Next: A Higgs factory

Need e+e- collisions at least at 250 GeV, four main alternatives (plus various less developed ideas):

ILC in Japan (linear)  FCC at CERN (ring)
CLIC at CERN (linear)  CEPC in China (ring)

Linear colliders: 13 (Higgs) -> 50 (max) km to get to 1-3 TeV
Rings ~100km, can be used for protons after
ESPP Update 2020 “High-priority future initiatives”

• An electron-positron Higgs factory is the highest-priority next collider. For the longer term, the European particle physics community has the ambition to operate a proton-proton collider at the highest achievable energy.

• “Europe, together with its international partners, should investigate the technical and financial feasibility of a future hadron collider at CERN with a centre-of-mass energy of at least 100 TeV and with an electron-positron Higgs and electroweak factory as a possible first stage.

• Such a feasibility study of the colliders and related infrastructure should be established as a global endeavour and be completed on the timescale of the next Strategy update.”

→ launch of Future Circular Collider Feasibility Study in summer 2021
Timeline of the FCC integrated programme

<table>
<thead>
<tr>
<th>Technical schedule</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feasibility Study: 2021-2025</td>
</tr>
<tr>
<td>If project approved before end of decade → construction can start beginning 2030s</td>
</tr>
<tr>
<td>FCC-ee operation ~2045-2060</td>
</tr>
<tr>
<td>FCC-hh operation 2070-2090++</td>
</tr>
</tbody>
</table>

### Timeline of the FCC integrated programme

**FCC Feasibility Study Status**
Michael Benedikt
Plenary ECFA Meeting, 19 November 2021

<table>
<thead>
<tr>
<th>Stage</th>
<th>Timeline</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feasibility Study: 2021-2025</td>
<td>10 years</td>
</tr>
<tr>
<td>FCC-ee, ~15 years operation</td>
<td>10 years</td>
</tr>
<tr>
<td>FCC-hh, ~25 years operation</td>
<td>70 years</td>
</tr>
</tbody>
</table>

#### FCC-ee accelerator and detector R&D and technical design
- Geological investigations, infrastructure detailed design and tendering preparation
- Tunnel site and technical infrastructure construction
- FCC-ee accelerator and detector construction, installation, commissioning

#### Superconducting magnets R&D
- Long model magnets, prototypes, pre-series
- High-field magnet industrialization and series production

#### Technical schedule

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Energy</th>
<th>L/(\text{i}P)</th>
<th>Int. L/(\text{i}P) (ab(^{-1}))</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>e^+e^- FCC-ee</td>
<td>(-90) GeV</td>
<td>Z 160</td>
<td>230 x (10^{34})</td>
<td>75</td>
</tr>
<tr>
<td>FCC-ee</td>
<td>100 TeV</td>
<td>5 x (10^{34})</td>
<td>20-30</td>
<td>2+2 experiments, Total ~25 years of operation</td>
</tr>
<tr>
<td>PbPb FCC-hh</td>
<td>(\sqrt{s_{\text{NN}}} = 39) TeV</td>
<td>3 x (10^{29})</td>
<td>100 nb(^{-1})/run</td>
<td>1 run = 1 month operation</td>
</tr>
<tr>
<td>ep FCC-ee</td>
<td>3.5 TeV</td>
<td>1.5 (10^{34})</td>
<td>2 ab(^{-1})</td>
<td>60 GeV e- from ERL, Concurrent operation with pp for ~20 years</td>
</tr>
<tr>
<td>e-Pb FCC-ee</td>
<td>(\sqrt{s_{\text{NN}}} = 2.2) TeV</td>
<td>0.5 (10^{34})</td>
<td>1 fb(^{-1})</td>
<td>60 GeV e- from ERL, Concurrent operation with PbPb</td>
</tr>
</tbody>
</table>

F. Gianotti
Feasibility study launched in July 2021

- More details in FCC Week 2021: [https://indico.cern.ch/event/995850/](https://indico.cern.ch/event/995850/)
  - Intermediate review mid 2023 – FSR end 2025 – First $e^+e^-$ collisions in 2040+
- Work has started on placement in Geneva area

- Number of surface points reduced to 8, with fourfold super-periodicity
  - This new layout is consistent with later choice of 2 or 4 Interaction Points (IP) for FCC-ee

P. Janot
ECFA Plenary Meeting
19 Nov 2021
Plans for high-risk area site investigations

JURA, VUACHE (3 AREAS)
- Top of limestone
- Karstification and filling-in at the tunnel depth
- Water pressure

LAKE, RHÔNE, ARVE AND USSES VALLEY (4 AREAS)
- Top of the molasse
- Quaternary soft grounds, water bearing layers

MANDALLAZ (1 AREAS)
- Water pressure at the tunnel level
- Karstification

BORNES (1 AREA)
- High overburden molasse properties
- Thrust zones

Site investigations planned for mid 2023 – mid 2025:
~40-50 drillings, 100 km of seismic lines
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.
- **Cost**: 5.9 BCHF for 380 GeV (stable wrt 2012)
- **Power**: ~110 MW at 380 GeV (reduced wrt 2012), corresponding to 50% of CERN’s energy consumption today
- **Comprehensive** Detector and Physics studies
Technology Driven Schedule from start of construction shown above.

A preparation phase of ~5 years is needed before (estimated resource need for this phase is ~4% of overall project costs)
CLIC is a mature design/study

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

Focusing on:
• The X-band technology readiness for the 380 GeV CLIC initial phase
• Optimizing the luminosity at 380 GeV
• Improving the power efficiency for both the initial phase and at high energies

Goals for these studies by ~2025:
• Improved 380 GeV parameters/performance/project plan
• Push multi-TeV options/parameters
## CLIC parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Unit</th>
<th>Stage 1</th>
<th>Stage 2</th>
<th>Stage 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Centre-of-mass energy</td>
<td>$\sqrt{s}$</td>
<td>GeV</td>
<td>380</td>
<td>1500</td>
<td>3000</td>
</tr>
<tr>
<td>Repetition frequency</td>
<td>$f_{\text{rep}}$</td>
<td>Hz</td>
<td>50</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>Number of bunches per train</td>
<td>$n_b$</td>
<td></td>
<td>352</td>
<td>312</td>
<td>312</td>
</tr>
<tr>
<td>Bunch separation</td>
<td>$\Delta t$</td>
<td>ns</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Pulse length</td>
<td>$\tau_{\text{RF}}$</td>
<td>ns</td>
<td>244</td>
<td>244</td>
<td>244</td>
</tr>
<tr>
<td>Accelerating gradient</td>
<td>$G$</td>
<td>MV/m</td>
<td>72</td>
<td>72/100</td>
<td>72/100</td>
</tr>
<tr>
<td>Total luminosity</td>
<td>$\mathcal{L}$</td>
<td>$10^{34}$ cm$^{-2}$ s$^{-1}$</td>
<td>1.5</td>
<td>3.7</td>
<td>5.9</td>
</tr>
<tr>
<td>Luminosity above 99% of $\sqrt{s}$</td>
<td>$\mathcal{L}_{0.01}$</td>
<td>$10^{34}$ cm$^{-2}$ s$^{-1}$</td>
<td>0.9</td>
<td>1.4</td>
<td>2</td>
</tr>
<tr>
<td>Total integrated luminosity per year</td>
<td>$\mathcal{L}_{\text{int}}$</td>
<td>fb$^{-1}$</td>
<td>180</td>
<td>444</td>
<td>708</td>
</tr>
<tr>
<td>Main linac tunnel length</td>
<td></td>
<td>km</td>
<td>11.4</td>
<td>29.0</td>
<td>50.1</td>
</tr>
<tr>
<td>Number of particles per bunch</td>
<td>$N$</td>
<td>$10^9$</td>
<td>5.2</td>
<td>3.7</td>
<td>3.7</td>
</tr>
<tr>
<td>Bunch length</td>
<td>$\sigma_z$</td>
<td>$\mu$m</td>
<td>70</td>
<td>44</td>
<td>44</td>
</tr>
<tr>
<td>IP beam size</td>
<td>$\sigma_x/\sigma_y$</td>
<td>nm</td>
<td>149/2.9</td>
<td>$\sim$ 60/1.5</td>
<td>$\sim$ 40/1</td>
</tr>
<tr>
<td>Normalised emittance (end of linac)</td>
<td>$\epsilon_x/\epsilon_y$</td>
<td>nm</td>
<td>900/20</td>
<td>660/20</td>
<td>660/20</td>
</tr>
<tr>
<td>Final RMS energy spread</td>
<td></td>
<td>%</td>
<td>0.35</td>
<td>0.35</td>
<td>0.35</td>
</tr>
<tr>
<td>Crossing angle (at IP)</td>
<td></td>
<td>mrad</td>
<td>16.5</td>
<td>20</td>
<td>20</td>
</tr>
</tbody>
</table>
Examples of R&D

Industrial questionnaire: Based on the companies feedback, the preparation phase to the mass production could take about five years. Capacity clearly available.

Structures and components production programme to study designs, operation, conditioning, manufacturing, industry qualification/experience

EU projects: ARIES, I-FAST, new TNA

Applications – injector, X-band modules, RF

- CompactLight Design Studies 2018-21 (right)
- INFN 1 GeV linac
- Flash RT CDR, next build it at CHUV
- "Design Studies" for ICS
- APERES, IFAST and TNA project

Further work on luminosity performance, possible improvements and margins, operation at the Z pole and gamma-gamma
- Z pole performance, 2.3x10^20 ~ 0.4x10^20 cm^-2 s^-1
  - The latter number when accelerator configured for Z running (e.g. early or end of first stage)
- Gamma – Gamma spectrum (example)
- Luminosity margins and increases
  - Baseline includes estimates static and dynamic degradations from damping ring to IP: 1.5 x 10^28 cm^-2 s^-1, a “perfect” machine will give: 4.3 x 10^29 cm^-2 s^-1,
  - so significant upside
  - In addition doubling the frequency (50 Hz to 100 Hz) would double the luminosity, at a cost of ~50 MW and ~5% cost increase
- Studies cover from beam-dynamics to technical studies of the required performances of stability, alignment, instrumentation, magnets, BDS, final focus, injectors including positions, damping rings – priority for next ESU
  - CLIC note and paper about these studies

X-band

High Eff. Klystrons L-band, X-band (for applications) collaborators and test-stands

High Efficiency implementations:
- New small X-band klystron, ordered
- Large with CPI, work with INFN
- L-band two stage, design done, prototyping for FCC

Also important, redesign of damping ring RF system (well underway) – no klystron development foreseen
The Circular Electron Positron Collider

- The CEPC aims to start operation in 2030’s, as a Higgs (Z / W) factory in China.
- To run at $\sqrt{s} \sim 240$ GeV, above the $ZH$ production threshold for $\sim 1$ M Higgs; at the $Z$ pole for $\sim$Tera $Z$; at the $WW^*$ pair and possible $tt\bar{t}$ pair production thresholds.
- Higgs, EW, flavor physics & QCD, probes of physics BSM.
- Possible $pp$ collider (SppC) of $\sqrt{s} \sim 50–100$ TeV in the future.
CEPC Roadmap and Schedule (Ideal)

- **2013-2025:** Key technology R&D, from CDR to TDR, site selection, international collaboration etc.
- **Ideal case:** Approval in the 15th Five-Year Plan, and start construction (~8 years)

### Ideal Accelerator Roadmap
- **2016-2021** MOST phase-1 accelerator R&D
- **2018-2023** MOST phase-2 accelerator R&D
- **2023-2028** MOST phase-3 accelerator R&D
- **2022-2023** Accelerator TDR completion
- **2023-2025** Site selection, engineering design, prototyping and industrialization
- **2026-2034** Construction and Installation

### Ideal Detector Roadmap
- **2016-2021** MOST phase-1 detector R&D
- **2018-2023** MOST phase-2 detector R&D
- **2023-2028** MOST phase-3 detector R&D
- **2027-2028** Detector TDR completed
- **2028-2034** Detector construction
- **2033-2034** Installation

**15th 5Y**
- Site selection, engineering design, technology & system verification
- Accelerator TDR, MoU, international collaboration

**HTS Magnet R&D Program**
100 km double-ring design (30 MW/beam, upgradable to 50).

New baseline for Linac (C-band, 20GeV) after the CDR.

### Operation mode

<table>
<thead>
<tr>
<th>$\sqrt{s}$ [GeV]</th>
<th>ZH</th>
<th>Z</th>
<th>$W^+W^-$</th>
<th>$t\bar{t}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>~240</td>
<td>~91.2</td>
<td>158-172</td>
<td>360</td>
<td></td>
</tr>
<tr>
<td>$L/IP$ [$\times 10^{34}$ cm$^2$/s$^1$]</td>
<td>CDR (2018)</td>
<td>Latest</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>32</td>
<td>10</td>
<td>5.0</td>
<td>115</td>
</tr>
</tbody>
</table>
**CEPC SCRF Test Facility**

- **New SC Lab Design (4500m²)**
- **SC New Lab is available in 2021**

Cryogenic system hall in 2020

---

**Collaboration With Industry**

- **CEPC 850MHz Klystron at Kunshan Co.**
- **CERN HL-LHC CCT SC magnet**
- **CEPC SC QDII coil winding at KEVE Co.**

**CIPC (CEPC Industrial Promotion Consortium) was established in Nov 2017. So far 70+ companies have joined.**

CEPC Detector SC coil winding tools at KEVE Co. (Glenmore -7m)

CEPC long magnet measurement tools

---

**Conceptual Detector Designs**

- **Baseline Design**
- **Particle Flow Approach**
- **Magnet (ST/2T)**
- **LumiCell**
- **Si Pixel Vertex**
- **FST concept (Full Silicon Tracker)**

**IDEA concept** (also proposed for FCC-ee)

- **2T Magnet**
- **Preshower** (µ-RWELL)
- **Dual-readout calorimeter**
- **Silicon wrapper**
- **Drift chamber**
- **Si Pixel Vertex**

**The 4th Concept**

PFA HCAL

- **PID (DC+10F)**
- **Crystal ECAL (Transverse bar)**

---

**CEPC Physics White Papers**

**Operation mode**

<table>
<thead>
<tr>
<th>ZH</th>
<th>Z</th>
<th>W+</th>
<th>tbar</th>
</tr>
</thead>
<tbody>
<tr>
<td>240</td>
<td>91.2</td>
<td>158-172</td>
<td>360</td>
</tr>
</tbody>
</table>

**Run time (years)**

| L / IP x 10^{34} cm^{-2} s^{-1} | 3 | 32 | 10 |
| L dt [ab^{-1}, 2 ab] | 5.6 | 16 | 2.6 |
| Event yields [2IPs] | 1 x 10^6 | 7 x 10^11 | 2 x 10^7 |

**Latest**

| L / IP x 10^{34} cm^{-2} s^{-1} | 5.6 | 115 | 16 | 0.5 |

The large samples: ~10^6 Higgs, ~10^{11} Z, and ~10^6 W bosons

- Physics goals are similar to FCC-ee, ILC, CLIC.
- 2019.7 Workshop@PKU: EW, Flavor, QCD working groups formed
- 2020.1 Workshop@HKUST-IAS: Review progress, EW draft ready
- 2021.4 Workshop@Yangzhou: BSM working group formed

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11/19/2021
ILC Site Candidate Location in Japan: Kitakami

- **Continuous granite region**
  - HITOKABE, SENMAYA and ORIKABE bedrock
- **Have capability to extend the ILC up to 50 km in future**
- **Boring geological survey**
  - Direct sampling down to the accelerator depth
- **Electromagnetic prospecting**
  - Cracks in the rock
- **Seismic prospecting**
  - Rock hardness

Tohoku ILC Project Development Center is established

Director
Atsuto Suzuki
[1] Design outline: ILC250 accelerator facility

ILC250 focuses on Higgs Factory; Length becomes 20 km

Total Cost of Acc. is \( \approx 6\text{B$S$F} \)
including human & Civil Tunnel cost \( \approx 1.1\text{B$S$F} \)

**Key Technologies**

Total Cost of Acc. is \( \approx 6\text{B$S$F} \)
including human & Civil Tunnel cost \( \approx 1.1\text{B$S$F} \)

**SRF accelerators are worldwide used for light source**

**ILC SRF technology is well-matured & Cost effective**

**Table:**

<table>
<thead>
<tr>
<th>Item</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>C.M. Energy</td>
<td>250 GeV</td>
</tr>
<tr>
<td>Length</td>
<td>20km</td>
</tr>
<tr>
<td>Luminosity</td>
<td>( 1.35 \times 10^{34} \text{cm}^{-2}\text{s}^{-1} )</td>
</tr>
<tr>
<td>Repetition</td>
<td>5 Hz</td>
</tr>
<tr>
<td>Beam Pulse Period</td>
<td>0.73 ms</td>
</tr>
<tr>
<td>Beam Current</td>
<td>5.8 mA (in pulse)</td>
</tr>
<tr>
<td>Beam size (y) at FF</td>
<td>( 7.7 \text{nm} @ 250\text{GeV} )</td>
</tr>
<tr>
<td>SRF Cavity G. ( Q_0 )</td>
<td>31.5 MV/m (35 MV/m) ( Q_0 = 1 \times 10^{-9} )</td>
</tr>
</tbody>
</table>
ILC is the big international project
Pre-Lab Phase is necessary before construction.

Boss is Nakada-san

ICFA

ILC International Development Team
International Org.

Executive Board

- Americas Liaison: Andrew Lanford (UC Irvine)
- Working Group 2 Chair: Shinichiro Michizono (KEK)
- Working Group 3 Chair: Hitoshi Murayama (UC Berkeley/U. Tokyo)
- KEK Liaison: Yasuhiro Okada (KEK)
- Europe Liaison: Steinar Stagnes (CERN)
- Asia-Pacific Liaison: Geoffrey Taylor (U. Melbourne)

Working Group 1
Pre-Lab Setup

Working Group 2
Accelerator

Working Group 3
Physics & Detectors

International Development Team (IDT) is established by ICFA

**IDT:** to prepare for smooth transition to the ILC Pre-lab
- Prepare a proposal for the organization and governance of the ILC Pre-Lab
- Prepare the work and deliverables of the ILC Pre-laboratory and workout a scenario for contributions with national and regional partners

Accelerator: Michizono-sab
Physics: Murayama-san
IDT-WG2 summarized the technical preparation as **work packages (WPs)** in the technical preparation document.

SRF is dominant, but also there are many interesting topics:

- **Actual cavity/CIM manufacturing**
  - SRF
    - ~41MILCU
    - 285 FTE-yr
    - WP-1
    - Cavity production
    - WP-2
    - Cryomodule assembly
    - WP-3
    - Crab cavity

- **e-Driven scheme**
  - **e-source**
    - ~2.5MILCU, 6 FTE-yr
    - WP-4
    - Electron source
  - **Undulator scheme**
    - ~6MILCU, 15 FTE-yr
    - WP-5
    - Undulator
    - WP-6
    - Rotating target
  - **Magnetic focusing**
    - WP-7
    - WP-8
    - Rotating target
    - WP-9
    - Magnetic focusing
    - WP-10
    - Capture cavity
    - WP-11
    - Target replacement

**ILC Pre-lab**

**Cost & FET**

- **BOS**
  - ~2MILCU, 16FTE-yr
  - WP-12
  - System design
  - WP-13
  - Collective effect
  - WP-14
  - Injection/extraction

- **Dump**
  - ~3MILCU, 12FTE-yr
  - WP-15
  - Final focus
  - WP-16
  - Final doublet

- WP-17
  - Main dump
- WP-18
  - Photon dump


- The technical preparation document was reviewed by the international review committee (chair: Tor Raubenheimer (SLAC)).
- The total global cost of the project is about 60 MILCU and about 360 FTE-year. (This does not include the cost of the infrastructure for the WPs.)
- The cost will be shared internationally as in-kind contribution.
Extendability of ECM is also important

**Anomaly in muon g-2 is confirmed.**

Light SUSY (color-single SUSY) particles are expected \( \sim 500 \text{GeV} \) (Neutralino, chargino, slepton).

With DM/LHC constraint degenerate case is expected.

**Higgs Factory**

Higgs coupling can be measured precisely. Accuracy is about 1%. No necessary mention here.

This show recoil mass distribution. We can detect Higgs \( \rightarrow \) invisible. Higgs portal DM is interesting topics.

**Diversities/applications**

Higgs Factory / high energy colliders are very important for us; But diversities and applications are important for faculty.

Beam dump experiments are interesting hunting for Axion / Paraphoton.

Light Source Laser/XFEL Nuclear Phys. Material Nano beam

Various proposals are welcome.

**2] Detectors**

The similar Performance is obtained in both detectors. Significantly improved from the LHC detectors.

Two detectors are proposed:

- **SI2**
  - 5T Magnet
  - Based on the Silicon pixel and strip detectors (except for HCAL)
  - \( \text{arXiv:2110.09965} \)

- **ILD**
  - TPC/High Granularity Calorimeter Readout Cell numbers is as larger as by factor 1000 of LHC
  - \( \text{arXiv:2003.01116} \)
Note on long-term planning

Preliminary (optimistic) schedule of HL-LHC

Shown integrated luminosities include 1 month/year of HI running and no MD or special runs after 2036

LS4 extended from 1 to 2 years (in view of ALICE and LHCb upgrades)

With proposed shift and extension of LS3, and inclusion of HI runs beyond LS3:
- 2500 fb⁻¹ are expected by end 2038 (current end-date of HL-LHC)
- 3000 fb⁻¹ (int. luminosity goal) would now be reached in ~2041

Note: it should not be assumed that future shifts of LS schedules, or new, ambitious upgrades of the experiments, entail an automatic shift/extension of HL-LHC end date, as this has an impact on the future of the field
(next collider cannot start before ~7 years from end of HL-LHC for technical and financial reasons)

→ next European Strategies will need to optimise the overall planning of the field based on HL-LHC performance and physics results, interest of the community, progress with next facility, etc.
Photon (from electrons) and hadron therapy (protons and ions)

50 mill patients treated with photons

FLASH VHEE (very high energy electron) therapy

CLIC technology for a FLASH VHEE facility being designed in collaboration with Lausanne University Hospital (CHUV)

An intense beam of electrons is produced in a photoinjector, accelerated to around 100 MeV and then is expanded, shaped and guided to the patient.

Flash: Very short and intense radiation, sparing of healthy tissue
Synchrotron Light Sources: about 50 storage ring based

60‘000 users world-wide

Established, mature technology
X-Ray Free Electron Lasers
From L. Rivkin EPFL