The Cool Copper Collider

Emilio Nanni

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Acknowledgements

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Strategy for Understanding the Higgs Physics: The Cool Copper Collider

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More Details Here (Follow, Endorse, Collaborate):
https://indico.slac.stanford.edu/event/7155/

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C3: Demonstration Research and Development Plan

Editors:

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C3: A “Cool” Route to the Higgs Boson and Beyond


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What’s Next for the Energy Frontier?

Wish list beyond HL-LHC:
1. Establish Yukawa couplings to light flavor $\Rightarrow$ needs precision
2. Establish self-coupling $\Rightarrow$ needs high energy
Why $e^+e^-$?

Initial state well defined & polarization $\Rightarrow$ High-precision measurements
Higgs bosons appear in 1 in 100 events $\Rightarrow$ Clean environment and trigger-less readout
Higgs Production at $e^+e^-$

ZH is dominant at **250 GeV**

- Above **500 GeV**
  - $Hvv$ dominates
  - ttH opens up
  - $HH$ production accessible with ZHH
  - An **orthogonal dataset** at 550 GeV to cross-check a deviation from the SM
  - From 500 to 550 GeV a factor 2 improvement to the **top-Yukawa** coupling
  - O(20%) precision on the Higgs **self-coupling**
Linear vs. Circular

Linear $e^+e^-$ colliders: ILC, C³, CLIC
- Reach higher energies (~TeV), and can use polarized beams
- Relatively low radiation
- Collisions in bunch trains

Circular $e^+e^-$ colliders: FCC-ee, CEPC
- Highest luminosity collider at Z/W W /ZH
- Limited by synchrotron radiation above 350 – 400 GeV
- Beam continues to circulate after collision
Various Proposals

ILC
250/500 GeV

CLIC
380/1000/3000 GeV

CEPC
240 GeV

FCC-ee
240/365 GeV

250/550 GeV
...> TeV

THE TOHOKU REGION OF JAPAN

CECOOL COPPER COLLIDER

Jura

LHC

Mandalaz

Prelaps

Aravis

CERN - FCC
A novel route to a linear $e^+e^-$ collider...
Breakthrough in the Performance of RF Accelerators

RF power coupled to each cell – no on-axis coupling
Full system design requires modern virtual prototyping

Electric field magnitude produced when RF manifold feeds alternating cells equally

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Full system design requires modern virtual prototyping

**RF Power**

**Beam**

Electric field magnitude produced when RF manifold feeds alternating cells equally

Optimization of cell for efficiency (shunt impedance)
- Control peak surface electric and magnetic fields

Key to high gradient operation

\[ R_s = \frac{G^2}{P} \text{ [MΩ/m]} \]

Cryo-Copper: Enabling Efficient High-Gradient Operation

Cryogenic temperature elevates performance in gradient
- Material strength is key factor
- Impact of high fields for a high brightness injector may eliminate need for one damping ring

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Operation at 77 K with liquid nitrogen is simple and practical
- Large-scale production, large heat capacity, simple handling
- Small impact on electrical efficiency

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\[
\eta_{cp} = LN \text{ Cryoplant} \\
\eta_{cs} = \text{Cryogenic Structure} \\
\eta_k = RF \text{ Source} \\
\frac{\eta_{cs}}{\eta_{cp}} \approx \frac{2.5}{0.5 \times [0.15]} \approx 0.75
\]

C³ combines these advances
- Dramatically improving efficiency and breakdown rate
- Distributed power to each cavity from a common RF manifold
- Operation at cryogenic temperatures (LN₂ ~80 K)
- Robust operations at high gradient: 120 MeV/m
- Scalable to multi-TeV operation

High Gradient Operation at 150 MV/m

High Power Test at Radiabeam (Room Temp and Cryo)
Requirements for a High Energy e⁺e⁻ Linear Collider

Using established collider designs to inform initial parameters
Quantifying impact of wakes requires detailed studies
- Most important terms – aperture, bunch charge (and their scaling with frequency)

Target initial stage design at 250 GeV CoM
- 2 MW single beam power

<table>
<thead>
<tr>
<th>Machine</th>
<th>CLIC</th>
<th>NLC</th>
<th>C³</th>
</tr>
</thead>
<tbody>
<tr>
<td>Freq (GHz)</td>
<td>12.0</td>
<td>11.4</td>
<td>5.7</td>
</tr>
<tr>
<td>a (mm)</td>
<td>2.75</td>
<td>3.9</td>
<td>2.6</td>
</tr>
<tr>
<td>Charge (nC)</td>
<td>0.6</td>
<td>1.4</td>
<td>1</td>
</tr>
<tr>
<td>Spacing (λ)</td>
<td>6</td>
<td>16</td>
<td>30/20</td>
</tr>
<tr>
<td># of bunches</td>
<td>312</td>
<td>90</td>
<td>133/75</td>
</tr>
</tbody>
</table>

https://clic-meeting.web.cern.ch/clic-meeting/clicatable2010.html
NLC, ZDR Tbl. 1.3,8.3
Accelerator Complex

8 km footprint for 250/550 GeV CoM $\Rightarrow$ 70/120 MeV/m
- 7 km footprint at 155 MeV/m for 550 GeV CoM – present Fermilab site
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
- New opportunities to improve Beam Delivery and footprint

<table>
<thead>
<tr>
<th>Collider</th>
<th>C$^3$</th>
<th>C$^3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>CM Energy [GeV]</td>
<td>250</td>
<td>550</td>
</tr>
<tr>
<td>Luminosity [$\times 10^{34}$]</td>
<td>1.3</td>
<td>2.4</td>
</tr>
<tr>
<td>Gradient [MeV/m]</td>
<td>70</td>
<td>120</td>
</tr>
<tr>
<td>Effective Gradient [MeV/m]</td>
<td>63</td>
<td>108</td>
</tr>
<tr>
<td>Length [km]</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>Num. Bunches per Train</td>
<td>133</td>
<td>75</td>
</tr>
<tr>
<td>Train Rep. Rate [Hz]</td>
<td>120</td>
<td>120</td>
</tr>
<tr>
<td>Bunch Spacing [ns]</td>
<td>5.26</td>
<td>3.5</td>
</tr>
<tr>
<td>Bunch Charge [nC]</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Crossing Angle [rad]</td>
<td>0.014</td>
<td>0.014</td>
</tr>
<tr>
<td>Site Power [MW]</td>
<td>$\sim 150$</td>
<td>$\sim 175$</td>
</tr>
<tr>
<td>Design Maturity</td>
<td>pre-CDR</td>
<td>pre-CDR</td>
</tr>
</tbody>
</table>

C$^3$ Parameters

C$^3$ - 8 km Footprint for 250/550 GeV
Technically limited timeline following community engagement through the full Snowmass process to define the parameters of the C^3 proposal.

<table>
<thead>
<tr>
<th>Accelerator</th>
<th>2019-2024</th>
<th>2025-2034</th>
<th>2035-2044</th>
<th>2045-2054</th>
<th>2055-2064</th>
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</thead>
<tbody>
<tr>
<td>Demo proposal</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Demo test</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CDR preparation</td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>TDR preparation</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Industrialization</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TDR review</td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Construction</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Commissioning</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 ab^{-1} @ 250 GeV</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RF Upgrade</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4 ab^{-1} @ 550 GeV</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Multi-TeV Upg.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

HL-LHC
Ongoing Prototype Structure Development

Incorporate the two key technical advances: Distributed Coupling and Cryo-Copper RF

Main linac utilizes meter-scale accelerating structures, technology demonstration underway
Implement optimized rf cavity designs to control peak surface fields

One meter (40-cell) C-band design with reduce peak E and H-field

Scaling fabrication techniques in length and including controlled gap
Main Linac C-band

LANL Test of single cell SLAC C-band structure

Injector Linac S-band
Cryomodule Design and Alignment

Up to 1 GeV of acceleration per 9 m cryomodule; ~90% fill factor with eight 1 m structures

Main linac will require 5 micron structure alignment
- Combination of mechanical and beam based alignment

Pre-alignment warm, cold alignment by wire, followed by beam based
- Mechanical motor runs warm or cold – no motion during power failure
- Piezo for active alignment

Investigating support and assembly design
Tunnel Layout for Main Linac 250/550 GeV CoM

Need to optimize tunnel layout – first study looked at 9.5 m inner diameter in order to match ILC costing model
- Must minimize diameter to reduce cost and construction time
Surface site (cut/cover) provides interesting alternative – concerns with length of site for future upgrade

Cryomodule Unit - 9 m
(630 MeV/1 GeV)
Cryomodule Design Scalable from 250 GeV to multi-TeV

X-band structure demonstrated full average power over short length (0.25 m)
Cryomodule design developed for cryoplant layout to cool 1.2 MW/km thermal load at 77K

Shared Nitrogen Supply and Return

Cryogenics Scale to multi-TeV

Air Separation Unit

Plant: 100 tons/day
Storage: 100 Tons
## Power Consumption and Sustainability

### 250 GeV CoM - Luminosity - 1.3x10^{34}

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reliquification Plant Cost</td>
<td>M$/MW</td>
<td>18</td>
</tr>
<tr>
<td>Single Beam Power (125 GeV linac)</td>
<td>MW</td>
<td>2</td>
</tr>
<tr>
<td>Total Beam Power</td>
<td>MW</td>
<td>4</td>
</tr>
<tr>
<td>Total RF Power</td>
<td>MW</td>
<td>18</td>
</tr>
<tr>
<td>Heat Load at Cryogenic Temperature</td>
<td>MW</td>
<td>9</td>
</tr>
<tr>
<td>Electrical Power for RF</td>
<td>MW</td>
<td>40</td>
</tr>
<tr>
<td>Electrical Power For Cryo-Cooler</td>
<td>MW</td>
<td>60</td>
</tr>
<tr>
<td>Accelerator Complex Power</td>
<td>MW</td>
<td>~50</td>
</tr>
<tr>
<td>Site Power</td>
<td>MW</td>
<td>~150</td>
</tr>
</tbody>
</table>

### Parameter Values

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature (K)</td>
<td></td>
<td>77</td>
</tr>
<tr>
<td>Beam Loading (%)</td>
<td></td>
<td>45</td>
</tr>
<tr>
<td>Gradient (MeV/m)</td>
<td></td>
<td>70</td>
</tr>
<tr>
<td>Flat Top Pulse Length (μs)</td>
<td></td>
<td>0.7</td>
</tr>
<tr>
<td>Cryogenic Load (MW)</td>
<td></td>
<td>9</td>
</tr>
<tr>
<td>Main Linac Electrical Load (MW)</td>
<td></td>
<td>100</td>
</tr>
<tr>
<td>Site Power (MW)</td>
<td></td>
<td>~150</td>
</tr>
</tbody>
</table>

### Compatibility with Renewables

Cryogenic Fluid Energy Storage

Intermittent and variable power production from renewables mediated with commercial scale energy storage and power production.

**Pulse Format**

- 133 1 nC bunches spaced by 30 RF periods (5.25 ns)
- Trains repeat at 120 Hz
- RF envelope 700 ns
RF source R&D Over the Timescale of the Next P5

RF source cost is the key driver for gradient and cost
Significant savings when items procured at scale of LC
Need to focus R&D on reducing source cost to drive economic argument for high gradient

Gradient/Cost Scaling vs RF Source Cost for 2 TeV CoM

Understand the Impact on Advanced Collider Concept Enabled by the Goals Defined in the DOE GARD RF Decadal Roadmap

High Efficiency Klystrons

Please See I. Syratchev’s Talk for Many Great Examples from Designs to Prototypes

Retro-fit High Efficiency 50 MW, 12 GHz klystron (CERN/cpi).

- Re-used solenoid.
- Increased life time (> factor 2)
- Reduced modulator power (~ factor 2)
- Increased power gain (10 dB)
- Reduced solenoidal field

Prototype fabrication is under negotiation within CPI/INFN/CERN collaboration.

Dipole mode wakefields immediate concern for bunch train
4σ Gaussian detuning of 80 cells for dipole mode (1st band) at $f_c=9.5$ GHz, w/ $\Delta f/f_c=5.6\%$
First subsequent bunch $s = 1$ m, full train ~75 m in length
- Damping needed to suppress re-coherence
Distributed Coupling Structures Provide Natural Path to Implement Detuning and Damping of Higher Order Modes

Individual cell feeds necessitate adoption of split-block assembly
Perturbation due to joint does not couple to accelerating mode
Exploring gaps in quadrature to damp higher order mode

H-field

300 μm gap to matched load

Accelerating Mode

Dipole Mode

Q ≈ 10^3 (vs 4x10^4)

Detuned Cavity Designs

Quadrant Structure

Abe et al., PASJ, 2017, WEP039
Implementation of Slot Damping

Need to extend to 40 GHz / Optimize coupling / Modes below $10^4$ V/pC/mm/m
NiCr coated damping slots in development
Outlook
C³ Demonstration R&D Plan

C³ demonstration R&D needed to advance technology beyond CDR level

Minimum requirement for Demonstration R&D Plan:

- **Demonstrate operation of fully engineered and operational cryomodule**
  - Simultaneous operations of min. 3 cryomodules
- Demonstrate operation during cryogenic flow equivalent to main linac at full liquid/gas flow rate
- Operation with a multi-bunch photo injector - high charges bunches to induce wakes, tunable delay witness bunch to measure wakes
- Demonstrate full operational gradient 120 MeV/m (and higher > 155 MeV/m) w/ single bunch
  - Must understand margins for 120 - targeting power for (155 + margin) 170 MeV/m
  - 18X 50 MW C-band sources - off the shelf units
- **Fully damped-detuned accelerating structure**
- Work with industry to develop C-band source unit optimized for installation with main linac

This demonstration directly benefits development of compact FELs, beam dynamics, high brightness guns, *etc.*

The other elements needed for a linear collider - the sources, damping rings, and beam delivery system – more advanced from the ILC and CLIC – need C³ specific design

- Our current baseline uses these directly; will look for further cost-optimizations for of C³
C³ Demonstration R&D Plan timeline

C³ R&D, System Design and Project Planning are ongoing

- Early career scientists should help drive the agenda for an experiment they will build/use
- Many opportunities for other institutes to collaborate on:
  - beam dynamics, vibrations and alignment, cryogenics, rf engineering, controls, detector optimization, background studies, etc.

High Energy Physics: Caterina Vernieri caterina@slac.stanford.edu
Accelerator Science & Engineering: Emilio Nanni nanni@slac.stanford.edu
The Complete C³ Demonstrator

Demonstrate fully engineered cryomodule
~50 m scale facility
3 GeV energy reach
Answer technical questions needed for CDR
Conclusion

Next C³ Workshop in Planning – Oct. 13-14th @ SLAC

https://indico.slac.stanford.edu/event/7315/

C³ can provide a rapid route to precision Higgs physics with a compact 8 km footprint

- Higgs physics run by 2040
- Possibly, a US-hosted facility

C³ time structure is compatible with SiD-like detector overall design and ongoing optimizations.

C³ can be quickly be upgraded to 550 GeV

C³ can be extended to a multi-TeV e+e- collider

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