Plans for Future Energy Frontier Accelerators to Drive Particle Physics Discoveries

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Overview

- Introduction
    - Snowmass and **AF 4**
- Community Input Received
- **AF4** Concept Maturity Evaluation
- **AF4** Outcomes
- Summary & Conclusions

What is Snowmass?

Snowmass is a **Particle Physics Community Planning Exercise** and is a scientific study. It provides an opportunity for the entire particle physics community to come together to identify and document a scientific vision for the future of particle physics in the U.S.

Snowmass cycle: ~8 Years, Snowmass 2021: 18 Months + 10 day Meeting in Seattle.

Snowmass and AF4


Seattle Meeting

Ten Frontiers:

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

Seven Working Groups within the AF:

- AF1: Beam Physics and Accelerator Education
  AF2: Accelerators for Neutrinos
- AF3: Accelerators for EW/Higgs
- **AF4: Multi-TeV Colliders**
- AF5: Accelerators for PBC and Rare Processes
- AF6: Advanced Accelerator Concepts
- AF7: Accelerator Technology R&D

Collect Community Input via LOIs and White Papers

Full list of LOI's:
https://snowmass21.org/loi

Coordination

Full list of white papers:
https://snowmass21.org/loi

Beam Mat. Int	CERN	M.Calviani	Future colliders	AF7-AF4	159	Marco.Calviani@cern.ch
Cooling R&D	JLAB	Y.Zhang	Hadron accel.	AF7-AF4	108	yzhang@jlab.org
Cosmic Ray	U.Del.	D.Soldin	Cosmic Ray Observ	CF7-CF0-EF6-EF7-AF4-AF0	83	soldin@udel.edu
Detector	MCC/INFN	C.Aime	MC	IF9-IF3-EF9-EF0-AF4-AF1	143	Collaboration
Diagnostics	LANL/SLAC	A.Scheinker		AF1-AF4	29	ascheink@lanl.gov
Dynamics	CERN	E.Adli	CLIC	AF1-AF4	161	erik.adli@fys.uio.no
Energy Rec.	RBT	A.Murokh	IFEL	AF6-AF4	79	murokh@radiabeam.com
Machine	CERN	O.Bruening	LHeC/FCC-eh	AF3-AF4-EF0	195	Oliver.Bruning@cern.ch
Machine	FNAL	PC.Bhat	Options	AF3-AF4-EF0	237	pushpa@fnal.gov
Machine	SLAC	E.A.Nanni	e+/e- LC	AF3-AF4-EF1-EF2	243	nanni@slac.stanford.edu
Machine	ANL	C.Jing	AFLC (linear C.)	AF6-AF4	88	c.jing@euclidtechlabs.com
Machine	LBNL	CB.Schroeder	Laser P. Linear C.	AF6-AF4	216	CBSchroeder@lbl.gov
Machine	BNL	S.Jindariani	MC	EF0-TF7-TF0-AF4-AF3-IF0	234	sergo@fnal.gov
Machine Learning	SLAC	BD.O'Shea	Future colliders	AF6-AF4-CompF3/F2	165	boshea@slac.stanford.edu
Machine option	FNAL	PC.Bhat	Future colliders	EF0-AF4-AF3	239	pushpa@fnal.gov
Magnets	FNAL	E.Barzi	MC	AF7-AF4	199	barzi@fnal.gov
MDI	FNAL	G.Ambrosio	Future colliders	AF7-AF4	54	giorgioa@fnal.gov
MDI	INFN	C.Aime	MC	TF7-TF0-EF4-EF0-AF4-AF0	46	author list
Neutrino	Imp.CL	K.Long	nuSTORM	NF6-NF2-EF0-AF2-AF4	82	k.long@imperial.ac.uk
Physics	FNAL	M.Swiatlowski	MC	EF1-EF4-AF3-AF4	177	mswiatlowski@triumf.ca
Physics	FNAL	H.Weber	MC	EF8-EF9-TF7-TF0-AF4-AF0	228	haweber@fnal.gov
Plasma Acc	SLAC	S.Gessner	Plasma LC	AF6-AF4	168	sgess@slac.stanford.edu
Plasma Acc	UCLA	C.Joshi	PWFA	AF6-AF6	251	cjoshi@ucla.edu
R&D for innov.	MIT	W.Barletta	Acc Science	AF7-AF4	64	wabarletta@lbl.gov
Synergy	CUNY	L.Anchordoqui	Astro and Coll. Physics	CF7-CF0-EF6-EF7-AF4-AF0	74	luis.anchordoqui@gmail.com
Target Mat.	INFN	R.Li Voti	MC-LEMMA	AF7-AF4	137	roberto.livoti@uniroma1.it
Wakefield Acc.	ANL	J.Shao	SWFA demo	AF6-AF4	42	jshao@anl.gov
Wakefield Acc.	ANL	C.Jing	SWFA demo	AF6-AF4	90	c.jing@euclidtechlabs.com

Dynamics	MCC	T.Rogers	MC	AF4-AF6	66	chris.rogers@stfc.ac.uk
Dynamics	FNAL	Y.Alexahin	MC	AF4-AF7	34	mokhov@fnal.gov
Dynamics	TAMU	P.McIntyre	Collider in Sea	AF4-AF0	24	mcintyre@physics.tamu.edu
Dynamics	JLAB	SA.Bogacz	MC	AF4-AF0	109	bogacz@jlab.org
Dynamics	FNAL	K.Yonehara	MC	AF4-AF0	33	yonehara@fnal.gov
General	FNAL	S.Nagaitsev	Future accelerators	AF4-AF3-EF0-NF0-RF0	25	nsergei@fnal.gov
Magnets	BNL	K.Amm	Future accel. and exp.	AF4-AF7	167	Collaboration
Magnets	BNL	S.Prestemon	Next G Colliders	AF4-AF7	187	soprestemon@lbl.gov
Magnets	IHEP	Q.Xu	SPPC	AF4-AF7	22	xuqj@ihep.ac.cn
Magnets	MIT	D.Park	MC	AF4	169	dk_park@mit.edu
MDI	INFN	N.Bartosik	MC	AF4-AF7-IF9-IF0	104	nazar.bartosik@to.infn.it
Physics		Dallavalle	TeV Lepton/tau neutrino	AF4-AF0-EF3-EF0-NF6-NF10	81	marco.dallavalle@cern.ch
RF	LBNL	T.Luo	MC/Muon cooling	AF4-AF7	93	tluo@lbl.gov
SRF	OxU	I.Konoplev	Linear and Circular	AF4-AF6	101	ivan.konoplev@physics.ox.ac.uk

Machine Concept LOI's:

Machine	CERN	S.Stapnes	CLIC	AF4-AF3-EF0	177	steinar.stapnes@cern.ch
Machine	TAMU	P.McIntyre	Collider in Sea	AF4-AF0	239	mcintyre@physics.tamu.edu
Machine	JLAB	Y.Zhang	eh Collider	AF4-AF0	144	yzhang@jlab.org
Machine	CERN	M.Benedikt	FCC-hh	AF4-AF1-EF0	153	Michael.Benedikt@cern.ch
Machine		Krasny	gamma-gamma		1	mieczyslaw.witold.krasny@cern.ch
Machine	FNAL	A.Grassellino	ILC	AF4-AF0	75	annag@fnal.gov
Machine	CERN	D.Schulte	MC	AF4-AF0-EF0	103	daniel.schulte@cern.ch
Machine	MCC/CERN	S.Schulte	MC	AF4-AF7	102	daniel.schulte@cern.ch
Machine	MCC/RAL	T.Rogers	MC at CERN	AF4-AF7-EF0	65	chris.rogers@stfc.ac.uk
Machine	INFN	M.Biagini	MC-LEMMA	AF4-AF7	135	marica.biagini@lnf.infn.it
Machine	MCC	S.Machida	MC/Neutrino	AF4-AF2	36	shinji.machida@stfc.ac.uk
Machine	IHEP	J.Tang	SPPC	AF4-AF0	21	tangjy@ihep.ac.cn

Collect Community Input via LOIs and White Papers

Full list of LOI'
https://snov

Coordination

1) **TeV-class Lepton Colliders:** CLIC, ILC multi-TeV, ERLs

2) **Hadron Energy Frontier Machines:** FCC-hh, SppC, Collider in the Sea

3) **Lepton Collider Energy Frontier Machines**: MuC, WFA

4) **Lepton-Ion Machines:** FCC-eh, MuIC

Beam Mat. Int	CERN	M.Ca
Cooling R&D	JLAB	Y.Zh
Cosmic Ray	U.Del.	D.Sc
Detector	MCC/INFN	C.A
Diagnostics	LANL/SLAC	A.Sch
Dynamics	CERN	E.A
Energy Rec.	RBT	A.Mu
Machine	CERN	O.Bru
Machine	FNAL	PC.E
Machine	SLAC	E.A.N
Machine	ANL	C.J
Machine	LBNL	CB.Sch
Machine	BNL	S.Jind
Machine Learning	SLAC	BD.O'
Machine option	FNAL	PC.E
Magnets	FNAL	E.Bo
MDI	FNAL	G.Am
MDI	INFN	C.A
Neutrino	Imp.CL	K.Lo
Physics	FNAL	M.Swia
Physics	FNAL	H.We
Plasma Acc	SLAC	S.Ge
Plasma Acc	UCLA	C.Jo
R&D for innov.	MIT	W.Ba
Synergy	CUNY	L.Ancho
Target Mat.	INFN	R.Li
Wakefield Acc.	ANL	J.Sh
Wakefield Acc.	ANL	C.Jing

Dynamics	MCC	T.Rogers				
Dynamics	FNAL	Y.Alexahin	MC			
Dynamics	TAMU	P.McIntyre	Collider in Sea	AF4-AF0	24	mcintyre@physics.tamu.edu
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General	FNAL	S.Nagaitsev	Future accelerators	AF4-AF3-EF0-NF0-RF0	25	nsergei@fnal.gov
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Magnets	MIT	D.Park	MC	AF4	169	dk_park@mit.edu
MDI	INFN	N.Bartosik	MC	AF4-AF7-IF9-IF0	104	nazar.bartosik@to.infn.it
Physics		Dallavalle	TeV Lepton/tau neutrino	AF4-AF0-EF3-EF0-NF6-NF10	81	marco.dallavalle@cern.ch
RF	LBNL	T.Luo	MC/Muon cooling	AF4-AF7	93	tluo@lbl.gov
SRF	OxU	I.Konoplev	Linear and Circular	AF4-AF6	101	ivan.konoplev@physics.ox.ac.uk

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					144	yzhang@jlab.org
					153	Michael.Benedikt@cern.ch
					1	mieczyslaw.witold.krasny@cern.ch
Machine	FNAL	A.Grassellino	ILC	AF4-AF0	75	annag@fnal.gov
Machine	CERN	D.Schulte	MC	AF4-AF0-EF0	103	daniel.schulte@cern.ch
Machine	MCC/CERN	S.Schulte	MC	AF4-AF7	102	daniel.schulte@cern.ch
Machine	MCC/RAL	T.Rogers	MC at CERN	AF4-AF7-EF0	65	chris.rogers@stfc.ac.uk
Machine	INFN	M.Biagini	MC-LEMMA	AF4-AF7	135	marica.biagini@lnf.infn.it
Machine	MCC	S.Machida	MC/Neutrino	AF4-AF2	36	shinji.machida@stfc.ac.uk
Machine	IHEP	J.Tang	SPPC	AF4-AF0	21	tangjy@ihep.ac.cn

Energy Frontier Desires > 10 TeV CoM Collider

Part of the Snowmass Goal: Enable communication between Frontiers.

- **Message from the Energy Frontier:** interest to explore particle collisions where the constituent center-of-mass energy is E(cm) > 10 TeV.
  - challenge for HEP community: collider concepts that can achieve >10 TeV energy scale have a broad spread in maturity
  - focus of AF4 has been a review of the machine options for hadron and lepton collider technologies that **may provide a path to this threshold**,
    - evaluate their maturity.

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- Earliest timescale for making a **construction decision** for such a discovery machine will be sometime in the next decade.

AF4 Maturity Evaluation

Design Maturity	Maturity Criteria #1 (Design Maturity)	Maturity Criteria #2 (R&D Maturity)
0	No end-to-end design concept prepared	Concept proposed, but no systematic design requirements and/or parameters available.
1	No end-to-end design concept prepared	Concept proposed, proof-of-principle R&D underway
2	**End-to-end preliminary design concept** under development	Ongoing R&D to address **fundamental physics/technical issues.**
3	**End-to-end preliminary design concept** available	**Sub-system operating parameters established** based on preliminary design concepts **for novel/critical sub-systems**
4	**End-to-end integrated design concept** under development	**Preliminary design concepts with operating parameters** established **for all sub-systems.** Sub-system design R&D underway.
5	**End-to-end integrated design concept** available. Enables **end-to-end performance evaluation**.	**Sub-system preliminary designs** exist. **Sub-system design R&D** continues.
6	**End-to-end performance evaluation** complete. **Reference** (pre-CDR level) **Design Report** under development.	**Sub-system performance risk assessment** complete.
7	**Reference Design** available. **Sub-system parameters** and **high potential alternatives** documented.	**Sub-system detailed design** and **performance R&D** for highest risk sub-systems underway.
8	**Conceptupal Design Report** in preparation.	**Sub-system specifications** with **validated operating parameters** established. **High risk sub-system R&D** underway.
9	**Conceptual Design Report** and **detailed cost estimate** available.	**High risk sub-system R&D** ongoing. **Risk mitigation strategy for sub-system performance** established.
10	Ready for **Construction Proposal.** Detailed Engineering Design being developed.	**Performance Optimization R&D** underway.

- Evaluations focused in two key criteria of the facility concept:
  - Design Maturity: What is the status of the full machine design?
  - R&D Maturity: What is the status of the R&D for each of the accelerator sub-systems required to fully specify the machine design?

Disclaimer: non-linear color scale, 0-10, with 10 the most mature.

Evaluation of Concept Maturity

Collider Concepts	Collider-in-Sea	WFA, MuC, MuIC, ReLIC (≤3 TeV), Multi-TeV ILC, CCC (TeV), SppC	FCC-hh, FCC-eh, CLIC, TeV ILC (Nb)
Technical Maturity	• Low maturity conceptual development. • Proof-of-principle R&D required. • Concepts not ready for facility consideration.	• Emerging accelerator concepts requiring significant basic R&D and design effort to bring to maturity.	• Designs have achieved a level of maturity to have reliable performance evaluations based on prior R&D and design efforts. • Critical project risks have been identified and sub-system focused R&D is underway where necessary.
Funding Approach	• Funding for basic R&D required. • Availability of "generic" accelerator test facility access often necessary.	• Efforts would benefit from directed R&D funding to mature collider concepts. • Availability of test facilities to demonstrate a broad range of technology concepts required. • Some large-ticket demonstrators are generally necessary before a detailed "reference" design can be completed.	• Funding approach typically transitions to "project-style" efforts with significant dedicated investment required.

- **Green-shaded:** designs sufficiently mature to enable an informed decision about the proposed approach for physics performance, cost, and risk.
- **Yellow-shaded:** concepts require significant technology R&D and more detailed design studies to fully evaluate their realistic physics potential and to understand both the risks and costs of the approach.
- **Red-shaded:** concepts are very preliminary concepts that cannot be qualitatively compared with other designs.

Evaluation of Concept Maturity

Collider Concepts	Collider-in-Sea	WFA, MuC, ReLIC (≤3 TeV), MuIC, CCC (TeV), Multi-TeV ILC, SppC	FCC-hh, FCC-eh, CLIC, TeV ILC (Nb)
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- **Blue:** Concepts offer a path to constituent center-of-mass collision energies > 10 TeV.
- **Orange:** electron-hadron machines.
- More details in AF4 report.

Evaluation of Concept Maturity

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Funding Approach	• Funding for basic R&D required. • Availability of "generic" accelerator test facility access often necessary.	• Efforts would benefit from directed R&D funding to mature collider concepts. • Availability of test facilities to demonstrate a broad range of technology concepts required. • Some large-ticket demonstrators are generally necessary before a detailed "reference" design can be completed.	• Funding approach typically transitions to "project-style" efforts with significant dedicated investment required.

- Concepts shown in yellow-shaded region have the potential to achieve sufficient maturity within the next decade for evaluation by the HEP community.
- It is important to note that the necessary technical maturity for these concepts, and hence the ability to evaluate both the overall physics performance as well as cost scale, cannot be delivered without dedicated Collider R&D research investment over the next several years.

AF4 Outcomes

- To provide reliable inputs to the HEP community, concepts in the red/yellow regions need to mature.
  - Need for a focused collider R&D program in the US.
  - Initiative has been part of the AF 4 discussion and Snowmass discussions in general.
  - White paper submission:

July 14, 2022

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

P.C. Bhat[1,†], S. Belomestnykh[1,5], A. Bross[1], S. Dasu[6], D. Denisov[4], S. Gourlay[7], S. Jindariani[1], A.J. Lankford[8,†], S. Nagaitsev[1,2,†], E.A. Nanni[3], M.A. Palmer[4], T. Raubenheimer[3], V. Shiltsev[1], A. Valishev[1], C. Vernieri[3], F. Zimmermann[9]

https://arxiv.org/pdf/2207.06213.pdf

Synergies

- Wakefield accelerators connect and couple to:
  - Light source, nuclear security, rare process physics applications
  - Compact Medical applications and unique treatment options

- Muon colliders couple to:
  - Material science applications
  - Rare processes with the most intense muon source ever developed
  - Neutrino physics program

- High field magnet R&D:
  - Benefits hadron and muon colliders
  - Industrial applications

- Lepton colliders:
  - multi-TeV research with EW/Higgs research

Summary

- AF4 collected and structured community input on multi-TeV colliders
- EF emphasized interest in colliders with > 10 TeV CoM energies
- AF4 evaluated concept maturity and found that a focused US collider R&D program would allow to provide informed decisions for the HEP community