Strategy for Understanding the Higgs Physics: The Cool Copper Collider

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Abstract

A program to build a lepton-collider Higgs factory, to precisely measure the couplings of the Higgs boson to other particles, followed by a higher energy run to establish the Higgs self-coupling and expand the new physics reach, is widely recognized as a primary focus of modern particle physics. We propose a strategy that focuses on a new technology and preliminary estimates suggest that can lead to a compact, affordable machine. New technology investigations will provide much needed enthusiasm for our field, resulting in trained workforce. This cost-effective, compact design, with technologies useful for a broad range of other accelerator applications, could be realized as a project in the US. Its technology innovations, both in the accelerator and the detector, will offer unique and exciting opportunities to young scientists. Moreover, cost effective compact designs, broadly applicable to other fields of research, are more likely to obtain financial support from our funding agencies.

1 Introduction

Future facilities to enable experimental enquiry of the five intertwined science drivers [1], identified by the particle physics community have been studied extensively. Three of the five HEP science drivers identified by the community are: the usage of the Higgs boson as a new tool for discovery, the identification of the new physics of dark matter, and exploration of unknown new particles, interactions and physical principles. Progress in these areas will be enabled by new collider facilities, at high energies and high luminosities.

An Higgs Factory would provide improved precision over the LHC, resolving Higgs properties 10-100 times better, and will enable a broad range of investigations across the fields of fundamental physics, including the mechanism of electroweak symmetry breaking, the origin of the masses and mixing of fundamental particles, the predominance of matter over antimatter, and the nature of dark matter.

The International Linear Collider [2] (ILC) based on superconducting RF technology has the most advanced design. The science case for the electron-positron Higgs factory has been well developed by the ILC community. Further refinements of the physics case were also made by the Future Circular Collider community, using their plans for a circular electron-positron facility (FCC-ee) [3]. As opposed to linear machines, circular colliders are strongly limited by synchrotron radiation above 350–400 GeV center of mass energy. Moreover the luminosity delivered at a linear collider allows for trigger-less operations, which could also open up to new physics signatures that are going undetected at the LHC.

The international community, represented by ICFA, has expressed interest in the ILC as a global project, and ILC is now under consideration for construction in Japan. However, for a long time now, Japan has not initiated a process to host this collider. In view of this, it is appropriate to consider other options.

The FCC-ee machine will require a large upfront civil engineering cost to build a 100-km tunnel. It is pipe-lined 7 years after the end of the HL-LHC program and expected to start in 2048. The ultimate goal of a proton machine (FCC-hh), which starts after the FCC-ee, is acknowledged as attractive. Yet again, it is prudent to investigate alternate plans based on technologies which could enable compact designs and possibly provide a roadmap to extend the energy reach at future colliders.

The goals for a worthwhile alternative plan are two fold: a) a near term, cost-effective Higgs factory that could fit within an existing laboratory site and b) a longer term prospect for accessing higher energies in lepton collisions, again in a cost-effective fashion.

The Cool Copper Collider (C^3) [4] is a relatively new proposal to build a Higgs Factory with a 250 GeV energy collision energy based on a technology that offers the option for an adiabatic upgrade to 550 GeV, and possible extension to the TeV scale. While several competing technologies for electron-positron colliders exist for a Higgs Factory, only high accelerating gradient linear machines are likely affordable to get to the TeV scale. We will then probe the Higgs self-coupling and top Yukawa to a precision that sheds light on a broad class of puzzles around the Higgs boson. Such a TeV scale upgrade also opens the gateway to access to TeV scale new physics, especially in unexplored/underexplored weakly coupled states that may well escape detection at the HL-LHC. New physics of this kind are well-motivated by general theoretical considerations, such as supersymmetry, compositeness considerations, as well generic models with hidden dynamics and dark matter. C^3 can also probe a broad range of TeV scale new physics, potentially explaining the g-2 and flavor physics anomalies.

Broader impacts of C^3 technologies are also important to consider. Its high-gradient technology will enable compact electron and X-ray photon sources, which are in high demand for medical, materials science and other applications. An invigorated community of particle and accelerator physicists, pushing the limits of technology for particle acceleration, detection, measurement and analysis, are likely to attract and train a strong workforce.

The C^3 concept is thus an attractive strategy to address our community's need for an e^+e^- Higgs factory. The purpose of this document is to encourage our community to support R&D and participate in defining the emerging C^3 option as part of the Snowmass community study process.

2 The C^3 Concept

C^3 is based on a fundamental study and optimization of electromagnetic cavities for high accelerating field on axis (the gradient) and low breakdown rates. This optimization yields a design with iris too small to propagate the fundamental cavity mode. This is solved by a second discovery of a distributed manifold supply to each cavity separately, with proper phase and proper fraction of the RF supply through the wave-guide coupling. The resulting structure, although far too complex for tradition assembly techniques, is straightforwardly built from about two meter long Cu slabs machined by numerically controlled milling machines. It is noteworthy that C^3 could not have been realized without modern supercomputers for the RF design and modern NC machining techniques.

The linac is cooled to 77 K by liquid nitrogen to reduce the RF power requirements, and increase the acceleration gradient, upwards of 150 MV/m[5, 6]. Thus, the acceleration gradient of the C^3 linacs[7] is an order of magnitude increase over the SLC, a factor 4 over that of the ILC[2], and a factor of two over the normal-conducting NLC design[8]. The C^3 plans to reuse the final focus design of the ILC, which is optimized for up to 1 TeV operation, recouping much of the progress made in its design.

The proposed C^3 has an 8 km footprint that can reach 250 GeV center of mass energy using innovative technologies, with the possibility of a relatively inexpensive upgrade to 550 GeV on the same footprint, adding only more RF sources.

The linac is constructed from 9 m cryomodules, each of which houses eight 1 m distributed coupling, accelerating structures supported on four 2 m rafts. Each raft supports two 1 m accelerator sections and a quadrupole with a mechanically integrated Beam Position Monitor, coarse and fine alignment movers, and position sensor fixtures. The cryomodule has four penetrations for RF power, each with two waveguides, with each waveguide powering one accelerating structure. The total cryogenic thermal load for the complex at 250 GeV is 9 MW. This thermal load is removed through nucleate boiling of liquid nitrogen. Liquid nitrogen flows by gravity through the cryomodule to replace the Nitrogen that has evaporated. Thus, the linac must be horizontal with straight segments of about 1 km. Nitrogen gas is removed from the linac at penetrations that are spaced at approximately 1 km and transported to a re-liquification plant before being reintroduced into the linac.

Great effort has been expended towards the design and optimization of the accelerator complex for earlier linear collider designs. This excellent work can be leveraged to understand the pre-conceptual layout for the full C^3 accelerator complex. In particular, the ILC designs for the electron and positron sources, the damping rings, and the beam delivery system can be taken over directly for C^3 , with small changes to accommodate the C^3 beam format. As the design matures, these systems will be revised and further optimized.

The baseline electron (polarized) and positron (unpolarized) sources are conventional LC designs. For the electron source, this consists of a polarized DC gun, buncher and accelerator. However, we are also exploring the possibility of a polarized RF gun. For the positron source, the closest design relevant to the C^3 bunch structure is the CLIC design[1]. Positron polarization is a possible upgrade once the full RF system is installed. An additional electron bunch train would be extracted from the Main Linac at high energy (125 GeV) and sent to an undulator for polarized photon production and transport to a positron production target. The positron beam must be transported to a damping ring before being accelerated by the Main Linac.

For the damping rings, a conservative design has two damping rings, one for the electrons and one for the positrons. A pre-damping ring is also utilized for the positron beam. Four electron and positron bunch trains are stored in each of the damping rings. The main damping rings have a $\sim$900 m circumference. The electron damping ring might be eliminated with the advent of a polarized RF photo-injector.

Scaling the beam delivery system (BDS) for a maximum single beam energy of 275 GeV from 500 GeV for the ILC TDR [9] reduces the length of the BDS by 500 m. Furthermore, we also remove the upstream polarimeter in favor of the downstream polarimeter reducing the length an additional 200 m. For C^3 , the downstream polarimeter can measure the polarization and the depolarization from beam-beam interactions by comparing interacting and separated beams. The length for the BDS is approximately 1.5 km on each side. Preliminary simulations of for 250 GeV CM indicate that a 1.2 km BDS is feasible for that energy [4].

3 The C^3 Higgs Factory at 250 GeV

The planned High Luminosity era of the LHC (HL-LHC), starting in 2029[2], will extend the LHC dataset by a factor 10 allowing an increase in the precision for most of the Higgs boson couplings measurements [11]. Studies based on the 3000 fb^{-1} HL-LHC dataset estimate that we could achieve 2-4% precision on the couplings to W, Z and third generation fermions. But the couplings to first and second generation fermions will still largely not be accessible and the self-coupling will only be probed with O(50%) precision.

There are good reasons to measure the Higgs boson properties at higher precision than will be possible at the HL-LHC. With the basic Higgs mechanism for mass generation now demonstrated, the next task for

[1] CLIC CDR 3.1.3.2

[2] This refers to the updated schedule presented in January 2022 [10], as the LHC schedule is evolving, the starting date of HL-LHC could change.

Higgs studies is to search for the influence of new interactions that can explain why the Higgs field has the properties required in the SM. If the new particles associated with these interactions are too heavy to be produced at the HL-LHC, they can still make an imprint on the pattern of Higgs boson couplings. If we wish to prove the existence of these effects and to understand their pattern, we will need a very precise understanding of the Higgs boson properties, with measurements of 1% or better. Through global analyses, such high precision measurements can also improve the interpretation of LHC data and lead to a stronger comprehensive map of where new physics might lie.

An e^+e^- Higgs factory has a distinctive duty to gain insight on the Higgs Yukawa couplings at the next level beyond the third generation fermions. In the SM, the Higgs Yukawa couplings are exactly proportional to mass. This simplistic picture deserves close scrutiny. Tagging of charm and strange quarks, as previously demonstrated at SLC/LEP, gives effective probes for advancing this program. There is a broader program to investigate the potential deeper connection of Higgs boson with flavor and CP violation. The cleaner e^+e^- environment aided by beam polarization could become a sensitive probe to reveal more subtle phenomena.

C^3 follows a program very similar to that proposed for the ILC. We thus expect similar results, subject to considerations described below, for similar integrated luminosities and detector capabilities. C^3 is expected to be less expensive for reaching the energy of 500-600 GeV. But its key point is that it provides a more secure basis for extension to higher energies [4].

4 Upgrade to 550 GeV

Although most of the gain in precision in Higgs boson couplings will be realized already at the 250 GeV stage, there are important reasons to continue the e^+e^- program to an energy of 500—600 GeV. First, this energy is above the crossover point at which the WW fusion reaction $e^+e^- \to \nu\bar{\nu}h$ overtakes the $e^+e^- \to Zh$ reaction and becomes the dominant mode of Higgs boson production. This means that, in the 550 GeV data, the Higgs boson is mainly produced by a different mechanism with different sources of systematic errors. A deviation from the SM predictions observed at 250 GeV can be cross-checked in this new dataset. The $\sigma \cdot BR$ for WW fusion to h with decay to WW^* depends quartically on the Higgs-W couplings and thus is a very powerful addition to the dataset. Second, this energy is needed to give a substantial cross section for the process $e^+e^- \to Zhh$, which allows us to measure the Higgs self-coupling. The expected 20% error on the Higgs self-coupling will allow us to exclude or demonstrate at 5 σ the large enhancements to the self-coupling typically needed in models of electroweak baryogenesis [12]. Third, this energy choice is well above the threshold for $e^+e^- \to t\bar{t}$, far enough that top quark pairs are produced with relativistic velocities. The statistical error on this measurement decreases by a factor 2 when one chooses 550 GeV rather than 500 GeV as the CM energy [13]. In principle, higher energy gives more of an advantage, but this must be balanced against increased cost and footprint. For the purpose of this paper, we have set the design energy of C^3 at 550 GeV. A crucial difference between models in which the Higgs boson is elementary and those in which the Higgs are composite is that, in the latter class, the top quark is also partially composite, with modified W and Z couplings. The 550 GeV measurements have great power to test for this property. Moreover, at 550 GeV, an e^+e^- collider is as powerful as HL-LHC in searches for Z' bosons and light quark and lepton compositeness and provides a complementary set of tests [14].

5 Upgrade to TeV-scale

The C^3 linacs can potentially be lengthened to increase the center of mass energy to about 1 TeV. Prior planning of the site for length extension and possible relocation of upstream components is necessary. Assuming one can get to this TeV-scale, the potential for $e^+e^- \to \nu\bar{\nu}$ HH measurement becomes possible with an integrated luminosity of few ab^{-1} [15]. New and exciting physics opportunities across the board are enabled with a TeV-scale upgrade. The Higgs precision enabled by the 550 GeV run will be further improved, particularly the Higgs trilinear coupling and top-Higgs Yukawa. These precision coupling improvements allow us to probe compositeness scale well beyond TeV, which is outside the realm of the LHC probes [16]. Weakly coupled new physics could be buried under the QCD background from a hadron collider environment. The TeV-scale C^3 will provide definite answers and insights about new physics within the kinematic threshold. For instance, weak scale lepton partners (such sleptons) and electroweak states (such as electroweakinos) that are well motivated can be discovered at C^3 . In particular, various recent hints from experimental data, such as the muon g-2 anomaly [17], lepton-flavor-universality-violations in B meson systems [18], all have a large fraction, if not the entire, motivated and allowed regions, lie at TeV scale. The TeV upgrade of C^3 can pair-produce these states and detect them or access them through the precision measurement on their loop-induced effects. Dark matter candidates, or more general, missing energy, can be revealed through missing energy searches [19]. Other exotic signatures, such as long-lived particles or dark showers, can also be probed at the upgrade C^3 [16]. TeV-scale lepton colliders share a lot of exciting physics opportunities and potential; we can see them in reviews, e.g. [20, 21].

6 Site Options

A C^3 e^+e^- collider could in principle be sited anywhere in the world. Projects of its magnitude will be presented and reviewed in international fora, and a community decision will be made regarding the actual site selection. Nevertheless, we note that the C^3 offers a unique opportunity to realize an affordable energy frontier facility in the US in the near term. We note that the entire C^3 program could be sited within the existing US national laboratories.

For instance, the Fermilab site can fit a 7-km footprint linear machine entirely within its boundaries, in North East-South East (NE-SE) orientation. The 8-km footprint currently proposed C^3 , reaching up to 550 GeV, can be accommodated at Fermilab, with about 5 km of the footprint inside the Lab site and extending the facility under the Common Wealth Edison power company's easement to the north of the Lab site - North-South (N-S) orientation. It is also possible to further extend the footprint up to 11 km in this orientation, still keeping the interaction region of the collider within the Lab campus. This siting location, was, in fact, one of the options studied for the ILC at Fermilab. Using the full 11 km length can provide upgrade paths to 750 GeV collision energy or higher.

Perhaps, further optimization of the final focus could let the 8 km machine for energy upgrade up to 550 GeV fit within the boundary of the laboratory itself, using NE-SE orientation. The details of these siting options are discussed in [**?**].

The initial exploration at the C^3 Higgs Factory could position the US to lead the drive to the TeV scale, requiring larger machines. Sites such as the DOE Hanford site have room to accommodate even bigger footprint machines within their site boundary.

If the ILC goes forward in Japan, an energy upgrade using C^3 accelerators could be built, re-using the ILC damping rings, tunnel, and other conventional facilities. Such a machine could reach TeV-scale as well.

7 Detector for C^3 Higgs Factory: SiD

There are two ILC detector designs, SiD and ILD, which would adapt well to C^3 . Of the two, the compact silicon-based detector in high magnetic field with excellent tracking and particle-flow calorimetry, SiD, is especially suited for the C^3 environment, with small modifications.

The SiD Detector features a compact, cost-constrained design that addresses the full range of searches for new physics and precision measurements at a future high energy electron-positron linear collider. Major design features are a robust silicon vertexing and tracking system, highly segmented calorimeters optimized for particle-flow, and a compact design with a 5T solenoid field.

Originally designed for operation at the ILC, the SiD design is readily adaptable to running at a future C^3 accelerator. The principal required design changes center on the differences in bunch timing structure at C^3 – 120 Hz and 5 ns bunch separation vs. 5 Hz and 336 ns bunch separation at the ILC. While detailed simulation studies are required to fully assess the effects of the beam induced backgrounds in the detector, SiD would be the baseline detector for C^3 . In particular, a dedicated optimization of the vertex detector design could absorb the different time structure without compromising the physics goals. The other subsystems will also be modified to achieve the physics goals. This is why we expect the projected physics performance for ILC can also be achieved by C^3 at 250 GeV [4]. Below we discuss the implications of this change and other possible design impacts for SiD at C^3 .

The SiD Consortium is currently considering upgrades to the detector design – the major change being the use of MAPS for the vertex detector, main tracker and the electromagnetic calorimeter. The beneficial aspects of MAPS are large scale sensors (via stitching) with reduced dead areas, 25×100 micron^2 pixels, faster charge collection, higher efficiency with less cross-pixel charge sharing, lower power, lower cost, and reduced material. MAPS design questions under consideration are the required timing resolution with the small C^3 bunch spacing, effects of insensitive balconies and dead pixels or columns, and the needed power reduction factor from power pulsing.

The SiD vertex detector consists of five barrel layers and forward/backward disks, with power pulsing and forced-air cooling. Requirements include a 3 micron (or less) hit spatial resolution, and a material budget of 0.1% X_0. For the ILC, the combination of the 5 T magnetic field and the envelope of the pair background allows a first sensor layer at 14 mm from the beam. The pair background and occupancy studies will be repeated for the specific C^3 environment. Other questions to be addressed for C^3 include the need for single bunch tagging and the required time resolution. The initial MAPS timing resolution goal is 3 ns (power limited) for ILC.

The main tracker for SiD has five barrel layers and four forward/backward disks. The tracker must provide excellent momentum resolution, for example for reconstruction of the recoil mass in the ZH final state. A material profile of less than 20% X_0 is required. The main question for C^3 is whether single bunch tagging is needed, and with which timing resolution.

For both the vertex detector and the main tracker, forced-air cooling and power pulsing are still foreseen for SiD at C^3 . The 8.3 ms intra-train interval for C^3 is more than adequate for power pulsing which only requires a few 100 microseconds to settle after turning on.

For the whole tracking system, studies are needed for the new MAPS upgrade of the occupancy levels from beam induced backgrounds, tracking efficiency (including any dead areas), and hit timing resolution requirement. Other possible areas to explore are the radius of the vertex detector inner layer, the beam pipe design, and the central magnetic field value (in relation to the pair background).

8 Broader Impacts

8.1 Applications of Compact Linacs

R&D on the C^3 concept is already being pursued at SLAC, UCLA, INFN, LANL and Radiabeam, along with closely related research in high gradient RF acceleration with CERN, KEK, PSI, MIT, and many other partners in the high gradient research community [22]. There is direct synergy with the development of compact electron accelerators for medical applications [23, 24, 25, 26] and the creation of compact X-ray free electron lasers [27, 28] (FELs). The small size and low cost of compact X-ray sources based on C^3 technology will find a wide range of customers, including individual university research laboratories and major medical research centers.

8.2 Workforce Development

The particle physics community has traditionally attracted the best students from the incoming classes in most university physics departments. The opportunity to work on fundamental problems while using state-of-the-art technologies, and when necessary develop them as necessary, is the leading motivator for the students. The C^3 will provide much needed impetus to make particle physics programs attractive to the young and future generations. Due to the long lead times involved in design, construction and operation of the programs, it is important to involve the new generation entering graduate classes early in the design process. Many of those early students who will develop expertise in compact accelerator development or new detector technologies will build the C^3 and conduct research using it, while others will contribute to the society at large.

9 Towards a C^3 Conceptual Design

Developing a conceptual design with a defensible cost estimate for a C^3 Higgs Factory is a requirement for proposing a project to the US funding agencies and attracting worldwide community interested in Higgs studies at C^3 . The R&D required to prepare a conceptual design for C^3 includes the following elements:

9.1 Demo Facility

We will need a full demonstration of the C^3 Main Linac technology on the GeV scale. This demonstration can be done in parallel with the preparation. The outstanding technical achievements of the ILC, CLIC and NLC collaborations are central to the rapid realization of the C^3 proposal. Many of the subsystems for the accelerator complex are interchangeable between linear collider concepts with manageable modifications to account for variations in pulse format and beam energy. Because these subsystem designs are already mature, the C^3 demonstration facility can focus on the specific set of technical milestones associated with the C^3 concept itself:

- Development of a fully engineered and operational cryomodule including linac supports, alignment, magnets, BPMs, RF/electrical feedthroughs, liquid and gaseous nitrogen flow, and safety features.
- Operation of the cryomodule under the full thermal load of the Main Linac and maximum liquid nitrogen flow velocity over the accelerators in the cryomodule, demonstrating an acceptable level of vibrations.
- Operation with a multi-bunch photo-injector to induce wake fields, using high charge bunches and a tunable-delay witness bunch.
- Achievement of 120 MeV/m accelerating gradient in single bunch mode for an energy gain of 1 GeV in a single cryomodule, including tests at higher gradients to establish breakdown rates.
- Acceleration and wakefield effect measurements with a fully damped-detuned structure.
- Development, in partnership with industry, of the baseline C-band RF source unit that will be installed with the Main Linac. The RF source unit will be modified from existing industrial product lines.

10 Outlook

With a five-year C^3 demonstrator project (described in [**?**]), the project will be ready for US DOE project review processes, on the way to attracting international participation in the C^3 facility.

The C^3 demonstrator project will involve multiple national laboratories and some university groups. The demonstrator itself could revitalize the HEP community, attracting bright students and postdoctoral fellows, especially those graduating from the LHC project currently underway in the USA. The commercialization of the accelerating structures and RF sources, through the demonstrator project, will enable long term partnerships with industry to build the C^3 and also build a new market for small-footprint X-ray sources.

The signatories of this white paper strongly believe that our community strategy for understanding the Higgs physics is significantly enhanced by the development of the C^3 project. We urge colleagues participating in the Snowmass community studies to strongly support the C^3 demonstrator project, with the aim of preparing a conceptual design report within five years.

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