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

Vladimir Shiltsev, Fermilab

IAS/HKUST Program on HEP (virtual), Jan 13, 2022

Colliders Landscape

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 $E \gg$ LHC

	Species	E_b , GeV	C , m	$\mathcal{L}_{peak}^{max}$	Years
AdA	e^+e^-	0.25	4.1	10^{25}	1964
VEP-1	e^-e^-	0.16	2.7	5×10^{27}	1964-68
CBX	e^-e^-	0.5	11.8	2×10^{28}	1965-68
VEPP-2	e^+e^-	0.67	11.5	4×10^{28}	1966-70
ACO	e^+e^-	0.54	22	10^{29}	1967-72
ADONE	e^+e^-	1.5	105	6×10^{29}	1969-93
CEA	e^+e^-	3.0	226	0.8×10^{28}	1971-73
ISR	pp	31.4	943	1.4×10^{32}	1971-80
SPEAR	e^+e^-	4.2	234	1.2×10^{31}	1972-90
DORIS	e^+e^-	5.6	289	3.3×10^{31}	1973-93
VEPP-2M	e^+e^-	0.7	18	5×10^{30}	1974-2000
VEPP-3	e^+e^-	1.55	74	2×10^{27}	1974-75
DCI	e^+e^-	1.8	94.6	2×10^{30}	1977-84
PETRA	e^+e^-	23.4	2304	2.4×10^{31}	1978-86
CESR	e^+e^-	6	768	1.3×10^{33}	1979-2008
PEP	e^+e^-	15	2200	6×10^{31}	1980-90
SppS	$p\bar{p}$	455	6911	6×10^{30}	1981-90
TRISTAN	e^+e^-	32	3018	4×10^{31}	1987-95
Tevatron	$p\bar{p}$	980	6283	4.3×10^{32}	1987-2011
SLC	e^+e^-	50	2920	2.5×10^{30}	1989-98
LEP	e^+e^-	104.6	26659	10^{32}	1989-2000
HERA	ep	30+920	6336	7.5×10^{31}	1992-2007
PEP-II	e^+e^-	3.1+9	2200	1.2×10^{34}	1999-2008
KEKB	e^+e^-	3.5+8.0	3016	2.1×10^{34}	1999-2010
VEPP-4M	e^+e^-	6	366	2×10^{31}	1979-
BEPC-I/II	e^+e^-	2.3	238	10^{33}	1989-
DAΦNE	e^+e^-	0.51	98	4.5×10^{32}	1997-
RHIC	p, i	255	3834	2.5×10^{32}	2000-
LHC	p, i	6500	26659	2.1×10^{34}	2009-
VEPP2000	e^+e^-	1.0	24	4×10^{31}	2010-
S-KEKB	e^+e^-	7+4	3016	$8 \times 10^{35} *$	2018-

Highest E Colliders

Highlights – LHC : pp 13→14 TeV cme

- 190 fb-1/IP by now, x2 design pp luminosity
- **ALICE:** $\sim 1\text{nb}^{-1}$ in 5TeV_{cme} $PbPb$, $0.3\text{ub}^{-1}\text{XeXe}$
- **High-Lumi upgrade** by 2028: double beam current, smaller β^* (new Nb_3Sn IR magnets), “crabbing”, leveling @14 TeV $\rightarrow 250\text{fb}^{-1}/\text{yr}$
- Followed by $\sim$ decade of ops to $3\text{-}4\text{ab}^{-1}$

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

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

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

- Startup in 2018, world record $L=3.1\text{e}34\text{cm}^{-2}\text{s}^{-1}$
- Design luminosity goal x40 of KEK-B
- Now $\sim 4\%$ of the goal, steady progress

NICA: Nuclotron-based Ion Collider fAcility

- 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)

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

- ~70% polarization
- Luminosity $\sim \times 100$ 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

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

2020 European Particle Physics Strategy Update

Outcome : 20 *EP*PSU Statements

2 statements on **Major developments from the 2013 Strategy**

- a) Focus on successful completion of HL-LHC upgrade remains a priority
- b) Continued support for long-baseline ν experiments in Japan and US and the Neutrino Platform

3 statements on **General considerations for the 2020 update**

- a) Preserve the leading role of CERN for success of European PP community
- b) Strengthen the European PP ecosystem of research centres
- c) Acknowledge the global nature of PP research

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

4 statements on **Other essential scientific activities**

- a) Support for high-impact, financially implementable, experimental initiatives world-wide
- b) Acknowledge the essential role of theory
- c) Support for instrumentation R&D - through roadmap
- d) Support for computing and software infrastructure

2 statements on **Synergies with neighbouring fields**

- a) Nuclear physics - cooperation with NuPECC
- b) Astroparticle - cooperation with APPEC

3 statements on **Organisational issues**

- a) Framework for projects in and out of Europe
- b) Strengthen relations with European Commission
- c) Support active role in supporting Open Science

4 statements on **Environmental and societal impact**

- a) Mitigate environmental impact of particle physics
- b) Invest in next generation of researchers
- c) Support knowledge and technology transfer
- d) Cultural heritage: public engagement, education and communication

Letters for itemization are introduced for identification

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”

<https://www.snowmass21.org/>

Snowmass'21 Timeline

- 2019
 - Announcement, organization of 10 Frontiers
- 2020
 - Organization of Topical Groups
 - Submission of *Letters of Interest (Lols)*
 - *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**

Energy Frontier
Neutrino Physics Frontier
Rare Processes and Precision
Cosmic Frontier
Theory Frontier
Accelerator Frontier
Instrumentation Frontier
Computational Frontier
Underground Facilities
Community Engagement

Snowmass 2021

Snowmass'21 Accelerator Frontier

Steve Gourlay (LBNL)

Tor Raubenheimer (SLAC)

Vladimir Shiltsev (FNAL)

Topical Group		Topical Group co-Conveners			
AF01	Beam Phys & Accel. Education	Z. Huang (Stanford)	M. Bei (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. Nanny (SLAC)	S. Posen (FNAL)	H. Weise (DESY)	
	Sub-Group Magnets	G. Sabbi (LBNL)	S. Zlobin (FNAL)	S. Izquierdo Bermudez (CERN)	
	Sub-Group Targets/Sources	C. Barbier (ORNL)	Y. Sun (ANL)	Frederique Pellemoine (FNAL)	
ITF	Implementation Task Force	T. Roser (BNL)			

9 out of 29 represent of Asia and Europe; 5 women

Future Collider Proposals: 8 Higgs/EW factories

Name	Details
CepC	e^+e^- , $\sqrt{s} = 0.24$ TeV, $L = 3.0 \times 10^{34}$
CLIC (Higgs factory)	e^+e^- , $\sqrt{s} = 0.38$ TeV, $L = 1.5 \times 10^{34}$
ERL ee collider	e^+e^- , $\sqrt{s} = 0.24$ TeV, $L = 73 \times 10^{34}$
FCC-ee	e^+e^- , $\sqrt{s} = 0.24$ TeV, $L = 17 \times 10^{34}$
gamma gamma	X-ray FEL-based $\gamma\gamma$ collider
ILC (Higgs factory)	e^+e^- , $\sqrt{s} = 0.25$ TeV, $L = 1.4 \times 10^{34}$
LHeC	ep , $\sqrt{s} = 1.3$ TeV, $L = 0.1 \times 10^{34}$
MC (Higgs factory)	$\mu\mu$, $\sqrt{s} = 0.13$ TeV, $L = 0.01 \times 10^{34}$

17 (!) High Energy Collider Concepts/Proposals

Name	Details
Cryo-Cooled Copper linac	e^+e^- , $\sqrt{s} = 2$ TeV, $L = 4.5 \times 10^{34}$
High Energy CLIC	e^+e^- , $\sqrt{s} = 1.5 - 3$ TeV, $L = 5.9 \times 10^{34}$
High Energy ILC	e^+e^- , $\sqrt{s} = 1 - 3$ TeV
FCC-hh	pp , $\sqrt{s} = 100$ TeV, $L = 30 \times 10^{34}$
SPPC	pp , $\sqrt{s} = 75/150$ TeV, $L = 10 \times 10^{34}$
Collider-in-Sea	pp , $\sqrt{s} = 500$ TeV, $L = 50 \times 10^{34}$
LHeC	ep , $\sqrt{s} = 1.3$ TeV, $L = 1 \times 10^{34}$
FCC-eh	ep , $\sqrt{s} = 3.5$ TeV, $L = 1 \times 10^{34}$
CEPC-SPPpC-eh	ep , $\sqrt{s} = 6$ TeV, $L = 4.5 \times 10^{33}$
VHE-ep	ep , $\sqrt{s} = 9$ TeV
MC – Proton Driver 1	$\mu\mu$, $\sqrt{s} = 1.5$ TeV, $L = 1 \times 10^{34}$
MC – Proton Driver 2	$\mu\mu$, $\sqrt{s} = 3$ TeV, $L = 2 \times 10^{34}$
MC – Proton Driver 3	$\mu\mu$, $\sqrt{s} = 10 - 14$ TeV, $L = 20 \times 10^{34}$
MC – Positron Driver	$\mu\mu$, $\sqrt{s} = 10 - 14$ TeV, $L = 20 \times 10^{34}$
LWFA-LC (e^+e^- and $\gamma\gamma$)	Laser driven; e^+e^- , $\sqrt{s} = 1 - 30$ TeV
PWFA-LC (e^+e^- and $\gamma\gamma$)	Beam driven; e^+e^- , $\sqrt{s} = 1 - 30$ TeV
SWFA-LC	Structure wakefields; e^+e^- , $\sqrt{s} = 1 - 30$ TeV

CLIC e^+e^- 3 TeV, 100 MV/m 50 km

pp 100 km : SPPC 75 TeV, 12 T magnets, FCChh 100/16 T

$\mu^+\mu^-$ 10-14 TeV cme
10-14 km, 16 T magnets

Possible Fermilab Site-Fillers

Circumference ~ 16 km

Linear ~ 7 km

Courtesy P.Bhat (FNAL)

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

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

Implementation Task Force

- 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

Steve Gourlay
(LBNL)

Philippe Lebrun
(CERN)

Thomas Roser
(BNL, Chair)

Tor Raubenheimer
(SLAC)

Katsunobu Oide
(KEK)

Jim Strait
(FNAL)

Vladimir Shiltsev
(FNAL)

Reinhard Brinkmann
(DESY)

John Seeman
(SLAC)

Sarah Cousineau
(ORNL)

Marlene Turner
(LBNL)

Spencer Gessner
(SLAC)

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 Snowmass'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 for 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

Cost is set by the scale (*energy, length, power*) and technology

- Accelerator technology
(magnets NC and SC, RF
and SCRF)

$\sim 50_{\pm 10} \%$

- Civil construction
technology

$\sim 35_{\pm 15} \%$

- Power production,
delivery and distribution
technology

$\sim 15_{\pm 10} \%$

State of the art NC (warm) magnets for 4th gen light sources :

- high quality
- buy from industry

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)

Supercond. magnets, for colliders and undulators:

- 8.3T in LHC
- 14.5T by US MDP (2020)
- 290 T/s fast cycling HTS (FNAL, 2021)

SC RF:

- 25 MV/m at $Q_0=1e10$ at 1.3 GHz EurXFEL
- ILC specs 31.5MV/m at FNAL
- Nitrogen doping $\rightarrow Q_0 \sim 3e10$
- Aim at $\sim 50\text{MV/m}$ in 1.3GHz

Acceleration in Plasma

Plasma waves can sustain high fields:

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

Excitation by (smth short and powerful):

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

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, $\lambda > 27 \text{ nm}$ laser)

Luminosity Efficiency : $\text{ab}^{-1}/\text{TWh}$