Snowmass Agora on Future Colliders: Linear e^+e^- Colliders

Summary report

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Introduction

In the context of the Snowmass 2021 Community Planning Exercise, the Accelerator and Energy Frontiers announced a series of events, intended for all Snowmass participants, to discuss physics and technical aspects of different collider concepts.

The first these virtual events, on ***Linear e^+e^- Colliders***, was held on December 15, 2021. The 2-hour long event's agenda included a couple of brief introductory talks followed by a physics talk and three talks dedicated to the most advanced linear collider proposals. Each speaker was asked to focus on a Higgs Factory (center-of-mass, CoM, energy of 250 GeV) option of their proposal, while briefly addressing possible energy and luminosity upgrades and associated challenges. The second hour of the event was dedicated to a Q&A session where the speakers answered questions submitted online ahead of the event as well as from the audience. All presentations are available at the event's Indico site at https://indico.fnal.gov/event/52161/overview

Physics at linear colliders – Tao Han

With the discovery of the Higgs boson, we have a consistent theory: relativistic and quantum mechanical renormalizable, unitary, vacuum (quasi) stable and potentially valid up to an exponentially high scale, possibly to the Planck scale. Yet, there are fundamental questions/puzzles to be answered, conceivably with physics not far above the electro-weak scale. Studies of the Higgs boson are critical to understand electro-weak phase transition, including Higgs boson self-coupling. Higgs boson could also be a portal to the physics not yet known today. Among options is the dark matter where Higgs could serve as a portal to the dark sector.

Numerical estimates indicate that about a percent level precision of Higgs couplings measurement will cover majority of the critical phase space related to the Higgs boson properties and its connections to new physics. To reach this level in our understanding of the sub-atomic world a Higgs factory is a must. Similar factories in the past, from pion/kaon (light quark) factories to top quark factories (Tevatron, LHC) developed our understanding of the particle physics over past 50 years. The number of Higgs boson events we are looking for is $O(10^5\text{-}10^6)$[*] defined by the well constrained kinematics of e^+e^- collisions, model-independent measurements, and required ability to go to below a percent level couplings accuracy as well as to access rare decay process.

Higher energies (above Higgs boson production threshold) are important providing opportunities to measure the top quark mass with 50 MeV precision to determine the Standard Model vacuum stability and to produce events with multiple Higgs bosons to measure shape of the Higgs potential and many others.

High energy physics is at an exciting time. The Standard Model is complete and is potentially valid to a very high energy scale. Yet, there are strong indications for the existence of new physics not far above the electro-weak scale. The Higgs factory with ~250 GeV collision energy is the clear target. Higher energy linear colliders offer great opportunities for discoveries of beyond Standard Model physics.

[*] For a peak luminosity of 1×10^{34} cm^{-2} s^{-1} and e^+e^- collisions at 250 GeV, 2×10^4 Higgs boson events will be produced per Snowmass Year (10^7 seconds).

International Linear Collider (ILC) – Hasan Padamsee

The ILC250 is based on a proven superconducting radio frequency (SRF) accelerator technology. This is a mature technology with well-understood cost and ready for construction. The baseline luminosity is 1.3×10^{34} cm^{-2}s^{-1} at 250 GeV center-of-mass energy with integrated luminosity of 960 fb^{-1} in the first 4 years. Both beams are polarized: electrons to 80%, positrons to 30%. There are opportunities for luminosity upgrades by a factor of 2 and 4 and energy upgrades to 0.5, 1, 2, and 3 TeV.

The key technologies for ILC are SRF accelerator technology, nano-beam technology for final focus, and low emittance damping rings. SRF was chosen as the ILC technology in 2005 for multiple reasons, including:

- power-efficient acceleration (high beam power to AC power efficiency) with the total AC power of ~110 MW for ILC250
- relaxed tolerances compared to room-temperature designs due to larger apertures
- allows larger vertical beam spot at collision (7.7 nm)
- due to low RF losses, RF pulse length and bunch separation (727 us and 554 ns) are large enough to allow corrections between pulses as well as within a bunch train (intra-train feedback)
- luminosity upgrades via increased beam power
- energy upgrades with gradient advances in SRF

The SRF TESLA technology is a mature technology with a broad global industrial base. It was initially developed at DESY in collaboration with many laboratories for the TESLA linear collider project. TESLA technology is now used in several accelerators at laboratories in all three regions: Asia, Americas, and Europe that plan to contribute to the ILC project. Examples of large SRF accelerators are: European XFEL (in operation at DESY, Hamburg, Germany), LCLS-II and LCLS-II-HE (under construction at SLAC, Stanford, USA), SHINE (in preparation in Shanghai, China). European XFEL cavity production data show that it is possible to mass-produce cavities meeting the ILC specifications. 831 cavities for the European XFEL provide the biggest sample of cavity production data. For an average gradient of 35 MV/m (ILC specification), the yield is 94% after re-treating cavities with gradients outside the ILC specification. Cavity vendors are qualified globally in Europe, America, and Asia. Cryomodules are built globally as well at DESY, CEA, FNAL, JLAB, KEK, China. Cryomodules meeting the ILC gradient specifications have demonstrated operation with beam at Fermilab and KEK.

Accelerator Test Facility 2 (ATF2) was built at KEK in 2008 as a test bench for the ILC Final focus scheme. The primary goals were to achieve a 37 nm vertical beam size at the interaction point (IP), and to demonstrate beam stabilization at the nm level. After scaling for the beam energies from 1.3 GeV (ATF2) to 250 GeV, the 37 nm beam size corresponds to the TDR design value of 5.7 nm at 250 GeV beam energy. The goal has been reached within 10% validating the final focus design. Experiments at CESR-TA (CESR Test Accelerator) at Cornell have demonstrated confidence in the ILC Damping Ring parameters.

The ILC cost was evaluated in 2012 for Technical Design Report (TDR) using a detailed, bottoms-up approach. The cost covers accelerator construction, 9 years + 1 year commissioning. It includes fabrication, procurement, testing, installation, and commissioning of the whole accelerator, tunnels, buildings etc., and operation of central lab. It does not cover costs during the preparation phase, design work, land acquisition, infrastructure. The overall cost of ILC250 is in the range 4.8 – 5.3 BILCU[†] (Tunnel and Bldg. = 1.01, Accelerator and Utility = 3.8 – 4.2), and does not include labor and detectors. The labor is evaluated at 10,000 person-years. The detectors cost is 0.7 BILC plus 2,200 person-years. There is an

[†] 1 ILCU = 1 US$ in 2012 prices

undergoing US-Japan collaboration R&D on ILC Cost Reduction. The anticipated saving from this R&D is ~10%.

Per International Development Team (IDT), the preparation period will be a four-year process, rough equivalent to the CD2 stage of U.S. DOE projects, and will include prototyping, production validation, etc.

The ILC Higgs factory luminosity upgrade strategy is based on increasing beam power while keeping the final beam spot size fixed at 7.7 nm. A factor of 2 increase over the baseline luminosity is achieved by doubling the number of bunches from 1312 to 2625. Another factor of 2 is gained by doubling the repetition rate from 5 Hz to 10 Hz.

The energy upgrade strategies are based on increasing the accelerating gradient of new cryomodules while maintain high quality factor of the SRF cavities. The upgrades to 1 (2) TeV could be achieved with gradient advances to 45 (55) MV/m via developing new niobium surface treatments and employing improved cavity shapes. Further upgrades are based on developing 70 MV/m traveling wave SRF accelerating structures.

Compact Linear Collider (CLIC) – Steinar Stapnes

The CLIC is based on a unique two-beam accelerating technique with high-gradient room temperature RF cavities (~20,500 structures at 380 GeV), ~11 km length in its initial phase. A staged program was developed with collision energies from 380 GeV (Higgs/top) up to 3 TeV (energy frontier). The baseline luminosity is 1.5×10^{34} $cm^{-2}s^{-1}$ at 380 GeV, with integrated luminosity of 180 fb^{-1} per year. CDR in 2012 focused on 3 TeV. Updated project overview documents in 2018 (Project Implementation Plan) focused on 380 GeV for Higgs and top. The next step is Project Readiness Report expected in 2025-2026, a step toward TDR.

AC power consumption is 168 MW at 380 GeV (reduced with respect to 2012 due to better estimates of nominal settings, more optimized drive beam complex, more efficient klystrons, etc.), corresponding to 60% of CERN's energy consumption today. The CLIC accelerator studies are mature: optimized design for cost and power; many tests in CTF3, FELs, light sources and test-stands; technical developments of all key elements. The focus of Project Readiness studies is on the X-band technology readiness for the 380 GeV CLIC initial phase; optimizing the luminosity at 380 GeV; improving the power efficiency for both the initial phase and at high energies. Goals for these studies by ~2025: improve 380 GeV parameters, performance, project plan; push multi-TeV options/parameters.

There is an ongoing X-band structures and components production program to study designs, operation/conditioning, manufacturing, industry qualification/experience. CLIC technology has found applications in smaller X-band and C-band linacs. One example is SwissFEL, which is a C-band (5.7 GHz) linac with 104 2-meter-long structures providing beam with an energy up to 6 GeV at a repetition rate of 100 Hz. Studies of linac applications provide great help to CLIC R&D.

Cost of the project is 5.9 BCHF for 380 GeV (stable with respect to 2012, was re-costed bottoms-up in 2017-18). The labor is estimated at ~11,500 FTE years for the 380 GeV construction.

The technology driven schedule includes a 5-year preparation phase (estimated resource need for this phase is ~4% of overall project costs) and 7 years for construction, installation, and commissioning.

A design was developed for a 380 GeV CLIC with X-band klystrons instead of the drive beam. This option would need larger tunnel for klystron gallery. Also, in this case the energy upgrades would require a drive beam. Challenges for this option are: i) the number of klystrons is a factor 10 higher than in the drive-beam version (~5,500), their lifetime is a concern; ii) cost is higher by 1.4 BCHF (RF cost per 2-meter module is approaching 1 MCHF).

The luminosity improvement studies are in progress, focused on further optimization of the collider performance. Another way is to double the repetition rate from 50 Hz to 100 Hz thus doubling the luminosity at a cost of additional 50 MW and ~5% cost increase.

The CLIC energy upgrade is relatively straightforward: extend the main linacs, increase the drive beam pulse length and power, and a second drive beam to get to 3 TeV. Costs of upgrades are: 5.1 BCHF from 380 GeV to 1.5 TeV; 7.3 BCHF from 1.5 TeV to 3 TeV.

Cool Copper Collider (C^3) – Emilio Nanni

C^3 is based on a cold normal conducting C-band RF technology, which promises dramatic improvement of efficiency and breakdown rate. An 8 km long 250 GeV Higgs Factory (with a relatively inexpensive upgrade to 550 GeV) has luminosity of 1.3×10^{34} cm^{-2}s^{-1} (2.4×10^{34} cm^{-2}s^{-1} at 550 GeV). A white paper was published in arXiv in November 2021. The estimated site power is ~150 MW at 250 GeV and ~175 MW at 550 GeV.

The key technology of C^3 is an RF structure distributing power to each cell in parallel from a common RF manifold. This allows optimization for cell efficiency (shunt impedance) while controlling peak surface electric and magnetic fields. Operation at ~80 K with liquid nitrogen improves the material strength and allows higher accelerating gradients. First proof-of-principle experiments demonstrated operation up to 150 MV/m with expected robust operation up to 120 MV/m. Further R&D in a few key areas is required (e.g., scaling modular units, developing cryogenic, cryomodule and alignment systems, integration of wakefield detuning/damping scheme into the structure design). A demonstration facility is proposed to support critical R&D topics.

One of the main challenges is alignment. The main linac will require 5-micron structure alignment, which will be achieved by a combination of mechanical pre-alignment and beam-based alignment.

While RF sources and modulators capable of powering C^3-250 are commercially available, the RF source cost is the key driver for the overall cost. R&D on reducing the RF source cost is needed. The plan is to leverage significant developments in performance of high-power RF sources (HEIKA collaboration). It will require industrialization after technology demonstration.

The 8-km long footprint allows achieving 250 GeV CoM with an accelerating gradient of 70 MV/m (assumed linac filling factor is 90%). This gradient is cost-optimal for the current large-volume unit cost of ~$7.5/peak-kW. Raising the gradient to 120 MV/m would increase the energy to 550 GeV within the same footprint (a full suite of cryomodules needed for the 550 GeV operation will be installed during the 250 GeV construction, but not all of them will be powered up.) This upgrade will require developing new RF sources and/or RF pulse compression scheme. Large portions of accelerator complex are compatible between LC technologies: beam delivery and IP modified from ILC (1.5 km for 550 GeV CoM); damping rings and injectors to be optimized with CLIC as baseline. Costing studies used other LC estimates as inputs. The total capital cost is estimated at 3.7 BILC.

The technically driven timeline includes 2 years for a pre-demo stage, 5 years for the technology demonstration, 3 years for a string test, and 8-10 years of construction and commissioning time.

This collider is potentially extendable to 3 TeV by simple extension of the linac while keeping the accelerating gradient at 120 MV/m.