Snowmass’21
Accelerator Frontier:
Summary of Discussions on Future HEP Facilities in the US

ICHEP’2022 – Bologna, Italy, July 8, 2022

Vladimir Shiltsev,
Stephen Gourlay, Tor Raubenheimer
(Snowmass’21 AF Conveners)
What is Snowmass:

“Snowmass is a particle physics community study”

Snowmass provides input to P5 (Particle Physics Project Prioritization Panel) which develops a 10-20 yrs strategy for the US HEP program.

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Particle Physics is global

Particle Physics is not isolated

https://www.snowmass21.org/
Previous Snowmass/P5 (2013/14)

• Major accelerator-related recommendations:
  – Contribute to LHC and HL-LHC
  – Engage in the ILC in Japan, contribute if it goes
  – Build >1 MW proton source PIP-II forν LBNF/DUNE
  – Provide beams for g-2 and mu2e experiments
  – Reassess Muon Accelerator Program and MICE

• A follow-up 2015 Accelerator R&D subpanel recommended several thrusts:
  – Beam Physics (incl. IOTA and PIP-III)
  – Sources and Targets (incl. multi-MW)
  – RF (high-Q, high-G, low cost)
  – Magnets and materials (16 T, low cost)
  – Advanced acceleration (towards wakefield colliders)
Few Examples – Facilities/Programs

(under construction) AUP LHC
Nb$_3$Sn IR quads for HI-LHC
CD-3 project
be ready LS3
FNAL
BNL
LBNL

(Fully assembled magnet)

(construction started) PIP-II
800 MeV proton SRF linac
@FNAL
Goal: 1.2MW for LBNF/DUNE
Beam to Booster in 2029
30% Int’l contrib.

(ongoing) muon beams for g-2 and mu2e experiments

(FNAL)
8 GeV $p$’s $\to$ target $\to$ $\mu$’s
Run-I (2021) major muon g-2 discovery

(completed) ILC@Fermilab
1st 1.3GHz full CM with beam
FAST facility
ILC type beam
31.5 MeV/m
255 MeV/CM
$G, Q_0$ specs
07/08/2022
Few Examples – Accelerator R&D

**Record 14.5T Dipole (at FNAL, part of the US MDP)**

- Nb3Sn conductor
- Stress control

**FACET-II User facility (SLAC)**

- BELLA: PWFA records (LBNL)
  - Unique beam
  - 10 GeV
  - 1 nC
  - 1x1x1 μm
  - 8 GeV/0.2m staging p.o.p
  - 5+0.1 GeV

**MAP/MICE: Ionization cooling of muons (140 MeV/c, RAL, UK)**

- MICE
  - ~10% in one pass

**IOTA Ring/Optical Stochastic cooling e- (100 MeV, FNAL)**

- soon – experiments with p’s
  - THz bandwidth

07/08/2022
(back to current) Snowmass’2021

- Started in 2020 → ~1 yr COVID delay → finish 2022:
  - Community of ~3000 people, incl. international
  - Snowmass **CSS Workshop** in Seattle next week (please, join!) >600 people
  - Final report to P5, that starts in September’22 (for ~ a year)

- **10 “Frontiers”: Energy, Theory, Cosmic, … Accelerator**

**Accelerator Frontier – Key Questions:**

1. What is needed to advance the physics?
2. What is currently available (state of the art) around the world?
3. What new accelerator facilities could be available on the next decade (or next next decade)?
4. What R&D would enable these future opportunities?
5. What are the time and cost scales of the R&D and associated test facilities as well as the time and cost scale of the facilities?
# Accelerator Frontier Conveners

**Topical Group** | **Topical Group co-Conveners**
--- | ---
**AF01** Beam Phys & Accel. Education | Z. Huang (Stanford) | M. Bai (SLAC) | S. Lund (MSU)
**AF02** Accelerators for Neutrinos | J. Galambos (ORNL) | B. Zwaska (FNAL) | G. Arduini (CERN)
**AF03** Accelerators for EW/Higgs | F. Zimmermann (CERN) | Q. Qin (ESRF) | G. Hoffstaetter (Cornell) A. Faus-Golfe (IN2P3)
**AF04** Multi-TeV Colliders | M. Palmer (BNL) | A. Valishev (FNAL) | N. Pastrone (INFN) J. Tang (IHEP)
**AF05** Accelerators for PBC and Rare Processes | E. Prebys (UC Davis) | M. Lamont (CERN) | Richard Milner (MIT)
**AF06** Advanced Accelerator Concepts | C. Geddes (LBNL) | M. Hogan (SLAC) | P. Musumeci (UCLA) R. Assmann (DESY)
**AF07** Accelerator Technology R&D | | | | 
**Sub-Group RF** | E. Nanni (LBNL) | H. Weise (DESY) | S. Belomestnykh (FNAL)
**Sub-Group Magnets** | G. Sabbi (LBNL) | S. Zlobin (FNAL) | S. Izquierdo Bermudez (CERN)
**Sub-Group Targets/Sources** | C. Barbier (ORNL) | Y. Sun (ANL) | Frederique Pellemeine (FNAL)
## Snowmass Activities: pre-Seattle

### Proponents’ Inputs

<table>
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| AF4: Multi-TeV Colliders | 56 | 10 |
| AF5: Accelerators for PBC and Rare Proc. | 37 | 7 |
| AF6: Advanced Accelerator Concepts | 71 | 10 |
| AF7: Accelerator Technology R&D | 137 | 43 |

- > 30 Topical Workshops
- 8 Cross-Frontier **Agoras**
  - All types of colliders: ee, linear/circular, mumu, pp, advanced
  - Experiments and accelerators for rare processes physics
- Special cross-Frontier Groups (e.g., AF-EF-TF)
  - eeCollider Forum, Muon Collider Forum, Implementation Task Force
Now – Draft Report Only, will be finalized in Seattle

AF Topical Group, ITF and Fora Summaries – mostly available

Below, only few topics will be briefly covered:
- Accelerators for Neutrinos
- Accelerators for Rare Processes/DM Searches
- Future Colliders
- Key Accelerator R&D

For each - key “messages” (vision):
- Proposed directions (“what”)
- Timeline (“when”) – e.g., by 2030, after 2030
- Challenges (“what’s needed”)
1. Multi-MW $\nu$ Beams for DUNE

**LBNF/DUNE Project – Phase I:**
- By 2032: **1.2 MW** proton beam (120 GeV) on target + near $\nu$-detector + 20 kton LAr $\nu$-detector in Lead, SD
- Expected rate of “physics” outcome – up to $\sim 3\sigma$ in $\delta_{CP}$, in the first 6 years (also $\Delta m^2_{32}$, $\sin^2\theta_{23}$, $\sin^22\theta_{13}$)
- To get to $\sim 5\sigma$ will get too long, plus – competitor experiment Hyper-K in Japan

**Proposed Plan - LBNF/DUNE Phase II:**
- By 2038: **2.4 MW** proton beam (120 GeV) on target + new near $\nu$-detector + extra 20 kton LAr $\nu$-detector
- Expected to get to $\sim 5\sigma$ in $\delta_{CP}$ in the following 6 years
- Accelerator options proposed/under active study now:
  - (understand max performance and limits with PIP-II linac)
  - New 8 GeV RCS [two options] with/w.o. new 1-3 GeV linac upgrade
  - New 8 GeV linac with or without new 8 GeV accumulator ring
  - In any case – need upgrade of MI RF power and new m-MW targets
  - See S.Nagaitsev talk earlier today
  - Fermilab has formed a special design group
2. >20 Proposed Experiments For Rare Processes

(most via Snowmass Whitepapers)

DM searches, Axion searches, CLFV experiments, muons, light mesons, beam dump experiments… calls for corresponding beam facilities @ FNAL, SLAC, Jlab

**Electron beams:**

~ GeV to multi-GeV

**Proton beams:**

~2 GeV CW-capable beam

~2 GeV pulsed beam from storage ring ~1MW

~8 GeV pulsed beam ~1MW

120 GeV Slow extraction or LBNF beam
Features:
- SLAC electron SRF linac $E=4$-8 GeV
- Low intensity, almost CW beamline, 1-500 $e^-/us$
- Beam dump and LDMX experiment
- CD-process started
Proposed PIP-II Accumulator Ring (PAR)

Features:
- Fixed $E=0.8$-1.0 GeV proton storage ring
- $C=480$ m in the form of a folded figure 8
- Power 100 kW for Dark Sector program, 100Hz
- There is also compact version $C=120$ m
Future Collider Proposals: 8 Higgs/EW factories

<table>
<thead>
<tr>
<th>Name</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>CepC</td>
<td>$e^+e^-, \sqrt{s} = 0.24 \text{ TeV, } L = 3.0 \times 10^{34}$</td>
</tr>
<tr>
<td>CLIC (Higgs factory)</td>
<td>$e^+e^-, \sqrt{s} = 0.38 \text{ TeV, } L = 1.5 \times 10^{34}$</td>
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<tr>
<td>ERL ee collider</td>
<td>$e^+e^-, \sqrt{s} = 0.24 \text{ TeV, } L = 73 \times 10^{34}$</td>
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<tr>
<td>FCC-ee</td>
<td>$e^+e^-, \sqrt{s} = 0.24 \text{ TeV, } L = 17 \times 10^{34}$</td>
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<tr>
<td>gamma gamma</td>
<td>X-ray FEL-based $\gamma\gamma$ collider</td>
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<td>ILC (Higgs factory)</td>
<td>$e^+e^-, \sqrt{s} = 0.25 \text{ TeV, } L = 1.4 \times 10^{34}$</td>
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<tr>
<td>LHeC</td>
<td>$ep, \sqrt{s} = 1.3 \text{ TeV, } L = 0.1 \times 10^{34}$</td>
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<tr>
<td>MC (Higgs factory)</td>
<td>$\mu\mu, \sqrt{s} = 0.13 \text{ TeV, } L = 0.01 \times 10^{34}$</td>
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<tr>
<td>Name</td>
<td>Details</td>
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<tr>
<td>---------------------------</td>
<td>-------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Cryo-Cooled Copper linac</td>
<td>$e^+e^-, \sqrt{s} = 2 \text{ TeV}, L = 4.6 \times 10^{34}$</td>
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<td>High Energy CLIC</td>
<td>$e^+e^-, \sqrt{s} = 1.5 - 3 \text{ TeV}, L = 5.9 \times 10^{34}$</td>
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<tr>
<td>High Energy ILC</td>
<td>$e^+e^-, \sqrt{s} = 1 - 3 \text{ TeV}$</td>
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<tr>
<td>FCC-hh</td>
<td>pp, $\sqrt{s} = 100 \text{ TeV}, L = 30 \times 10^{34}$</td>
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<tr>
<td>SPPC</td>
<td>pp, $\sqrt{s} = 75/150 \text{ TeV}, L = 10 \times 10^{34}$</td>
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<td>Collider-in-Sea</td>
<td>pp, $\sqrt{s} = 500 \text{ TeV}, L = 50 \times 10^{34}$</td>
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<tr>
<td>LHeC</td>
<td>$e\nu$, $\sqrt{s} = 1.3 \text{ TeV}, L = 1 \times 10^{34}$</td>
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<td>FCC-eh</td>
<td>$e\nu$, $\sqrt{s} = 3.5 \text{ TeV}, L = 1 \times 10^{34}$</td>
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<td>CEPC-SPPpC-eh</td>
<td>$e\nu$, $\sqrt{s} = 6 \text{ TeV}, L = 4.5 \times 10^{33}$</td>
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<td>VHE-ep</td>
<td>$e\nu$, $\sqrt{s} = 9 \text{ TeV}$</td>
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<td>MC – Proton Driver 1</td>
<td>$\mu\mu$, $\sqrt{s} = 1.5 \text{ TeV}, L = 1 \times 10^{34}$</td>
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<tr>
<td>MC – Proton Driver 2</td>
<td>$\mu\mu$, $\sqrt{s} = 3 \text{ TeV}, L = 2 \times 10^{34}$</td>
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<td>MC – Proton Driver 3</td>
<td>$\mu\mu$, $\sqrt{s} = 10 - 14 \text{ TeV}, L = 20 \times 10^{34}$</td>
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<tr>
<td>MC – Positron Driver</td>
<td>$\mu\mu$, $\sqrt{s} = 10 - 14 \text{ TeV}, L = 20 \times 10^{34}$</td>
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<td>LWFA-LC (e+e- and $\gamma\gamma$)</td>
<td>Laser driven; $e^+e^-, \sqrt{s} = 1 - 30 \text{ TeV}$</td>
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<tr>
<td>PWFA-LC (e+e- and $\gamma\gamma$)</td>
<td>Beam driven; $e^+e^-, \sqrt{s} = 1 - 30 \text{ TeV}$</td>
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<tr>
<td>SWFA-LC</td>
<td>Structure wakefields; $e^+e^-, \sqrt{s} = 1 - 30 \text{ TeV}$</td>
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- **CLIC** $e^+e^-$ 3 TeV, 100 MV/m 50 km
- **SPPC** pp 100 km: SPPC 75 TeV, 12 T magnets, FCChh 100/16 T
- **μ+μ-** 10-14 TeV cme 10-14 km, 16 T magnets
**(New!) LC-Higgs Factories on FNAL Site**

Must fit ~7 km incl BDS

Requires gradients of at least 72MV/m

Compact → lower cost (wrt ILC/CLIC)

**Option 1:** Cool Copper Collider ($C^3$)

- 5.7GHz
- 77K

**Option 1:** HELEN (Travelling Wave ILC)

- 1.3GHz
- 2K
FNAL Citing – $O(10 \text{ TeV})$ Muon Collider

- First design concept of up to 10 TeV collider developed
- Operation at 125 GeV, 1 and 3 TeV can be envisioned as intermediate stages
- Capitalize on existing facilities and expertise:
  - PIP-II and upgrades,

**Muon Colliders Forum:**

a) aim for 10 TeV cme
b) DOE support+join IMCC (CERN-led Int’l Muon Collider Collaboration)
c) Carry out R&D and deliver pre-CDR ca 2030
The Accelerator Implementation Task Force (ITF) is charged with developing metrics and processes to facilitate a comparison between collider projects.

- 10 int’l experts, 2 Snowmass Young’s, 3 liaisons to Energy & Theory Frontiers

ITF addressed (four subgroups):

- Physics reach (impact), beam parameters
- Size, complexity, power, environment
- Technical risk, technical readiness, validation and R&D required
- Cost and schedule
From the ITF Report Draft: Tables 1-3, 5

<table>
<thead>
<tr>
<th>Project</th>
<th>CME (TeV)</th>
<th>Lumi per IP (10^34)</th>
<th>Years, pre-project R&amp;D</th>
<th>Years to 1st physics</th>
<th>Cost range (2021 B$)</th>
<th>Electric Power (MW)</th>
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<tbody>
<tr>
<td>FCCee-0.24</td>
<td>0.24</td>
<td>8.5</td>
<td>0-2</td>
<td>13-18</td>
<td>12-18</td>
<td>280</td>
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<tr>
<td>ILC-0.25</td>
<td>0.25</td>
<td>2.7</td>
<td>0-2</td>
<td>&lt;12</td>
<td>7-12</td>
<td>140</td>
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<tr>
<td>CLIC-0.38</td>
<td>0.38</td>
<td>2.3</td>
<td>0-2</td>
<td>13-18</td>
<td>7-12</td>
<td>110</td>
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<tr>
<td>HELEN-0.25</td>
<td>0.25</td>
<td>1.4</td>
<td>5-10</td>
<td>13-18</td>
<td>7-12</td>
<td>110</td>
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<tr>
<td>CCC-0.25</td>
<td>0.25</td>
<td>1.3</td>
<td>3-5</td>
<td>13-18</td>
<td>7-12</td>
<td>150</td>
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<tr>
<td>MC-Higgs</td>
<td>0.13</td>
<td>0.01</td>
<td>&gt;10</td>
<td>19-24</td>
<td>4-7</td>
<td>~200</td>
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<tr>
<td>CLIC-3</td>
<td>3</td>
<td>5.9</td>
<td>3-5</td>
<td>19-24</td>
<td>18-30</td>
<td>~550</td>
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<tr>
<td>ILC-3</td>
<td>3</td>
<td>6.1</td>
<td>5-10</td>
<td>19-24</td>
<td>18-30</td>
<td>~400</td>
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<tr>
<td>MC-3</td>
<td>3</td>
<td>2.3</td>
<td>&gt;10</td>
<td>19-24</td>
<td>7-12</td>
<td>~230</td>
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<tr>
<td>MC-FNAL</td>
<td>6-10</td>
<td>20</td>
<td>&gt;10</td>
<td>19-24</td>
<td>12-18</td>
<td>O(300)</td>
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<tr>
<td>MC-10</td>
<td>10-14</td>
<td>20</td>
<td>&gt;10</td>
<td>&gt;25</td>
<td>12-18</td>
<td>O(300)</td>
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<td>FCChh-100</td>
<td>100</td>
<td>30</td>
<td>&gt;10</td>
<td>&gt;25</td>
<td>30-50</td>
<td>~560</td>
</tr>
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Future Colliders R&D Program - Initiative

Submitted to the Proceedings of the US Community Study on the Future of Particle Physics (Snowmass 2021)

June 30, 2022

U.S. National Accelerator R&D Program on Future Colliders

P.C. Bhat\textsuperscript{1,\dagger}, S. Belomestnykh\textsuperscript{1,\dagger}, D. Denisov\textsuperscript{3}, S. Gourlay\textsuperscript{6}, S. Jindariani\textsuperscript{1}, A.J. Lankford\textsuperscript{8,\dagger}, S. Nagaitsev\textsuperscript{1,2,\dagger}, E.A. Nanni\textsuperscript{4}, M.A. Palmer\textsuperscript{3}, T. Raubenheimer\textsuperscript{4}, V. Shiltsev\textsuperscript{1}, A. Valishev\textsuperscript{1}, F. Zimmermann\textsuperscript{7}

We propose that the U.S. establish a national integrated R&D program on future colliders in the DOE Office of High Energy Physics (OHEP) and charge the program:

- to carry-out technology R&D and accelerator design for future collider concepts,
- to enable synergistic engagement in projects proposed abroad (e.g. FCC, ILC, CLIC, IMCC),
- to develop design reports on collider options, by the time of the next Snowmass and P5 (2029–2030), particularly for options that are feasible to be hosted in the U.S.,
- to develop R&D plans for the decade beyond 2030.
Multi-MW targets:
- 2.4MW PIP-III
- 4-8 MW for muon collider

Magnets for colliders and RCSs:
- 16T dipoles
- 30T solenoids
- 1000 T/s fast cycling ones coordinate with US MDP

Advanced:
- collider quality beams
- efficient drivers
- close coordination with Int’l (Euro Roadmap, EUPRAXIA,..)

SC/NC RF:
- 72-120 MV/m C³
- 72 MV/m TW SRF
- new materials, high $Q_0$
- efficient power sources
ICHEP’22 presentations on AF/related topics Thursday, July 7:

- A. Faus-Golfe (AF3) on CLIC and ILC
- N. Pastrone (AF4) on energy frontier colliders
- S. Nagaitsev on multi-MW proton beams at FNAL
- D. Druitti and R. Reimann on the muon g-2 ring
- V. Pronskykh on the mu2e target
- S. Nagaitsev on the optical stochastic cooling
- D. Calzolari on MDI of multi-TeV muon collider

Later in this session:

- D. Schulte on the energy frontier muon colliders
- P. Burrows – on ILC and CLIC

Special thanks to

- My co-conveners S. Gourlay and T. Raubenheimer
- T. Roser (ITF chair) and P. Bhat (FNAL collider group leader)
- Accelerator Frontier Topical Group conveners and liaisons to EF, NF and TF

In preparation of the Snowmass in Seattle, tons of material available at:

https://snowmass21.org/accelerator/start