2022 EuroNNAC Workshop,

La Biodola, Elba

Conclusions from the 2021 Snowmass Process (Relevant to AACs)

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Outline

- What is Snowmass?
- What are the Main Snowmass Outcomes Relevant for the AAC Community?
    - AAC-Relevant Snowmass Messages to P5
- What did we (AAC community) learn from Snowmass?
- Summary & Conclusion

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 does **not!** prioritize or rank.
Snowmass provides information for the Particle Physics Project Prioritization Panel (P5)
⇒ P5 does the prioritization

Snowmass Structure (1/2)

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

\+ **Implementation Task Force**
\+ **Muon and e+e- collider forum**

Snowmass Structure (2/2)

Ten Frontiers:

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- Community Engagement

AF:

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\+ **Implementation Task Force**

Accelerator Frontier questions:

- What is needed to advance the physics?
- What is currently available (state of the art) around the world?
- What new accelerator facilities could be available in the next decade (or next next decade)?
- What R&D would enable these future opportunities?
- 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?

AF WG Conveners

Link to reports: https://snowmass21.org/accelerator/start

AF6: Advanced Accelerator Concepts

Interchange between Snowmass and the European LDG activity

Cameron Geddes
Lawrence Berkeley National Lab

Mark Hogan
SLAC National Accelerator Lab

Pietro Musumeci
University of California, Los Angeles

Ralph Assmann
Deutsches Elektronen-Sychrotron

AF4: Multi-TeV Colliders

Mark Palmer

Nadia Pastrone

Jingyu Tang

Marlene Turner

Alexander Valishev

Implementation Task Force (ITF)

Steve Gourlay (LBNL)

Philippe Lebrun (CERN)

Thomas Roser (BNL, Chair)

John Seeman (SLAC)

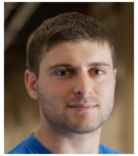
Tor Raubenheimer (SLAC)

Katsunobu Oide (KEK)

Jim Strait (FNAL)

Reinhard Brinkmann (DESY)

Marlene Turner (LBNL)



Spencer Gessner (SLAC)

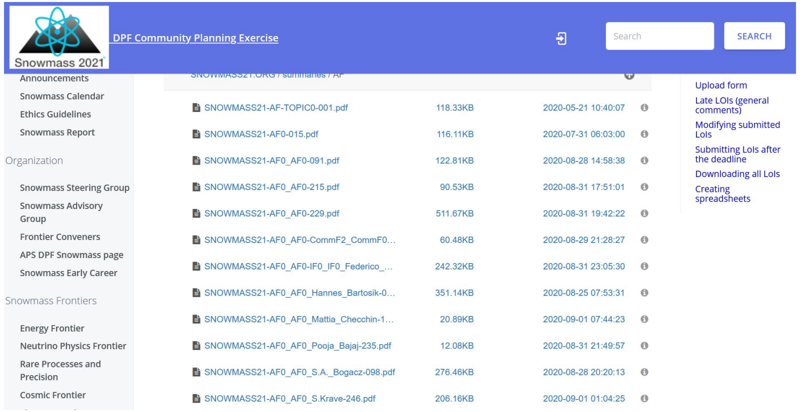
Sarah Cousineau (ORNL)

Vladimir Shiltsev (FNAL)

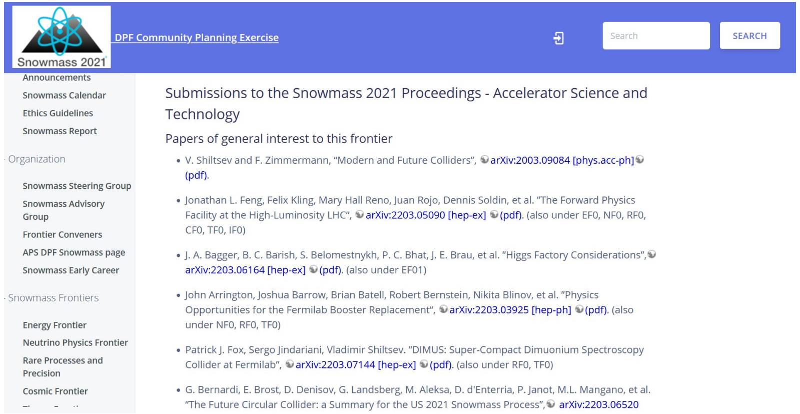
e+e- collider forum: Maria Chamizo Llatas, Sridhara Dasu, Ulrich Heintz, Emilio A. Nanni, John Power, Stephen Wagner

Community Input to the AF

LOIs (more than 300):
https://snowmass21.org/loi



White Papers (116):
https://snowmass21.org/submissions/af



\+ Proponent submitted spreadsheets and parameter tables for the ITF

AF Community Discussions

- **e+e- collider forum**
  - Report: (https://indico.fnal.gov/event/54953/sessions/20614/attachments/156153/205981/e_e_forum_report%20%284%29.pdf)
- **Agora series** (colloquium style)
  - #5 on Future Colliders: Advanced Colliders
  - https://indico.fnal.gov/event/53848/
- **Physics limits of ultimate beams workshops**
  - https://indico.fnal.gov/event/47217/
- **PASAIG,** Plasma and Advanced Structure Accelerator Interest Group
  - https://aacseminarseries.lbl.gov/pasaig

What are the Main Snowmass Outcomes Relevant for the AAC Community?

Message from the EF

While a Higgs/EW factory at 250 to 360 GeV is still the highest priority for the next large accelerator project, the **motivation for a TeV or few TeV e+e− collider has diminished**. Instead, the community is focused on a **10+TeV (parton c.m.e) discovery collider** that would follow the Higgs/EW Factory.

Strong renewed interest in a muon collider at Snowmass

AF4 Evaluated Maturity of Collider Concepts

Review of hadron and lepton colliders options, with focus on evaluating the maturity of the various concepts and the type of support that will be required to provide the high energy physics (HEP) community with the design inputs required for a machine decision.

Collider Concepts	Collider-in-Sea	WFA, MuC, ReLIC (≤3 TeV), MuIC, Multi-TeV ILC (Nb_3Sn), 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.

Figure 1 The AF4 evaluation of the maturity level of various concepts. Further details for the evaluation of the various concepts can be found in the "Concept Assessments" Section. The color code is that the concepts shown in blue offer a path to constituent center-of-mass energies >10 TeV, while those shown in orange are electron-hadron machines, and those shown in black are lepton collider concepts which will reach only into the 1-few TeV range.

- Earliest timescale for making a construction decision for a 10+ TeV machine will be sometime in the next decade.
- Interest remains in the possibility of alternative paths exploring the TeV-scale including lepton-ion and g-g colliders.
- Significant R&D required to mature concepts in the yellow shaded area. Green maturity level required for decision making and informed comparison. 10+ TeV options highlighted in blue.

AF6 (+AAC Community) Prepared 1-15 TeV Collider Parameter Sets

AAC Community responded by providing parameter sets for cme up to 15 TeV as Input to the ITF and the AF (see details in white papers and ITF report)

Proposal Name	CM energy nom. (range) [TeV]	Lum./IP @ nom. CME [10^{34} cm^{-2}s^{-1}]	Years of pre-project R&D	Years to first physics	Construction cost range [2021 B$]	Est. operating electric power [MW]
Muon Collider	10 (1.5-14)	20 (40)	>10	>25	12-18	~300
LWFA - LC (Laser-driven)	15 (1-15)	50	>10	>25	18-80	~1030
PWFA - LC (Beam-driven)	15 (1-15)	50	>10	>25	18-50	~620
Structure WFA (Beam-driven)	15 (1-15)	50	>10	>25	18-50	~450
FCC-hh	100	30 (60)	>10	>25	30-50	~560
SPPS	125 (75-125)	13 (26)	>10	>25	30-80	~400

Table 3: Main parameters of the colliders with 10 TeV or higher parton CM energy. Total peak luminosity for multiple IPs is given in parenthesis. The cost range is for the single listed energy. Collisions with longitudinally polarized lepton beams have substantially higher effective cross sections for certain processes. The relevant energies for the hadron colliders are the parton CM energy, which can be substantially less than hadron CM energy quoted in the table.

AF6 report:

"…to **reducing the dimensions, CO_2 footprint and costs of future high energy physics machines**, with the potential to **reduce power consumption** and offer e+e- and $\gamma-\gamma$ machines to and beyond 15 TeV energies."

Selling points:

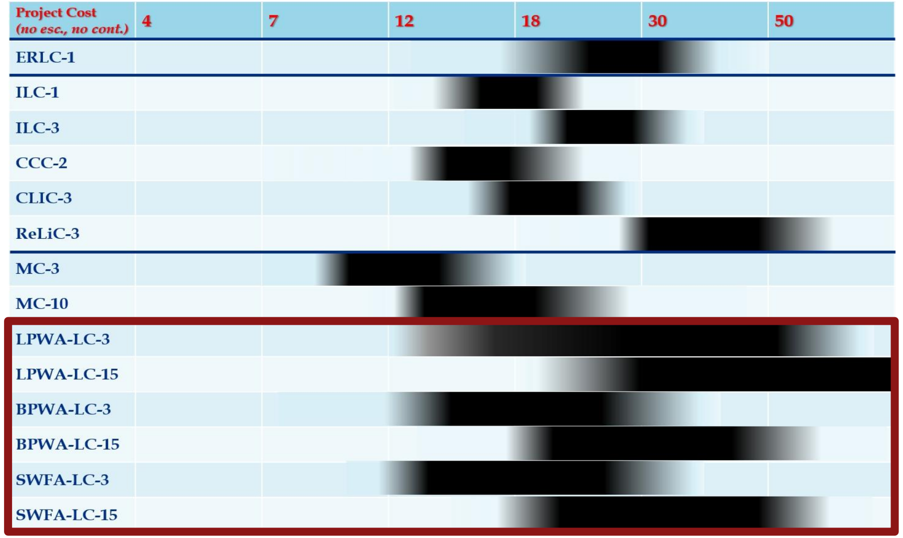
1) Compact
2) Low power consumption
3) Low cost

ITF Evaluated and Compared Collider Properties

Proposal Name	Power Consumption	Size	Complexity	Radiation Mitigation
FCC-ee (0.24 TeV)	290	91 km	I	I
CEPC (0.24 TeV)	340	100 km	I	I
ILC (0.25 TeV)	140	20.5 km	I	I
CLIC (0.38 TeV)	110	11.4 km	II	I
CCC (0.25 TeV)	150	3.7 km	I	I
CERC (0.24 TeV)	90	91 km	II	I
ReLiC (0.24 TeV)	315	20 km	II	I
ERLC (0.24 TeV)	250	30 km	II	I
XCC (0.125 TeV)	90	1.4 km	II	I
MC (0.13 TeV)	200	0.3 km	I	II
ILC (3 TeV)	~400	59 km	II	II
CLIC (3 TeV)	~550	50.2 km	III	II
CCC (3 TeV)	~700	26.8 km	II	II
ReLiC (3 TeV)	~780	360 km	III	I
MC (3 TeV)	~230	10-20 km	II	III
LWFA (3 TeV)	~340	1.3 km (linac)	II	I
PWFA (3 TeV)	~230	14 km	II	II
SWFA (3 TeV)	~170	18 km	II	II
MC (14 TeV)	~300	27 km	III	III
LWFA (15 TeV)	~1030	6.6 km	III	I
PWFA (15 TeV)	~620	14 km	III	II
SWFA (15 TeV)	~450	90 km	III	II
FCC-hh (100 TeV)	~560	91 km	II	III
SPPC (125 TeV)	~400	100 km	II	III

Collider Cost Estimate

- Based on 30 parameter model developed by the ITF
- Upper bound (if build right now)
- Lower bound (estimated after technology R&D), however it is noted in the report that additional cost reduction R&D may further reduce costs



ITF Compares 1-15 TeV Lepton Collider Luminosity and TRL

Peak Luminosity per IP

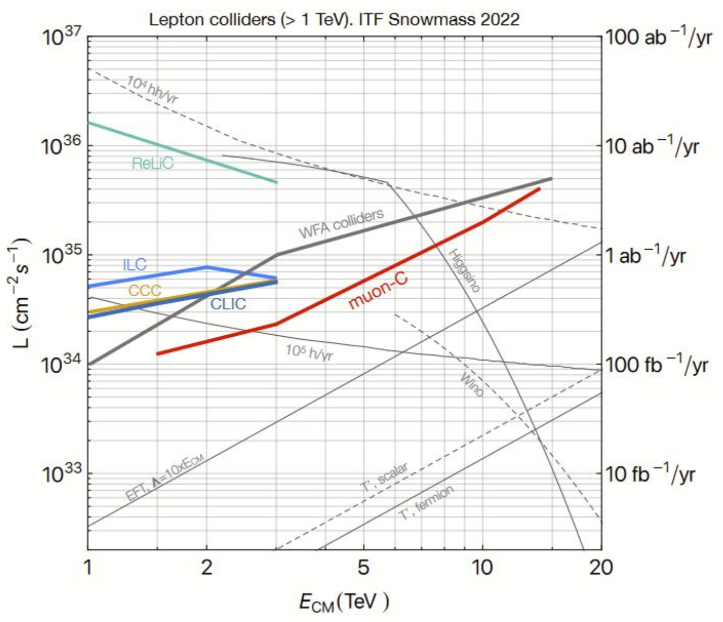


Figure 2: Peak luminosity per IP vs CM energy for the high energy lepton collider proposals as provided by the proponents. The right axis shows integrated luminosity for one Snowmass year (10^7 s). Also shown are lines corresponding to yearly production rates of important processes. The luminosity requirement for 5σ discovery of the benchmark DM scenarios Higgsino and Wino are also shown, see Refs.[21, 22]

Proposal Name (c.m.e. in TeV)	Collider Design Status	Lowest TRL Category	Technical Validation Requirement	Cost Reduction Scope	Performance Achievability	Overall Risk Tier
FCCee-0.24	II					1
CEPC-0.24	II					1
ILC-0.25	I					1
CCC-0.25	III					2
CLIC-0.38	II					1
CERC-0.24	III					2
ReLiC-0.24	V					2
ERLC-0.24	V					2
XCC-0.125	IV					2
MC-0.13	III					3
ILC-3	IV					2
CCC-3	IV					2
CLIC-3	II					1
ReLiC-3	IV					3
MC-3	III					3
LWFA-LC 1-3	IV					4
PWFA-LC 1-3	IV					4
SWFA-LC 1-3	IV					4
MC 10-14	IV					3
LWFA-LC-15	V					4
PWFA-LC-15	V					4
SWFA-LC-15	V					4
FCChh-100	II					3
SPPC-125	III					3
Coll.Sea-500	V					4

AAC-Relevant messages from Snowmass to P5

Snowmass does **not!** prioritize or rank.
Snowmass ⇒ P5 ⇒ ARD sub panel ⇒ Advanced Accelerator Development Strategy

P5 is starting starting now, panel formed in early fall.
Chaired by Hitoshi Murayama
(University of California, Berkeley)

P5 Prioritizations expected mid-2023

Community Input → **WG + ITF Reports** → **AF Report** → **Snowmass Report** → **P5 Report**

Input from the WGs → AF

AF6 (selected highlights, more in the report)

Support:

- …vigorous research on advanced accelerators…
- A targeted R&D program addressing high energy advanced accelerator-based colliders
- Recognize research in near-term application as essential for progress towards HEP colliders
- Advanced accelerators workforce development
- Enhanced driver R&D to develop the efficient, high repetition rate high average power laser and charged particle beam technology
- Upgrades for beam test facilities
- A study for a collider demonstration facility and physics experiments at an intermediate energy
- A doe-hep sponsored workshop in the near term should update and formalize the U.S. Advanced accelerator strategy and roadmaps

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ITF (see report for complete list):

- Recommend that R&D to **reduce the cost and the energy consumption** of future collider projects is given high priority.
- etc…

Input from the WGs → AF

AF6 (selected highlights, more in the report)
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- …vigorous research on advanced accelerators…
- A targeted R&D program addressing high energy advanced accelerator-based colliders
- Recognize research in near-term application as essential for progress towards HEP colliders
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- Enhanced driver R&D to develop the efficient, high repetition rate high average power laser and charged particle beam technology
- Upgrades for beam test facilities
- A study for a collider demonstration facility and physics experiments at an intermediate energy
- A doe-hep sponsored workshop in the near term should update and formalize the U.S. Advanced accelerator strategy and roadmaps

ITF (see report for complete list):

- suggests that Snowmass CSS recommends that R&D to **reduce the cost and the energy consumption** of future collider projects is given high priority.
- etc…

AF4 (see report for complete list):

- Support & fund collider R&D to provide viable options to the 10+ TeV energy scale.
- etc…

AF Summary Report - Selected Highlights (1/2)

- **Support technical exploration of 10+TeV Collider options**
    - … the discovery machines such as O(10 TeV c.m.e.) **muon colliders** have rapidly gained significant momentum. To be in a position for making decisions on collider projects viable for construction in the 2040s and beyond at the time of the next Snowmass/P5, these concepts could be explored technically and documented in pre-CDR level reports by the end of this decade.
    - (mentioned later in the report in the same context)…R&D is in progress on other concepts such as wakefield based e +e − or γγ systems which may present additional future options.

- Advanced wakefield accelerator concepts should strive toward **demonstration of collider quality beams**, efficient drivers and staging, and development of self-consistent parameter sets for potential colliders based on wakefield acceleration in plasma and structures (in **close coordination with international programs** such as the European Roadmap, EuPRAXIA, etc.);

AF Summary Report - Selected Highlights (2/2)

- In accelerator and beam physics - the focus should be on **experimental, computational and theoretical studies on acceleration** and control of high intensity/high brightness beams, high performance computer modeling and AI/ML approaches, and design integration and optimization. The program should also include the **overall energy efficiency** of future facilities and re-establish a program of beam physics research on general collider-related topics towards future e^+e^- colliders and muon colliders.

- In the context of AAC: **At this time, there are no parameter sets for a plasma or structure based linear collider that self-consistently address the known accelerator physics challenges in a linear collider** –... However, acceleration of beams with ultra-high gradients (GeV/m and beyond) **will reduce the dimensions and thus potentially reduce the costs and power consumption of future high energy physics machines with the potential to offer e^+e^- and γγ colliders at and beyond 15 TeV.** Recognizing this promise, the last Snowmass and P5/HEPAP recommended, and DOE developed with the community, an organized Advanced Accelerator Development Strategy, and work has been aligned to this strategy

What did we (AAC community) learn from Snowmass ?

AAC collider option have not been included in the AF report.
Concepts are mentioned as promising R&D efforts.

To-do List for the AAC Community (1/2)

Before AAC colliders can/should be discussed for an option:

- Produce a **consistent parameter set**, and refine the wakefield collider parameters.
  - Be clear about assumptions
  - Connect components, move away from single component design.
  - Include a description of a linac arm for positrons acceleration (e.g., hollow channels plus focusing)
  - Clarify how many orders of magnitude we are away from the state of the art.
  - Cost estimates, including the impact of some of the stringent component tolerances, should be made to understand if the potential cost benefit of the new technologies can be realized.
- Evaluate overall **efficiency** (driver, wakefield, witness)
- Define **tolerances** (transverse stability requirements, in particular for e+)
- Evaluate **source design**: e.g. what is the design of a positron source that operates at ~50 kHz?
- Need collaboration structure. Oversight committee. Reference documents.

To-do List for the AAC Community (2/2)

Detector studies for particle physicists; predict HEP event rates.

- Simulations of **beamstrahlung to determine the luminosity spectrum**. Need to validate tools used for extrapolation (current results e.g. Guinea Pig can't be trusted in the 10s of TeV parameter regime).
  - Describe fraction of useful luminosity for round beam case
- **BDS system design is beyond the state of the art**. Is there a realistic design at all? with short focal length plasma lenses? How is round beam final focus done at IP (including realistic energy spread)?
  - If used, how can plasma lens FF be compatible with current detectors? How do we integrate vertex detectors?

Need for AAC concepts to engage with HEP community, started via ITF⇒ continue by engaging the conventional accelerator community and keep being engaged through cycle.

Summary & Conclusions

Summary & Conclusions

- Snowmass is a **Particle Physics Community Planning Exercise**, provides input to P5 to produce scientific vision for the future of particle physics in the U.S. and happens every ~8 years. P5 will prioritize.
- Interest has shifted from a TeV-Scale Collider to a **10+ TeV Scale Collider**
- AF Report **encourages R&D on AAC** technologies but does not acknowledge them as being promising 10+ TeV collider options yet
- To be included they asked the AAC Community to develop **consistent collider parameters sets**, that include detector considerations and to document them together with the technology gaps

Thank you for your attention!

Backup

AF4 maturity scale

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.

EF desires a 10+ TeV Lepton Collider

Covers new R&D concepts for particle acceleration, generation, and focusing.

Highlights from the executive summary:

- Goal: to reducing the dimensions, CO2 footprint and costs of future high energy physics machines, with the potential to reduce power consumption and offer e+e- and $\gamma - \gamma$ machines **to and beyond 15 TeV energies**.
- While recent results indicate that the main building blocks of future advanced accelerators are workable and promising, significant development is still required. There are still several challenges to be addressed including how to achieve the high wall-plug efficiency and high repetition rates needed to fulfill future collider luminosity requirements, how to preserve small energy spreads and beam emittance over many acceleration stages and, for plasmas, efficient positron acceleration.
- Integrated design study: ..The european minimum requested funding for the design study is 75 FTE-years… The us should match and coordinate with this effort.

Technology	PWFA	PWFA	PWFA	SWFA	SWFA	SWFA	LWFA	LWFA	LWFA
Aspect Ratio	Flat	Flat	Round	Flat	Flat	Round	Flat	Flat	Round
CM Energy	1	3	15	1	3	15	1	3	15
Single beam energy (TeV)	0.5	1.5	7.5	0.5	1.5	7.5	0.5	1.5	7.5
Gamma	9.78E+05	2.94E+06	1.47E+07	9.78E+05	2.94E+06	1.47E+07	9.78E+05	2.94E+06	1.47E+07
Emittance X (mm mrad)	0.66	0.66	0.1	0.66	0.66	0.1	0.1	0.02	0.1
Emittance Y (mm mrad)	0.02	0.02	0.1	0.02	0.02	0.1	0.01	0.007	0.1
Beta* X (m)	5.00E-03	5.00E-03	1.50E-04	5.00E-03	5.00E-03	1.50E-04	2.50E-02	1.40E-02	1.50E-04
Beta* Y (m)	1.00E-04	1.00E-04	1.50E-04	1.00E-04	1.00E-04	1.50E-04	1.00E-04	1.00E-04	1.50E-04
Sigma* X (nm)	58.07	33.53	1.01	58.07	33.53	1.01	50.55	9.77	1.01
Sigma* Y (nm)	1.43	0.83	1.01	1.43	0.83	1.01	1.01	0.49	1.01
N_bunch (num)	5.00E+09	5.00E+09	5.00E+09	3.13E+09	3.13E+09	3.13E+09	1.20E+09	1.20E+09	7.50E+09
Freq (Hz)	4200	14000	7725	11000	36000	19800	46856	46856	3435
Sigma Z (um)	5	5	5	40	40	40	8.4	8.4	2.2
Beamstrahlung param	15	78	6590	1	6	515	2	37	22466
n_gamma	1.5	1.5	5.7	2.2	2.2	8.4	0.8	1.5	5.7
Single Beam Power (MW)	1.7	16.8	46.4	2.8	27.0	74.4	4.5	13.5	31.0
Two Beam Power (MW)	3.4	33.6	92.8	5.5	54.1	148.7	9.0	27.0	61.9
Geo. Lumi (cm-2 s-1)	1.01E+34	1.01E+35	1.50E+36	1.03E+34	1.01E+35	1.51E+36	1.05E+34	1.13E+35	1.50E+36
Beamstrahlung lumi	1.99E+34	1.99E+35	1.52E+36	2.03E+34	2.00E+35	1.52E+36	2.09E+34	2.17E+35	1.52E+36
Wall plug to drive laser/beam eff	0.4	0.4	0.4	0.774	0.774	0.774	0.4	0.4	0.5
Laser/beam drive to main eff	0.375	0.375	0.375	0.42	0.42	0.42	0.2	0.2	0.12
Wall plug to main beam eff	0.15	0.15	0.15	0.32508	0.32508	0.32508	0.08	0.08	0.06
Site power Wall to main only (MW)	22	224	619	17	166	457	113	338	1032
Lumi/Power (1e34/MW)	0.04	0.04	0.08	0.06	0.06	0.11	0.01	0.03	0.05
GUINEA-PIG Total Lumi	1.83E+34	1.85E+35	4.2E+37	2.08E+34	2.13E+35	4.2E+36	1.53E+34	2.58E+35	6E+36
GUINEA-PIG Lumi 1% (20%)	6.86E+33	6.23E+34	5E+35	8.49E+33	6.14E+34	5E+35	1.03E+34	8.72E+34	5E+35
GP Total Lumi/Power	0.08	0.08	6.79	0.12	0.13	0.92	0.01	0.08	0.58
GP Lumi 1%/Power (20%)	0.03	0.03	0.08	0.05	0.04	0.11	0.01	0.03	0.05
Length of 2 Linacs (km)	1	3	14	5	15	75	0.44	1.3	6.5
Length of Facility	14	14	14	8	18	90	3.5	4.5	9.5