Global Planning for Colliders: 
EPPSU, Snowmass, China, Russia...

Vladimir Shiltsev, Fermilab

IAS/HKUST Program on HEP (virtual), Jan 13, 2022
58 years since 1st collisions

- Spring 1964 AdA and VEP-1

31 operated since

- (see RMP review)

7 in operation now

- see next slides

2 under construction

- NICA and EIC

At least 2 more types needed

- Higgs/Electroweak factories
- Frontier $E >> LHC$

<table>
<thead>
<tr>
<th>Species</th>
<th>$E_b$, GeV</th>
<th>$C$, m</th>
<th>$L_{\text{max}}^{\text{peak}}$, $10^{25}$</th>
<th>Years</th>
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<tbody>
<tr>
<td>AdA</td>
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<td>ISR</td>
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<td>943</td>
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<td>DCI</td>
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<td>PETRA</td>
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<td>10$^{32}$</td>
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<td>HERA</td>
<td>$ep$</td>
<td>30+920</td>
<td>6336</td>
<td>7.5 $\times$ $10^{31}$</td>
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<tr>
<td>PEP-II</td>
<td>$e^+e^-$</td>
<td>3.1+9</td>
<td>2200</td>
<td>1.2 $\times$ $10^{34}$</td>
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<td>KEKB</td>
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<td>3.5+8.0</td>
<td>3016</td>
<td>2.1 $\times$ $10^{34}$</td>
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<tr>
<td>VEPP-4M</td>
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<td>366</td>
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<td>BEPC-I/II</td>
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<td>238</td>
<td>10$^{33}$</td>
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<td>DAΦNE</td>
<td>$e^+e^-$</td>
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<tr>
<td>RHIC</td>
<td>$p_i$</td>
<td>255</td>
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<tr>
<td>LHC</td>
<td>$p_i$</td>
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<td>26659</td>
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<tr>
<td>VEPP2000</td>
<td>$e^+e^-$</td>
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<td>24</td>
<td>4 $\times$ $10^{31}$</td>
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<td>S-KEKB</td>
<td>$e^+e^-$</td>
<td>7+4</td>
<td>3016</td>
<td>8 $\times$ $10^{35}$ *</td>
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</tbody>
</table>
Highest $E$ Colliders

Highlights – LHC: $pp$ 13$\rightarrow$14 TeV cme

- 190 fb$^{-1}$/IP by now, x2 design $pp$ luminosity
- ALICE: $\sim$1nb$^{-1}$ in 5TeV$_{cme}$ PbPb, 0.3ub$^{-1}$XeXe
- *High-Lumi upgrade* by 2028: double beam current, smaller $\beta^*$ (new Nb$_3$Sn IR magnets), “crabbing”, leveling @14 TeV $\rightarrow$ 250 fb$^{-1}$/yr
- Followed by ~decade of ops to 3-4 ab$^{-1}$

Highlights - RHIC $pp$/ep/ions 510 GeV cme

- RHIC: >0.5 fb$^{-1}$ in 510 GeV cme polarized $pp$ ($P=55\%$)
- RHIC: $>10$ nb$^{-1}$ 4-100 GeV/u ions (Au, Zr, …)

Highlights – Super-KEKB: $e^+e^-$ 7+4 GeV

- Startup in 2018, world record $L=3.1e34$ cm$^{-2}$s$^{-1}$
- Design luminosity goal x40 of KEK-B
- Now $\sim$4% of the goal, steady progress
**NICA: Nuclotron-based Ion Collider fAlicy**

- Protons to ions (Au)
  \[ \sqrt{s_{NN}} = 4-11 \text{ GeV} \]
- Polarized $p$ and $d$
- Superconducting magnets
- Stochastic and electron cooling for high luminosity $10^{27}$

- Construction started in 2013
- More than 80% done
- Booster beam (2021)
- 1st collider magnet in the tunnel (Dec 28, 2021)
- Collisions in 2023-24
Electron Ion Collider (EIC)
Brookhaven National Laboratory

- 275 GeV protons, 100 GeV/u (existing RHIC, upgraded)
- 10 GeV electrons (5-18 GeV storage ring, new)

$\sqrt{s} = 20$ GeV to 100 GeV

- $\sim 70\%$ polarization
- Luminosity $\sim x100$ HERA (with Strong Hadron Cooling)

- CD-1 in July 2021
- Construction is expected to begin in 2024
- Operations early in the next decade.
Of Note: Super Charm/Tau-Factory (Novosibirsk)

Discussions on-going in 2022 on the “mission need” (CD-0)
In case of positive outcome construction by the end of 2020’s

\[ E_{\text{cme}} = 3-7 \text{ GeV} \]
\[ L = 10^{35} \text{ cm}^{-2} \text{ s}^{-1} \]
\[ C = 870 \text{ m} \]
Crab waist
Pol. e-

\[ e^+ \text{ DR} \] – positron damping ring
\[ \text{DW} \] – damping wiggler
\[ \text{SS} \] – Siberian Snake
\[ \text{CV} \] – electron-positron converter
Pol. e-/e-- polarized/un-polarized electron source

\( \text{courtesy E. Levichev} \)
2020 European Particle Physics Strategy Update

- **2017**
  - Jan. 2018: Call for proposals for venues for Open Symposium and Strategy Drafting Session

- **2018**
  - Feb. 2018: Call for scientific input
  - March 2018: Call for nominations of PPG & ESG members
  - June 14, 2018: Council decision on venues and dates
  - Sept. 27, 2018: Council to launch the Strategy Update process & establish the PPG and ESG

- **2019**
  - Dec. 18, 2018: Closing submission of community input
  - May 13-16, 2019: Open Symposium Granada, ES
  - Sept. 2019: Physics Briefing Book available
  - March 2020: Strategy Update to be submitted to Council

- **2020**
  - Jan. 20-24, 2020: Strategy Update Drafting Session Bad Honnef, GE
  - June 2020: Council updates the Strategy

Consultation & consensus building

- Physics results appearing after May 2019 were taken into account in the process
### 20 EPPSU Statements

**Outcome:**

<table>
<thead>
<tr>
<th>2 statements on Major developments from the 2013 Strategy</th>
</tr>
</thead>
<tbody>
<tr>
<td>a) Focus on successful completion of HL-LHC upgrade remains a priority</td>
</tr>
<tr>
<td>b) Continued support for long-baseline ν experiments in Japan and US and the Neutrino Platform</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>3 statements on General considerations for the 2020 update</th>
</tr>
</thead>
<tbody>
<tr>
<td>a) Preserve the leading role of CERN for success of European PP community</td>
</tr>
<tr>
<td>b) Strengthen the European PP ecosystem of research centres</td>
</tr>
<tr>
<td>c) Acknowledge the global nature of PP research</td>
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<table>
<thead>
<tr>
<th>2 statements on High-priority future initiatives</th>
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</thead>
<tbody>
<tr>
<td>a) Higgs factory as the highest-priority next collider and investigation of the technical and financial feasibility of a future hadron collider at CERN</td>
</tr>
<tr>
<td>b) Vigorous R&amp;D on innovative accelerator technologies - through roadmap</td>
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<table>
<thead>
<tr>
<th>4 statements on Other essential scientific activities</th>
</tr>
</thead>
<tbody>
<tr>
<td>a) Support for high-impact, financially implementable, experimental initiatives world-wide</td>
</tr>
<tr>
<td>b) Acknowledge the essential role of theory</td>
</tr>
<tr>
<td>c) Support for instrumentation R&amp;D - through roadmap</td>
</tr>
<tr>
<td>d) Support for computing and software infrastructure</td>
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<thead>
<tr>
<th>2 statements on Synergies with neighbouring fields</th>
</tr>
</thead>
<tbody>
<tr>
<td>a) Nuclear physics - cooperation with NuPECC</td>
</tr>
<tr>
<td>b) Astroparticle - cooperation with APPEC</td>
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</table>

<table>
<thead>
<tr>
<th>3 statements on Organisational issues</th>
</tr>
</thead>
<tbody>
<tr>
<td>a) Framework for projects in and out of Europe</td>
</tr>
<tr>
<td>b) Strengthen relations with European Commission</td>
</tr>
<tr>
<td>c) Support active role in supporting Open Science</td>
</tr>
</tbody>
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<thead>
<tr>
<th>4 statements on Environmental and societal impact</th>
</tr>
</thead>
<tbody>
<tr>
<td>a) Mitigate environmental impact of particle physics</td>
</tr>
<tr>
<td>b) Invest in next generation of researchers</td>
</tr>
<tr>
<td>c) Support knowledge and technology transfer</td>
</tr>
<tr>
<td>d) Cultural heritage: public engagement, education and communication</td>
</tr>
</tbody>
</table>

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2 statements on **High-priority future initiatives**

a) Higgs factory as the highest-priority next collider and investigation of the technical and financial feasibility of a future hadron collider at CERN

b) Vigorous R&D on innovative accelerator technologies - through roadmap
HEP Planning in the US: Snowmass

"Snowmass is a particle physics community study"

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

Snowmass

1.5-2 yrs

P5

~ 1 yr

DOE/NSF

~5-7 yrs of hard work

Particle Physics is global
Particle Physics is not isolated

https://www.snowmass21.org/
Snowmass’21 Timeline

• 2019
  – Announcement, organization of 10 Frontiers

• 2020
  – Organization of Topical Groups
  – Submission of *Letters of Interest (LoIs)*
  – Virtual *Community Planning Meeting* Oct 5-8

• 2021
  – PAUSE due to COVID
  – Restart: work in TGs/Frontiers toward *White Papers*

• 2022
  – White paper submissions, preliminary TG & F reports
  – *Community Summer Study* – July 17-26, 2022
  – Final TG/Frontier reports
  – *Snowmass Book (SG)* – October’22
# Snowmass’21 Accelerator Frontier

![Steve Gourlay (LBNL)](image1)
![Tor Raubenheimer (SLAC)](image2)
![Vladimir Shiltsev (FNAL)](image3)

### Topical Group Co-Conveners

<table>
<thead>
<tr>
<th>Topical Group</th>
<th>Co-Conveners</th>
</tr>
</thead>
<tbody>
<tr>
<td>AF01 Beam Phys &amp; Accel. Education</td>
<td>Z. Huang (Stanford), M. Bei (SLAC), S. Lund (MSU)</td>
</tr>
<tr>
<td>AF02 Accelerators for Neutrinos</td>
<td>J. Galambos (ORNL), B. Zwaska (FNAL), G. Arduini (CERN)</td>
</tr>
<tr>
<td>AF03 Accelerators for EW/Higgs</td>
<td>F. Zimmermann (CERN), Q. Qin (ESRF), G. Hoffstaetter (Cornell), A. Faus-Golfe (IN2P3)</td>
</tr>
<tr>
<td>AF04 Multi-TeV Colliders</td>
<td>M. Palmer (BNL), A. Valishev (FNAL), N. Pastrone (INFN), J. Tang (IHEP)</td>
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<tr>
<td>AF05 Accelerators for PBC and Rare Processes</td>
<td>E. Prebys (UC Davis), M. Lamont (CERN), Richard Milner (MIT)</td>
</tr>
<tr>
<td>AF06 Advanced Accelerator Concepts</td>
<td>C. Geddes (LBNL), M. Hogan (SLAC), P. Musumeci (UCLA), R. Assmann (DESY)</td>
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<td>AF07 Accelerator Technology R&amp;D</td>
<td>E. Nanny (SLAC), S. Posen (FNAL), H. Weise (DESY)</td>
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<td>Sub-group RF</td>
<td>G. Sabbi (LBNL), S. Zlobin (FNAL), S. Izquierdo Bermudez (CERN)</td>
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<tr>
<td>Sub-Group Magnets</td>
<td>C. Barbier (ORNL), Y. Sun (ANL), Frederique Pellemoine (FNAL)</td>
</tr>
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<td>Sub-Group Targets/Sources</td>
<td>T. Roser (BNL)</td>
</tr>
<tr>
<td>ITF Implementation Task Force</td>
<td>T. Roser (BNL)</td>
</tr>
</tbody>
</table>

9 out of 29 represent of Asia and Europe; 5 women
# Future Collider Proposals: 8 Higgs/EW factories

<table>
<thead>
<tr>
<th>Name</th>
<th>Details</th>
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<tbody>
<tr>
<td>CepC</td>
<td>$e^+e^-, \sqrt{s} = 0.24 \text{ TeV}, L = 3.0 \times 10^{34}$</td>
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<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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<td>ERL ee collider</td>
<td>$e^+e^-, \sqrt{s} = 0.24 \text{ TeV}, L = 73 \times 10^{34}$</td>
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<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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<td>LHeC</td>
<td>$e^+p, \sqrt{s} = 1.3 \text{ TeV}, L = 0.1 \times 10^{34}$</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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**Diagram:**
- **CepC/CLIC:**
  - 100 km
  - 100 MW RF
- **FCC-ee:**
  - 72 MV/m
  - 11 km
- **ILC:**
  - SRF 31.5 MV/m
  - 21 km
<table>
<thead>
<tr>
<th>Name</th>
<th>Details</th>
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<tbody>
<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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<td>High Energy ILC</td>
<td>$e^+e^-, \sqrt{s} = 1 - 3 \text{ TeV}$</td>
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<td>FCC-hh</td>
<td>$pp, \sqrt{s} = 100 \text{ TeV}, L= 30 \times 10^{34}$</td>
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<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>$ep, \sqrt{s} = 1.3 \text{ TeV}, L= 1 \times 10^{34}$</td>
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<tr>
<td>FCC-eh</td>
<td>$ep, \sqrt{s} = 3.5 \text{ TeV}, L= 1 \times 10^{34}$</td>
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<tr>
<td>CEPC-SPPpC-eh</td>
<td>$ep, \sqrt{s} = 6 \text{ TeV}, L= 4.5 \times 10^{33}$</td>
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<tr>
<td>VHE-ep</td>
<td>$ep, \sqrt{s} = 9 \text{ TeV}$</td>
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<tr>
<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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<tr>
<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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<tr>
<td>LWFA-LC (e+e- and γγ)</td>
<td>Laser driven; $e^+e^-, \sqrt{s} = 1 - 30 \text{ TeV}$</td>
</tr>
<tr>
<td>PWFA-LC (e+e- and γγ)</td>
<td>Beam driven; $e^+e^-, \sqrt{s} = 1 - 30 \text{ TeV}$</td>
</tr>
<tr>
<td>SWFA-LC</td>
<td>Structure wakefields; $e^+e^-, \sqrt{s} = 1 - 30 \text{ TeV}$</td>
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</table>
Possible Fermilab Site-Fillers

Circumference ~16 km

1. $e^+e^-$ Site Filler, $\sqrt{s} = 90-240$ GeV
2. Muon Collider, $\sqrt{s} = 0.126 - 8 \ (10)$ TeV
3. $pp$ Site Filler Collider, $\sqrt{s} = 24-28$ TeV

Linear ~7 km

1. $C^3$ (Cool Copper Cavity) $e^+e^-$ Collider, $\sqrt{s} = 90 – 500$ GeV
2. NC RF (CLIC-Klystron) $e^+e^-$ Collider, $\sqrt{s} = 90 – 500$ GeV
3. SRF- Travelling Wave $e^+e^-$ Linear Collider, $\sqrt{s} = 250$ GeV

Shiltsev | Colliders Global
The Accelerator Implementation Task Force is charged with developing metrics and processes to facilitate a comparison between projects.

- 10 int’l experts and 2 Snowmass Young’s

This year worked in four subgroups:

- Size, complexity, power, environment
- Physics reach (impact), beam parameters
- Technical risk, technical readiness, validation
- Cost, schedule

Plan to finish preliminary analysis and start talking to proponents in Dec-Jan, to be ready to submit report (Snowmass WP) by May 2022.
ITF Comparison Metrics for Colliders

1. Physics Reach (8 criteria)
2. Beam parameters (7)
3. Size and Complexity of Facility (8)
4. Technical risk (5)
5. Schedule (6)
6. Validation and Preparation (4)
7. Construction Cost (7)
8. Operation and Maintenance (5)
9. Environmental Impact (4)
10. Economic/technological impact
11. Cultural/educational impact
In the context of the Snowmass 2021 Community Planning Exercise, the Accelerator and Energy Frontiers are pleased to announce a series of events, intended for all Snowmass participants, to critically discuss physics and technical aspects of different HEP collider concepts.

- Linear e+e- colliders
- **Circular e+e- colliders**
- Muon colliders
- Circular pp and ep
- Advanced colliders

The events will take place once a month from December 2021 till April 2022, on Wednesdays 3-5 p.m. CST. The detailed agenda will be announced soon. We request you to please save the following dates:

- Dec. 15, 2021
- Jan. 19, 2022
- Feb. 16, 2022
- Mar. 16, 2022
- Apr. 13, 2022

**OPEN TO ALL**

Please register at:

https://indico.fnal.gov/event/52534/
Next Step: in Europe – Accelerator R&D Roadmap
Next Step: in Europe – Accelerator R&D Roadmap

Status:

- All 5 group reports submitted
- Interim report “European Strategy – Accelerator R&D Roadmap” compiled and published in 2021
- CERN council met in Dec’21
- Final report (recommendations and roadmap) will be published in Feb’22
- Roadmap implementation will begin in 2022
Summary on Worldwide Planning for Colliders

• **Colliders have shown remarkable progress so far:**
  - 31 built since early 1960s, 7 operational now
  - Colliders push the envelope of accelerator technologies – eg recent:
    • Records in RF gradients, $B$-field, $dB/dt$ rate, MWs beam targets, etc
  - Instigated breakthroughs in beam physics – eg recent:
    • Several new beam cooling schemes, plasma acceleration to $O(5\text{GeV})$, etc
  - Three collider projects are in different stages of construction
    • Hi-Lumi LHC, NICA and EIC, … plus Novosibirsk C/Tau pre-CD0

• **Planning for future is at full speed:**
  - European Strategy Update finished in 2020
  - The US Snopwmass’21 process to finish this year
  - HEP community wants two types of colliders:
    • (first) Higgs/Electroweak factories : linear or circular
    • (then) Multi-TeV colliders : either $pp$, or $\mu\mu$, or $ee$
  - European Accelerator R&D roadmap is developed, be published soon
  - Snowmass outcome will provide base fore the 2023 P5 recommendations in 2023
Thanks for your attention!

Useful reference:
Modern and Future Colliders - V. Shiltsev, F. Zimmermann Rev. Mod. Phys. 93, 015006 (2021)
Back up slides
Cost of Accelerators

Future circular hadron colliders (proposed)
Multi-TeV lepton colliders (proposed)
Small-scale light sources
Large accelerator facilities for R&D, industrial, and security applications
Upgrades of existing light sources, proton beams, nuclear physics facilities, and FELs
Large medical accelerator facilities

X-ray FELs
Large nuclear physics and multi-MW proton-beam facilities
Frontier electron-ion collider (proposed)

Third- and fourth-generation light sources
LHC upgrade
Smaller nuclear physics and <1 MW proton-beam facilities, small electron-ion colliders

$10+ B$
$3–10 B$
$1–3 B$
$0.3–1 B$
$0.1–0.3 B$
$10–30 M$
$30–100 M$

see C.Hoehr’s talk today
Cost is set by the scale (energy, length, power) and technology

- Accelerator technology (magnets NC and SC, RF and SCRF)
  ~50±10%

- Civil construction technology
  ~35±15%

- Power production, delivery and distribution technology
  ~15±10%
State of the art NC (warm) magnets for 4th gen light sources:
- high quality
- buy from industry

Supercond. magnets, for colliders and undulators:
- 8.3T in LHC
- 14.5T by US MDP (2020)
- 290 T/s fast cycling HTS (FNAL, 2021)

NC RF:
- 28 MV/m in SwissFEL (‘17)
- 100MV/m in CLIC structures
- Aim for 117 MV/m in cold copper (LN$_2$) structures (SLAC)

SC RF:
- 25 MV/m at $Q_0$=1e10 at 1.3 GHz EurXFEL
- ILC specs 31.5MV/m at FNAL
- Nitrogen doping $\rightarrow$ $Q_0$~3e10
- Aim at ~50MV/m in 1.3GHz
**Acceleration in Plasma**

Plasma waves can sustain high fields:

\[ E_0 = \frac{m_e c \omega_p}{e} \approx 100 \left( \frac{\text{GeV}}{m} \right) \cdot \sqrt{n_0 \left( 10^{18} \text{ cm}^{-3} \right)} \]

Excitation by (smth short and powerful):

- Laser 4.3 GeV \((10^{18} \text{ cm}^{-3} \ 9\text{cm})\) e- bunch 9 GeV \((\sim 10^{17} \text{ cm}^{-3} \ 1.3\text{m})\)
- p+ bunch 2 GeV \((\sim 10^{15} \text{ cm}^{-3} \ 10\text{m})\)

**Latest news – summer 2021:**

- **EuPRAXIA** (European plasma accelerator, 5 GeV e-and FELs, 50 institutes in 15 countries, 569M€) is included in the **ESRFI 10-20 yrs roadmap**
- First **LWFA FEL** at SIOM/CAS, Shanghai (6 mm He gas, 200 TW laser → 0.5 GeV e-beam → 27 nm laser)

W.Wang et al Nature 595, 516 (2021)
Luminosity Efficiency: $a b^{\frac{1}{-1/TWh}}$

Nature Physics, 17, 289 (2021)