 8 to 11. The potential for excellent performance with significantly reduced cost and power per unit of GeV argues for a vibrant R&D program and ambitious test facilities to continue development to make it possible to reach higher energy if physics requires it.

31.4.1 Compact Linear Collider

31.4.1.1 Short description of the facility and upgrade path

The Compact Linear Collider (CLIC) is a TeV scale high-luminosity linear e^+e^- collider developed by a 48 institution international collaboration. The CLIC-study is hosted by CERN. The machine is based on a novel two-beam acceleration technique providing acceleration gradients at the level of 100 MV/m with normal conducting RF structures. The CLIC layout at 3 TeV is shown in Figure 31-2. The conceptual design is detailed [10]. The CLIC accelerator can be built in energy stages, re-using the existing equipment for each new stage. At each energy stage the center-of-mass energy can be tuned to lower values within a range of a factor three and with limited loss of luminosity performance. Stages at 350 GeV, 1.5 TeV and 3 TeV are currently being studied. The first and second stage use only a single drive-beam generation complex to feed both linacs, while in Stage 3 each linac is fed by a separate complex. The initial stage can include a klystron powered part, or be fully klystron based, and therefore an initial klystron based stage is currently also under study. The relevance and importance of an initial stage largely focused on Higgs measurements will depend on the overall physics scenario at the time and the status of these measurements at other machines. However, the e^+e^- collision energies available at Stage 2 and 3 may be unique to CLIC, and provide potentially direct access to BSM phenomena and also improved access to some important Higgs measurements. A staged implementation of CLIC as described would open the door to an impressive long-term and timely physics program at the energy frontier, beyond the LHC program. The machine is therefore considered as an option for a post-LHC facility at CERN.

31.4.1.2 Major R&D issues

The CLIC design is based on three key technologies, which have been investigated experimentally: The normal-conducting accelerating structures in the main linac have a gradient of 100 MV/m, in order to limit the length of the machine. The RF frequency of 12 GHz and detailed parameters of the structure have been derived from an overall cost optimization at 3 TeV. Experiments at KEK, SLAC and CERN verified the structure design and established its gradient and breakdown-rate performance. The drive beams run parallel to the colliding beams through a sequence of power extraction and transfer structures, where they produce short, high-power RF pulses that are transferred into the accelerating structures. These drive beams are generated in a central complex. The drive-beam generation and use has been demonstrated in a dedicated test facility (CTF3) at CERN. The high luminosity is achieved by very small beam emittances, generated in the damping rings and maintained during the transport to the collision point. These emittances are ensured by appropriate design of the beam lines and tuning techniques, as well as by precision pre-alignment and an active stabilization system that decouples the magnets from the ground motion. Prototypes of both

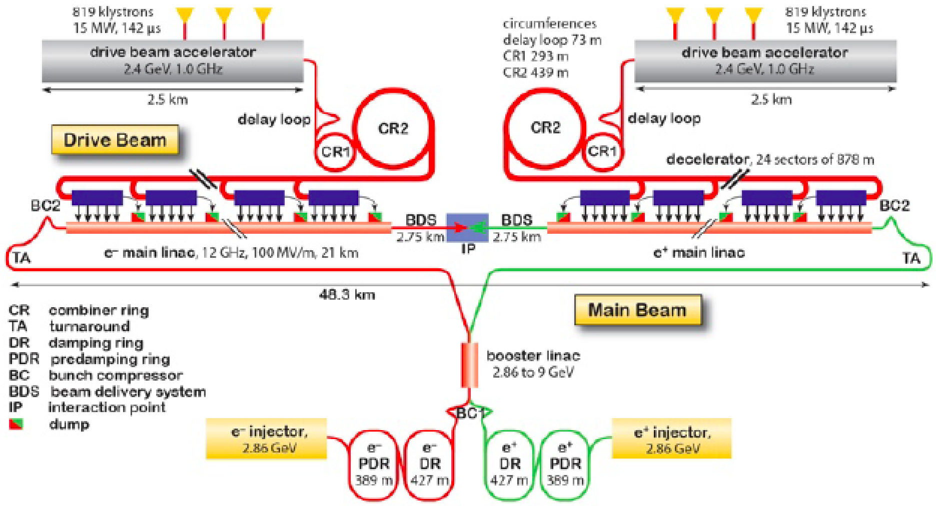

Figure 31-2. *CLIC layout and parameter at 3 TeV.*

systems have demonstrated performance close to or better than specifications. Related system parameters have been benchmarked in CTF3, in advanced light sources, in the ATF2 and CesrTA, and in other setups. For the period 2013-2017 further development goals are defined and a work-program implemented across the collaboration: One important element is a re-evaluation of the CLIC energy stages, with particular attention to optimization and possible reduction in cost and power. Technical studies will address stability and alignment, timing and phasing, stray fields and dynamic vacuum including collective effects. Other studies will address failure modes and operation issues. The collaboration will continue to identify and carry out system tests at CTF3, ATF2 and for the CLIC injector. Further X-band structure development and tests are required as well as construction of integrated modules integrating a number of central functional elements. Initial site studies will continue, and preliminary footprints for an initial machine as well as an ultimate 3 TeV layout, will continue to be refined.

31.4.1.3 Power and cost driver

The power consumption and costs of the CLIC machine have been estimated for two different versions of a 500 GeV first stage, A (with 80 MV/m structures) and B (with 100 MV/m structures) The nominal electrical power consumption of all CLIC accelerator systems and services, including the experimental area and the detectors and taking into account losses from distribution on site, range between 235 and 589 MW from 500 GeV to 3 TeV. The energy consumption at CERN was 1.35 TWh in 2012, equivalent to the Stage 2 CLIC machine, so further reduction of power consumption is desirable.

Because CLIC can vary its power consumption over a wide range, it can be operated as a peak-shaving facility, matching the daily and seasonal fluctuations in power demand on the network. There are several possibilities under study for reducing power consumption or improving the energy footprint of the machine, e.g., lower current density in magnet windings and cables, permanent or superferric magnets in place of normal-conducting, higher efficiency klystrons and modulators, waste heat recovery. Furthermore, the on-going work to optimize the energy stages of CLIC will include power reduction as a key issue.

31.4.1.4 Tentative schedule

2013-2017: CLIC has laid a detailed development program covering the period until 2017-18 when LHC will have results at full energy. The main elements are described above.
2017-2023: An initial Project Preparation Phase is needed before initiating construction. During the Preparation Phase it is essential to optimize component performance and to reduce cost, in preparation for large industrialization contracts.
2023-2030: A construction start for CLIC could be around 2023. The construction time for the initial phase is estimated to be around 7 years allowing the machine to become operational at end of the LHC project.

31.4.1.5 Possible technology application

The most important examples of the use of high-gradient normal-conducting technology developed for CLIC are: compact linacs for proton and carbon ion cancer treatment, future free electron lasers (FELs) for photon-science, which encompasses biology, chemistry, material science and many other fields, compton-scattering gamma ray sources providing MeV-range photons for laser-based nuclear physics (nuclear-photonics) and fundamental processes (QED studies for example). There are also potential applications such as nuclear resonance fluorescence for isotope detection in shipping containers and mining. Also synchrotron-based light sources and the CLIC damping rings share similar issues and challenges, which are addressed in a collaborative effort.

31.4.2 Plasma Wake-Field Accelerators

31.4.2.1 Short description of the facility and upgrade path

Plasma Wake-Field Acceleration (PWFA) can potentially provide a 1000-fold or more increase in acceleration gradient with higher power efficiency than standard technologies. Most of the advances in beam-driven plasma wakefield acceleration were obtained by a UCLA/USC/SLAC collaboration working at the SLAC FFTB. These experiments have shown that plasmas can accelerate and focus both electron and positron high energy beams, and an accelerating gradient in excess of 50 GeV/m can be sustained in an 85 cm-long plasma. The FFTB experiments were essentially proof-of-principle experiments that showed the great potential of plasma accelerators. The FACET test facility at SLAC will operate between 2012-2016 to study several issues that are directly related to the applicability of PWFA to a high-energy collider, in particular two-beam acceleration where the witness beam experiences high beam loading (required for high efficiency), small energy spread and small emittance dilution (required to achieve luminosity). The PWFA-LC concept presented in this document is an attempt to find a design that takes advantage of the PWFA and at the same time benefits from the extensive R&D for conventional linear colliders over the last twenty years, especially ILC and CLIC. A PWFA collider has the potential to reduce both power consumption and cost.

We present a novel design of a beam-driven PWFA linear collider with effective accelerating gradient on the order of 1 GV/m and extendable in the multi-TeV colliding beam energy range. The acceleration in plasma is a single bunch process, and this allows great flexibility in the interval between bunches. In the preferred scheme sketched on Figure 31-3, the main bunches collide in continuous-wave (CW) mode at several kHz repetition frequency. They are accelerated and focused with multi-GV/m fields generated in plasma cells powered by drive bunches with excellent transfer efficiency. The drive bunches are themselves accelerated by a CW superconducting rf recirculating linac taking advantage of the RF technology developed by ILC.

This SCRF provides excellent power efficiency and a flexible number of bunches. Each plasma cell requires beamline space for optical matching as well as injection and extraction of the drive bunches, but even with these spaces, the average accelerating field is 1 GeV/m. There is also an excellent drive to main beam power efficiency of 50% and an overall wall plug to beam transfer efficiency of 20%. Beam driven plasma is the only technology providing at the same time large accelerating gradient and high wall plug to beam transfer efficiency. The flexibility in the bunch spacing means that PWFA technology can also be used in a pulsed mode to accelerate a beam with parameters and train structure similar to that of the ILC. The only exception is the bunch length which must be reduced by a factor of 15 from 300 to 20 microns. If the PWFA technology will be shown to be feasible, it could be considered as a possible alternative for an ILC energy upgrade to the TeV energy range without any modification of the ILC facility. With such an upgrade, the ILC/PWFA complex at 1 TeV would fit within the 21 km of the initial configuration rather than the 52 km described in the ILC TDR.

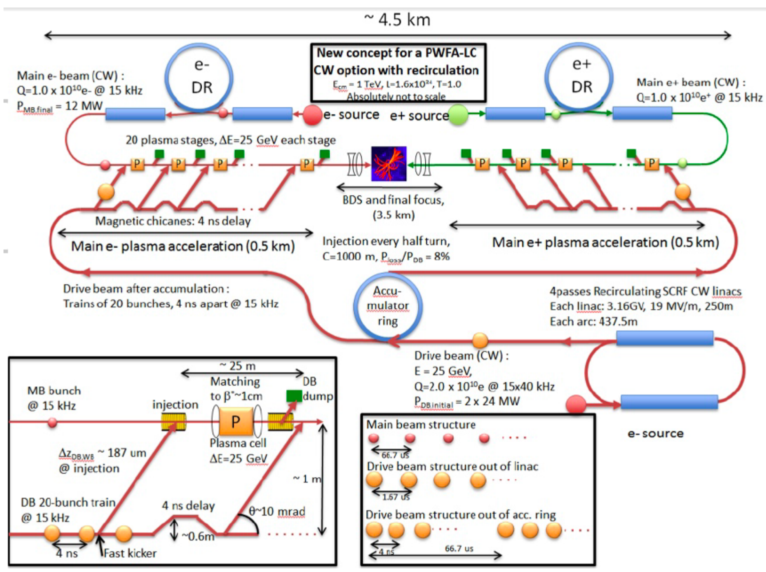

Figure 31-3. *Layout of a beam driven PWFA facility at 1 TeV.*

31.4.2.2 Major R&D issues

The dramatic progress of the past decade was made possible by the parallel development of high peak current, 100fs level electron beams and long, uniform, high-density plasmas. The high-density provides accelerating fields of several 10's of GeV/m and the MT/m focusing in the ion bubble allows sustained interactions over a meter. For the trailing main beam, the accelerating fields are independent of radius and the focusing fields are linear in radius and independent of position along the bunch – all highly desirable qualities. For positrons and the extremely low emittance beams needed for collider applications, it will likely be necessary to modify the plasma density profile to preserve the accelerating qualities and mitigate emittance growth due to ion motion or non-linear (aberrated) radial focusing[3]. Continued rapid progress requires sustained parallel efforts on several fronts: theory and analytic models, simulation tools capable of resolving nm beams simulated over meter distances, engineering designs for plasma sources compatible with megawatt beams, and experimental facilities that can provide electron and positron beams with relevant energy and density to test proposed concepts. Development of a concept for a PWFA Linear Collider brings into focus the key beam and plasma physics challenges that must be addressed at experimental facilities such as FACET. The parameters for a plasma-based linear collider are chosen based on years of extensive R&D on the beam generation and focusing subsystems of a conventional rf linear collider. The remaining experimental R&D is directly related to the beam acceleration mechanism. In particular, the primary R&D milestones to be experimentally demonstrated are: High-gradient positron acceleration High beam loading with both electrons and positrons (required for high efficiency), Small energy spreads (required to achieve luminosity and luminosity spectrum), Preservation of small emittances (required to achieve luminosity), ion motion Average bunch repetition rates in the 10's of kHz (required to achieve luminosity), and Multiple plasma stages to achieve the desired energy.

31.4.2.3 Power and cost driver

The proposed design has very power efficient drive beam acceleration in a CW recirculating linac and high beam power transfer efficiency through the plasma, limiting the overall power consumption to about half that of CLIC at high energy. The large accelerating gradient also limits the size of the facility and the cost. The major cost drivers are expected to be the powerful drive beam recirculating linac generating multi-MW of beam power with its RF power system.

31.4.2.4 Tentative schedule

The FACET experimental program will directly address a number of critical issues listed above over the next four years. To address the remaining issues, would require a new facility dedicated to studying beam-driven plasma wakefield acceleration, presently called FACET-II. An extensive design and simulation effort must proceed in parallel with the FACET experimental effort to both support the experimental program and to fully develop the PWFA-LC design concepts outlined here. Over the next 20 years a schedule for development and use of this novel technology for applications with gradually increasing complexity in a staged approach towards an application in high energy colliders can be envisioned. Pending the success of feasibility studies by the beginning of the next decade, low energy applications like compact X-FEL or high brightness beam source could become available for further validation and operational experience. Larger scale applications in high energy colliders might be possible by the end of the next decade.

31.4.2.5 Possible technology application

The concept described in this document is derived for High Energy applications, but PWFA technology may be used for other very attractive applications taking advantage of large accelerating beams in the plasma, especially

- generation of beams with extremely small emittances, so called Trojan horse technique,
- a compact X-FEL using the plasma as a high-gradient accelerator and a source of high-brightness beams.

31.4.3 Laser Plasma Accelerators

31.4.3.1 Short description of the facility and upgrade path

Laser plasma accelerators (LPAs) have produced high quality (1% energy spread, 1 mrad divergence) electron beams at 1 GeV. This has been demonstrated by experiments at LBNL using a 60 TW laser pulse in a 3 cm long plasma channel. The present experimental program at LBNL includes research using the 1 PW BELLA laser system (40 J, 35 fs, 1 Hz), with the main goal of demonstrating high quality electron beams at 10 GeV using a meter-scale plasma channel. Other experiments at LBNL include the staging of two LPA modules at the 1 GeV level and the development of novel laser-triggered electron injection methods to improve the electron beam quality. A preliminary straw-man design of a LPA-based collider has been carried out that is based on staging of many meter-scale 10 GeV LPA modules. This straw-man design was based on order-of-magnitude scaling laws that govern some of the important physics considerations for a LPA, as well as optimistic assumptions on the efficiencies (energy transfer from laser to plasma and from plasma to electron beam) that could be obtained in a LPA

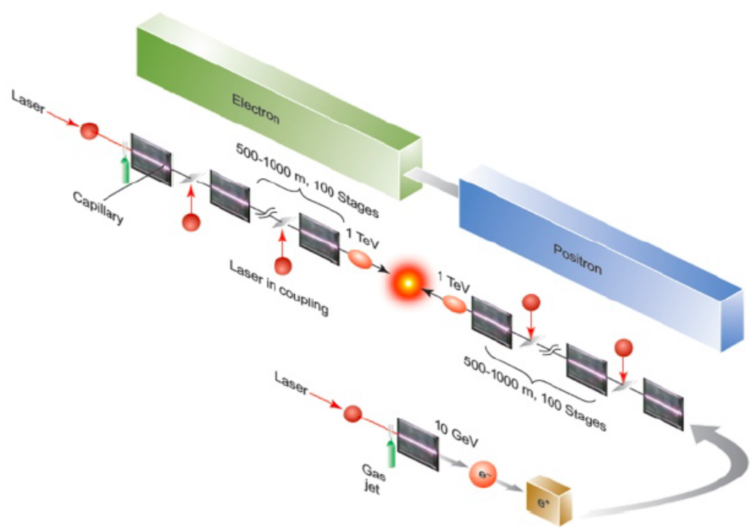

Figure 31-4. *Tentative layout of a 2 TeV laser plasma accelerator.*

31.4.3.2 Power and cost driver

One outcome from this preliminary study is that the laser system required for such a collider must have high average power (≈ 100 MW total; 1 MW per stage), high repetition rate (kHz to MHz), and high efficiency (≈ 10%). These requirements on average laser power, rep-rate, and efficiency still well beyond the current state-of-the-art for short-pulse, high peak power lasers (e.g., currently at the ≈ 100 W average power level). However, high-efficiency diode-pump lasers and fiber lasers are rapidly evolving technologies that could close this technology gap within the next years. High average power lasers for future accelerators are discussed [?].

31.4.3.3 Major R&D issues

Further R&D on LPA physics is also necessary to address the viability of LPA to high-energy physics applications. This comprehensive experimental, theoretical and computation program would include the following

- 10 GeV level beams from a single LPA stage (BELLA experiment)
- staging: demonstrate staged LPAs at 5 GeV+5 GeV
- beam loading studies including phase space manipulation techniques for longitudinal shaping of bunches to optimize efficiency
- tailored plasma channels to mitigate dephasing and near-hollow plasma channels to mitigate emittance growth from scattering
- positron acceleration in LPA including positron beam trapping and acceleration
- novel methods for electron beam cooling via plasma-wave-based radiation generation
- survival of spin polarization in LPA
- gamma-gamma collider (laser technology development)
- adiabatic plasma lens to reduce final focus length

To proceed with a comprehensive R&D research program on LPAs, LBNL has plans to develop a national high peak power laser user facility, BELLA II, that would consist of multiple high power laser systems, multiple beams lines, multiple shielded experimental areas, etc. This national facility would be able to support a large number of users and operate several experiments simultaneously.

31.4.3.4 Tentative schedule

The development of laser and plasma technology realistically requires

- 5-10 years time frame
  - 3 kW (3 J at 1 kHz) laser for driving 1 GeV LPA at 1 kHz
  - 1-10 kHz capillary discharge based systems
  - laser beam shaping for emittance control through mode shaping
  - development of hollow or near-hollow channel technology
- 10-20 years time frame
  - 30-300 kW average power, short pulse laser technology
  - high repetition rate plasma structures (¿10 kHz)

31.4.3.5 Possible technology application

In addition to research on LPAs for high-energy physics applications, BELLA II would also perform research relevant to the broader needs of the Office of Science, such as on the development of coherent XUV sources (LPA-driven free electron laser) for ultrafast science, incoherent gamma-ray sources (Compton/Thomson scattering) for homeland security, and laser-driven compact proton accelerators for medical science.

31.4.4 Dielectric Laser Accelerators

31.4.4.1 Short description of the facility and upgrade path

DLA produces the desired luminosity with much lower bunch charge and, hence, a significantly smaller beamstrahlung energy loss than for other technologies. Other advanced collider schemes such as beam-driven plasma and terahertz schemes also rely upon a traditional pulse format for the electron/positron beam and would therefore compare similarly in this regard. The unique operating regime makes DLA a promising technology for future collider applications, see Figure 31-5.

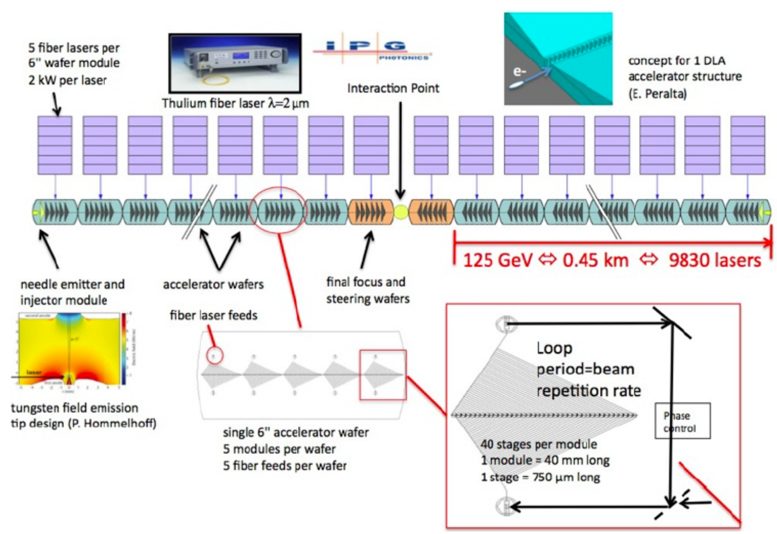

Figure 31-5. *Layout of a dielectric laser accelerator.*

31.4.4.2 Power and cost driver

The DLA concept leverages well-established industrial fabrication capabilities and the commercial availability of tabletop lasers to reduce cost, while offering significantly higher accelerating gradients, and therefore a smaller footprint. Power estimates for the DLA scenario are comparable with conventional RF technology, assuming similar power efficiency (near 100%) for guided wave systems can be achieved, 40% wall plug laser efficiencies (feasible with solid state Thulium fiber laser systems), and 40% laser to electron beam coupling (consistent with published calculations).

31.4.4.3 Major R&D issues

Progress towards an energy scalable DLA architecture requires an R&D focus on fabrication and structure evaluation to optimize existing and proposed concepts. Low-charge high-rep rate electron sources must be developed to evaluate performance over many stages of acceleration. Initial proof-of-principle demonstrations of dielectric laser acceleration have already yielded first demonstrations of gradient in these structures. The future challenge will be to develop this technique into a useful acceleration method. Among the issues that need to be resolved are: (1) understanding IR laser damage limits of semiconductor materials at picosecond pulse lengths; (2) development of high (near 100%) efficiency schemes for coupling fiber or free space lasers into DLA structures; (3) developing integrated designs with multiple stages of acceleration; and (4) understanding phase stability issues related to temperature and nonlinear high-field effects in dielectrics.

31.4.4.4 Tentative schedule

Proof of principle experiments and feasibility studies will continue through 2015. Pending approval, an R&D demonstration module incorporating multiple stages of acceleration, efficient guided wave systems, high repetition rate fiber laser system, and component integration could be developed on a 5-year time scale. After that there could be a proposal to construct a demonstration facility of the path toward multi-GeV beam energies, followed by a design report and technology preparations for construction of a Higgs factory collider.

31.4.4.5 Possible technology application

This research has significant near and long-term applications beyond energy frontier science, including radiation production for compact medical x-ray sources, university-scale free electron lasers, NMR security scanners, and food sterilization. These additional applications are beginning to be explored. A dielectric laser-driven deflector was recently proposed by Plettner and Byer, that uses a pair of dielectric gratings excited transversely by a laser beam and separated by a gap of order the laser wavelength where a beam of electrons would travel. By changing the sign of the excitation between successive structures, e.g. by alternating the direction of illumination, an optically powered undulator could be constructed to create laser driven micro-undulators for production of attosecond-scale radiation pulses synchronized with the electron bunch. Unlike other electromagnetic undulator concepts, the undulator period in this scheme is set by the length of each deflection stage and can therefore be much larger than the driving wavelength. Undulators based upon this concept could attain very short (mm to sub-mm) periods with multi-Tesla field strengths: an undulator with a 250 μm period driven by a 2 μm solid state laser would have a gain length of 4 cm and an X-ray photon energy of 10 keV when driven by a 500 MeV electron beam. Since DLA structures operate optimally with optical-scale electron bunch formats, high repetition rate (10s of MHz) attosecond-scale pulses are a natural combination.

31.5 Circular Electron-Positron Collider

TLEP [11] is a proposal for an e^+e^- storage ring of 80-km circumference that could potentially operate with very high luminosity at the Z peak (90 GeV), with luminosity falling rapidly with $\sqrt{s}$ up to a maximum E_{cm} of 350 GeV(top quark pair threshold). The possibility of transverse beam polarization at the Z peak, and possibly up to the WW threshold, could give TLEP unparalleled accuracy ($\leq$ 100 keV per measurement) on the beam energy calibration by resonant depolarization. A preliminary study indicates that an 80 km tunnel could be constructed around CERN and other sites have been discussed. The long tunnel is being considered for a ∼100 TeV hadron collider (VHE-LHC) as part of a future circular collider study (FCC).

The potential for high luminosity makes TLEP an attractive facility for the study of the Higgs boson. For electro-weak precision measurements (such as m_Z, Γ_Z, m_W), the availability of precise energy calibration and of well-known longitudinal polarization are also essential. TLEP builds on three unique characteristics of circular machines: i) high luminosity (albeit with high beam and AC power), ii) the availability of several interaction points, iii) excellent beam energy accuracy. For a given RF power, the luminosity of a storage ring collider rises linearly with its circumference. For a given tunnel size, and assuming the machine operates at the beam-beam limit, luminosity rises linearly with the total dissipated synchrotron radiation (SR) power, which is approximately proportional to the total available power from the electric grid. Therefore, the analysis can be scaled to different machine circumferences. The energy reach depends strongly on the machine circumference: a machine of 27-km circumference can reach 240 GeV, the limit is over 350 GeV for a machine of 80km circumference.

31.5.1 The accelerator

TLEP uses SCRF and low β* insertions and the storage ring needs to be fed by an accelerator situated in the same tunnel for continuous top-up injection. Multi-bunch operation is necessary for high luminosity below the top energy, so two beam pipes are required for electron and positron beams. A first version of the parameters of TLEP has been produced. The SR power dissipated in the tunnel is a design parameter which has been fixed at 100MW. In order to achieve high luminosities, β_y* has been set to 1mm, which, compared to the longitudinal size of the beams (2-3mm), gives an hourglass factor of around 0.7. For TLEP-H (E_{cm}= 240 GeV) and TLEP-t (350 GeV), beamstrahlung reduces the beam lifetime significantly. For successful operation the beam lifetime has to be longer than the refilling time. The beamstrahlung lifetime depends on the momentum acceptance, on the number of electrons in a bunch and on the horizontal and longitudinal beam sizes, but not on the vertical beam size. Beamstrahlung effects have been simulated using a detailed collision simulator, Guinea-pig. The simulations give reasonable lifetimes for values of momentum acceptance above 2.5% and an emittance ratio $\kappa_\epsilon \equiv \epsilon_x/\epsilon_y$ of 500. These parameters appear conceptually feasible but remain challenging and require careful design and study. Both the optics design to ensure such large momentum acceptance and the design of alignment procedures and online corrections needed to ensure the small emittance ratio will be key elements of the accelerator design. A high horizontal to vertical emittance ratio of 1000 is routinely achieved at synchrotron radiation facilities, but will be challenging in a collider.It may be achievable in TLEP with modern beam instrumentation and perhaps active magnet supports.

In Higgs factory mode at a center-of-mass energy of 240 GeV, a luminosity of 5×10^{34} cm^{-2}s^{-1} is possible for each IP. A storage ring with four IPs is currently being considered to allow direct extrapolation from LEP2, assuming beam-beam parameter values around 0.1 per IP. Most of the components of the proposed superconducting RF system are available for frequencies around 700-800 MHz. Assuming a gradient of 20MV/m, the rings would need an effective length of 600m of acceleration and a total length probably in excess of a km, somewhat larger than that of LEP2. For high current operation, both the high-power coupler in cw mode and Higher-order Mode damping are challenging and require R&D. The design study will address the optimization of the RF system as well as dedicated R&D to increase the power efficiency of the system.

A unique capability of circular machines is the possibility to make accurate beam energy measurements using resonant depolarization. Transverse beam polarization should be available at the Z pole and possibly up to 80 GeV per beam. Running with a few dedicated non-colliding bunches would allow the energy to be measured continuously, allowing measurements of the Z mass and width with a precision of 0.1 MeV or better and the W mass with a precision of 1 MeV or better. In addition, if high longitudinal polarization is available, it could enable a measurement of the polarization asymmetry with a precision of the order of 10^{-5} or a precision on $\sin 2\theta_{W,eff}$ of the order of 10^{-6}.

31.5.2 Technical challenges

The RF system is a main power consumption and cost driver, so high efficiency is essential. While the efficiency for CW operation can be higher (50-60%) than for pulsed operation, these values were only achieved at LEP-2 at the highest energies when operating in saturation without overhead for feedback.To ensure high luminosity at the Z-pole, a very high beam current (over 1A per beam) is needed. The higher order modes in the 600 meters of cavity section, in particular those of multi-cell cavities, can cause serious beam instabilities. Single-cell cavities such as those adopted at KEKB may be necessary. One solution is to use different cavities for low energy operation but this is obviously expensive.

Optics with ultra-low emittance, low β^* values and large momentum acceptance are extremely challenging. The large beamstrahlung energy loss requires a momentum acceptance in the range of 2-2.5% to avoid excessive beam loss. A significant design effort is required to demonstrate feasibility, including extensive beam tracking in the presence of beam-beam effects. The latest designs adopt tighter focusing in the arc to obtain a very low vertical emittance with the vertical-horizontal ratio fixed. This can also affect the momentum acceptance.

Procedures to achieve low vertical emittance with a high horizontal to vertical emittance ratio must be developed. LEP achieved an emittance ratio of 250, but modern light sources achieve values higher than 2000, but with much lower bunch current and without IR optics. Detailed studies of beam dynamics, including the entire top-up injection system, remain to be done. Impedance issues and the strong beam-beam parameters require careful study, particularly at low center-of-mass energies with very high currents and short bunches. The very slow radiation damping should also be noted (several hundred milliseconds). All the instability phenomena must be carefully examined.

Top-up injection: For the targeted 1000 s overall beam lifetime, 1% of the beam needs to be replenished every 10 s. This calls for an injector ring, continuously ramping and injecting in the collider ring. In the SPS used in electron injection mode, the ramping speed was in excess of 60 GeV/s. The details and integration of the injector require a dedicated design.

TLEP operation at the Z, WW and ZH energies requires many bunches (4400, 600 and 80 in the current design), therefore a separate beam pipe is required for e^+ and e^- with possibly a twin or double magnet design. To simultaneously address vacuum, heat extraction and other issues without impeding magnet operation is a complex design problem.A separate beam pipe may also be required at high energies because of the so-called sawtooth effect, which is the orbit difference between electron and positron beams due to the localized synchrotron radiation loss and energy replenishment in RF sections.

If TLEP will use the tunnel built for a high energy hadron collider, integration and possible synergies should be properly addressed early on.

31.5.3 Polarization

The beam polarization can be used for accurate beam energy calibration as was done at LEP at the Z-pole. Two transverse polarimeters need to be designed for e^+ and e^- beams. The sterile bunch operation needed for continuous calibration needs special consideration. Significant polarization is not available at a beam energy beyond about 80GeV because of the larger beam energy spread. The transverse polarization may still be available at W-pair production since only a few percent polarization is sufficient for energy calibration. To make use of the polarization for collision experiments is much harder. The spontaneous polarization time at the Z-pole is a few hundred hours whereas the beam lifetime due to radiative Bhabha scattering is of order of one hour. Hence acceleration of polarization build up using wigglers is indispensable (the sterile bunch for energy calibration does not suffer from radiative Bhabha scattering). However, these wigglers would cause synchrotron radiation loss which is much larger than that in the arc. With the RF power being limited, polarization for collision experiments might be available only at much lower beam current, and hence much lower luminosity. Moreover, the wigglers also cause large energy spread which can depolarize the beam. The localized energy deposition at the wigglers is also a concern. In addition, spin rotators such as the one used at HERA are necessary for longitudinal polarization operation. A very careful design of the rotators is needed so that they do not cause additional depolarization.

31.5.4 Power consumption

The luminosity of TLEP is proportional to the SR power dissipated in the ring, which is proportional to the RF power. The current TLEP parameters are based on an assumption of 100MW of power dissipation in the tunnel (around 1kW per meter of bend), which results in a total power consumption of around 300 MW with today's technology.

The total RF system efficiency is estimated to be 54%-59%. A thyristor 6-pulse power converter for this application has an efficiency of 95%, whereas a switch mode converter runs at 90% efficiency. A klystron operated at saturation (as in the last year of LEP2) without headroom for RF feedback runs at a 65% efficiency. These efficiency estimates assume fast RF feedback is not necessary for TLEP. RF distribution losses are 5-7%. To estimate the cryogenic power consumption, the LHC figures (900W/W at 1.9 K) are used to arrive at 23 MW at 175 GeV (fundamental frequency dynamic load only). The final power consumption would be 1.5 times the dynamic load consumption (to account for static heat loads, HOM dissipation in cavities, overhead for cryogenics distribution etc.), leading to a consumption of 34 MW at 175 GeV. The RF power budget of the accelerator ring is included in this calculation, as the total current in both rings is constant, with the exception of the ramp acceleration power: for a 1.6 s ramp length and 155 GeV energy swing, the total ramp power is estimated to be 5 MW. RF power efficiency R&D will have very large pay-off in terms of construction and operating costs. The power consumption of the rest of the systems adds another 80 MW of power, excluding the experiments.

31.5.5 Main cost drivers

TLEP is a project in its infancy, so a detailed cost estimate does not yet exist, but the main cost drivers have been identified. TLEP is envisaged to be built next to an existing large laboratory, such as CERN, which minimizes some costs. The TLEP tunnel with its infrastructure is the most significant cost item, but the tunnel is intended to later house the next suite of hadron/e-p/ion collider(s) including a very high energy proton collider (VHE-LHC), ensuring its long-term exploitation. For the TLEP machine proper, the main cost driver is the RF system with its cryogenic infrastructure.

31.5.6 Timescale

A design study to explore the capabilities and challenges of TLEP has just started. The aim of the study is to produce a conceptual design report by 2015 and a more detailed technical document by 2018, by which time the results of the 13 TeV run of the LHC will be available. These results would be crucial for defining the strategy for High Energy Physics for the next 20-30 years, and TLEP will be ready with a complete report to aid in the process. Tunnel construction could start while the LHC is still running with the aim of first physics shortly after the end of LHC operation.

31.6 Muon Accelerators

Muon accelerators offer the U.S. High Energy Physics community the potential for both a high intensity and precise source of neutrinos to support a world-leading research program in neutrino physics and a chance to return to the Energy Frontier through a Muon Collider at center-of-mass energies from the Higgs at 126 GeV up to the multi-TeV scale. The U.S. Muon Accelerator Program (MAP) is an ongoing multi-year program to assess the feasibility of muon accelerators for both applications. The supporting complex required for the two capabilities is highly synergistic, as shown in Figure 31-6, thus providing opportunities to support a unique breadth of physics output relative to the investment required as well as to stage the complex in a cost-effective and technically robust fashion. Critical path R&D items are discussed below.

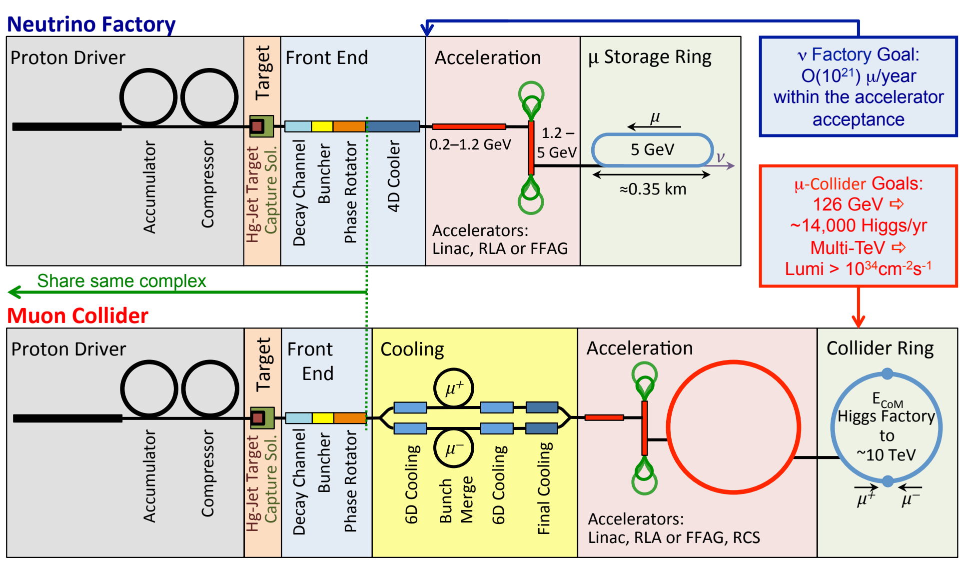

Figure 31-6. *Block diagrams of the neutrino factory and muon collider concepts showing the synergies between the two complexes. This leads to a very clear staging scenario that can provide both Intensity and Energy Frontier capabilities for the HEP community.*

31.6.1 Muon Accelerator Staging Scenarios

For the proposed staging plan, baseline parameter specifications have been developed for a series of facilities, each capable of providing physics output, and at each of which the performance of systems required for the next stage can be reliably evaluated. The plan thus provides clear decision points before embarking upon each subsequent stage. The staging plan builds on two existing and proposed facilities, specifically:

- Project X at Fermilab as the megawatt-class proton driver for muon generation
- Sanford Underground Research Facility (SURF), as developed for the LBNE detector. Neutrino Factory beams could initially be directed to an existing LBNE and ultimately to an upgraded detector that is optimized to take full advantage of those beams.

The performance characteristics of each stage provide unique physics reach:

- nuSTORM (Neutrinos from STORed Muons): a short baseline Neutrino Factory (NF) enabling a definitive search for sterile neutrinos, as well as neutrino cross-section measurements that will ultimately be required for precision measurements at any long baseline experiment. nuSTORM could store 8×10^{17} muons/year and provide 3×10^{17}/year each of ν_e and ν_μ towards a short baseline detector. The nuSTORM ring would provide a proving ground for the operation of high intensity muon storage rings. The spent beam, which is removed at the end of the injection straight, could provide an intense beam, $\sim 10^{10}$ muons/pulse, suitable for advanced systems tests of muon cooling technologies.
- NuMAX (Neutrinos from Muon Accelerators at Project X): an initial long baseline Neutrino Factory, optimized for a detector at SURF − a precise and well-characterized neutrino source that exceeds the capabilities of conventional superbeam technology. Such a facility could initially be deployed without muon cooling and store $\sim 2 \times 10^{20}$ μ^+ and μ^- per year (simultaneously) in its ring. This would provide $\sim 8 \times 10^{19}$ electron and muon neutrinos (and their antineutrinos) directed towards a long-baseline detector per year. Incremental upgrades (target and muon cooling) would lead to the NuMAX+ configuration.
- NuMAX+: a full intensity Neutrino Factory, as the ultimate source to enable precision CP violation measurements in the neutrino sector. Such a facility would increase the neutrino fluxes by a factor of 6 (to $\sim 5 \times 10^{20}$ neutrinos of each species per year) over those available in the NuMAX configuration and, in conjunction with a magnetized detector, would enable measurements of the CP-violating phase with a resolution of a few degrees, equivalent to the sensitivities achieved with the CKM matrix in the quark sector.
- Higgs Factory: a collider whose baseline configurations are capable of providing between 3,500 and 13,500 Higgs events per year with an energy resolution of a few MeV, thus allowing precision measurement of the Higgs mass and width. Such a facility would be of particular interest if the observed Higgs were found to be a doublet state.
- Multi-TeV Collider: muon colliders up to a maximum energy of $\sim$ 10 TeV can be envisioned before site radiation limits due to the decay muons become dominant. Above $\sim$ 2 TeV, the absence of synchrotron radiation for muon colliders means that the luminosity provided for a given wall power can significantly exceed that which can be provided with any proposed e^+e^- collider configuration. In the event that the LHC reveals evidence for a supersymmetry, the ability to explore the spectrum into the several TeV range is a particularly appealing aspect of the muon collider concept. At multi-TeV energies, a

muon collider could provide precision measurements of key couplings such as the Higgs self-coupling. Furthermore, at these energies, the dominant role of the electroweak fusion process effectively makes such a machine an electroweak boson collider with significant discovery potential.

Collider parameters for a Higgs Factory as well as 1.5 and 3.0 TeV colliders are provided in Table 31-7. These machines would fit within the footprint of the Fermilab site. The ability to deploy these facilities in a staged fashion offers major benefits:

- The strong synergies among the critical elements of the accelerator complex maximize the size of the experimental community that can be supported by the overall facility.
- The staging plan reduces the investment required at each step to levels that will hopefully fit within the future budget profile of the U.S. high energy physics program.

The nuSTORM capabilities could be deployed now. The NuMAX options and initial Higgs Factory could be based on the 3 GeV proton source of Project X Stage II operating with 1 MW and, eventually, 3 MW proton beams. This opens the possibility of launching the initial NuMAX, which requires no cooling of the muon beams, within the next decade. Similarly, the R&D required for a decision on a collider could be completed by the middle of the next decade. A Muon Collider in the multi-TeV range would offer exceptional performance due to the absence of synchrotron radiation effects, no beamstrahlung issues at the interaction point, and anticipated wall power requirements at the 200 MW scale, well below the widely accepted 300 MW maximum affordable power for a future HEP facility. This timeline, showing the targeted dates where critical decisions should be possible, is summarized in Figure 31-8.

31.6.2 Critical R&D and Cost Drivers

The U.S. Muon Accelerator Program (MAP) has the task of assessing the feasibility of muon accelerators for Neutrino Factory and Muon Collider applications. Critical path R&D items important to the performance of one or more of these facilities include:

- Development of a high power target station which is ultimately capable of handling more than 4 MW of power. Liquid-metal jet technology has been shown to be capable of handling the necessary beam power [13]. While the complete engineering design of a multi-MW target station, including a high field capture solenoid (nominally 20 T hybrid normal and superconducting magnet with about 3 GJ stored energy) is challenging, target stations with similar specifications are required for other planned facilities (e.g., spallation sources), and our expectation is that the engineering challenges can be successfully addressed over the course of the next decade. In the meantime, a muon accelerator complex can begin producing world-class physics with the proton beam powers that will become available with Project X Stage II.
- Muon cooling is required in order to achieve the beam parameters for a high performance NF and for all MC designs under consideration. An ionization cooling channel requires the operation of RF cavities in tesla-scale magnetic fields. Promising recent results from the MuCool Test Area (MTA) at Fermilab point towards solutions to the breakdown problems of RF cavities operating in this environment [14]. These advances, along with technology concepts developed over the past decade, are expected to allow MAP to establish a baseline 6D cooling design on the 2-year timescale [15]. In addition, the Muon Ionization Cooling Experiment is expected to begin producing relevant results in the same time frame [16].

Muon Collider Baseline Parameters					
		Higgs Factory		Multi-TeV Baselines	
Parameter	***Units***	Startup Operation	Production Operation		
CoM Energy	TeV	0.126	0.126	1.5	3.0
Avg. Luminosity	$10^{34}cm^{-2}s^{-1}$	0.0017	0.008	1.25	4.4
Beam Energy Spread	%	0.003	0.004	0.1	0.1
Higgs/10^{7}sec		3,500	13,500	37,500	200,000
Circumference	km	0.3	0.3	2.5	4.5
No. of IPs		1	1	2	2
Repetition Rate	Hz	30	15	15	12
β^*	cm	3.3	1.7	1 (0.5-2)	0.5 (0.3-3)
No. muons/bunch	10^{12}	2	4	2	2
No. bunches/beam		1	1	1	1
Norm. Trans. Emittance, ε_{TN}	π mm-rad	0.4	0.2	0.025	0.025
Norm. Long. Emittance, ε_{LN}	π mm-rad	1	1.5	70	70
Bunch Length, σ_s	cm	5.6	6.3	1	0.5
Beam Size @ IP	μm	150	75	6	3
Beam-beam Parameter / IP		0.005	0.02	0.09	0.09
Proton Driver Power	MW	$4^{\#}$	4	4	4

$^{\#}$ Could begin operation with Project X Stage 2 beam

Figure 31-7. *Muon Accelerator Program baseline Muon Collider parameters for both Higgs Factory and multi-TeV Energy Frontier colliders. An important feature of the staging plan is that collider activity could begin with Project X Stage II beam capabilities at Fermilab.*

- High intensity, low energy beams (200 MeV/c, optimal for muon ionization cooling) are susceptible to a range of potential collective effects. Evaluating the likely impact of these effects on the muon beams required for NF and MC applications, through simulation and experiment, is an important deliverable of the MAP feasibility assessment.
- For the MC, muon decays in the ring impact both the magnet and shielding design for the collider itself as well as backgrounds in the detector. Detector backgrounds have been shown to be manageable via pixelated detectors with good time resolution. Thus, this issue appears to present no impediment to moving forward with full detector studies and machine-detector interface design efforts.

A thorough evaluation of these issues is crucial for an informed community decision on muon accelerator facilities. Furthermore, the proposed staging plan enables the performance, at each stage, of confirming R&D for the next stage in the plan, to inform the decision process.

The muon collider design remains in a technical feasibility assessment phase and a mature cost model does not yet exist. Nevertheless, clear cost drivers for the design have been identified. For the R&D program itself, the principal cost driver is the demonstration of ionization cooling which is the most novel capability required for such a machine. Major cost drivers for the facility will be the proton driver and high-power target system, costs which could be wholly shared between the neutrino factory and collider facilities. The cooling and acceleration systems, which are only partially shared between the neutrino factory and collider applications, will also be major cost drivers. It should be noted that significant cost trade-offs between the cooling and early stage acceleration are anticipated because the emittance of the cooled beam is strongly coupled to the acceptance required for the accelerator design. The collider ring, with its small circumference at low energy is not expected to be a cost driver, but will become more significant at the TeV-scale. Thus collider costs are expected to scale somewhat linearly with energy, but with a large offset due to the proton source, front end and cooling systems which are necessary irrespective of the final collider energy.

31.6.3 Summary

To summarize, muon accelerators can enable a broad and world-leading high energy physics program which can be based on the infrastructure of Fermilab. While any decision to move forward with muon accelerator based technologies rests on the evolving physics requirements of the field, as well as the successful conclusion of the MAP feasibility assessment later this decade, the ability of muon accelerators to address crucial questions on both the Intensity and Energy Frontiers, as well as to provide a broad foundation for a vibrant U.S. HEP program, argues for a robust development program to continue. This will enable a set of informed decisions by the U.S. community starting near the end of this decade. More details on the muon accelerator program and its staging plan can be found in Reference [17].

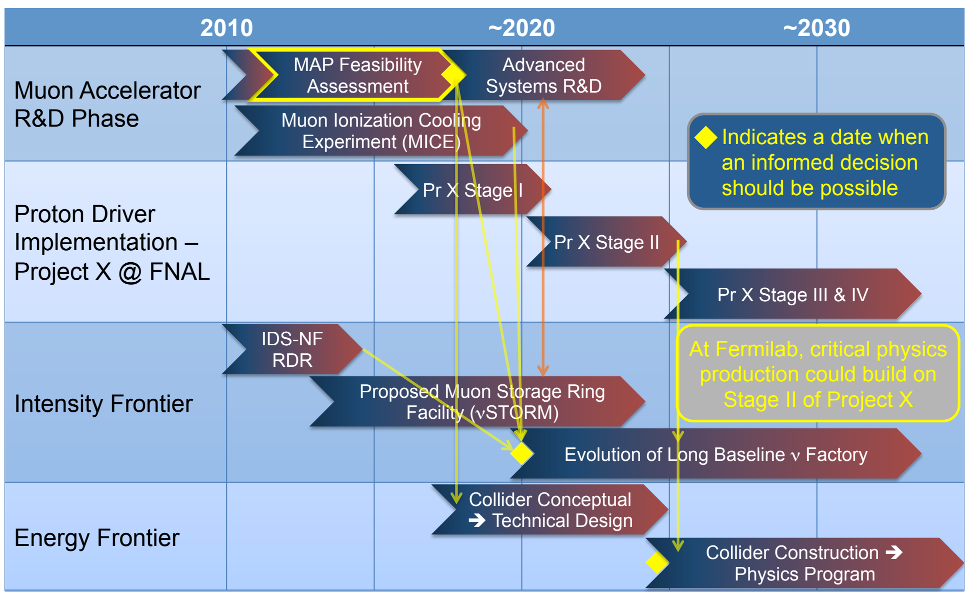

Figure 31-8. *Muon accelerator timeline including the MAP Feasibility Assessment period. It is anticipated that decision points for moving forward with a Neutrino Factory project supporting Intensity Frontier physics efforts could be reached by the end of this decade, and a decision point for moving forward with a Muon Collider physics effort supporting a return to the Energy Frontier with a U.S. facility could be reached by the middle of the next decade. These efforts are able to build on Project X Phase II capabilities as soon as they are available. It should also be noted that the development of a short baseline neutrino facility, i.e., nuSTORM, would significantly enhance MAP research capabilities by supporting a program of advanced systems R&D.*

31.7 Photon Collider

In a Higgs factory photon collider, two electron beams are accelerated to 80 GeV and converted to 64 GeV photon beams by colliding with low energy (3.5 eV) high intensity (5 J per pulse) lasers via the Inverse Compton Scattering (ICS) process. The two high energy photon beams then collide and generate Higgs particles through the s-channel resonance $\gamma\gamma \rightarrow H$. Among various options for a Higgs factory, a photon collider has the distinct advantage that the 80 GeV energy required for the electron beam is lower than for other colliders. Photon colliders have been discussed as options to accompany proposed linear or circular colliders or as a standalone facility [18, 23]. The photon collider was considered in detail at a conceptual level in the earlier TESLA [19] designs.

A key technology for photon collider is the required laser system. It must be able to deliver high average power (hundreds of kW or higher), high repetition rate (tens of kHz or higher), and high wall plug efficiency (several tens of a percentage). Thanks to a new collaboration between the International Committee for Ultra Intense Lasers (ICUIL) and the International Committee for Future Accelerators (ICFA), the laser community has been making tremendous and rapid progress along the directions to meet the requirements of a photon collider. A recent breakthrough in fiber laser technology showed that by using a coherent amplification network, the fiber laser can deliver a pulse with an energy of 10 J at a repetition rate of 10 kHz. Alternatively, the Mercury laser developed at the Lawrence Livermore National Lab came into operation in 2005. One Mercury box can deliver 20 pulses, 7 J each, at 100 Hz repetition rate. About twenty Mercury boxes would be able to provide the laser required for a photon collider, but a practical implementation would require significant reduction in the cost of the pumping diode.

31.7.1 Parameters of the photon collider at the ILC

The ILC TDR [6] does not explicitly include the photon collider option. An implementation at the ILC requires careful planning of the interaction region. In the TESLA design, there was a second interaction point and a specialized detector [20]. For the study of single Higgs bosons, an electron beam energy of about 105 GeV is required and a laser wavelength of $1\mu m$. If the ILC were upgraded to a luminosity of 4×10^{34} $\mathrm{cm}^{-2}\mathrm{s}^{-1}$ for e-e- collisions, the photon collider could produce 20000 Higgs bosons per year. One possible route to higher luminosity would be through low emittance polarized RF guns, which are not yet available, but could potentially increase the luminosity by a factor of 10 without requiring damping rings.

31.7.2 Photon collider based on recirculating linacs

The SAPPHiRE [21] project proposes to use the 60 GeV recirculating polarized electron linac developed for electron-proton collisions with LHC protons (LHeC) as a photon collider. This ring would contain two 10 GeV superconducting linacs. To reach 60 GeV energy, the electron beam makes three turns. To reach 80 GeV for the photon collider, would require an additional two arcs. The footprint of the machine is rather small with an arc radius of 1 km and the total circumference of 9 km. However, the total length of all arcs is 72 km. Another proposal of a photon collider based on recirculating linacs is HFiTT [22] in Tevatron Tunnel. The two electron beams would be accelerated in opposite directions in 8 turns to 80 GeV and then converted to high energy photon beams. These proposals using two 80 GeV electron beams have the advantage of the minimal electron energy to produce a Higgs. However, it was pointed out that the performance in measuring

CP parameters, which is one of the advantage of photon colliders, is poor because of the large x-parameter. For effective measurements, electron beams of about 110 GeV are necessary.

31.7.3 Photon collider based on advanced acceleration mechanism

In addition to a Higgs factory, a photon collider also opens another window for far future electron colliders using very high gradient acceleration techniques such as plasma wakefield acceleration which may accelerate high quality electron beams but not be able to accelerate high quality positron beams. The photon collider only requires accelerated electrons and can still access annihilation reactions with precisely understood point-like interactions. A photon collider could not only measure the properties of the Higgs boson but also demonstrate the technologies needed for photon collider experiments at higher energies.

31.8 Efficiency

Any future facility at the energy or the intensity frontier faces the challenges of generating and handling very large beam power. For example, in the case of linear colliders, the beam power is proportional to the product of the luminosity and the colliding beam energy. Since the luminosity is usually required to increase with the square of the colliding beam energy to compensate for reduction of the interaction cross section, the necessary beam power finally varies with the third power of the colliding beam energy. Similar beam power is also required in lepton circular colliders to compensate for the energy loss from synchrotron radiation, which also increases with the third power of the beam energy. To produce the needed beam power without excessive wall plug consumption requires a high beam acceleration efficiency to keep the operating costs within affordable limits. At the same time, high accelerating fields are required to limit the size and construction cost of the facility. The development of high acceleration fields with excellent wall plug to beam transfer efficiency constitutes a major challenge of high energy facilities. It is key to pushing the energy frontier in the future.

31.8.1 Acceleration efficiency

Depending on the technology, the beam is accelerated with power flowing from the wall-plug to a drive (RF, beam or laser) which generates accelerating fields in a medium (structures, plasma or dielectrics) from which part of the power is finally transferred to the beam. An important criterion is therefore the acceleration efficiency defined as the wall plug to beam transfer efficiency of the accelerating system. An additional criterion is the overall efficiency of the complex including the injectors, beam delivery, and conventional facilities. The power transfer efficiencies of the different systems of the various technologies are compared in Table 31-3. The acceleration efficiency of the different technologies is displayed in Figure 31-9 as a function of the achievable accelerating field. Finally the figure of merit defined as the luminosity per MW of the various technologies is compared in Figure 31-10 over a wide colliding beam energy range.

Table 31-3. *Power transfer efficiency in percent.*

<table>
<tr><th></th><th>Circular</th><th>ILC
SC-RF</th><th>Klystron
NC-RF</th><th>CLIC
2 beam</th><th>Plasma
beam</th><th>Plasma
laser</th><th>Dielectric</th><th>Muon</th></tr>
<tr><td>Overall</td><td>30</td><td>6.5</td><td>5</td><td>4.8</td><td>15</td><td>4.5</td><td>13</td><td>5</td></tr>
<tr><td>Acceleration</td><td>45</td><td>10</td><td>8.5</td><td>8</td><td>21</td><td>6</td><td>15</td><td>15</td></tr>
<tr><td>Field to beam</td><td>95</td><td>45</td><td>30</td><td>27</td><td>66</td><td>40</td><td rowspan="2">50</td><td>40</td></tr>
<tr><td>Drive to field</td><td rowspan="2">55</td><td rowspan="2">45</td><td>42</td><td rowspan="2">38</td><td>76</td><td>50</td><td>55</td></tr>
<tr><td>Drive generation</td><td>70</td><td>44</td><td>30</td><td>30</td><td>80</td></tr>
</table>

31.8.2 Need for innovative R&D

Since the acceleration efficiency corresponds to the product of the individual efficiencies of each of the systems involved in the wall plug to beam power transfer, each of the systems has to be as efficient as possible. As shown in Table 1, a large part of the limitation of the overall efficiency is due to the drive generation, namely:

- RF generation by klystrons with an efficiency in the 50 to 65% range used in a large number of schemes (circular colliders, linear colliders based on RF structures like ILC or beam driven like CLIC and PWFA and muon colliders)
- laser generation with an efficiency in the 10 to 30% range used in laser driven colliders like LPA and DLA.

Innovative R&D on efficient RF generation and lasers would be extremely beneficial to all designs. It should be strongly supported as a key to reduce the operating costs of the facilities required to push both the energy and intensity frontiers.

31.9 Concluding remarks

The study group agrees on the following recommendations for the future of development of lepton and photon collider and technology for the energy frontier:

- We welcome the initiative for ILC in Japan. An experienced cadre of U.S. accelerator physicists and engineers is capable and ready to work on this project as part of a balanced portfolio of high energy physics.
- A vigorous, integrated R&D program toward demonstrating feasibility of a muon collider is highly desirable.
- All variants of wakefield accelerators require an integrated proof-of-principle test. US is a world leader in these physics programs with high intellectual content.
- Should a linear collider not be built over the next decade and should the renewed interest in a very large circumference hadron collider be sustained, the possibility of a circular Higgs factory deserves careful consideration.

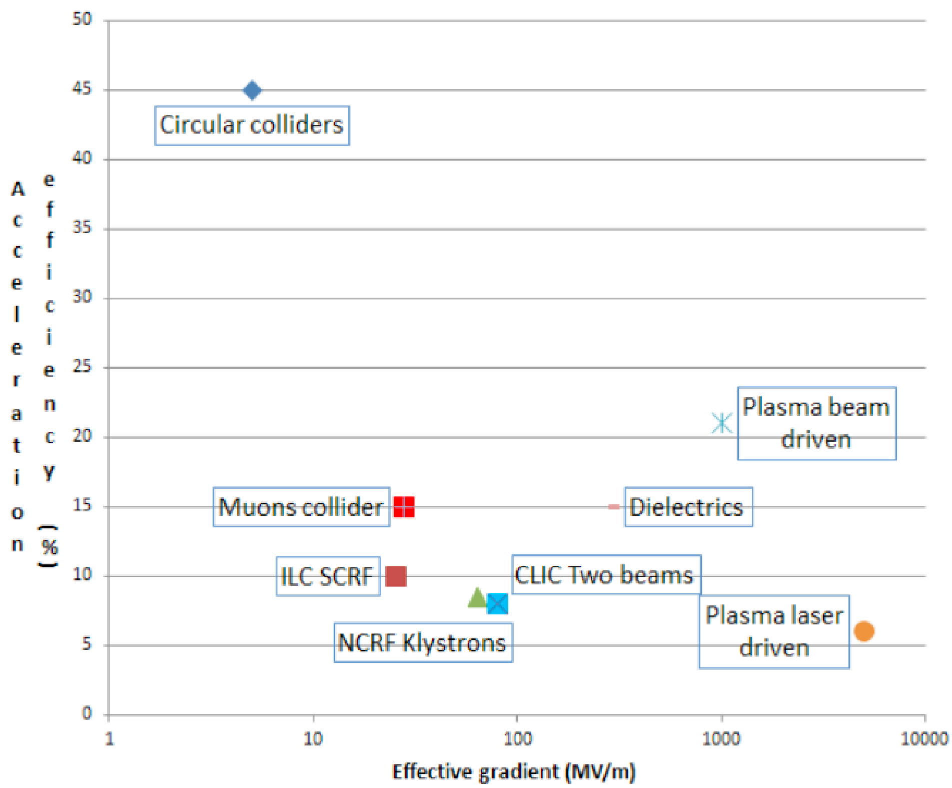

Figure 31-9. *Acceleration efficiency as a function of effective field gradient.*

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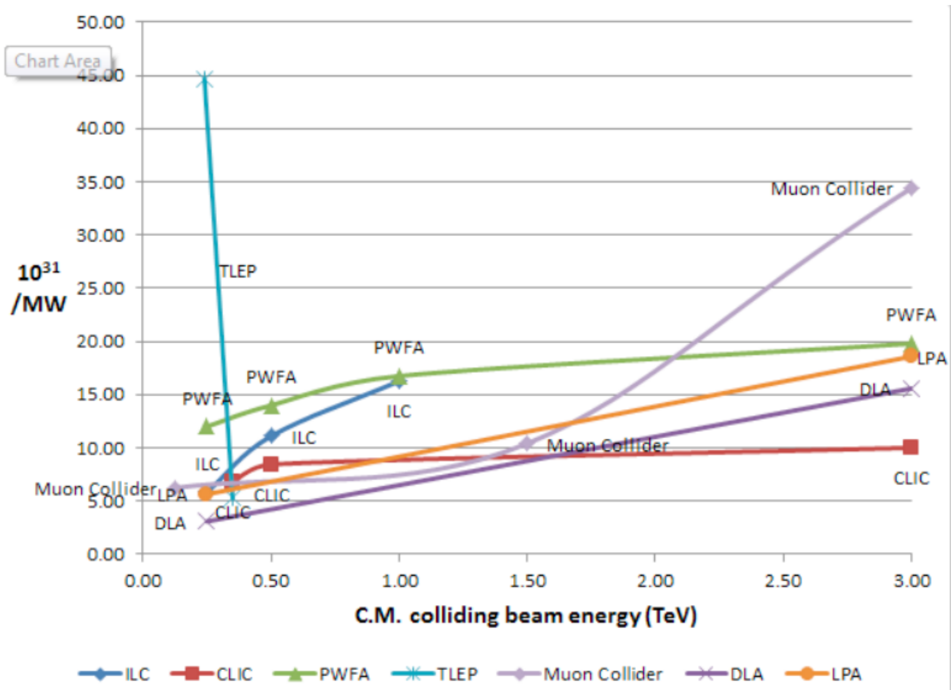

Figure 31-10. *Luminosity per MW as a function of center-of-mass energy.*

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