Future Colliders from the Accelerator Perspective

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6/4/2024
Experimental validation of the Standard Model of Particle Physics

What determines the performance of an accelerator? How do accelerators work across different scales in size and energy?
What’s Next for the Energy Frontier?

- Many options in consideration beyond HL-LHC
- Precision studies with Higgs Factories
- Discovery physics on the >TeV scale
Linear vs. Circular

Linear $e^+e^-$ colliders: ILC, C$^3$, 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/WW/ZH
- Limited by synchrotron radiation above 350 – 400 GeV (~ $\gamma^4/\rho^2$)
- Beam continues to circulate after collision
Higgs Factory Proposals

ILC
250/500 GeV

CEPC
240 GeV

FCC-ee
240/365 GeV

COOL COPPER COLLIDER

CLIC 380/1000/3000 GeV

250/550 GeV
... > TeV
Future Muon, Wakefield and hh Colliders

New magnet technology Nb$_3$Sn – 16 T (vs 8 T in the LHC with NbTi)
current record 14T (CERN), Fermilab $\rightarrow$ 15 T

...either in a new or old tunnel

Wakefield

Muon Collider

FCC-hh
Landscape of High Energy Colliders

Snowmass Implementation Task Force comparisons of machine concepts

Future studies focusing on physics potential for operation AND construction

ILC and the Accelerator Technology

~20 km

Parameters | Value
--- | ---
Beam Energy | 125 + 125 GeV
Luminosity | 1.35 / 2.7 x 10^{10} cm^2/s
Beam rep. rate | 5 Hz
Pulse duration | 0.73 / 0.961 ms
# bunch / pulse | 1312 / 2625
Beam Current | 5.8 / 8.8 mA
Beam size (y) at FF | 7.7 nm
SRF Field gradient | \(< 31.5 > MV/m (+/-20%)\), \(Q_0 = 1\times10^{10}\)
#SRF 9-cell cavities (CM) | \(~ 8,000 (~ 900)\)
AC-plug Power | 111 / 138 MW

Nano-Beam Technology

SRF Technology

TDR was published in 2013.
SRF technology for ILC-250 beyond present limits

- Advanced shape standing wave SRF cavities – Low Loss (LL), ICHIRO,
- Reentrant (RE) – increase peak quench magnetic field by 10-20%, potentially bringing accelerating gradient limit to $\lesssim 60$ MV/m
- Traveling wave (TW) SRF offers better cryogenic efficiency and higher accelerating gradient up to $\sim 70$ MV/m – possible application: ILC energy upgrade, HELEN collider, ACE at Fermilab
- Advanced SRF materials – Nb3Sn cavities can potentially reach $\sim 90$ MV/m
The Compact Linear Collider (CLIC)

- **Timeline:** Electron-positron linear collider at CERN for the era beyond HL-LHC
- **Compact:** Novel and unique two-beam accelerating technique with high-gradient room temperature RF cavities (~20’500 structures at 380 GeV), ~11km in its initial phase
- **Expandable:** Staged programme with collision energies from 380 GeV (Higgs/top) up to 3 TeV (Energy Frontier)
- CDR in 2012 with focus on 3 TeV. Updated project overview documents in 2018 (Project Implementation Plan) with focus 380 GeV for Higgs and top.

Recent talks (with more references): [eeFACT1](#) and [eeFACT2](#)

The CLIC accelerator studies are mature:
- Optimised design for cost and power
- Many tests in CTF3, FELs, light-sources and test-stands
- Technical developments of “all” key elements

Accelerating structure prototype for CLIC: 12 GHz (L~25 cm)
On-going CLIC studies towards next ESPP update

Project Readiness Report as a step toward a TDR
Assuming ESPP in ~ 2026, Project Approval ~ 2028, Project (tunnel) construction can start in ~ 2030.

The X-band technology readiness for the 380 GeV CLIC initial phase - more and more driven by use in small compact accelerators

Optimizing the luminosity at 380 GeV – already implemented for Snowmass paper, further work to provide margins will continue.

Luminosity margins and increases:
- Initial estimates of static and dynamic degradations from damping ring to IP gave: $1.5 \times 10^{34} \text{cm}^2 \text{s}^{-1}$
- Simulations taking into accord static and dynamic effects with corrective algorithms give 2.8 on average, and 90% of the machines above $2.3 \times 10^{34} \text{cm}^2 \text{s}^{-1}$ (this is the value currently used)

Improving the power efficiency for both the initial phase and at high energies, including more general sustainability studies

Power estimate bottom up (concentrating on 380 GeV systems)
- Very large reductions since the CDR, better estimates of nominal settings, much more optimised drive-beam complex and more efficient klystrons, injectors more optimized, main target damping ring RF significantly reduced, recent L-band klystron studies

Energy consumption ~0.6 TWh yearly, CERN is currently (when running) at 1.2 TWh (~90% in accelerators)
Accelerator Complex

8 km footprint for 250/550 GeV CoM ⇒ 70/120 MeV/m
Large portions of accelerator complex compatible between LC technologies
- Beam delivery / IP modified from ILC (1.5 km for 550 GeV CoM), compatible w/ ILC-like detector
- Damping rings and injectors to be optimized with CLIC as baseline

**C³ Parameters**

<table>
<thead>
<tr>
<th>Collider</th>
<th>C³</th>
<th>C³</th>
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<tbody>
<tr>
<td>CM Energy [GeV]</td>
<td>250</td>
<td>550</td>
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<td>Luminosity [x10^{34}]</td>
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<td>Gradient [MeV/m]</td>
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<td>Effective Gradient [MeV/m]</td>
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<td>Length [km]</td>
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<td>Num. Bunches per Train</td>
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<td>Train Rep. Rate [Hz]</td>
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<td>120</td>
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<td>Bunch Spacing [ns]</td>
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<td>Bunch Charge [nC]</td>
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<td>Crossing Angle [rad]</td>
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<td>Site Power [MW]</td>
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<td>Design Maturity</td>
<td>pre-CDR</td>
<td>pre-CDR</td>
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**C³ Main Linac Cryomodule**

9 m (600 MeV/ 1 GeV)

**C³ - 8 km Footprint for 250/550 GeV (to scale)**

Trains repeat at 120 Hz

133 1 nC bunches spaced by 30 RF periods (5.25 ns)

RF envelope 700 ns
System level optimization essential for achieving performance

RF Structure Optimization

- 3.55 mm iris radius
- $2.0 = \frac{E_{\text{max}}}{E_{\text{acc}}}$
- $1.23 = \frac{H_{\text{coup}}}{H_{\text{wall}}}$

Electric Field

Magnetic Field

M. Shumall, Z. Li

Vibration Measurements and Analysis

- Y Displacement
- RMS Displacement (um)

Z. George, V. Borzenets, A. Dhar, D. Palmer

Main Linac Beam Dynamics

- Accelerating Cavities
- Quadrupoles
- MS Error [um]

White (C³), Schulte (CLIC)

Alignment Parameters

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<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Value</th>
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<td>Raft Components</td>
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<td>Short Range (~10m)</td>
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<td>Long Range (&gt;200m)</td>
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<td>Structure Vert. Vibration</td>
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<td>Quad Vert. Vibration</td>
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Two-Phase Fluid Simulations

FAMU-FSU College of Engineering

K. Shoele

Precision Short and Long Range Alignment

H. Van Der Graaf

100 nm resolution

Approved effort to test cold

FCC integrated program

Comprehensive long-term program maximizing physics opportunities

- **Stage 1**: FCC-ee (Z, W, H, t̅t̅) as Higgs factory, electroweak & top factory at highest luminosities
- **Stage 2**: FCC-hh (~100 TeV) as natural continuation at energy frontier, with pp & AA collisions; also eh option

- Highly synergetic and complementary programme boosting the physics reach of both colliders (e.g. model-independent measurements of the Higgs couplings at FCC-hh thanks to input from FCC-ee; and FCC-hh as “energy upgrade” of FCC-ee)
- Common civil engineering and technical infrastructures, building on and reusing CERN’s existing infrastructure
- FCC integrated project allows the start of a new, major facility at CERN within a few years of the end of HL-LHC

A similar two-stage project CEPC/SPPC is under study in China
FCC-ee accelerator R&D - examples

- **Efficient RF power sources**
  - (400 & 800 MHz)
  - High efficiency klystrons & scalable solid-state amplifiers
  - FPC & HOM coupler, cryomodule, thin-film coatings

- **Efficient SC cavities**
  - 400 MHz 1- & 2-cell Nb/Cu, 4.5 K
  - Elliptical cavity (SWELL) for high beam current & for high gradient, seamless by nature – links to past work at ANL (Liu & Nassiri, PRAB 13, 012001)

- **Energy efficient twin aperture arc dipoles**
  - Reduce energy consumption by O(50 MW)

- **Under study**: CCT HTS quad’s & sext’s for arcs

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I. Syratchev

A. Milanese

M. Koratzinos, B. Auchmann
Stage 2: FCC-hh: highest collision energies

~order of magnitude performance increase in both energy & luminosity wrt LHC

~100 TeV cm collision energy (vs 14 TeV for LHC)

20 ab⁻¹ per experiment over 25 years of operation (vs 3 ab⁻¹ for LHC)

similar performance increase as from Tevatron to LHC

key technology: high-field magnets

from LHC technology
8.3 T NbTi dipole

via
HL-LHC technology
12 T Nb₃Sn quadrupole

FNAL dipole demonstrator
4-layer cos⁹
14.5 T Nb₃Sn in 2019

HTS technology
Hybrid Nb-Ti/HTS
Muon Collider Concept

- Leading concept for Muon Collider is a proton driven target for muon production followed by 6D cooling to reduce the beam emittance
- Alternative concept – positron driven muon production

Challenges:
- Muon cooling for proton driven source
- High flux positron source

ArXiv: 1808.01858
Muon Cooling

Technology requirements for MuC cooling:

- Large bore solenoidal magnets: From 2 T (500 mm IR), to 14 T (50 mm IR)
- Normal conducting rf that can provide high-gradients within a multi-T fields
- Absorbers that can tolerate large muon intensities
- Integration: Solenoids coupled to each other, near high power rf & absorbers
Accelerator R&D areas:
- High power proton driver
- Short lifetime of muons in injector (~microsec)
- **Cooling to reduce emittance**
- Injection and acceleration
- Mitigating radiation

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<th>Parameter</th>
<th>Symbol</th>
<th>Unit</th>
<th>Target value</th>
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<td>Centre-of-mass energy</td>
<td>$E_{cm}$</td>
<td>TeV</td>
<td>3 10 14</td>
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<tr>
<td>Luminosity</td>
<td>$\mathcal{L}$</td>
<td>10$^{34}$ cm$^{-2}$ s$^{-1}$</td>
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<td>Collider circumference</td>
<td>$C_{coll}$</td>
<td>km</td>
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<tr>
<td>Muons/bunch</td>
<td>$N$</td>
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<tr>
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<td>Beam power</td>
<td>$P_{coll}$</td>
<td>MW</td>
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<td>IP beam size</td>
<td>$\sigma$</td>
<td>$\mu$m</td>
<td>3 0.9 0.63</td>
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</table>

arXiv:2203.08033
Wakefield Accelerator Technologies

Structure Wakefield Accelerators

Argonne, SLAC, and LBNL are the stewards of SWFA, PWFA, and LWFA technology in the US, with university participation.

Beam Driven Plasma @ SLAC

Laser Driven Plasma @ LBNL

Key advantages:
- Ultra-large gradients (1-100 GeV/m)
- Ultra-short bunches (suppress beamstrahlung)
Conclusions

- Accelerators are powerful tools for scientific discovery
- A great variety of parameters are achievable – species, power, wavelength, repetition rate
- Technology is evolving rapidly to enable new capabilities
- Ultimately accelerator technology will set the limits of collider performance
- Exciting time with great options for the community

Questions?