Technology path towards future colliders

Caterina Biscari
ALBA Synchrotron

ECFA-EPS Joint Session
Input to this talk mainly from Granada Symposium

Thanks to all those who submitted inputs, plus speakers, plus participants

Inputs to the Strategy on accelerators

• e+e- colliders
• hh colliders
• ep colliders
• FCC
• Gamma factories
• Plasma acceleration
• Muon colliders
• Beyond colliders
• Technological developments

Questions on Accelerator Science and Technology

• What is the best implementation for a Higgs factory?
• Choice and challenges for accelerator technology: linear vs. circular?
• Path towards the highest energies: how to achieve the ultimate performance (including new acceleration techniques)?
• How to achieve proper complementarity for the high intensity frontier vs. the high-energy frontier?
• Energy management in the age of high-power accelerators?

Disclaimer: Only main technologies will be mentioned.
Linear colliders technology highlights

- rf cavities
- nanobeam
## Features of Normal conducting and Superconducting RF

<table>
<thead>
<tr>
<th>Normal conducting (CLIC)</th>
<th>Superconducting (ILC)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Gradient:</strong> 72 to 100 MV/m</td>
<td><strong>Gradient:</strong> 31.5 to 35 (to 45) MV/m,</td>
</tr>
<tr>
<td>- Higher energy reach, shorter facility</td>
<td>- Higher efficiency, steady state beam power from RF input</td>
</tr>
<tr>
<td><strong>RF Frequency:</strong> 12 GHz</td>
<td><strong>RF Frequency:</strong> 1.3 GHz</td>
</tr>
<tr>
<td>- High efficiency RF peak power</td>
<td>- Large aperture gives low wakefields</td>
</tr>
<tr>
<td>- Precision alignment &amp; stabilization to compensate wakefields</td>
<td></td>
</tr>
<tr>
<td><strong>$Q_0$:</strong> order $&lt; 10^5$,</td>
<td><strong>$Q_0$:</strong> order $10^{10}$,</td>
</tr>
<tr>
<td>- Resistive copper wall losses compensated by strong beam loading – 40% steady state rf-to-beam efficiency</td>
<td>- High Q</td>
</tr>
<tr>
<td></td>
<td>- losses at cryogenic temperatures</td>
</tr>
<tr>
<td><strong>Pulse structure:</strong> 180 ns / 50 Hz</td>
<td><strong>Pulse structure:</strong> 700 µs / 5 Hz</td>
</tr>
<tr>
<td><strong>Fabrication:</strong></td>
<td><strong>Fabrication</strong></td>
</tr>
<tr>
<td>- driven by micron-level mechanical tolerances</td>
<td>- driven by material (purity) &amp; clean-room type chemistry</td>
</tr>
<tr>
<td>- High-efficiency RF peak power production through long-pulse, low freq. klystrons and two-beam scheme</td>
<td>- High-efficiency RF also from long-pulse, low-frequency klystrons</td>
</tr>
</tbody>
</table>

A. Yamamoto, 190513bb
Normal Conducting Linac Technology Landscape

Components:

- Laboratory with commercial
  - Accelerating structures
  - pulse compressors
  - alignment
  - Stabilization, etc.

- Systems Facilities:
  (100 MeV-range)
  - XBoxes at CERN
  - (NEXTEF KEK)
  - Frascati
  - NLCTA SLAC
  - Linearizers at Electra, PSI, Shanghai and Daresbury
  - Test stand at Tsinghua
  - Deflectors at SLAC, Shanghai, PSI and Trieste
  - NLCTA
  - SmartLight
  - FLASH

- Full commercial supply
  - X-band klystrons
  - solid state modulator,

- C-band (6 GHz), low-emittance GeV-range facilities
  - Operational:
    - SACLA
    - SwissXFEL (8 GeV)

- X-band (12 GHz) GeV-range facilities
  - Planning:
    - EuPraxia
    - e-SPS
    - CompactLight

- CLIC

A. Yamamoto, 190513bb

Courtesy: W. Wuensch
Advances in SRF Technology for Accelerators

Progress (1988~)
- TRISTAN
- LEP-II
- HERA
- CEBAF
- CESR
- KEKB
- BES
- cERL

In Operation: → # cavities
- SNS: 1 GeV
- CEBAF 12 GeV → 80
- ISAC-II, ARIEL
- Super-KEKB
- Eu-XFEL → 800

Under Construction:
- LCLS=II → 300
- FRIB → 340
- PIP-II → 115
- ESS → 150
- Shine → 600

To be realized:
- HL-LHC-Crab → 20
- EIC
- ILC-250 → 8,000
- FCC
- CEPC/SPPS

> 2,000 SRF cavities realized, in last 10 years!
Challenges in SRF Cavity Technology

- **Bulk-Nb:**
  - **High-G and -Q optimization**
    - Low-T treatment w/ or w/o N-infusion.
  - **Large-Grain (LG) directly sliced from ingot**
    - For possible less contamination and cost-reduction

- **Thin-film Coating**
  - **Nb thin-film** coating on Cu-base cavity structure
    - Important for lower frequency and/or low-beta application.
    - A New approach to realize flatter Q-slope (higher-Q)
    - **High Power Impulse Magnetron Sputtering (HiPIMS)**, instead of
      - **DC Magnetron Sputtering (DCMS)**
  - **Nb\textsubscript{3}Sn / MgB\textsubscript{2}** film coating on Nb or Cu
    - To reach much higher G, with higher B\textsubscript{c} (B\textsubscript{sh})

A. Yamamoto, 190513bb
RF technology

- Accelerator Technologies are ready to go forward for lepton colliders (ILC, CLIC, FCC-ee, CEPC), focusing on the Higgs Factory construction to begin in > ~5 years.

- SRF accelerating technology is well matured for the realization including cooperation with industry.

- Continuing R&D effort for higher performance is very important for future project upgrades.
  - Nb-bulk, 40 – 50 MV/m: ~ 5 years for single-cell R&D and the following 5 – 10 years for 9cell cavities statistics to be integrated. Ready for the upgrade, 10 ~ 15 years.

A. Yamamoto

FEL communities develop NC + SC rf cavities
- Operating (SwissFEL, EuXFEL,..)
- in construction (LCLS,..)
- in design stage
And so do ERL (PERLE,..)
Develop nano-beam technology for ILC/CLIC

- Goal: Realize small beam-size and the Stabilize beam position

<table>
<thead>
<tr>
<th>B Energy [GeV]</th>
<th>ILC-250</th>
<th>125</th>
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</thead>
<tbody>
<tr>
<td>CLIC-380</td>
<td>190</td>
<td></td>
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<tr>
<td>ATF2 (achieved)</td>
<td>1.3</td>
<td></td>
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</table>

Advances in light sources (diffraction limited storage rings)

- Demonstrated by MaxIV
- In progress at ESRF, Sirius, APS, ALS,....

From A. Yamamoto, 190513bb

Damping Ring (140m)
Low emittance e- beam

1.3 GeV S-band e- LINAC (~70m)

C. Biscari – Ghent - 13 July 2019

Technology path towards future colliders

ECFA-EPS Joint session
Challenges of Linear Colliders Higgs Factories

\[ \mathcal{L} \propto H_D \ \frac{N}{\sigma_x} \ \frac{N n_b f_r}{\sigma_y} \text{~} 10^{34} \]

- Luminosity Spectrum (Physics)
  - \( \delta E/E \approx 1.5\% \) in ILC
  - Grows with \( E \): 40\% of CLIC lumi 1\% off \( \sqrt{s} \)

- Beam Current (RF power limited, beam stability)
  - Challenging \( e^+ \) production (two schemes)
  - CLIC high-current drive beam bunched at 12 GHz (klystrons + 1.4 BCHF)

- Beam Quality (Many systems)
  - Record small DR emittances
  - 0.1 \( \mu \)m BPMs
  - IP beam sizes
    - ILC 8nm/500nm
    - CLIC 3nm/150nm

Shiltsev | EPPSU 2019 Future Colliders

C. Biscari – Ghent - 13 July 2019
### Overview of CLIC and ILC parameters

<table>
<thead>
<tr>
<th>CLIC illustrations</th>
<th>CLIC parameters</th>
<th>ILC parameters</th>
<th>ILC illustrations</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1" alt="CLIC illustrations" /></td>
<td>E: 380, 1500, 3000 GeV (L: 11-50 km)</td>
<td>E: 250, 500, 1000 GeV (L: 20-40 km)</td>
<td><img src="image2" alt="ILC illustrations" /></td>
</tr>
<tr>
<td>Lum: 1.5-5.9 $10^{34}$ cm$^{-2}$ s$^{-1}$</td>
<td>Lum: 1.35 (2.7) – 1.8($3.6$) $10^{34}$ cm$^{-2}$ s$^{-1}$ *</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Prep. phase 2020-2025</td>
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<tr>
<td>Constr.+comm. 7y, ready before 2035</td>
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<td></td>
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<tr>
<td>Power: ~ 170 MW – 580 MW**</td>
<td>Power: ~ 130 – 300 MW</td>
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</table>

* Doubling by increasing frequency (to be) studied. ** Power at 1.5 and 3 TeV not updated from CDR 2012

**Staged approach to higher energies**

- CLIC γ: 75% of 180 days
- ILC γ: 75% of 240 days

* NCRF X-band now established and industrially available, used in small systems and being introduced in larger ones, relevant reference experience with C-band for larger systems (Swissfel).
* SCRF in extensive use in several FELs with parameters close to ILC parameters, the primary one being the E-XFEL at DESY. Technology optimization underway, linking to evolving SCRF R&D for grad. and Q.
* Nanobeam addressed in design & specifications, benchmarked simulations, low emittance ring progress, extensive prototype and method development (for alignment, stabilization, instrumentation, algorithms and feedback systems, system and facility tests : FACET, light-sources, FELs, ATF2)
* Extensive prototyping of all parts of these accelerators, for lab-test, use/test in test-facilities, light-sources or FELs (magnets, instrumentation, controls, vacuum, etc)
* CERN hosted international project (follow LHC model)
* Japan hosted international project, initial ideas about European capabilities available ([link](#))

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Technology path towards future colliders
Circular colliders technology highlights

- Size
- Synchrotron radiation
- High field magnets
Proton or lepton collisions

14 TeV lepton collisions
Are comparable to 100 TeV proton collisions
e+ e- colliders

- Synchrotron radiation power, mitigated by long tunnel (100 km)
- Limit set to **100 MW @ FCC-ee** (60 MW @ CepC) by limiting the current => L decreases as E increases
- New beam-beam instability; short beam lifetime => large acceptance

**High efficient RF sources:**
- Klystron 400/800 MHz $\eta$ from 65% to >85%

**High efficiency SRF cavities:**
- 10-20 MV/m and high $Q_0$; Nb-on-Cu, Nb$_3$Sn

**Crab-waist collision scheme:**
- *Super KEK-B* nanobeams experience will help

**Energy Storage and Release R&D:**
- Magnet energy re-use > 20,000 cycles

**Efficient Use of Excavated Materials:**
- 10 million cu.m. out of 100 km tunnel

Shiltsev
Luminosity Challenge (e+ e-)

Luminosity cannot be fully demonstrated before the project implementation
• Luminosity is a feature of the facility not the individual technologies
• Have to rely on experiences, theory and simulation and foresee margins

FCC-ee and CEPC are based on experience from LEP, DAPHNE, KEKB, PEP II, superKEKB, ...
• Gives confidence that we understand performance challenges
• New beam physics occurs in the designs,
  • e.g. beamstrahlung is unique feature of FCC-ee and CEPC
  • Identified and anticipated in the design, should be able to trust simulations
• The technologies required are improved versions of those from other facilities

Linear colliders are based on experiences from SLC, FELs, light sources, ...
• Gives confidence that we understand the performance challenges
• Gives us confidence that we can do better than SLC
• Still performance goal more ambitious, e.g. beam size of nm scale
  • Creates additional challenges and requires additional technologies, e.g. stabilization
• A part of the technologies are improved versions of those from other facilities
• Some had to be purpose-developed for linear colliders

From D. Schulte
Maturity (e+e-)

• CEPC and FCC-ee, LHeC
  – Do not see a feasibility issue with technologies or overall design
  – But more hardware development and studies essential to ensure that the performance goal can be fully met
    • E.g. high power klystrons, strong-strong beam-beam studies with lattice with field errors, …
• ILC and CLIC
  – Do not see a feasibility issue with technology or overall design
  – Cutting edge technologies developed for linear colliders
    • ILC technology already used at large scale
    • CLIC technology in the process of industrialization
  – More hardware development and studies required to ensure that the performance goal can be fully met
    • e.g. undulator-based positron source, BDS tuning, …
• Do not anticipate obstacle to commit to either CEPC, FCC-ee, ILC or CLIC
  – But a review is required of the chosen candidate(s)
  – More effort required before any of the projects can start construction
pp colliders (+ ion-p, e-p)
Advances in SC Magnets for Accelerators

Past:
- ISR-IR
- Tevatron (Fermilab)
- TRISTAN-IR (KEK)
- HERA (DESY)
- Nuclotron (JINR)
- LEP-IR (CERN)
- KEKB-IR (KEK)

Present:
- RHIC (BNL)
- LHC (CERN)
- SRC (RIKEN) ….. SC-Cyclotron

Under Construction
- FAIR (GSI) ….. Fast-cycle Shnchr.
- HL-LHC (CERN)
- NICA (JINR)

Future:
- EIC (e-Ion)
- FCC-hh / HE-LHC
- SppC

1980: Tevatron-D, HL-LHC 11T-D (Nb$_3$Sn)
2000: HERA-D,
2020: RHIC-D, LHC.D (NbTi)

A. Yamamoto
After 10 years of development, the US and EU development produced the Nb$_3$Sn conductor for HILUMI.
High field magnet development

Dipole Field for Hadron Collider

- In LHC, 14 T dipoles give 23.5 TeV
- But timeline is NOT the same

HTS

- 12 T Nb$_3$Sn dipoles
- HiLumi technology in LHC: 21 TeV c.o.m.

FCC

- 7 T Nb-Ti dipole (low cost LHC, 4.2 K):
- 44 TeV c.o.m. (100 km)

LHC1.5

- Energy tripler 100km

Year


Central field (T)

HTS

- 14 T

Nb$_3$Sn

- 12 T

Nb-Ti

- 7 T

Tevatron

- 2.2 T

HERA

- 3.9 T

RHIC

- 4.5 T

SPS & Main Ring (resistive)

Technology path towards future colliders

ECFA-EPS Joint session
HL-LHC : 11 T magnets

Bordry

11 T in full swing production: LS2 installation in 2020!
Great care given the stress sensitivity of Nb$_3$Sn

+MgB$_2$ 18.5 kA Superconducting Link Demonstrated

The 1st Series, 5.5 m long Dipole, powered as a single aperture in the initial test:
Reached $B_c = 11.2$ T (at nominal current)
I-nominal, after 1 quench,
$B_c = 12.1$ T (at ultimate current)
I-ultimate) after 6 quenches.

$+\text{Nb}_3\text{Sn}$ Quadrupole (MQXF) at IR
US: 4.5 m Prototype:
- Completed and tested
CERN: 1-m short Models:
- Successfully demonstrated the performance
CERN: 7 m Prototype under development
s.c. magnet technology

- $\text{Nb}_3\text{Sn}$ superconducting magnet technology for hadron colliders, still requires step-by-step development to reach 14, 15, and 16 T.

- It would require the following time-line (in my personal view):
  - $\text{Nb}_3\text{Sn}$, 12~14 T: 5~10 years for short-model R&D, and the following 5~10 years for prototype/pre-series with industry. It will result in 10 – 20 yrs for the construction to start,
  - $\text{Nb}_3\text{Sn}$, 14~16 T: 10-15 years for short-model R&D, and the following 10 ~ 15 years for prototype/pre-series with industry. It will result in 20 – 30 yrs for the construction to start, (consistently to the FCC-integral time line).
  - $\text{NbTi}$, 8~9 T: proven by LHC and $\text{Nb}_3\text{Sn}$, 10 ~ 11 T being demonstrated. It may be feasible for the construction to begin in > ~ 5 years.

- Continuing R&D effort for high-field magnet, present to future, should be critically important, to realize highest energy frontier hadron accelerators in future.
14 T magnet tested at FNAL!

- 15 T dipole demonstrator
- Staged approach: In first step pre-stressed for 14 T (as planned for the first stage)
- Second test foreseen in fall 2019 with additional pre-stress for 15 T
The difference between a 14 T and a 16 T magnet is very large, in terms of quantity of conductor needed, number of coils, and complexity of the construction. Though, on paper, a 16 T magnet is possible and is costing about twice the cost of a LHC magnet for twice the field. Achieving such a construction on a large series may be extremely difficult. A two layer design with a target field in the range of 12 T to 14 T is considered by the magnet community present during the FCC week as ‘consensus’ for a collider in the next decades.

The design work has shown that all the considered options have a potential for FCC. This has motivated the decision of exploring experimentally all options to answer the outstanding questions of which design meets best the requirements, which margin field level (~12-14 T) should be selected.

In the last three years, the FCC Conductor Development Program coordinated by CERN has succeeded in engaging the Japanese (Jastec and Furukawa via the KEK coordination), the Russian (TVEL) and the Korean (KAT) companies in developing for the first time very high-performance Nb$_3$Sn wire. Critical current densities of up to about 1250 A/mm$^2$ at 16 T have been achieved, and kilometers length of wire have been produced in industry and delivered to CERN for first cabling trials.

In the US, the FCC current density target (1500 A/mm$^2$ at 16 T) has been achieved! Industrialization and cost reduction has yet to come.
R&D of 12T Twin-aperture Dipole Magnet

**R&D Roadmap for the next 10~15 years**

1. NbTi+Nb₃Sn, 2*φ10 aperture
2. Nb₃Sn+HTS, 2*φ20 aperture
3. All HTS, 2*φ40 aperture

- Magnetic flux distribution
- 3D coil layout
- 3D magnetic field distribution
- Components and assembly
Goal:

a) 1) To increase the $J_c$ of iron-based superconductor (IBS) by 10 times, reduce the cost to 20 Rmb/kAm @ 12T & 4.2K, and realize the industrialization of the conductor;

b) 2) To reduce the cost of ReBCO and Bi-2212 conductors to 20 Rmb/kAm @ 12T & 4.2K;

c) 3) Realization and Industrialization of IBS magnets and SRF cavities.

Working groups: 1) Fundamental sciences study; 2) IBS conductor R&D; 3) ReBCO conductor R&D; 4) Bi-2212 conductor R&D; 5) Performance evaluation; 6) Magnet and SRF technology.
HTS in Europe

Towards HTS-based dipoles operating at $T > 1.9\,\text{K}$

Summary

- High-$J_e$ HTS conductors are setting the grounds for accelerator magnets in the 20 T range
- The ARIES R&D tapes with thinner substrate (50 $\mu$m stainless steel) from exhibit very reproducible performance
- In spite of the tape shape, we got $J_e \approx 1150\,\text{A/mm}^2$ @ 4.2 K, 19 T
- Fujikura new tape with EuBCO + BHO, with $J_e \approx 1300\,\text{A/mm}^2$ @ 4.2 K, 19 T, is a commercial product
- SuperOx implemented a new composition and its new tape reached $J_e \approx 2000\,\text{A/mm}^2$ @ 4.2 K, 19 T and 1000 A/mm² @ 20 K, 19 T
- In light of the present results, should we target also accelerator magnets operating at higher temperatures?

C. Senatore, FCC week

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Technology path towards future colliders

ECFA-EPS Joint session
Beam vacuum systems:
HTS coated conductors for FCC-hh beam screen impedance reduction

All experiments on samples, supported by theoretical modelling, indicate that the Coated Conductors solution attains FCC-hh performance goals (impedance reduction in high magnetic field) and accelerator compatibility (e-cloud, SR radiation tolerance...)

Ready to undertake scaling-up to real-scale proof-of-concept device
Energy Recovery Linacs

**ERL: technology for possible applications in HEP, low energy and industrial areas**

- Joint 802 MHz cavity development [LHeC+FCC]
- Very preliminary ideas on FCC-ee design with ERL technique: [extension to higher energy, less SR power, higher lumi > WW]  Llatas, Litvinenko, Roser FCC Brussels

**LHeC:** 1 TeV ep collider with $10^{34}$ luminosity: P/10! Dump at injection. Possible injector to FCC-ee in recirculating mode [O.Bruening]

**Existing test facilities**

**PERLE** BINP, CERN, Daresbury, Liverpool, Jlab, Orsay+. Could be 6 GeV injector to FCC-ee →

**ERLs** in: Berlin, BINP, Cornell, Daresbury, Darmstadt, Jlab, KEK, Mainz..

High current and $E \sim 1$GeV: low energy physics [$1000 \times L(ELI)$], lithography, photofission

From M.Klein.
## Technical Challenges in Energy-Frontier Colliders

<table>
<thead>
<tr>
<th>Major Challenges in Technology</th>
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<tbody>
<tr>
<td>...Find the people who want to do it</td>
</tr>
<tr>
<td>High-field SC magnet (SCM)</td>
</tr>
<tr>
<td>- Nb3Sn: Jc and Mechanical stress</td>
</tr>
<tr>
<td>Energy management</td>
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<td>High-Q SRF cavity at &lt; GHz, Nb Thin-film Coating</td>
</tr>
<tr>
<td>Synchrotron Radiation constraint</td>
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<td>Energy efficiency (RF efficiency)</td>
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<tr>
<td>High-precision Low-field magnet</td>
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<tr>
<td>Large-scale production of Acc. Structure</td>
</tr>
<tr>
<td>Two-beam acceleration in a prototype scale</td>
</tr>
<tr>
<td>Precise alignment and stabilization, timing</td>
</tr>
</tbody>
</table>

### FCC-NbTi
- **Ref.**: CDR (to be filled)
- **E (CM) [TeV]**: 100
- **Luminosity [1E34]**: < 30
- **AC-Power [MW]**: 580
- **Cost-estimate Value* [Billion]**: 24 or +17 (aft. ee) [BCHF]
- **B [T]**: ~ 6
- **E: [MV/m] (GHz)**: ~ 16

### FCC-hh
- **Ref.**: CDR
- **E (CM) [TeV]**: 100
- **Luminosity [1E34]**: < 30
- **AC-Power [MW]**: 580
- **Cost-estimate Value* [Billion]**: 24 or +17 (aft. ee) [BCHF]
- **B [T]**: ~ 6
- **E: [MV/m] (GHz)**: ~ 16

### SPPC
- **Ref.**: CDR (to be filled)
- **E (CM) [TeV]**: 75 – 120
- **Luminosity [1E34]**: TBD
- **AC-Power [MW]**: TBD
- **Cost-estimate Value* [Billion]**: TBD
- **B [T]**: 12 – 24
- **E: [MV/m] (GHz)**: TBD

### FCC-ee
- **Ref.**: CDR
- **E (CM) [TeV]**: 0.18 - 0.37
- **Luminosity [1E34]**: 460 – 31
- **AC-Power [MW]**: 260 – 350
- **Cost-estimate Value* [Billion]**: 10.5 +1.1 [BCHF]
- **B [T]**: 10 – 20 (0.4 - 0.8)
- **E: [MV/m] (GHz)**: TBD

### CEPC
- **Ref.**: CDR
- **E (CM) [TeV]**: 0.046 - 0.24 (0.37)
- **Luminosity [1E34]**: 32~ 5
- **AC-Power [MW]**: 150 – 270
- **Cost-estimate Value* [Billion]**: 5 [B$]
- **B [T]**: 20 – (40) (0.65)
- **E: [MV/m] (GHz)**: TBD

### ILC
- **Ref.**: TDR update
- **E (CM) [TeV]**: 0.25 (-1)
- **Luminosity [1E34]**: 1.35 (~ 4.9)
- **AC-Power [MW]**: 129 (~ 300)
- **Cost-estimate Value* [Billion]**: 4.8- 5.3 (for 0.25 TeV) [BILCU]
- **B [T]**: 31.5 – (45) (1.3)
- **E: [MV/m] (GHz)**: TBD

### CLIC
- **Ref.**: CDR
- **E (CM) [TeV]**: 0.38 (-3)
- **Luminosity [1E34]**: 1.5 (~ 6)
- **AC-Power [MW]**: 160 (~ 580)
- **Cost-estimate Value* [Billion]**: 5.9 (for 0.38 TeV) [BCHF]
- **B [T]**: 72 – 100 (12)
- **E: [MV/m] (GHz)**: TBD

*Cost estimates are commonly for "Value" (material) only.

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A. Yamamoto, 190513bb

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## Technical Challenges in Energy-Frontier Colliders

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<td>- High-field magnet</td>
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<td>- Energy management</td>
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<td><strong>Lepton Colliders:</strong></td>
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<tr>
<td>- SRF cavity: High-Q and -G (to prepare for upgrade)</td>
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<td>- NRF acc. Struct.: large scale, alignment, tolerance, timing</td>
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<td>- Energy management</td>
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### Hadron Colliders
- High-field magnet
- Energy management

### Lepton Colliders
- SRF cavity: High-Q and -G (to prepare for upgrade)
- NRF acc. Struct.: large scale, alignment, tolerance, timing
- Energy management

### Major Challenges in Technology

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</tr>
</thead>
<tbody>
<tr>
<td>~ 100</td>
<td></td>
<td>~ 30</td>
<td>980</td>
<td>24</td>
<td>+17 (aft. ee) [BCHF]</td>
<td>~ 6</td>
<td>~ 6</td>
<td>...Find the people who want to do it</td>
</tr>
</tbody>
</table>

- **High-field SC magnet (SCM)**
  - Nb3Sn: Jc and Mechanical stress
  - Energy management

- **High-field SCM**
  - IBS: Jcc and mech. stress
  - Energy management

- **High-Q SRF cavity at < GHz, Nb Thin-film Coating**
  - Synchrotron Radiation constraint
  - Energy efficiency (RF efficiency)

- **High-Q SRF cavity at < GHz, LG Nb-bulk/Thin-film**
  - Synchrotron Radiation constraint
  - High-precision Low-field magnet

- **High-G and high-Q SRF cavity at GHz, Nb-bulk**
  - Higher-G for future upgrade
  - Nano-beam stability, e+ source, beam dump

### Cost Estimates

Cost estimates are commonly for "Value" (material) only.
Advanced technologies

- Muon collider
- Plasma acceleration
Proton-driven Muon Collider Concept

Muon-based technology represents a unique opportunity for the future of high energy physics research: the multi-TeV energy domain exploration.

Short, intense proton bunches to produce hadronic showers

Muons are captured, bunched and then cooled

Pions decay into muons that can be captured

Acceleration to collision energy

Two schemes for $\mu$ production
- Proton (like in the figure)
- Positrons, still requiring consolidation

D. Schulte

C. Biscari – Ghent - 13 July 2019

Technology path towards future colliders

ECFA-EPS Joint session

---

**Muon Collider Parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Higgs</th>
<th>Multi-TeV</th>
<th>Accounts for Site Radiation Mitigation</th>
</tr>
</thead>
<tbody>
<tr>
<td>CoM Energy</td>
<td>TeV</td>
<td>0.126</td>
<td>1.5</td>
<td>3.0</td>
</tr>
<tr>
<td>Avg. Luminosity</td>
<td>$10^{34}$ cm$^{-2}$s$^{-1}$</td>
<td>0.008</td>
<td>1.25</td>
<td>4.4</td>
</tr>
<tr>
<td>Beam Energy Spread</td>
<td>%</td>
<td>0.004</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>Higgs Production/10$^7$sec</td>
<td></td>
<td>13,500</td>
<td>37,500</td>
<td>200,000</td>
</tr>
<tr>
<td>Circumference</td>
<td>km</td>
<td>0.3</td>
<td>2.5</td>
<td>4.5</td>
</tr>
<tr>
<td>No. of IPs</td>
<td></td>
<td>1</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Repetition Rate</td>
<td>Hz</td>
<td>15</td>
<td>15</td>
<td>12</td>
</tr>
<tr>
<td>$*$</td>
<td>cm</td>
<td>1.7</td>
<td>(0.5-2)</td>
<td>0.5 (0.3-3)</td>
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<tr>
<td>No. muons/bunch</td>
<td>$10^{12}$</td>
<td>4</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Norm. Trans. Emittance, $\mu_{\text{N}}$</td>
<td>mm-rad</td>
<td>0.2</td>
<td>0.025</td>
<td>0.025</td>
</tr>
<tr>
<td>Norm. Long. Emittance, $\mu_{\text{IN}}$</td>
<td>mm-rad</td>
<td>1.5</td>
<td>70</td>
<td>70</td>
</tr>
<tr>
<td>Bunch Length, $l$</td>
<td>cm</td>
<td>6.3</td>
<td>1</td>
<td>0.5</td>
</tr>
<tr>
<td>Proton Driver Power</td>
<td>MW</td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Wall Plug Power</td>
<td>MW</td>
<td>200</td>
<td>216</td>
<td>230</td>
</tr>
</tbody>
</table>
Answers to the Key Questions (D. Schulte)

• Can muon colliders at this moment be considered for the next project?
  • Enormous progress in the proton driven scheme and new ideas emerged on positron one
  • But at this moment not mature enough for a CDR, need a careful design study done with a coordinate international effort

• Is it worthwhile to do muon collider R&D?
  • Yes, it promises the potential to go to very high energy
  • It may be the best option for very high lepton collider energies, beyond 3 TeV
  • It has strong synergies with other projects, e.g. magnet and RF development
  • Has synergies with other physics experiments
  • Should not miss this opportunity?

• What needs to be done?
  • Muon production and cooling is key => A new test facility is required.
    • Seek/exploit synergy with physics exploitation of test facility (e.g. nuSTORM)
  • A conceptual design of the collider has to be made
  • Many components need R&D, e.g. fast ramping magnets, background in the detector
  • Site-dependent studies to understand if existing infrastructure can be used
    • limitations of existing tunnels, e.g. radiation issues
    • optimum use of existing accelerators, e.g. as proton source
  • R&D in a strongly coordinated global effort

From D. Schulte
Muon Colliders, Granada 2019
Proposed tentative timeline

- **Detector**
  - R&D detectors
  - Prototypes
  - MDI & detector simulations
  - Large Proto/Slice test

- **MACHINE**
  - Design
    - Baseline design
    - Design optimisation
    - Project preparation
    - Approve
  - Test Facility
    - Design
    - Construct
    - Exploit
  - Technologies
    - Design / models
    - Prototypes / t. f. comp.
    - Prototypes / pre-series

**Steps and Milestones**
- 2021: Design
- 2023: Design optimisation
- 2024: Project preparation
- 2025: Approve
- 2026: Construction
- 2028: Exploitation
- 2030: Technologies
- 2032: Prototype / pre-series

**Key Points**
- Ready to decide on test facility
- Cost scale known
- Ready to commit to collider
- Cost known
- Ready to construct

**Technical Limitations**
- Years?
Plasma acceleration based colliders

**Drive beams**
Lasers: ~40 J/pulse  
Electrons: 30 J/bunch  
Protons: SPS 19kJ/pulse, LHC 300kJ/bunch

**Witness beams**
Electrons: $10^{10}$ particles @ 1 TeV ~few kJ

Key achievements in last 15 years in plasma based acceleration using lasers, electron and proton drivers

- Focus is now **on high brightness beams, tunability, reproducibility, reliability, and high average power**

The road to colliders passes through **applications** that need compact accelerators (Early HEP applications, FELs, Thomson scattering sources, medical applications, injection into next generation storage rings ... )

Many key challenges remain as detailed in community developed, consensus based roadmaps (ALEGRO, AWAKE, Eupraxia, US roadmap,...)

Strategic investments are needed:

- **Personnel** – advanced accelerators attract large numbers of students and postdocs
- **Existing facilities** (with upgrades) and a few new ones (High average power, high repetition rate operation studies; fully dedicated to addressing the challenges towards a TDR for a plasma based collider)
- **High performance computing** methods and tools
Current initiatives of coordinated programs: EuPRAXIA, ALEGRO, AWAKE.

EuPRAXIA


The EuPRAXIA Strategy for Accelerator Innovation:
The accelerator and application demonstration facility EuPRAXIA is the required intermediate step between proof of principle and production facility.

PRESENT PLASMA E- ACCELERATION EXPERIMENTS

Demonstrating 100 GV/m routinely
Demonstrating many GeV electron beams
Demonstrating basic quality

EuPRAXIA INFRASTRUCTURE

Engineering a high quality, compact plasma accelerator 5 GeV electron beam for the 2020’s
Demonstrating user readiness
Pilot users from FEL, HEP, medicine, ...

PLASMA ACCELERATOR PRODUCTION FACILITIES

Plasma-based linear collider in 2040’s
Plasma-based FEL in 2030’s
Medical, industrial applications soon

ALEGRO

Advanced LinEar collider study GROup, ALEGRO: formed at initiative of the ICFA ANA panel in 2017.

Mission of the ALEGRO community:

- Foster and trigger Advanced Linear Collider related activities for applications of high-energy physics.
- Provide a framework to amplify international coordination, broaden the community, involving accelerator labs/institutes.
- Identify topics requiring intensive R&D and facilities.

Goal:

- Long-term design of a e+/e-/gamma collider with up to 30 TeV: the Advanced Linear International Collider (ALIC)

Construction of dedicated Advanced and Novel Accelerators (ANA) facilities are needed over the next 5 to 10 years in order to reliably deliver high-quality, multi-GeV electron beams from a small number of stages.
  - Today: Existing facilities explore different advanced and novel accelerator concepts and are proof-of-principle experiments.
ALEGRO delivered a document detailing the international roadmap and strategy of Advanced Novel Accelerators (ANAs).
## Status of Today and Goals for Collider Application

<table>
<thead>
<tr>
<th></th>
<th>Current</th>
<th>Goal</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Charge (nC)</strong></td>
<td>0.1</td>
<td>1</td>
</tr>
<tr>
<td><strong>Energy (GeV)</strong></td>
<td>9</td>
<td>10</td>
</tr>
<tr>
<td><strong>Energy spread (%)</strong></td>
<td>2</td>
<td>0.1</td>
</tr>
<tr>
<td><strong>Emittance (um)</strong></td>
<td>&gt;50-100 (PWFA), 0.1 (LFWA)</td>
<td>&lt;10^{-1}</td>
</tr>
<tr>
<td><strong>Staging</strong></td>
<td>single, two</td>
<td>multiple</td>
</tr>
<tr>
<td><strong>Efficiency (%)</strong></td>
<td>20</td>
<td>40</td>
</tr>
<tr>
<td><strong>Rep Rate (Hz)</strong></td>
<td>1-10</td>
<td>10^{3-4}</td>
</tr>
<tr>
<td><strong>Acc. Distance (m)/stage</strong></td>
<td>1</td>
<td>1-5</td>
</tr>
<tr>
<td><strong>Positron acceleration</strong></td>
<td>acceleration</td>
<td>emittance preservation</td>
</tr>
<tr>
<td><strong>Proton drivers</strong></td>
<td>SSM, acceleration</td>
<td>Emittance control</td>
</tr>
<tr>
<td><strong>Plasma cell (p-driver)</strong></td>
<td>10 m</td>
<td>100s m</td>
</tr>
<tr>
<td><strong>Simulations</strong></td>
<td>days</td>
<td>Improvements by 10^7</td>
</tr>
</tbody>
</table>

Table 1: Facilities for accelerator R&D in the multi-GeV range relevant for ALIC and with emphasis on specific challenges.

- **kBELLA**: Design study, LWFA, e-, 10 GeV, KHz rep rate
- **EnPRAIA**: Design study, LWFA or PWFA, e-, 5 GeV, reliability
- **AWAKE**: Operating, PWFA, e^-/p^+ collider
- **FACET II**: Start 2019, PWFA, e^-, 10 GeV boost, beam quality, e^+ acceleration
- **Flash FWD**: Operating, PWFA, e^-, 1.5 GeV, beam quality

Achieved Individually and NOT simultaneously
Energy Efficiency

• Energy efficiency is not an option, it is a must!
• **Energy efficiency and energy management** must be addressed.
• Investing in dedicated R&D to improve energy efficiency pays off in terms of **savings and societal return** through development of technologies which serve the society at large.
• District heating, energy storage, magnet design, RF power generation, cryogenics, SRF cavity technology, beam energy recovery are areas where energy efficiency can significantly be improved.
• Higher-temperature high-gradient Nb/Cu accelerating cavities and highly-efficient RF power sources developed in the frame of the FCC-ee R&D programme will find numerous other applications; could improve the sustainability and performance for accelerators of nearly all types and sizes around the world.
• The resource-saving strategy includes studies to avoid water cooling wherever possible and developing schemes to supply waste heat to nearby consumers. A pilot program at LHC is on-going.
• The detailed technical design of the FCChh will also investigate energy recovery opportunities within the accelerator infrastructure, for example, by working with industrial partners on either storing heat for later use or its conversion into mechanical or electrical energy.

*From ESPPu Open Symposium, Granada*

*E. Jensen: Energy Efficiency*
Example: He consumption @FCC-hh

- **Nelium** (Neon+ Helium) for cooling down to 40 + He for going to 1.9K
- The most power-hungry element @ FCC-hh is the cryogenic refrigeration system needed to cool the 16 T superconducting magnets down to 1.9 K.
- With respect to an LHC-class system, which would for an FCC-hh collider consume 290 MW of electrical power, the nelium technology and temperature choices lead to a reduction by 50 MW or 17% in the baseline configuration. **Slowly ramping up** the field of the magnets and with constant power substantially reduces the power demand, for all main dipoles from 270 MW for a constant-voltage ramp of 20 minutes to 100 MW for a constant-power ramp of 30 minutes.
- The external peak power demand during the ramp phase can be reduced further by **recovering the energy stored** in the superconducting magnets at the end of a cycle (50 MWh for the main dipoles), to buffer it locally, and **to reuse it** during the subsequent ramp-up. Losses in electricity transmission will be reduced by cooperating with industry to bring medium voltage DC distribution systems to market grade so that they can power the accelerator subsystems.
- R&D on **High efficiency klystrons** to go from 65% to 80% in power conversion efficiency (with LC communities)
- SC thin-film coating technology for operating high-gradient RF cavities at higher temperature, lowering the electricity need.
- Yearly energy consumption forecast of 4 TWh, compared to 1.4 TWh expected for the HL-LHC.
Figure of merit for proposed lepton colliders

Disclaimers:
1. This is not the only possible figure of merit
2. The presented numbers have different levels of confidence/optimism; they are still subject to optimisations

electricity cost ~200 euro per Higgs boson (F. Zimmerman)
### Proposed HEP Projects and Grid Power Consumption

<table>
<thead>
<tr>
<th>Project</th>
<th>ECM [TeV]</th>
<th>L / IP [10^{34}cm^2s^{-1}]</th>
<th>P_{Grid} [MW]</th>
<th>power driving effects</th>
</tr>
</thead>
<tbody>
<tr>
<td>FCC-ee (Z)</td>
<td>0.091</td>
<td>230</td>
<td>259</td>
<td>SR Power: 50MW/beam</td>
</tr>
<tr>
<td>FCC-ee (t)</td>
<td>0.365</td>
<td>1.5</td>
<td>359</td>
<td>SR power: 50MW/beam</td>
</tr>
<tr>
<td>FCC-hh</td>
<td>100</td>
<td>30</td>
<td>580</td>
<td>SR power: 2.4MW/beam @ 50K, cryogenics</td>
</tr>
<tr>
<td>ILC</td>
<td>1</td>
<td>4.9</td>
<td>300</td>
<td>beam power: 13.6 MW/beam, cryogenics</td>
</tr>
<tr>
<td>CLIC</td>
<td>3</td>
<td>5.9</td>
<td>582</td>
<td>beam power: 14 MW/beam</td>
</tr>
<tr>
<td>muon coll.</td>
<td>6</td>
<td>12</td>
<td>270</td>
<td>mu decay, 1.6MW/drive beam, cycling magnets, but scaling advantages, least developed</td>
</tr>
</tbody>
</table>

\[
P_{SR} \propto \left( \frac{E}{E_0} \right)^4 \frac{1}{R}
\]

\[
L_{\text{lin.col.}} \propto H_D \sqrt{\frac{\delta E}{\epsilon_{y,n}}} P_{\text{beam}}
\]

\[
L_{\text{mu.col.}} \propto B \frac{N_0}{\epsilon_n} \gamma P_{\text{beam}}
\]

→ need more R&D towards efficient concepts & technology, and energy management
## ‘Traditional-technologies’ colliders

<table>
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</thead>
<tbody>
<tr>
<td>ILC</td>
<td>ee</td>
<td>0.25</td>
<td>2</td>
<td>11</td>
<td>129 (upgr. 150-200)</td>
<td>4.8-5.3 GILCU + upgrade</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.5</td>
<td>4</td>
<td>10</td>
<td>163 (204)</td>
<td>7.98 GILCU</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.0</td>
<td></td>
<td></td>
<td>300</td>
<td>?</td>
</tr>
<tr>
<td>CLIC</td>
<td>ee</td>
<td>0.38</td>
<td>1</td>
<td>8</td>
<td>168</td>
<td>5.9 GCHF</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.5</td>
<td>2.5</td>
<td>7</td>
<td>(370)</td>
<td>+5.1 GCHF</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>5</td>
<td>8</td>
<td>(590)</td>
<td>+7.3 GCHF</td>
</tr>
<tr>
<td>CEPC</td>
<td>ee</td>
<td>0.091+0.16</td>
<td>16+2.6</td>
<td>149</td>
<td>5 G$</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.24</td>
<td>5.6</td>
<td>7</td>
<td>266</td>
<td></td>
</tr>
<tr>
<td>FCC-ee</td>
<td>ee</td>
<td>0.091+0.16</td>
<td>15+10</td>
<td>4+1</td>
<td>259</td>
<td>10.5 GCHF</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.24</td>
<td>5</td>
<td>3</td>
<td>282</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.365 (+0.35)</td>
<td>1.5 (+0.2)</td>
<td>4 (+1)</td>
<td>340</td>
<td>+1.1 GCHF</td>
</tr>
<tr>
<td>LHeC</td>
<td>ep</td>
<td>60 / 7000</td>
<td>1</td>
<td>12</td>
<td>(+100)</td>
<td>1.75 GCHF</td>
</tr>
<tr>
<td>FCC-hh</td>
<td>pp</td>
<td>100</td>
<td>30</td>
<td>25</td>
<td>580 (550)</td>
<td>17 GCHF (+7 GCHF)</td>
</tr>
<tr>
<td><strong>FCC-NbTi</strong></td>
<td>pp</td>
<td>37.5</td>
<td>10</td>
<td>20</td>
<td>240</td>
<td>14 GCHF (including tunnel)</td>
</tr>
<tr>
<td>HE-LHC</td>
<td>pp</td>
<td>27</td>
<td>20</td>
<td>20</td>
<td>240</td>
<td>7.2 GCHF</td>
</tr>
</tbody>
</table>
### Personal (A. Yamamoto) View on Relative Timelines

<table>
<thead>
<tr>
<th>Timeline</th>
<th>~ 5</th>
<th>~ 10</th>
<th>~ 15</th>
<th>~ 20</th>
<th>~ 25</th>
<th>~ 30</th>
<th>~ 35</th>
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</thead>
<tbody>
<tr>
<td><strong>Lepton Colliders</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SRF-LC/CC</td>
<td>Proto/pre-series</td>
<td>Construction</td>
<td>Operation</td>
<td>Upgrade</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NRF—LC</td>
<td>Proto/pre-series</td>
<td>Construction</td>
<td>Operation</td>
<td>Upgrade</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Hadron Collider (CC)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8~(11)T NbTi/(Nb3Sn)</td>
<td>Proto/pre-series</td>
<td>Construction</td>
<td>Operation</td>
<td>Upgrade</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12~14T Nb3Sn</td>
<td>Short-model R&amp;D</td>
<td>Proto/Pre-series</td>
<td>Construction</td>
<td>Operation</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>14~16T Nb3Sn</td>
<td>Short-model R&amp;D</td>
<td>Prototype/Pre-series</td>
<td>Construction</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Note: LHC experience: NbTi (10 T) R&D started in 1980’s --> (8.3 T) Production started in late 1990’s, in ~ 15 years*

A. Yamamoto

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C. Biscari – Ghent - 13 July 2019

Technology path towards future colliders

ECFA- EPS Joint session

45
Special thanks to

Akira Yamamoto, Frank Zimmerman, Philip Burrows, Vladimir Shiltsev, Mike Seidel, Erk Jensen, Lucio Rossi, Daniel Schulte, Wim Leemans, Edda Gschwendtner, Mike Lamont, Michael Benedikt, Steinar Stapnes, Ursula Bassler, Fredry Bordry, Max Klein, plus many others

and

Lenny Rivkin
Back up slides
Expect Shortage of Expert Accelerator Workforce

- "Oide Principle":
  1 Accelerator Expert can spend **intelligently** (only) \( \sim 1 \text{ M$ a year} \)

- + it takes significant time to get the team together (XFEL, ESS)

- Scale of the team: 10B$/10 years=1 B$/yr \rightarrow need 1000 experts \leftarrow world's total now \sim 4500

K. Oide (KEK)
Ours is a very dynamic field!
(Luminosity upgrades for ILC, CLIC)

Proposed dates from projects

Would expect that technically required time to start construction is \(O(5-10\) years\) for prototyping etc.

<table>
<thead>
<tr>
<th>Project</th>
<th>Start construction</th>
<th>Start Physics (Higgs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CEPC</td>
<td>2022</td>
<td>2030</td>
</tr>
<tr>
<td>ILC</td>
<td>2024</td>
<td>2033</td>
</tr>
<tr>
<td>CLIC</td>
<td>2026</td>
<td>2035</td>
</tr>
<tr>
<td>FCC-ee</td>
<td>2029</td>
<td>2039 (2044)</td>
</tr>
<tr>
<td>LHeC</td>
<td>2023</td>
<td>2031</td>
</tr>
</tbody>
</table>

D. Schulte
FCC integrated project is fully aligned with HL-LHC exploitation and provides for seamless continuation of HEP in Europe with highest performance EW factory followed by highest energy hadron collider.
ESG request for parameters of a lower-energy hadron collider

<table>
<thead>
<tr>
<th>parameter</th>
<th>FCC-hh</th>
<th>FCC-hh-6T</th>
<th>HE-LHC</th>
<th>HL-LHC</th>
<th>LHC</th>
</tr>
</thead>
<tbody>
<tr>
<td>collision energy cms [TeV]</td>
<td>100</td>
<td>37.5</td>
<td>27</td>
<td>14</td>
<td>14</td>
</tr>
<tr>
<td>dipole field [T]</td>
<td>16</td>
<td>6</td>
<td>16</td>
<td>8.33</td>
<td>8.33</td>
</tr>
<tr>
<td>beam current [A]</td>
<td>0.5</td>
<td>0.6</td>
<td>1.1</td>
<td>1.1</td>
<td>0.58</td>
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<tr>
<td>synchr. rad. power/ring [kW]</td>
<td>2400</td>
<td>57</td>
<td>101</td>
<td>7.3</td>
<td>3.6</td>
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<tr>
<td>peak luminosity [10^{34} cm^{-2}s^{-1}]</td>
<td>5</td>
<td>30</td>
<td>10 (lev.)</td>
<td>16</td>
<td>5 (lev.)</td>
</tr>
<tr>
<td>events/bunch crossing</td>
<td>170</td>
<td>1000</td>
<td>~300</td>
<td>460</td>
<td>132</td>
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<tr>
<td>stored energy/beam [GJ]</td>
<td>8.4</td>
<td>3.75</td>
<td>1.4</td>
<td>0.7</td>
<td>0.36</td>
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</tbody>
</table>

- **NbTi technology from LHC, magnet with single-layer coil providing 6 T at 1.9 K:**
  - Corresponding beam energy 18.75 TeV or 37.5 TeV c.m.
  - Significant reduction of synchrotron radiation wrt FCC-hh (factor 50) and corresponding cryogenic system requirements.

- **Luminosity goal 10 ab^{-1} over 20 years or 0.5 ab^{-1} annual luminosity:**
  - Beam current 0.6 A or 20% higher than for FCC-hh, 1.2E11 ppb (FCC-hh: 1.0 ppb).
  - Stored beam energy 3.75 GJ vs 8.4 GJ for FCC-hh.

- **Analysis of physics potential, technology requirements and cost ongoing.**
## Proposed Schedules and Evolution

<table>
<thead>
<tr>
<th></th>
<th>$T_0$</th>
<th>+5</th>
<th>+10</th>
<th>+15</th>
<th>+20</th>
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<th>+26</th>
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<tbody>
<tr>
<td><strong>ILC</strong></td>
<td>0.5/ab 250 GeV</td>
<td>1.5/ab 250 GeV</td>
<td>1.0/ab 500 GeV</td>
<td>0.2/ab 2$m_{top}$</td>
<td>3/ab 500 GeV</td>
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<tr>
<td><strong>CEPC</strong></td>
<td>5.6/ab 240 GeV</td>
<td>16/ab $M_Z$</td>
<td>2.6/ab 2$m_W$</td>
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<tr>
<td><strong>CLIC</strong></td>
<td>1.0/ab 380 GeV</td>
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<td></td>
<td>2.5/ab 1.5 TeV</td>
<td>5.0/ab =&gt; until +28 3.0 TeV</td>
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<tr>
<td><strong>FCC</strong></td>
<td>150/ab $ee, M_Z$</td>
<td>10/ab $ee, 2M_W$</td>
<td>5/ab $ee, 240$ GeV</td>
<td>1.7/ab $ee, 2m_{top}$</td>
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<td>hh,eh =&gt;</td>
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<tr>
<td><strong>LHeC</strong></td>
<td>0.06/ab</td>
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<td>0.2/ab</td>
<td>0.72/ab</td>
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<td><strong>HE-LHC</strong></td>
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<td>10/ab per experiment in 20y</td>
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<tr>
<td><strong>FCC eh/hh</strong></td>
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<td>20/ab per experiment in 25y</td>
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</table>

D. Schulte