Snowmass Report on Lepton and Photon Collider

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1 Excecutive Summary

(text by Bill)

1 Support initiative for an ILC in Japan (deep involvement urged by our community) as justified by EF report (capable and fully support as part of a balanced program)

- degree of readiness

- identify U.S. contribution on machine technology - SRF, high power targetry (source) and beam delivery, damping rings, beam dynamics

1b Upgrade path to towards luminosity & energy upgrades ($> 10^{34}, > 500 GeV$)

2 Increase impetus toward a muli-TeV lepton collider

a) - vigorous integrated R&D program toward demonstration feasibility of a muon collider (current support insufficient)

- explore connection with intensity frontier, tools for intense nu-source

b) CLIC and wake field accelerators

3 Circular e+e-

- TLEP

- design study started and planned for the next 2-3 year (CDR)

- limited sqrt(s), but larger luminosity (function of sqrt(s))

- an potential alternative in case ILC does not come through

- investment in infrastructure; VLHC size tunnel

4 Gamma Gamma

- US technology contribution (industrial strength high power laser)

- laser and beam driven

2 Introduction

The Snowmass Community Summer Study 2013 [1] 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 (R%D) 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 [2].

We begin this report with a review the physics landscape relevant to future lepton and photon colliders in Section 3. A more detailed discussion can be found in [3]. The Large Hadron Collider (LHC) with its first three years of data taking has begun to explore the energy region up to 1 TeV. The LHC experiments have discovered a Higgs boson that within current experimental precision is consistent to that of the Standard Model and have measured its mass as about 125 GeV [4, 5]. The LHC is currently being upgraded in energy to up to 14 TeV. The proposed luminosity upgrade for HL-LHC would deliver a data sample corresponding to an integrated luminosity to the ATLAS and CMS experiments of three inverse attobarns. The data will allow measurements with a precision sufficient to test the Standard Model predictions of Higgs boson couplings at the level of a few %. A future lepton or photon collider can provide a factory for measurements of the properties of the Higgs 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.

The International Linear Collider (ILC) is a linear e^+e^- collider with a center-of-mass collision energy tunable between 200 and 500 GeV and a luminosity exceeding 10^{34} cm^{-2}s^{-1} at 500 GeV. The ILC is upgradeable in luminosity by a factor of two and in energy to 1 TeV. The design and technical details have been developed over more than 20 years and are discussed in the ILC Technical Design Report (TDR) [8]. ILC is the most mature project among the lepton colliders and is discussed in Section 4.

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) [21]. It is discussed in Section 5 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. Preliminary parameter studies show a potential for high luminosity at lower energies. Beam dynamics, polarization, power consumption are challenges that need further study. They are discussed in Section 6.

Muon colliders can potentially reach higher energy because the larger mass of the muon means they produce less synchrotron radiation but they are unstable and decay in flight. Muon colliders are discussed in Section 7 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 8.

3 Physics Landscape

(text by Markus)

- Higgs factory (at 250 GeV and beyond)
- Energy frontier
- Electroweak, top physics, ...
- Need more answers from LHC on relevant energy scale

- Emphasis on specialties of photon and muon collider

4 International Linear Collider

The International Linear Collider (ILC) is intended to satisfy physics requirements, established by ICFA in 2003 [7], of 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} cm^{-2}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 1 shows a schematic layout of the ILC.

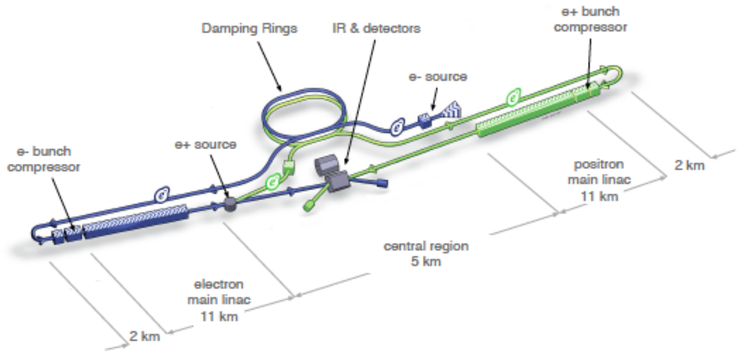

Figure 1: Schematic layout of the ILC.

The ILC Technical Design Report (TDR) design [8] is based on a broad and globally-based R&D program [9]. The technical readiness of the ILC project was assessed in late 2012 [10]. Three general technical categories comprise the readiness assessment

- superconducting linac (SRF) technology,
- beam-based demonstrations using integrated systems,
- specific component and system design and performance.

The maturity of the ILC project cost estimate was reviewed in early 2013 [11] 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 [12]. 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) [13]. 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.

4.1 Technical Readiness Assessment – SRF

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

- production of SRF cavities capable of reproducibly achieving at least 35 MV/m [14],

- assembly of a cryomodule consisting of eight or more cavities operating at a gradient of 31.5 MV/m [15],
- a linac string-test (or integration test) of more than one cryomodule [16],
- development of industrial SRF production capability.

The latter includes industrial cavity production and cost-model analysis [17].

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 [18]. Remaining SRF-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, âĂŸplug-compatibleâĂŹ component interfaces that allow independent development programs.

Production of SRF 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 ïňĄeld 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 ± 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 ïňĄeld 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 SRF 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.

4.2 Technical Readiness Assessment – Beam Dynamics Demonstrations

Two sets of beam dynamics and beam manipulation tests were done in addition to the beam-based SRF 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 [19]. 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 [20]. Results of the latter are expected to be integrated into the final focus design.

4.3 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.

4.4 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.

4.5 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.

4.6 Extending ILC performance

In a staged approach starting with 250 GeV e^+e operation for the Higgs boson study, it should be possible to reach the physics goals for Higgs branching ratios and properties with 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 ee collider if there is a physics need.

Extension of the ILC to 1 TeV is straightforward. It requires lengthened linac tunnels and additional cryomodules, but will 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.

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 1; 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.

Table 1: 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

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. 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.

4.7 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 SRF-related components built by industry and consideration of broad application of SRF,
- political promotion of ILC as a center for scientific and technological innovation,
- studies of specific sites.

The latter are strongly supported by local prefectural governments.

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 SRF 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.

5 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, we present 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.

5.1 Compact Linear Collider

5.1.1 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 2. The conceptual design is detailed in CDR version 1 and 3 [21, ?] and summarized in [?]. 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 are 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 an important option for a post-LHC facility at CERN.

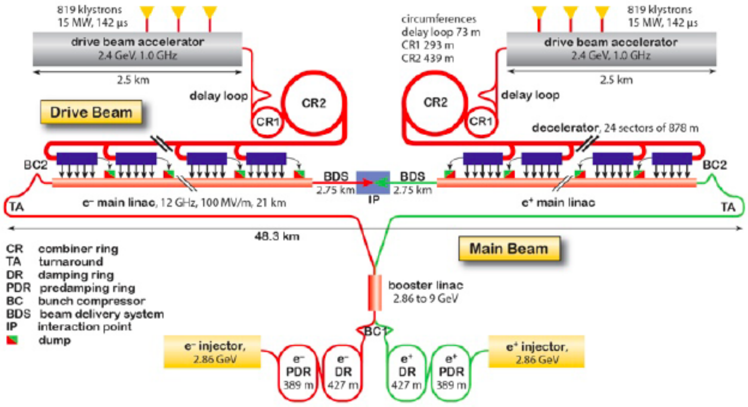

Figure 2: CLIC layout and parameter at 3 TeV.

5.1.2 Major R&D issues

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, 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 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.

5.1.3 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 overall energy consumption can be estimated as shown in Figure 2, with assumptions about beam interruptions and running scenarios (150 days operation and reduced power during commissioning). 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 desireable.

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.

5.1.4 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.

5.1.5 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.

5.2 Plasma Wake-Field Accelerators

5.2.1 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[1]. 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[2] 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 3 and parameters summarized in Table 1 and Table 2, the main bunches collide in 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.Âă 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%. As pointed out in Figure 11, 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 the ILC. The only exception is the bunch length which must be reduced by a factor of 15 from 300 to 20 microns. If PWFA technology has been 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 Higgs factory rather than the 52 km described in the ILC TDR.

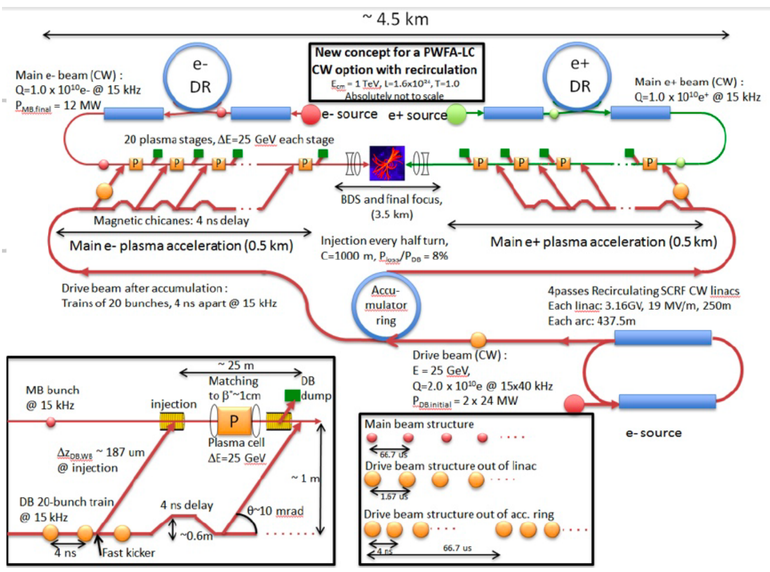

Figure 3: Layout of a beam driven PWFA facility at 1 TeV.

5.2.2 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 10âĂŹs 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 âĂŞ 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 âĂŞ the plasma. 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 10âĂŹs of kHz (required to achieve luminosity), and Multiple plasma stages to achieve the desired energy.

5.2.3 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 as shown on Fig 9 and 10. 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.

5.2.4 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 follow on 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.

5.2.5 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: 1. Generation of beams with extremely small emittances, so called Trojan horse technique []. 2. A Compact X-FEL using the plasma as a high-gradient accelerator and a source of high-brightness beams.

5.3 Laser Plasma Accelerators

5.3.1 Short description of the facility and upgrade path

Laser plasma accelerators (LPAs) [E. Esarey et al., RMP (2009)] 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 [W.P. Leemans et al., Nat. Phys. (2006)]. 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 [Schroeder et al., PRSTAB (2010) and (2012) with a tentative layout in Figure 4; ICFA-ICUIL task force report see ICFA Beam Dynamics Newsletter 56] that is based on staging of many meter-scale 10 GeV LPA modules (scaled examples at 250 GeV and 3 TeV based on this design are shown in tables 1 and 2). 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

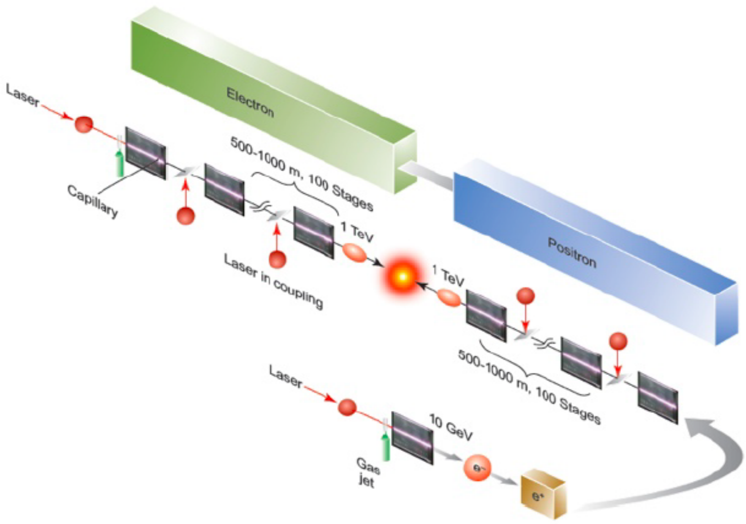

Figure 4: Tentative layout of a 2 TeV laser plasma accelerator.

5.3.2 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 are greatly 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 here [**?**] .

5.3.3 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 e+ 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.

5.3.4 Tentative schedule

The development of laser and plasma technology realistically requires: 5- 10 years time frame: 3 kW (3 J @ 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)

5.3.5 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.

5.4 Dielectric Laser Accelerators

5.4.1 Short description of the facility and upgrade path

Strawman parameters for a dielectric laser accelerator (DLA) based 3TeV collider and Higgs factory are presented in Table 1 and Table 2. In these examples, 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. Although the numbers in Tables 1 and 2 are merely projections used for illustrative purposes, they highlight the fact that the unique operating regime makes DLA a promising technology for future collider applications (Figure 5).

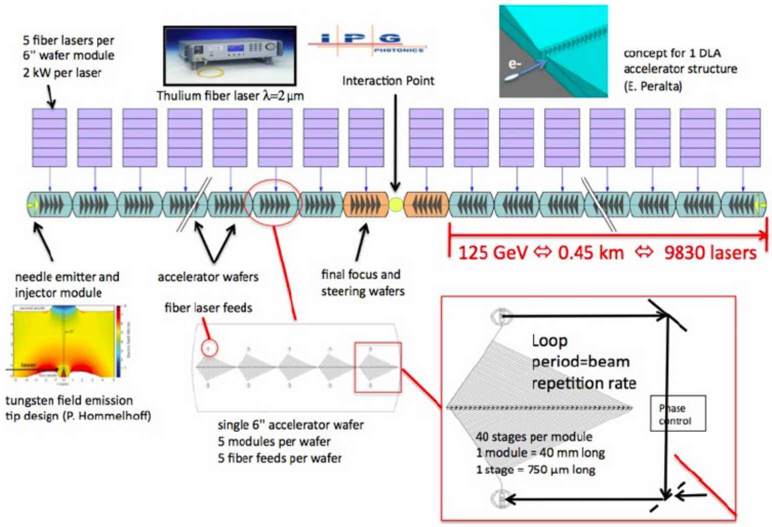

Figure 5: Layout of a dielectric laser accelerator.

5.4.2 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).

5.4.3 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.

5.4.4 Tentative schedule

Proof of principle experiments and feasibility studies will continue through 2015 (Figure 6). 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.

5.4.5 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 [Plettner:PRSTAB08], 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 Âţm period driven by a 2 Âţm 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.

5.5 Summary

Table one main parameter of multi-TeV range collider options.

6 Circular Electron-Positron Collider

TLEP [?, ?] is an e^+e^- storage ring of 80-km circumference that can operate with very high luminosity from the Z peak (90 GeV) to the top quark pair threshold (350 GeV). It can achieve transverse beam polarization at the Z peak and WW threshold, giving it 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. Such a tunnel would allow a 100 TeV proton-proton collider to be established in the same ring (VHE-LHC), offering a long term vision for the HEP community.

For the study of the Higgs boson, the type of e^+e^- collider, linear or circular, is of little importance, what matters are the deliverable luminosity, maturity of design, risk, timescale and cost. For Electroweak 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 offers a potential alternative to the linear collider. It benefits from three unique characteristics of circular machines: i) high luminosity and reliability, 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. 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.

6.1 The accelerator

TLEP is a storage ring with 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 should be foreseen for electron and positron beams. A first version of the parameters of TLEP has been produced (see Table ?? for the main parameters) [?]. The SR power dissipated in the tunnel is a design parameter which has been fixed to 100MW. In order to achieve high luminosities, $\beta_y{}^*$ has been fixed to 1mm, which, compared to the longitudinal size of the beams (2-3mm), gives an hourglass factor of around 0.7. For TLEP-H (ECM= 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 simulate using a detailed collision simulator, Guinea-pig [?]. The simulations give reasonable lifetimes for minimal values momentum acceptance of 2.5% and an emittance ratio $\kappa_\epsilon \epsilon_x/\epsilon_y$ of 500. These parameters require careful design and procedures but are achievable. 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 and should be achievable in TLEP with modern beam instrumentation and perhaps active magnet supports.

In Higgs factory mode a luminosity of 5×10^{34} $\mathrm{cm}^{-2}\mathrm{s}^{-1}$ is achieved for each of four IPs for a center-of-mass energy of 240 GeV. A storage ring with four IPs is considered to allow straightforward extrapolation from LEP2 [?], which gives beam-beam parameter values around

0.1 per IP. If it is decided to have fewer interaction regions, the total facility luminosity is expected to scale roughly as square-root of the number of interaction regions. Most of the components of the proposed superconducting RF system are readily available for frequencies around 700-800 MHz. A gradient of 20MV/m requires 600m of acceleration and a total of 900m of RF cavities, giving an RF system size similar to that of LEP2. Higher accelerating gradients (35MV/m) are achievable today but lead to excessive power requirements for CW operation, which are unnecessary for this project. The design study will address the optimization of the RF system as well as a dedicated R&D to increase the power efficiency of the system beyond the already high value of 50-60% achievable today in CW mode.

A unique capability of circular machines is the beam energy measurement accuracy using resonant depolarization, which allows an instantaneous precision of better than 100 KeV on the beam energy. The beam energy spread being smaller at TLEP than at LEP, transverse beam polarization should be available from the Z pole up to at least 80 GeV per beam. Running with a few dedicated non-colliding bunches will 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, movable spin rotators as designed for HERA would allow a program of longitudinal polarized beams at the Z peak, resulting, for one year of data taking, in a measurement of the beam polarization asymmetry with a precision of the order of 10^{-5} or a precision on $\sin 2_{Weff}$ of the order of 10^{-6}.

6.2 Technical challenges

The efficiency of the RF system, a main power consumption and cost driver, will be the subject of the main dedicated hardware R&D. While the efficiency for CW operation is much higher (50-60%) than for pulsed operation of the linear colliders, there remain substantial gains to make. Strong synergies exist with nearly CW machines such as the ESS and other multi-MW systems operating around 800 MHz.

Optics with low β^* values and large momentum acceptance: to fight beamstrahlung requires a momentum acceptance in the range 2-2.5%. This requires a dedicated design effort followed by extensive beam tracking in presence of beam-beam effects.

Procedures to achieve low vertical emittance: a high horizontal to vertical emittance ratio is a good mitigation technique against beamstrahlung beam lifetime limits. LEP achieved an emittance ratio of 250, but modern light sources achieve values higher than 2000 [?]. The challenge is to design the procedures which, would allow a low vertical emittance, approaching the values achieved at light sources, to be achieved reproducibly.

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.

An integrated magnet and beam pipe design TLEP operation at the Z, WW and ZH requires many bunches (4400, 600 and 80 in the current design), therefore a separate beam pipe for e^+ and e^- is called for together with a twin or double magnet design. To simultaneously address vacuum, heat extraction and other issues without impeding magnet operation is a complex design problem.

Integration issues with the future VHE-LHC proton collider should be addressed early on and possible synergies identified. The two projects should enjoy very close collaboration on the technical side.

6.3 Polarization

Much can to be learned from LEP and HERA. Two transverse polarimeters need to be designed for e^+ and e^- beams. The sterile bunch operation needed for continuous calibration needs special consideration. Spin rotator design longitudinal polarization operation at the Z peak and selective bunch depolarization are required. Wigglers are necessary at the Z pole and induce large local power deposition. Achieving longitudinal spin states at higher energies requires a clever arrangement of the experimental spin rotators and is not guaranteed at this point.

6.4 Power consumption

The luminosity yield of TLEP is proportional to the SR power dissipated in the ring, which is proportional to the RF power. The TLEP design has been performed assuming 100MW of power dissipation in the tunnel (around 1kW per meter of bend), which defines a total power consumption of almost 300 MW in the present state-of-the-art.

The estimated total RF system efficiency 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 LEP2) without headroom for RF feedback runs at a 65% efficiency. A 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. The power requirements of the RF system at 120 and 175 GeV are summarised in Table **??**. For lower energies the power will not exceed the values quoted here. As mentioned above a dedicated 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 is discussed in [?] and adds another 80 MW of power, excluding the experiments. Table **??** shows the breakdown of power consumption at 175 GeV. Consumption at different energies will not exceed this number.

6.5 Main cost drivers

TLEP is a project at its infancy, therefore a detailed cost estimate does not exist yet. However, the main cost drivers have been identified. It should be highlighted that TLEP is envisaged to be build next to an existing large laboratory, CERN. The existence of a large, mature laboratory next to TLEP historically has helped keeping costs low. The most expensive ingredient of TLEP is the tunnel and its infrastructure. This, however, should be seen as an investment into the future since the tunnel could later house next suite of hadron/e-p/ion collider(s) including a very high energy proton collider (VHE-LHC), ensuring more than 50 years of top-tier research. For the TLEP machine proper the main cost driver is the RF system with its cryogenic infrastructure.

6.6 Design study

A design study to explore the capabilities and challenges of TLEP has just started [?] and an interim structure with a steering group and an international advisory committee has been defined. Three main areas of work have been identified, accelerator, detector and phenomenology studies, each with an appointed coordinator. More than 200 collaborators have signed up to contribute to the study.

6.7 Timescale

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 first results of the nominal energy run of the LHC would be available. These results would be crucial for defining 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 can commence while the LHC is still running, shortly after an eventual approval of the project around 2020. Aim is for first physics at around 2030.

7 Muon Accelerators

Muon accelerators have the potential to offer the U.S. High Energy Physics community 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. Muon accelerators potentially provide world-leading experiments for physics at both the Intensity and Energy Frontiers. The U.S. Muon Accelerator Program (MAP) is an ongoing multi-year program to assess the feasibility of muon accelerators for both applications. Critical path R&D items are discussed below.

7.1 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.
- NuMAX (Neutrinos from Muon Accelerators at Project X): an initial long baseline Neutrino Factory, optimized for a detector at SURFâĂŤa precise and well-characterized neutrino source that exceeds the capabilities of conventional superbeam technology.
- NuMAX+: a full intensity Neutrino Factory, upgraded from NuMAX, as the ultimate source to enable precision CP violation measurements in the neutrino sector.
- Higgs Factory: a collider whose baseline configurations are capable of providing between 3,500 and 13,500 Higgs events per year with exquisite energy resolution.
- Multi-TeV Collider: lepton collider operating at multi-TeV.

Collider parameters for a Higgs Factory as well as 1.5 and 3.0 TeV colliders are provided in Table 6. 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 7.

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	$10^{34}\text{cm}^{-2}\text{s}^{-1}$	0.0017	0.008	1.25	4.4
Beam Energy Spread	%	0.003	0.004	0.1	0.1
Higgs/10^7sec		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 6: 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.

7.2 Critical R&D

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 [23]. 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 [24]. 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 [25]. In addition, the Muon Ionization Cooling Experiment is expected to begin producing relevant results in the same time frame [26].

- 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 [27]. Thus, this issue appears to present no impediment to moving forward with full detector studies and machineâĂŞdetector 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.

7.3 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 accerlator program can be found here [28]

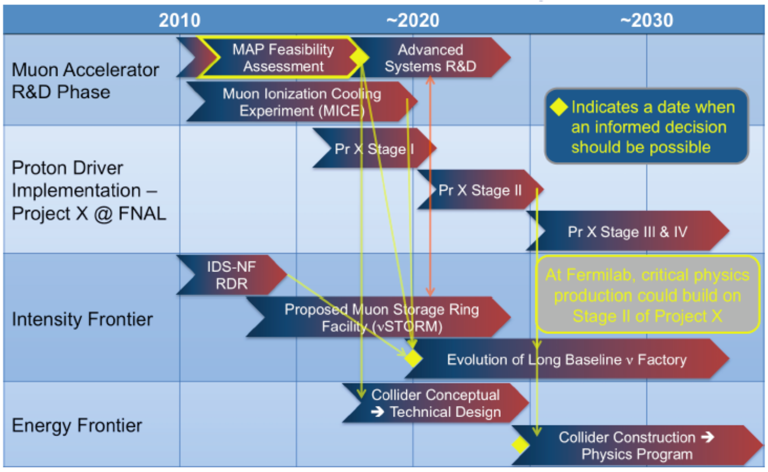

Figure 7: Muon accelerator timeline including the MAP Feasibility Assessment period. It is anticipated that decision points for moving forward with a Neutrino Factory project supporting Intensity Frontier physics efforts could be reached by the end of this decade, and a decision point for moving forward 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.

8 Photon ColliderÂă

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 $\gamma\gamma \to H$. Among various options for a Higgs factory [1], 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. The photon collider was considered in detail at a conceptual level in both the earlier TESLA [2] and NLC [?] 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) [3], 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. [4]. Alternatively, the Mercury laser developed at the Lawrence Livermore National Lab [5] 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.

8.0.1 Parameters of the photon collider at the ILC

The ILC TDR [8] 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. 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.

8.0.2 Photon collider based on recirculating linacs

The SAPPHiRE [?] project proposes to use the 60 GeV recirculating polarized electron linac developed for ep collisions with LHC protons (LHeC) as a photon collider. This ring would contain two 10 GeV superconducting linacs, see Figure **??**. 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.

8.0.3 Photon collider based on a circular electron-positron collider

For a circular Higgs factory, such as the Higgs Factory in Tevatron Tunnel (HFiTT) [?], the two electron beams would be accelerated in opposite directions to 80 GeV and then converted to high energy photon beams. The layout is shown in Figure **??**.

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

9 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.

9.1 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 8. The acceleration efficiency of the different technologies is displayed in Figure 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 **??** over a wide colliding beam energy range.

	Circular	ILC	Klystrons	CLIC	Plasma driven		Dielectrics	Muons
		SC-RF	NC-RF	TwoBeams	Beam	Laser		
Overall efficiency	30	6.5	5	4.8	15	4.5	13	5
Acceleration efficiency	45	10	8.5	8	21	6	15	15
Field to beam transfer efficien	95	45	30	27	66	40	50	40
Drive to Field transfer efficienc	55	45	42	38	76	50		55
Drive generation efficiency			70		44	30	30	80

Figure 8: Power transfer efficiency [FIXME].

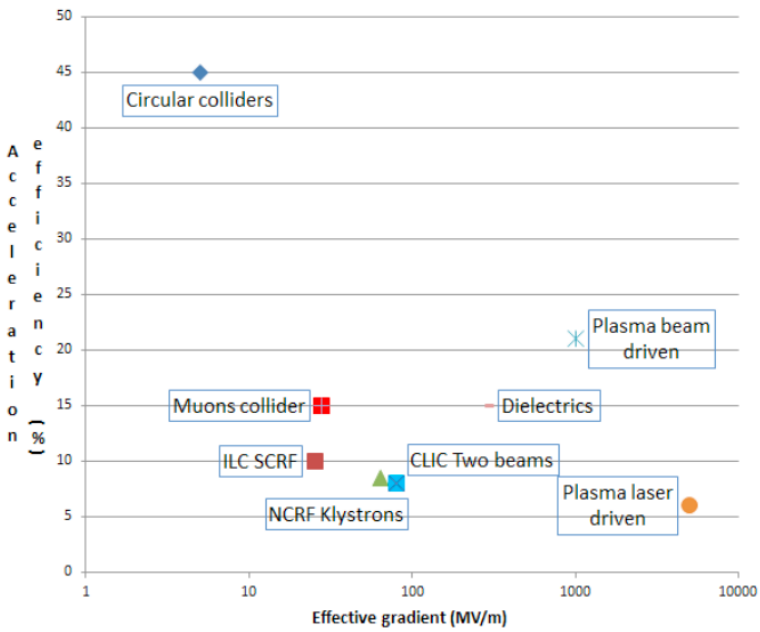

Figure 9: Acceleration efficiency as a function of effective field gradient [FIXME].

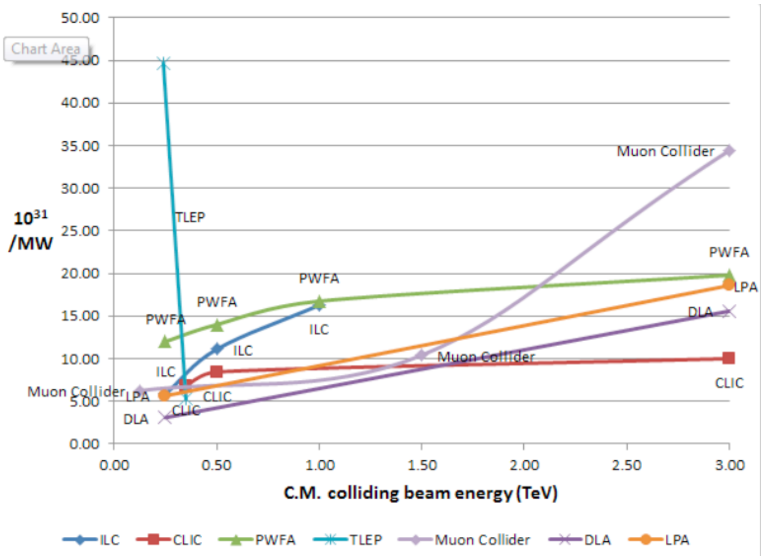

Figure 10: Luminosity per MW as a function of center-of-mass energy [FIXME].

9.2 Need for inovative 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.

Inovative 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.

10 Summary and comparisons

- Comparisons (tables and plots)
- timing
- costing (what are cost drivers)
- power
- luminosity
- text by Bill

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