Sustainability studies for the Cool Copper Collider

Martin Breidenbach¹, Brendon Bullard¹, Emilio Nanni¹, Dimitris Ntounis¹,², Caterina Vernieri¹,²

1) SLAC National Accelerator Laboratory, 2) Stanford University

International Linear Colliders Workshop
May 18, 2023
Introduction

- Community consensus that Higgs factory should be the next major collider after HL-LHC
- The Cool Copper Collider ($C^3$) is a linear $e^+e^-$ collider concept with a compact 7-8 km footprint
  - Enabled by normal conducting copper RF cavities, low surface fields/breakdown rates → high gradient!
- Climate change poses significant threat to humanity and health of Earth's ecosystems
  - How can we continue to build and operate large colliders sustainably?
  - Evaluate emissions due to construction and operation, compare to other Higgs factory options on the basis of physics reach

The Energy Frontier 2021 Snowmass Report

$C^3$ Main Linac Cryomodule
9 m (600 MeV/ 1 GeV)

E. Nanni, C. Vernieri
SLAC P5 Town Hall

Sustainability studies for the Cool Copper Collider
Physics reach

All $e^+e^-$ Higgs factories can operate in the 250 GeV ZH mode

Only linear colliders can operate at 550 GeV, enables 20% precision on Higgs self-coupling

Snowmass 2021 energy frontier report

Sustainability studies for the Cool Copper Collider
Sensitivity comparison for each collider concept

- Taking into account effects of luminosity and polarization to evaluate measurement sensitivity:
  - \( \text{C}^3/\text{ILC-250} \) performs similarly to \( \text{CLIC-380} \), \( \text{C}^3/\text{ILC-550} \) outperforms \( \text{CLIC-380} \)
  - \( \text{C}^3/\text{ILC-550} \) matches or exceeds physics reach of \( \text{FCC} \) in all coupling sensitivity metrics
  - Compare colliders based on their total carbon footprint

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>( hZZ )</td>
<td>1.5</td>
<td>0.22</td>
<td>0.17</td>
<td>0.17</td>
<td>0.072</td>
<td>0.34</td>
</tr>
<tr>
<td>( hWW )</td>
<td>1.7</td>
<td>0.98</td>
<td>0.20</td>
<td>0.41</td>
<td>0.41</td>
<td>0.62</td>
</tr>
<tr>
<td>( hbb )</td>
<td>3.7</td>
<td>1.06</td>
<td>0.50</td>
<td>0.64</td>
<td>0.44</td>
<td>0.98</td>
</tr>
<tr>
<td>( h\tau^+\tau^- )</td>
<td>3.4</td>
<td>1.03</td>
<td>0.58</td>
<td>0.66</td>
<td>0.49</td>
<td>1.26</td>
</tr>
<tr>
<td>( hgg )</td>
<td>2.5</td>
<td>1.32</td>
<td>0.82</td>
<td>0.89</td>
<td>0.61</td>
<td>1.36</td>
</tr>
<tr>
<td>( hc\bar{c} )</td>
<td>-</td>
<td>1.95</td>
<td>1.22</td>
<td>1.3</td>
<td>1.1</td>
<td>3.95</td>
</tr>
<tr>
<td>( h\gamma\gamma )</td>
<td>1.8</td>
<td>1.36</td>
<td>1.22</td>
<td>1.3</td>
<td>1.5</td>
<td>1.37</td>
</tr>
<tr>
<td>( h\gamma Z )</td>
<td>9.8</td>
<td>10.2</td>
<td>10.2</td>
<td>10</td>
<td>4.17</td>
<td>10.26</td>
</tr>
<tr>
<td>( h\mu^+\mu^- )</td>
<td>4.3</td>
<td>4.14</td>
<td>3.9</td>
<td>3.9</td>
<td>3.2</td>
<td>4.36</td>
</tr>
<tr>
<td>( htt )</td>
<td>3.4</td>
<td>3.12</td>
<td>2.82</td>
<td>3.1</td>
<td>3.1</td>
<td>3.14</td>
</tr>
<tr>
<td>( hh\bar{h} )</td>
<td>0.5</td>
<td>0.49</td>
<td>0.20</td>
<td>0.33</td>
<td>-</td>
<td>0.50</td>
</tr>
<tr>
<td>( \Gamma_{tot} )</td>
<td>5.3</td>
<td>1.8</td>
<td>0.63</td>
<td>1.1</td>
<td>1.1</td>
<td>1.44</td>
</tr>
</tbody>
</table>

Snowmass Higgs physics topical group report
Tunnel construction for FCC-ee

Snowmass climate impacts report analyzes FCC construction using bottom-up and top-down approaches

- Only takes into account main tunnel (excludes access shafts, experimental halls, etc.)

Bottom-up approach

Driven by manufacture of concrete

FCC inner/outer diameter 5.5/6.5m
Concrete is 15% cement, which releases 1 ton CO$_2$ per ton

237 kton CO$_2$ (for 7 mil m$^3$ spoil, concrete density 1.72 ton/m$^3$)

Top-down approach

Includes secondary emissions (e.g. construction machinery)

Rough estimates of 5-10k kg CO$_2$ per meter of tunnel length

With 5k kg CO$_2$/m, yields 500 kton CO$_2$

Roughly factor of 2 difference between base material emissions and secondaries

More recent update on FCC civil engineering (L. Broomiley)
Collider project inputs

- ARUP analysis indicates 80% of construction emissions arise from materials (A1-A3), remaining from material transport and construction process
  - More thorough than Snowmass report - rely on it for inputs for other Higgs factory parameters!
  - Approximate global warming potential (GWP) for tunnels ~6 tn/m for CLIC/ILC, apply for circular collider concepts

<table>
<thead>
<tr>
<th>Project</th>
<th>Main tunnel length (km)</th>
<th>GWP (tCO₂e)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Main tunnel</td>
<td>+ Other (±30%)</td>
</tr>
<tr>
<td>FCC</td>
<td>90.6</td>
<td>545</td>
</tr>
<tr>
<td>CEPC</td>
<td>100</td>
<td>600</td>
</tr>
<tr>
<td>ILC</td>
<td>13</td>
<td>80</td>
</tr>
<tr>
<td>CLIC</td>
<td>11</td>
<td>70</td>
</tr>
</tbody>
</table>

Design of additional tunnels (shafts, klystron gallery, caverns) will be used to improve rough +30/+25% estimates

Thanks to Steinar Stapnes for helpful discussions and feedback!
Excavation models

**Bored tunnel**

Total of 600k m$^3$ total excavation, **225k m$^3$ concrete**

- 200k m$^3$ of excavation comes from tunnel volume, *concretes include all site requirements!*

**Cut and cover**

Preferred option for reduced construction costs and emissions (but not required)

- Much of the displaced earth is pushed on top (shielding), only ~40k m$^3$ must be transported away
- Same amount of concrete required as for tunnel, assume emissions can be reduced to **65 kton CO$_2$**

**Releases**

58 kton CO$_2$ from concrete

*Double it to account for top-down vs. bottom-up (120 kton CO$_2$)*
Operations emissions

- Driven by carbon footprint of energy production used during operations
  - Site power requirements have room for optimization, consider nominal beam parameters
  - Carbon intensity (equivalent emissions of gCO₂/kWh) key parameter, depends on location/power sources
  - “The United States has set a goal to reach 100 percent carbon pollution-free electricity by 2035” (from April 2021 US emissions target report - is this a realistic assumption?)

Estimated power consumption for C³-250

National grid storage capacity expected to reach 120 GWh by 2040 - 8 hours of storage at 150 MW < 1% of grid capacity

Resource Sensitivity Scenarios

- 12-hour Pumped-Hydro Storage
- 10-hour Battery Storage
- 8-hour Battery Storage
- 6-hour Battery Storage
- 4-hour Battery Storage
- 2-hour Battery Storage

NREL Storage Futures Study

Sustainability studies for the Cool Copper Collider
C³ has flexibility in site choice.

Carbon intensity for electricity generation varies across US, driven by hydro in Northwest, solar in Southwest, and nuclear in Northeast.

Not representative of C³ operations beginning in ~2040! Need projections.

PJM 2022 estimate used in Janot, Blondel 2022.

Sustainability studies for the Cool Copper Collider.
Project carbon intensities in 2022 into 2040 based on **Low Uptake** scenario of energy source portfolio (national level)

- CAISO: 194 → 70 gCO₂/kWh
- PJM: 381 → 130 gCO₂/kWh

→ **both estimations using projections from US and international agencies give comparable projections**

(Note: Silicon Valley Clean Energy can provide 175 MW of clean energy in 2-3 year timeframe)
Operations parameters

\[ T_{\text{annual}} \cdot \left( \frac{1}{\epsilon} - 1 \right) \]

*Note that beam-on time not spent in collision mode will not be consecutive*

Sketch of beam schedule

\[ P_{\text{inst.}} \]

\[ \kappa \cdot P_{\text{inst.}} \]

Normal conducting RF uses less power when not in collisions than superconducting RF

<table>
<thead>
<tr>
<th>Higgs Factory</th>
<th>CLIC</th>
<th>ILC</th>
<th>C³</th>
<th>CEPC</th>
<th>FCC-ee</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \sqrt{s} ) [GeV]</td>
<td>380</td>
<td>250/500</td>
<td>250/550</td>
<td>240/360</td>
<td>240/345/365</td>
</tr>
<tr>
<td>Instantaneous power ( P ) [MW]</td>
<td>110</td>
<td>111/173</td>
<td>150/175</td>
<td>340</td>
<td>290/350/350</td>
</tr>
<tr>
<td>Annual collision time ( T ) ([10^7 \text{ s}])</td>
<td>1.20</td>
<td>1.60</td>
<td>1.60</td>
<td>1.30</td>
<td>1.08</td>
</tr>
<tr>
<td>Operational efficiency ( \epsilon ) [%]</td>
<td>75</td>
<td>75</td>
<td>75</td>
<td>60</td>
<td>75</td>
</tr>
<tr>
<td>Site power fraction during downtime ( \kappa ) [%]</td>
<td>30</td>
<td>50</td>
<td>30</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>Run length [years]</td>
<td>8</td>
<td>11/9</td>
<td>10/10</td>
<td>10/5</td>
<td>3/1/4</td>
</tr>
</tbody>
</table>

Sustainability studies for the Cool Copper Collider
Energy consumption and emissions

**Total energy consumption over full run time**

- **Linear**
- **Circular**

Total Energy Consumption [TWh]

- **C³** and **CEPC** consumption driven by long run times

**Carbon footprint from operations only**

**Carbon Footprint of Operations**

- **Linear**
- **Circular**

Carbon Footprint [Mtn CO₂-eq.]

Differentiation in environmental impact driven by carbon intensity at target site for each project
Impacts of construction

**Emissions from construction**

Carbon Footprint of Construction

- **Linear**
- **Circular**

Common construction emission per km among linear/circular concepts - *differentiation from total length!*

**Total carbon impact**

Total Carbon Footprint

- **Operations**
- **Construction**

CEPC least sustainable, driven by energy production and long run times, ILC challenging from operation and construction

Sustainability studies for the Cool Copper Collider
C³ power optimizations

Possible options for beam power reduction with several different approaches

Impact on luminosity and ultimate physics performance not yet evaluated

<table>
<thead>
<tr>
<th>Scenario</th>
<th>RF System (MW)</th>
<th>Cryogenics (MW)</th>
<th>Total (MW)</th>
<th>Reduction (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
<td>40</td>
<td>60</td>
<td>100</td>
<td>-</td>
</tr>
<tr>
<td>RF Source Efficiency Increased 15%</td>
<td>31</td>
<td>60</td>
<td>91</td>
<td>9</td>
</tr>
<tr>
<td>RF Pulse Compression</td>
<td>28</td>
<td>42</td>
<td>70</td>
<td>30</td>
</tr>
<tr>
<td>Double Flat Top</td>
<td>30</td>
<td>45</td>
<td>75</td>
<td>25</td>
</tr>
<tr>
<td>Halve Bunch Spacing</td>
<td>30</td>
<td>45</td>
<td>75</td>
<td>25</td>
</tr>
<tr>
<td>All Scenarios Combined</td>
<td>12</td>
<td>24</td>
<td>36</td>
<td>64</td>
</tr>
</tbody>
</table>

Emissions due to operations have clear road toward further reduction since clean energy in California is already accessible, *operations emissions of C³ can be virtually eliminated* (limited by emissions from manufacturing solar panels)

Carbon capture in concrete can offset emissions, but scalability not yet demonstrated

→ **great potential for green Higgs factory with C³!**
Conclusions

✧ C³ is a candidate for a compact linear e⁺e⁻ Higgs factory with low carbon impact

✧ Lower energy consumption over circular colliders to achieve same (or better) physics goals
  • C³ physics reach enhanced by polarized electrons, ability to access $\sqrt{s} = 550$ GeV running mode

✧ Significantly reduced emissions associated to construction than alternative Higgs factory concepts
  • Emissions from conventional concrete manufacturing, factor 4-8 lower emissions for C³ than FCC

✧ Can be built anywhere, but compelling to build in US due to expected grid electrification
  • By 2040, carbon intensity of electricity generation to be on par with EU, far below Japan and China

✧ Finalizing details of sustainability analysis, paper to follow

Thank you for your attention - stay tuned!
Backup
Focus on linear accelerators

Total Carbon Footprint

<table>
<thead>
<tr>
<th>Collider Project</th>
<th>Operations</th>
<th>Construction</th>
</tr>
</thead>
<tbody>
<tr>
<td>CLIC</td>
<td>0.5</td>
<td>0.1</td>
</tr>
<tr>
<td>ILC</td>
<td>3.2</td>
<td>0.3</td>
</tr>
<tr>
<td>C3 (Bored)</td>
<td>0.8</td>
<td>0.2</td>
</tr>
<tr>
<td>C3 (C&amp;C)</td>
<td>0.8</td>
<td>0.2</td>
</tr>
</tbody>
</table>

*Preliminary*
Collider project inputs

Linear Collider Options

1. CLIC Drive Beam
   5.6m internal dia. Geneva.
   (380GeV, 1.5TeV, 3TeV)

2. CLIC Klystron
   10m internal dia. Geneva.
   (380GeV)

3. ILC
   Arched 9.5m span. Japan.
   (250GeV)

Reference: CLIC Drive Beam tunnel cross section, 2018
Reference: CLIC Klystron tunnel cross section, 2018
Reference: Tohoku ILC Civil Engineering Plan, 2020
Projected daily energy load curves by region (US)

Energy outlook March 16 2023

Hourly U.S. electricity generation and load by fuel for selected cases and representative years

<table>
<thead>
<tr>
<th>Reference case, 2022</th>
<th>Reference case, 2050</th>
<th>Low Oil and Gas Supply case, 2050</th>
<th>Low Zero-Carbon Technology Cost case, 2050</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load, excluding storage</td>
<td>Curtailment</td>
<td>Stand-alone storage</td>
<td>Pumped hydro storage</td>
</tr>
<tr>
<td>Load, excluding storage</td>
<td>Curtailment</td>
<td>Stand-alone storage</td>
<td>Pumped hydro storage</td>
</tr>
</tbody>
</table>

Data source: U.S. Energy Information Administration, Annual Energy Outlook 2023 (AEO2023)

Note: Negative generation represents charging of energy storage technologies such as pumped hydro storage and battery storage. Hourly dispatch estimates are illustrative and are developed to determine curtailment and storage operations. Final dispatch estimates are developed separately and may differ from total utilization as this figure shows. Standalone solar photovoltaic (PV) includes both utility-scale and end-use PV electricity generation.
### Table 5: For each of the Higgs factory projects considered

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Center-of-mass energies considered</strong> $\sqrt{s}$ [GeV]</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>380</td>
<td>250, 500</td>
<td>250, 550</td>
<td>240,360</td>
<td>240, 340-350, 365</td>
<td></td>
</tr>
<tr>
<td><strong>Site Power $P$ [MW]</strong></td>
<td>110</td>
<td>111 at 250 GeV</td>
<td>$\sim$ 150 at 250 GeV</td>
<td>340</td>
<td>290 at 240 GeV</td>
</tr>
<tr>
<td>173 at 500 GeV</td>
<td>$\sim$ 175 at 550 GeV</td>
<td></td>
<td></td>
<td>$\sim$ 350 at 340 – 350, 365 GeV</td>
<td></td>
</tr>
<tr>
<td><strong>Annual collision time $T_{annual}$ [10^7 s/year]</strong></td>
<td>1.20</td>
<td>1.60</td>
<td>1.60</td>
<td>1.30</td>
<td>1.08</td>
</tr>
<tr>
<td><strong>Operational Efficiency $\epsilon$</strong></td>
<td>0.75</td>
<td>0.75</td>
<td>0.75</td>
<td>0.60</td>
<td>0.75</td>
</tr>
<tr>
<td><strong>Site power fraction during downtime $\kappa$</strong></td>
<td>0.3</td>
<td>0.5</td>
<td>0.3</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td><strong>Running time $T_{run}$ [years]</strong></td>
<td>8</td>
<td>11 at 250 GeV</td>
<td>10 at 250 GeV</td>
<td>10 at 240 GeV</td>
<td>3 at 240 GeV</td>
</tr>
<tr>
<td>9 at 500 GeV</td>
<td>10 at 550 GeV</td>
<td>5 at 360 GeV</td>
<td>1 at 340 – 350 GeV</td>
<td>4 at 365 GeV</td>
<td></td>
</tr>
<tr>
<td><strong>Instantaneous Luminosity/IP $\mathcal{L}_{inst}$ [$10^{34}$ cm$^{-2}$ s$^{-1}$]</strong></td>
<td>2.3</td>
<td>1.35 at 250 GeV</td>
<td>1.3 at 250 GeV</td>
<td>8.3 at 240 GeV</td>
<td>8.5 at 240 GeV</td>
</tr>
<tr>
<td>1.8 at 500 GeV</td>
<td>2.4 at 550 GeV</td>
<td>0.83 at 360 GeV</td>
<td>0.95 at 340 – 350 GeV</td>
<td>1.55 at 365 GeV</td>
<td></td>
</tr>
<tr>
<td><strong>Target Integrated Luminosity $\mathcal{L}_{int}$ [ab$^{-1}$]</strong></td>
<td>1.5</td>
<td>2 at 250 GeV</td>
<td>2 at 250 GeV</td>
<td>20 at 240 GeV</td>
<td>5 at 240 GeV</td>
</tr>
<tr>
<td>4 at 500 GeV</td>
<td>4 at 550 GeV</td>
<td>1 at 360 GeV</td>
<td>0.2 at 340 – 350 GeV</td>
<td>1.5 at 365 GeV</td>
<td></td>
</tr>
</tbody>
</table>

---

**Additional operating parameters**

**Sustainability studies for the Cool Copper Collider**