Accelerators summary

Caterina Biscari and Lenny Rivkin, Phil Burrows, Frank Zimmermann

Open Symposium towards updating the European Strategy for Particle Physics
May 13-16, 2019, Granada, Spain
Accelerators related inputs

About 60 different inputs + national inputs which include accelerators
• e+e- colliders
• hh colliders
• ep colliders
• FCC
• Gamma factories
• Plasma acceleration
• Muon colliders
• Beyond colliders
• Technological developments

Input to speakers:
- Contributions of the community
- Coherent parameters (Integrated luminosity, duty cycle, readiness definition, ...)
- What about costs and time schedule?

Output from speakers
- comprehensive summary of 2-3 slides, including open questions, challenges, opportunities and objectives
In particular for the 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?
Q1: What is the best implementation for a Higgs factory? Choice and challenges for accelerator technology: linear vs. circular?
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<td>0.25</td>
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<td>11</td>
<td>129 (upgr. 150-200)</td>
<td>4.8-5.3 GILCU + upgrade</td>
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<td>0.38</td>
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<td>8</td>
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<td>5.9 GCHF</td>
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<td>1.5</td>
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<td>3</td>
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<td>8</td>
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<td>+7.3 GCHF</td>
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<td>ee</td>
<td>0.091+0.16</td>
<td>16+2.6</td>
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<td>0.24</td>
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<td>0.091+0.16</td>
<td>150+10</td>
<td>4+1</td>
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<td>0.365 (+0.35)</td>
<td>1.5 (+0.2)</td>
<td>4 (+1)</td>
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<td>LHeC</td>
<td>ep</td>
<td>60 / 7000</td>
<td>1</td>
<td>12</td>
<td>(+100)</td>
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<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>
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<td>HE-LHC</td>
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<td>27</td>
<td>20</td>
<td>20</td>
<td>7.2 GCHF</td>
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# Proposed Schedules and Evolution

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<th>$+20$</th>
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<td>1.5/ab 250 GeV</td>
<td>1.0/ab 500 GeV</td>
<td>0.2/ab $2m_{top}$</td>
<td>3/ab 500 GeV</td>
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<td>CEPC</td>
<td>5.6/ab 240 GeV</td>
<td>16/ab $M_Z$</td>
<td>2.6/ab $2M_W$</td>
<td>SppC =&gt;</td>
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<tr>
<td>CLIC</td>
<td>1.0/ab 380 GeV</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>FCC</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>
<td>hh, eh =&gt;</td>
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<tr>
<td>LHeC</td>
<td>0.06/ab</td>
<td>0.2/ab</td>
<td>0.72/ab</td>
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Proposed dates from projects

Would expect that technically required time to start construction is $O(5-10$ years) for prototyping etc.
Ours is a very dynamic field!
(Luminosity upgrades for ILC, CLIC)
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 simulations
- 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. stabilisation
- A part of the technologies are improved versions of those from other facilities
- Some had to be purpose-developed for linear colliders

All studies prioritised their work because of limited resources
- Depending on your preference you will see holes in any of them that you find are unacceptable
- Or you will be convinced that this very issue is a mere detail ...
Maturity

• 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 industrialisation
  — 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

• Guidance on project choice is necessary
  — Physics potential
  — Strategic considerations
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.
Q2: Path towards the highest energies: how to achieve the ultimate performance (including new acceleration techniques)?
## 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>
</table>
| ![CLIC Illustrations](image1.jpg) | **E**: 380, 1500, 3000 GeV (L: 11-50 km)  
Lum: 1.5-5.9 $10^{34}$ cm$^{-2}$ s$^{-1}$*  
Prep. phase 2020-2025  
Constr.+comm. 7y, ready before 2035  
Cost: CLIC-380: 5.9 BCHF,  
Upgrades: deltas of 5 and 7 BCHF  
Power: $\sim$ 170 MW – 580 MW** | **E**: 250, 500, 1000 GeV (L: 20-40 km)  
Lum: 1.35 (2.7) – 1.8(3.6) $10^{34}$ cm$^{-2}$ s$^{-1}$*  
Prep. phase 2020-2023(4)  
Constr.+comm. 9-10y, ready before 2035  
Cost: ILC-250: 4.9-5.3 BILCU,  
ILC-500: 8 BILCU (2012 $)  
Power: $\sim$ 130 – 300 MW | ![ILC Illustrations](image2.jpg) |
| ![CLIC Illustrations](image3.jpg) | **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)** |
| ![CLIC Illustrations](image4.jpg) | **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)** |

* Doubling by increasing frequency (to be) studied, ** Power at 1.5 and 3 TeV not updated from CDR 2012
FCC integrated project technical schedule

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.
Consideration on timeline:
LHC possible because SSC developed the superconductor…

Only 2 y to make a short magnet «near to final». Conductor available (SSC)

Decision for Nb-Ti

Industry contracts Nb-Ti

7 years from start R&D to 1st Industry proto

12 y from first working prototype to last magnet


9 T - 1 m single bore
10 T-1m Nb3Sn dipole
9 T-10 m long prototype
9 T-15 m final prototype
Last LHC dipole

L.Rossi - LHC future @ Open symposium EUSPP-Granada May 2019-SUMMARY
HE-LHC 27 TeV

- Needs some 1700 large magnets in Nb$_3$Sn (1200 dipole 15 m long) operating at 16 T. (same as FCC-hh)
- It needs a new generation of Nb$_3$Sn, beyond HiLumi (like FCC-hh): the 23 y timeline presented is realistic (21 for the magnets) but $t_0$ is probably 2025 or more because of SC development.
- The set up of a SC Open Lab for fostering development of superconductors (F. Bordry and L. Bottura proposal) is critical for HEP HC progress.
- A further upgrade to 42 TeV in HTS at 25 T possible to envisage for longer time. 24 T dipole is the long term goal also of the Chinese SppC. (Recently an HTS 32 T special solenoid and a commercial HTS 26 T NMR solenoid have been announced!)
High field magnet development

**Dipole Field for Hadron Collider**

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

- **Nb₃Sn**
  - 12 T Nb₃Sn dipoles
  - HiLumi technology in LHC: 21 TeV c.o.m.

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

**Timeline**

- **1975:** SPS & Main Ring (resistive)
- **1985:** Tevatron
- **1985:** HERA
- **1995:** RHIC
- **2005:** SSC
- **2015:** LHC
- **2025:** HL-LHC
- **2035:** FCC
- **2040:** HTS

**Energy tripler 100km**
s.c. magnet technology

• Nb$_3$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):
  • Nb$_3$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,
  • Nb$_3$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).
  • NbTi, 8~9 T: proven by LHC and Nb$_3$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.

A. Yamamoto, 190512b

Intensify HTS accelerator magnet development
## Personal (A. Yamamoto) View on Relative Timelines

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<tr>
<th>Timeline</th>
<th>~ 5</th>
<th>~ 10</th>
<th>~ 15</th>
<th>~ 20</th>
<th>~ 25</th>
<th>~ 30</th>
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<td>SRF-LC/CC</td>
<td>Proto/pre-series</td>
<td>Construction</td>
<td>Operation</td>
<td>Upgrade</td>
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<td>NRF—LC</td>
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<td><strong>Hadron Collider (CC)</strong></td>
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<tr>
<td>8~(11)T NbTi /(Nb3Sn)</td>
<td>Proto/pre-series</td>
<td>Construction</td>
<td>Operation</td>
<td>Upgrade</td>
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<tr>
<td>12~14T Nb3Sn</td>
<td>Short-model R&amp;D</td>
<td>Proto/Pre-series</td>
<td>Construction</td>
<td>Operation</td>
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<tr>
<td>14~16T Nb3Sn</td>
<td>Short-model R&amp;D</td>
<td>Prototype/Pre-series</td>
<td>Construction</td>
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**Note:** LHC experience: **NbTi (10 T)** R&D started in 1980’s --> (8.3 T) Production started in late 1990’s, in ~ 15 years
## Technical Challenges in Energy-Frontier Colliders proposed

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<td>&lt; 30</td>
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<td>20 – (40)</td>
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<td>0.38 (- 3)</td>
<td>1.5 (- 6)</td>
<td>160 (- 580)</td>
<td>5.9 (for 0.38 TeV) [BCHF]</td>
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<td>Two-beam acceleration in a prototype scale</td>
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<td>Precise alignment and stabilization. timing</td>
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*Cost estimates are commonly for “Value” (material) only.
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

Muon are captured, bunched and then cooled

Pions decay into muons that can be captured

Acceleration to collision energy

Collision
Answers to the Key Questions

• **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**
Proposed tentative timeline

**Machine**
- Baseline design
- Design optimisation
- Project preparation
- Approve

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

**Technologies**
- Design / models
- Prototypes / t. f. comp.
- Prototypes / pre-series

**Yearly Milestones**
1. Ready to decide on test facility
2. Cost scale known
3. Ready to commit to collider
4. Cost known
5. Ready to construct

**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: 1010 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.
Status of Today and Goals for Collider Application

<table>
<thead>
<tr>
<th></th>
<th>Current</th>
<th>Goal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charge (nC)</td>
<td>0.1</td>
<td>1</td>
</tr>
<tr>
<td>Energy (GeV)</td>
<td>9</td>
<td>10</td>
</tr>
<tr>
<td>Energy spread (%)</td>
<td>2</td>
<td>0.1</td>
</tr>
<tr>
<td>Emittance (um)</td>
<td>&gt;50-100 (PWFA), 0.1 (LFWA)</td>
<td>&lt;10^{-1}</td>
</tr>
<tr>
<td>Staging</td>
<td>single, two</td>
<td>multiple</td>
</tr>
<tr>
<td>Efficiency (%)</td>
<td>20</td>
<td>40</td>
</tr>
<tr>
<td>Rep Rate (Hz)</td>
<td>1-10</td>
<td>10^{3-4}</td>
</tr>
<tr>
<td>Acc. Distance (m)/stage</td>
<td>1</td>
<td>1-5</td>
</tr>
<tr>
<td>Positron acceleration</td>
<td>acceleration</td>
<td>emittance preservation</td>
</tr>
<tr>
<td>Proton drivers</td>
<td>SSM, acceleration</td>
<td>Emittance control</td>
</tr>
<tr>
<td>Plasma cell (p-driver)</td>
<td>10 m</td>
<td>100s m</td>
</tr>
<tr>
<td>Simulations</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: LWFA, e-, 10 GeV, KHz rep rate
- EuPRAXIA: LWFA or PWFA, e-, 5 GeV, reliability
- AWAKE: 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
The future is in accelerating muons in plasma!

Vladimir Shiltsev
Q3: How to achieve proper complementarity for the high intensity frontier vs. the high-energy frontier?
Intensity frontier vs. Energy Frontier

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>SPS*</td>
<td>450</td>
<td></td>
<td>Synchrotron</td>
<td></td>
</tr>
<tr>
<td>Fnal M. Injector</td>
<td>120</td>
<td>0.7</td>
<td>Synchrotron</td>
<td></td>
</tr>
<tr>
<td>J-PARC*</td>
<td>3</td>
<td>1</td>
<td>Linac/Synchrotron</td>
<td>SCM</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>0.49 ~ 1.3</td>
<td>Synchrotron</td>
<td></td>
</tr>
<tr>
<td>PIP-II</td>
<td>60 -120</td>
<td>.2</td>
<td>Linac (SRF) Synchrotron</td>
<td>SRF</td>
</tr>
<tr>
<td>PSI-HIPA*</td>
<td>0.59</td>
<td>1.4</td>
<td>Cycrotron</td>
<td></td>
</tr>
<tr>
<td>FAIR (SIS100)</td>
<td>29</td>
<td>0.2</td>
<td>Synchrotron</td>
<td>SCM</td>
</tr>
<tr>
<td>(ESS) ESSnuSB *</td>
<td>2</td>
<td>2</td>
<td>Linac</td>
<td>SRF</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>2 ~ 5 (+5)</td>
<td>Synchrotron</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2 x 5</td>
<td></td>
<td>Linac</td>
<td></td>
</tr>
<tr>
<td>CEBAF</td>
<td>12</td>
<td>1</td>
<td>LINAC+Ring</td>
<td>SRF</td>
</tr>
<tr>
<td>Super-KEKB</td>
<td>---</td>
<td>---</td>
<td>Collider</td>
<td></td>
</tr>
<tr>
<td>HL-LHC</td>
<td>2 x 7,000</td>
<td>---</td>
<td>Collider</td>
<td>SCM, SRF</td>
</tr>
<tr>
<td>EIC*</td>
<td>---</td>
<td>---</td>
<td>Collider</td>
<td>SCM, SRF</td>
</tr>
</tbody>
</table>

Common Issues:
- SC Mag. & SRF technology
- Target, Collimator, Beam Dump
- Radiation
- Energy Management

Science is complementary, and
Technology is based on common technology,
Let us work together and maximize synergy!!
Fermilab and J-PARC: Proton Beam Power on $\nu$ Target

- PIP-II 800 MeV Linac
- PIP-III 8 GeV Linac or RCS
- RF Upgrades incl. 2$^{nd}$ harm. RF
- Magnet PS Upgrade 2.48 s $\rightarrow$ 1.32 s
- RF Upgrades
The **BSM PBC projects** offer significant discovery potential over a wide range of masses and couplings.

- Very sensitive low energy experiments target the sub-eV mass area.
- SPS Fixed Target beam-dump-like experiments and long lived particle searches at LHC have unique capabilities to target the MeV-GeV domain.
- The precision tests of flavor violation (lepton and quark), as well as of CP violation, probe new particles in a mass range exceeding LHC direct searches.

**in addition: QCD and others facilities**

---

**Rare decays and precise measurements**
- KLEVER ($K^0 \rightarrow \pi^0 \nu \bar{\nu}$)
- TauFV@BDF: $\tau \rightarrow 3\mu$
- REDTOP ($\eta$ decays)
- MUonE (hadronic vacuum polarization for $(g-2)_\mu$)
- EDM proton storage ring

**Hidden sector with “beam dumps”**
- NA64++ ($\gamma$, $\mu$)
- NA62++
- Beam Dump Facility at North Area (SHiP)
- LDMX@eSPS
- AWAKE++

**QCD measurements**
- COMPASS++, DIRAC++
- NA61++, NA60++
- Fixed target (gas, crystals) in ALICE & LHCb

**Long-lived particles from LHC collisions**
- FASER, MATHUSLA, CODEX-b, milliQAN

**Non-accelerator projects**
- Exploit CERN’s technology (RF, vacuum, magnets, optics, cryogenics) for experiments possibly located in other labs.
- E.g. axion searches: IAXO (helioscope), JURA (Light Shining through Wall)

**Other facilities:**
- $\gamma$-factory from Partially Stripped Ions; nuSTORM

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courtesy FG
Q4: Energy management in the age of high-power accelerators?
Energy Efficiency

• Energy efficiency is not an option, it is a must!
• Proposed HEP projects are using $\mathcal{O}(\text{TWh}/y)$, where energy efficiency and energy management must be addressed.
• Investing in dedicated R&D to improve energy efficiency pays off since savings can be significant.
• This R&D leads to 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 be significantly be improved.
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
Expect Shortage of Expert Accelerator Workforce

• “Oide Principle”: 1 Accelerator Expert can spend **intelligently** (only) $\sim 1$ 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)
# Proposed Schedules and Evolution

<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>
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Proposed dates from projects

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

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Proposed dates from projects

Would expect that technically required time to start construction is $O(5-10$ years) for prototyping etc.
## A linear collider as part of an overall strategy?

<table>
<thead>
<tr>
<th>2020 to ~2045</th>
<th>Goal</th>
<th>Status ~2035-45</th>
<th>Options open ~2040-50</th>
</tr>
</thead>
<tbody>
<tr>
<td>2020 - 2038 LHC/HL-LHC</td>
<td>- on-going -</td>
<td>Programme completed</td>
<td>Could be extended</td>
</tr>
<tr>
<td>2020 - ~2035 construction 2035-2045 operation  • CLIC or ILC</td>
<td>Fast access to a high quality e+e- data, at the lowest possible cost (at ~LHC scale). The scientific case is well established. Build in capabilities for higher energies and new technologies.</td>
<td>Physics guidance from HL, LC stage 1 and PBC (and others) Technical experience for LC stage 1</td>
<td>Possibilities: continue running at same or increased energy, use same/improved technology or introduce NAT</td>
</tr>
<tr>
<td>Develop hadron and muon machines towards construction readiness in 2030-2040 range</td>
<td>R&amp;D for future machine with a timeline 10-20 years (mainly HF magnets and pp designs, and muon machine studies and designs)</td>
<td>Physics guidance from HL, LC stage 1 and PBC (and others) HF magnet R&amp;D progress, hadron machine design options, muon TDR</td>
<td>Aim to put proton (FCC type or more modest) and/or muon machines into operation</td>
</tr>
<tr>
<td>Develop NAT technologies for LC colliders</td>
<td>R&amp;D for much higher energy LCs (and linear accelerators in general), similar timeline</td>
<td>Possibly TDR for use in a LC facility</td>
<td>Around 2040-50: Introduce these technologies – if available – in LC facility (line above)</td>
</tr>
<tr>
<td>&quot;Physics Beyond Collider&quot; (PBC) projects</td>
<td>Cover (among others) light dark matter searches</td>
<td>Progress</td>
<td>Continue ?</td>
</tr>
<tr>
<td>Other projects – CEPC among them</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
</tbody>
</table>

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**Operational physics facilities**

**Blue: Ring based facility**, **Red: Linear facility**

---

Steinar Stapnes
Many thanks for the contributions from:

Akira Yamamoto
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