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As introduced by Steve on Wednesday, the XFEL Compton Collider or XCC is an alternative Higgs factory where Higgs bosons are produced in s-channel γγ annihilation. The XCC Snowmass whitepaper was submitted to Snowmass groups EF01 and AF03 and was reviewed by the Implementation Task Force. A major update to the XCC whitepaper will be submitted to JINST at the end of this month.

Let me first discuss some accelerator physics details. 63 GeV electron beams collide with 1 keV X-ray free electron laser beams at points 60 µm upstream of the e-e- interaction point to produce tightly focused colliding beams of 62.5 GeV photons. The Higgs boson production rate is 80,000 Higgs bosons per 10^7 seconds year. There is no positron source complex. There are no damping rings so long as polarized high brightness e- injectors can be built. The baseline accelerator technology is the same 70 MV/m LN_2 cooled distributed coupling structures that Emilio described in his C^3 talk. The 4.2 km footprint (3.2 km Linac + 1 km for XFEL and final focus lines) would accommodate an energy upgrade to 380 GeV center-of-mass with the same structures running at 120 MV/m. As a backup, the XCC could begin operation with room temperature C-band structures at 55 MV/m, a technology which is essentially ready today. To avoid quantum diffusion energy spread, the X-ray free electron laser is operated at 30 GeV instead of 63 GeV. There is a 300 m extraction gap to increase the radius of curvature of the 30 GeV extraction line to 130 km in order to control coherent synchrotron radiation.

The staging of an e+e- collider with an initial γγ collider at the Higgs resonance is not new. For example, former KEK director Sugawara made such a proposal for the ILC in 2009. A report was written, but the idea was ultimately rejected in large part due to a relatively weak physics case. However, the 2009 ILC γγ collider proposal utilized an optical laser. With an X-ray laser, the physics case for a 1st stage collider Higgs factory is strengthened considerably. So much so, in fact, that the optimum 2^{nd} stage of the facility could again be a γγ collider, this time at 380 GeV center-of-mass energy to study the Higgs self-coupling with γγ annihilation to two Higgs bosons.

Due to its lower cost (the XCC whitepaper had an estimate of $2.3 billion capital cost vs. $3.7 billion for C^3-250) and smaller footprint, the XCC could begin operation on an earlier timescale; indeed, the lower cost might mean the difference between approval and denial in an era with many other DOE HEP commitments.

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The XCC is very different from previous $\gamma\gamma$ collider concepts. The $\gamma\gamma$ luminosity spectrum is shown in the left-hand plot. Since only 20% of the electrons are converted to photons in the Compton collision there is also substantial luminosity from e-γ, γe- and e-e- collisions, not shown here. With the XCC, a low integrated $\gamma\gamma$ luminosity is concentrated in one spike where Higgs bosons are produced and not much else. In this blowup the 4 MeV width of the Higgs boson is visible in a plot containing the full structure of the leading edge of the luminosity spectrum. The leading-edge width is too large to make a meaningful direct energy scan measurement of the Higgs width (a 100% direct measurement of the 4 MeV width is the best you can hope for given a 0.05% to 0.1% e- beam energy spread). However, the even narrower width of the e- γ luminosity spectrum can be used to measure the absolute Higgs gamma gamma partial via the detection of a monochromatic electron in e-γ →e-H when running $\gamma\gamma$ collisions at energies above the Higgs resonance (such as 380 GeV center-of-mass). The absolute gamma gamma partial width measurement plays the same role as the Higgs recoil ZZ partial width measurement in e+e- collisions in obtaining model independent coupling measurements.

The XCC luminosity spectrum is contrasted with that of a straw man optical laser $\gamma\gamma$ collider which assumes the same electron beams as XCC but with an optical wavelength laser substituted for the XFEL. The optical laser version requires a larger electron beam energy (87 vs 63 GeV), has a large spread in $\gamma\gamma$ center of mass energies near the Higgs resonance, and its high integrated luminosity leads to a large background. A comparison of the background rate is shown in this column, where background is defined as the number hadron events with visible mass > 40% sqrt(s). The XCC background is comparable to ILC's. Even here though, most of the XCC background is from distinctive, boosted, e-γ-→e-Z and νW. The minimum bias events arise from a large e-e- beamstrahlung luminosity at very low $\gamma\gamma$ center of mass energies. If the e-γ →e-Z , νW and minimum bias events turn out to be problematic, their rate can be greatly reduced at the cost of some loss in Higgs rate by going from round to asymmetric electron beams.

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In this physics comparison we assume either that both Stage I and II are e+e- colliders (ILC/C3) or both stages are γγ colliders (XCC). Both stages I and II assume 10 years of running. In Stage I the ILC/C3 and XCC are each dedicated to the production of single Higgs bosons. Despite its factor of 4 less luminosity the XCC produces nearly 3 times as many Higgs bosons due to the resonance production of the Higgs.

The middle table shows the Higgs coupling measurement errors in the kappa framework assuming no BSM decays. The same fitting program was used for ILC/C3 and XCC. With the exception of H→ γγ and H→ γZ, the XCC was assumed to have the same branching ratio errors as ILC/C3. The decays H→ γγ and H→ γZ are treated separately since they are characterized by monochromatic photons of energies 62.5 GeV and 29.3 GeV, respectively at XCC. The background is γγ→ γγ and e-γ → e-γ for H→ γγ and e-γ → e-Z for H→ γZ with a final state electron radiating nearly all of its energy in the beampipe. The BR errors for H→ γγ and H→ γZ were then calculated using a 13 fb γγ→ γγ cross section and the rate for nearly full energy electron bremsstrahlung in a 1% X0 beampipe. Note that in contrast to e+e- Higgs factories, where a premium is placed on the tracker momentum resolution for the Higgs recoil measurement, an XCC detector will place a premium on excellent electromagnetic calorimetry to measure monochromatic photons.

ILC/C3 and XCC show different strengths. The couplings best measured by ILC/C3 are shaded in blue and those by XCC in green. The Z and W couplings are better measured at ILC/C3 due to the Higgsstrahlung and WW fusion production mechanisms. The XCC has better errors for decays such as H→gg and H→cc due simply to the larger number of Higgs events. The γγ coupling is best measured at XCC due to the γγ production mechanism, and the γZ coupling stands out at the XCC due to its unique signature.

In Stage II 4.9 ab-1 is accumulated by XCC at 380 GeV. The electron and laser photon sqrt(s) is kept fixed (x=1000), so that the X-ray photon energy is now 0.34 keV. To achieve the higher luminosity, the XCC electron RMS bunch length is reduced from 20 µm to 10 µm , the laser pulse energy is doubled from 0.7 to 1.4~J, and the Compton conversion point is pulled in closer to the e-e- IP from 60 µm to 40 µm.

In Stage II, the ILC/C3 produces 1e6 more single Higgs events for a total of 1.5e6 single Higgs events for stages I+II. ILC/C3 and XCC produce 2e6 and 2.9e6 ttbar events, respectively. Of greatest interest is the fact that the XCC produces more than twice as many double Higgs events, due mainly to the 0.4 fb cross-section for γγ→HH, which is twice the cross section for e+e- → ZHH at 500 GeV. This is very important since the Higgs self-coupling measurement is severely statistics limited. The double Higgs final state at XCC is simpler than the ZHH final state at ILC/C3. The Z boson in e+e- → ZH is great for measuring the Z coupling to the Higgs or the invisible Higgs width (see shaded blue entries in the Stage I+II table on the right) but it can be an unwanted complication otherwise (e.g., think the combinatorics of ZHH->6 jets vs HH-> 4jets). The improvement in Higgs self-coupling sensitivity at the XCC could therefore extend beyond its 1/sqrt(2) statistical advantage. The XCC Yukawa coupling error was obtained by simply considering the interference between the t-channel ttbar amplitude and the 1.3% contribution from the tree level s-channel production through a virtual Higgs; the XCC ttbar cross-section measurement has not yet been incorporated into an EFT fit.

The complementarity seen between XCC and ILC/C3 would also exist between XCC and FCC-ee, although it would be even stronger in this case given the absence of a Higgs self-coupling measurement.

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The technical challenges include an electron accelerator with 70 to 120 MV/m. This is common with C3. All future e+e- linear collider final focus systems have been designed for flat beams. R&D is needed to design a system to focus round e- beams to 5.5 nm in both x and y. The X-ray laser and Compton collision technology challenges are significant, but well defined and synergistic with advances in photon science XFEL technology. The issue of the production of 700 mJ/pulse 1 keV photon XFEL beam is purposefully left off this list because the XFEL design in the XCC whitepaper has been validated with full GENESIS simulation. The focusing of the beam to a 70 nm FWHM waist is an issue. But an initial study indicates that X-ray focusing systems assuming the XCC repetition rate and 70 nm FWHM waist are feasible using large (1 to 2 m) Kirkpatrick-Baez (KB) mirrors (1 m FEL quality substrates are produced today). Other technical challenges include the XFEL and e- beam layouts around the IP, and the timing stability of the XFEL laser beam and e- beam at the Compton IP (the XFEL and e- beams meet nearly head-on at the Compton IP).

Demonstration projects would leverage existing facilities and should be relatively inexpensive. For example, a full simulation of the LCLS-I accelerator and XFEL shows that a 1 keV, 100 mJ/pulse system could be tested with LCLS-I by simply adding a new higher brightness electron injector.

We are asking for support for 5 to 6 FTE's for a few years to write a CDR. Due to common accelerator technology, we propose that the XCC CDR be incorporated into the C3 CDR as a 2nd collider configuration option, with the choice between e+e- and γγ to be made at a later date (much like a CDR might contain several site options).

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I am not suggesting that the XCC be sited here in France near the Swiss border. The purpose is to provide a visual of the 4.2 km XCC drawn to scale next to FCC-hh along with dates and potential Higgs self-coupling results.