Advanced Accelerator Concepts
Wakefield colliders & the U.S. Snowmass Process

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Thanks to: Marlene Turner, Spencer Gessner (liasons to ITF & AF4)

22 September 2023

Thank You to the AF6 & Advanced Accelerator Community

Report of the Accelerator Frontier Topical Group 6 on Advanced Accelerator Concepts for Snowmass 2021
https://arxiv.org/abs/2208.13279

Includes citations for this talk

Also: novel RF, other concepts (not the focus of this talk)

Thanks for coordination and work with the Implementation Task Force and AF4 collider Groups, the overall AF, EF, TF, CoF, CmF, and the overlapping European Strategy for Particle Physics Roadmap group.

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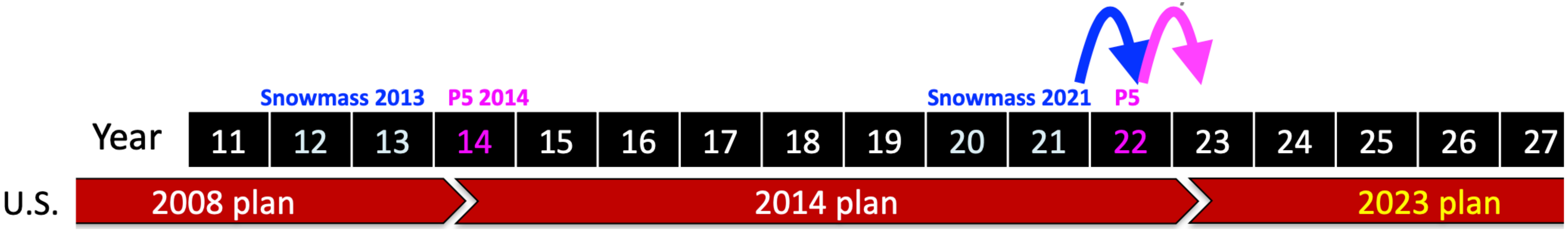
Strategic Planning Process for U.S. Particle Physics

- Particle physics is the largest driver of U.S. investment in advanced accelerators
  - Light sources and other DOE nearer term applications based from stewardship of collider technology
  - NSF programs are broadly based
- DOE and NSF programs in particle physics are guided by decadal planning
  - Snowmass community science study defined important questions, promising opportunities
  - 2-year discussion across the field develops and provides community input / interest on opportunities
  - Particle physics Project Prioritization Panel "P5" formulates a 10-year plan and 20 year vision within funding constraints. Subpanel of High Energy Physics Advisory Panel, advising DOE & NSF.



Snowmass 2013 P5 2014 Snowmass 2021 P5

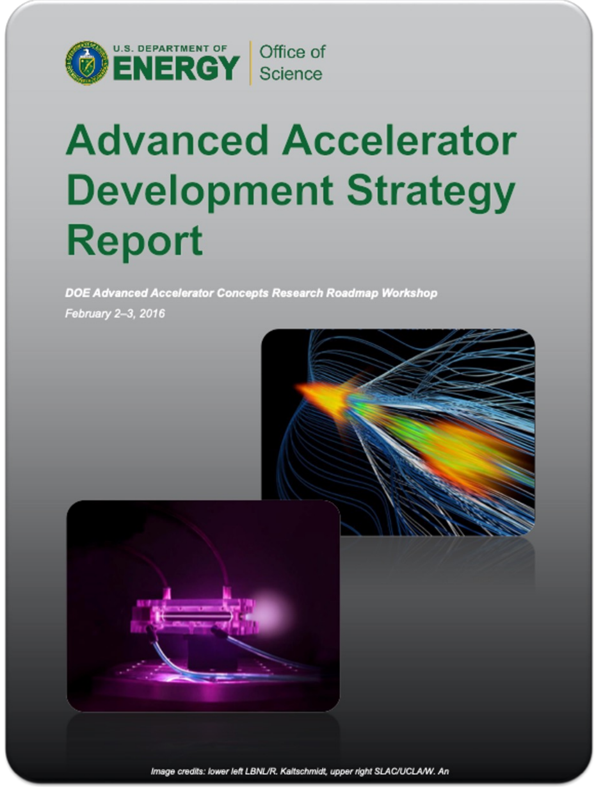
Year	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27

U.S. 2008 plan 2014 plan 2023 plan

  - Parallel: International benchmarking panel, to be released Nov 2nd (https://science.osti.gov/hep/hepap/Meetings)
  - Parallel: National Academies studies define overall scientific vision-Elementary Particle Physics ongoing
  - Related to: planning for other U.S. science areas such as nuclear physics, fusion and plasmas; international planning including the European Strategy for Particle Physics, Japan, others

2016 Advanced Accelerator Development Strategy Guides Technical Efforts

- Roadmaps developed following Snowmass 2013 and ensuing P5 and HEPAP sub-panel
  - Community representatives organized workshops and worked with DOE HEP to define roadmaps for three AAC technologies: LWFA, PWFA and SWFA towards colliders and near term applications

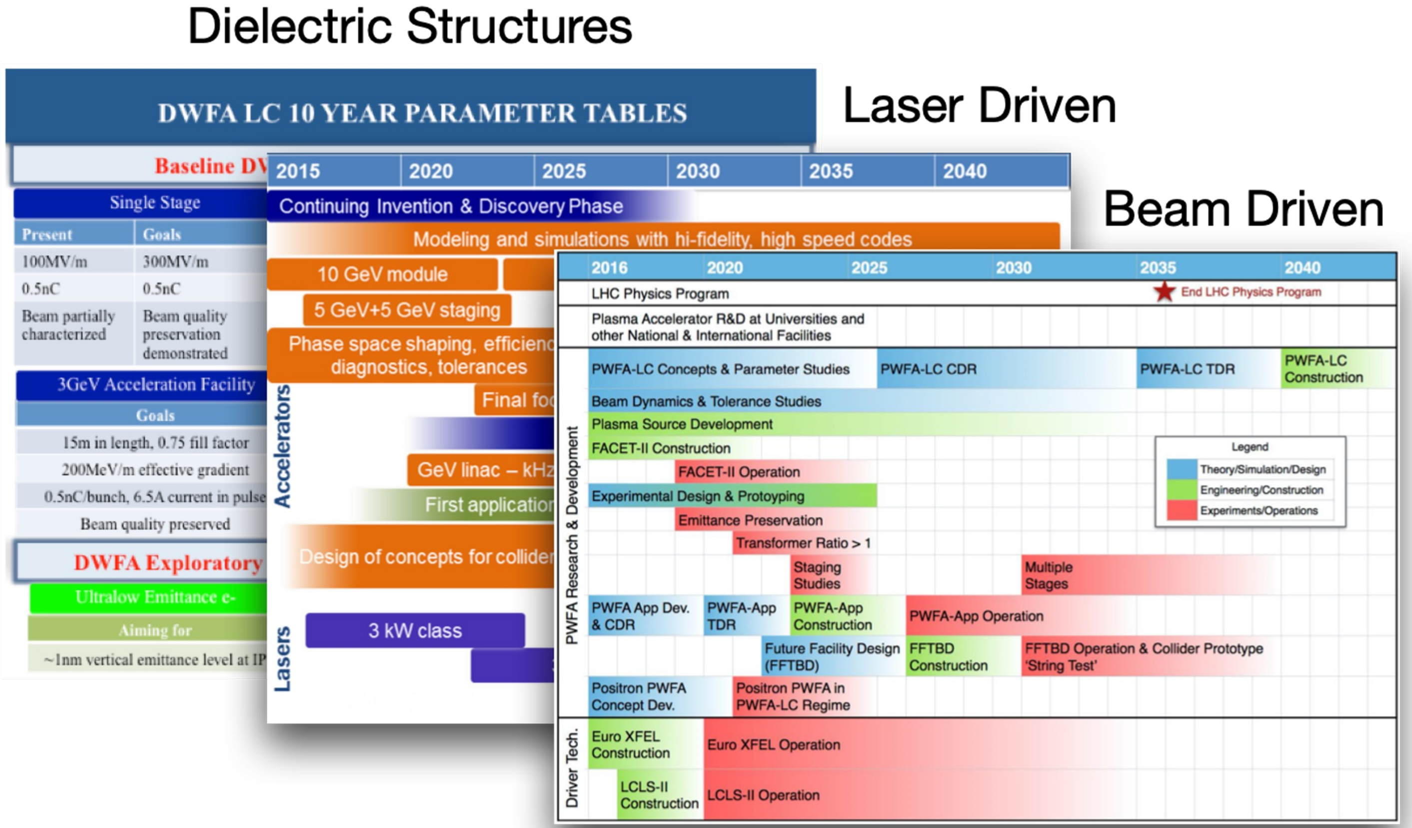


U.S. DEPARTMENT OF ENERGY | Office of Science

Advanced Accelerator Development Strategy Report

DOE Advanced Accelerator Concepts Research Roadmap Workshop
February 2–3, 2016

Image credits: lower left LBNL/R. Kaltschmidt, upper right SLAC/UCLA/W. An



Dielectric Structures

DWFA LC 10 YEAR PARAMETER TABLES

Baseline DV

Single Stage

Present	Goals
100MV/m	300MV/m
0.5nC	0.5nC
Beam partially characterized	Beam quality preservation demonstrated

3GeV Acceleration Facility

Goals

15m in length, 0.75 fill factor
200MeV/m effective gradient
0.5nC/bunch, 6.5A current in pulse
Beam quality preserved

DWFA Exploratory

Ultralow Emittance e-
Aiming for
~1nm vertical emittance level at IP

Laser Driven

2015 | 2020 | 2025 | 2030 | 2035 | 2040

Continuing Invention & Discovery Phase
Modeling and simulations with hi-fidelity, high speed codes
10 GeV module
5 GeV+5 GeV staging
Phase space shaping, efficienc
diagnostics, tolerances
Final fo
GeV linac – kHz
First applicatio
Design of concepts for collider
3 kW class

Beam Driven

2016 | 2020 | 2025 | 2030 | 2035 | 2040

LHC Physics Program
★ End LHC Physics Program
Plasma Accelerator R&D at Universities and other National & International Facilities

PWFA Research & Development:
PWFA-LC Concepts & Parameter Studies
PWFA-LC CDR
PWFA-LC TDR
PWFA-LC Construction
Beam Dynamics & Tolerance Studies
Plasma Source Development
FACET-II Construction
FACET-II Operation
Experimental Design & Protoyping
Emittance Preservation
Transformer Ratio > 1
Staging Studies
Multiple Stages
PWFA App Dev. & CDR
PWFA-App TDR
PWFA-App Construction
PWFA-App Operation
Future Facility Design (FFTBD)
FFTBD Construction
FFTBD Operation & Collider Prototype 'String Test'
Positron PWFA Concept Dev.
Positron PWFA in PWFA-LC Regime

Driver Tech.:
Euro XFEL Construction
Euro XFEL Operation
LCLS-II Construction
LCLS-II Operation

Legend
🟦 Theory/Simulation/Design
🟩 Engineering/Construction
🟥 Experiments/Operations

2022 AF6 Assessed and Planned Advanced Accelerator Options For Future Colliders With Related Snowmass Groups

- Energy, Theory Frontier – motivation for high energy colliders, physics analysis of collider options
  - Physics pull that drives accelerator needs, assessment of detector performance, theory
- Community Engagement – near term applications, DEI…; Computational – simulation tools
- Accelerator Frontier – needs to advance physics; state of art; facilities available in next decade; R&D to enable future opportunities; time and cost scales of R&D and test facilities
  - AF6 – Advanced Accelerator Concepts for future colliders, relationship to other applications Conveners were also observers for European LDG activity
  - AF4 – Multi-TeV colliders – Assessment of collider options and readiness https://indico.fnal.gov/event/22303/contributions/246818/attachments/157318/205796/AF4_Summary_Rev3.pptx
  - Implementation Task Force – Compared collider properties (https://arxiv.org/abs/2208.06030)
  - Joint AF/EF evaluation of lepton options: e+e- Collider Forum (https://arxiv.org/abs/2209.03472) & Muon Collider Forum (https://arxiv.org/abs/2209.01318)
  - Agora #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 & Advanced Structure Accelerator Interest Group (https://aacseminarseries.lbl.gov/pasaig)

Strong Energy & Theory Frontier Interest in 10+ TeV

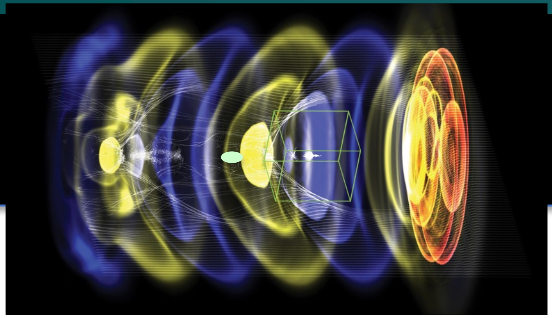
- Higher energy scale than emphasized in the last Snowmass driven by evolving data

- Leptons offer clean collisions and strong physics potential
  - Motivates R&D to reduce cost and energy consumption and provide viable options at 10+ TeV
  - Similar physics is anticipated to be accessible with muons or e+e-
  - $\gamma\gamma$ colliders likely access significant portion of physics, analysis less complete
  - Muon collider forum: included detailed EF analysis driven by renewed muon collider effort and presence, spanning accelerator, energy, instrumentation (detection) and theory frontiers
  - e+e- collider forum: identified potential for similar signatures, potential LC benefit via AF6 methods

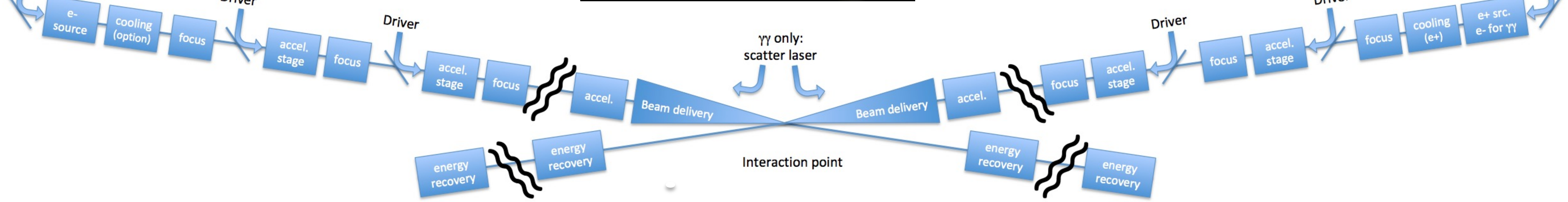
- Challenging energy scale emphasizes
  - R&D on new technologies
  - Energy efficiency
  - Leverage of nearer term applications

Addressing WakeField Collider Challenges

Wake of intense laser or beam creates very high fields in plasmas, structures



Laser (red) or beam drives density wave (blue to yellow) in plasma/structure, accelerating e- (white), e+ (blue) with fields ~ 10 GeV/m



focus

- Source – potential direct nm electron emittance
- Accelerator: stages to minimize length, power
  - Charge consistent with collision limits ~ nC implies O(10 GeV)
  - Each stage: 10 Joule-Class laser or beam driver
  - Precision alignment required- active feedback

next

- Rep rate for Luminosity ~ 10's of kHz
- Positron methods: fast cooling potential, non-symmetric acceleration in plasmas,
- Interaction region: strong focusing, energy recovery

Reinforced by strong near term applications

Free Electron Lasers

The international journal of science / 22 July 2021

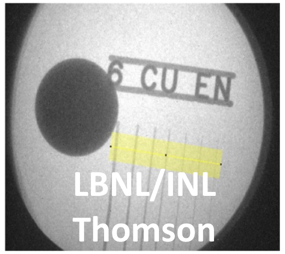
nature

COMPACT SOURCE

Plasma-based acceleration paves way to smaller free-electron lasers

W. Wang et. al, Nature Vol 595 (2021)
Now more than four groups

Precision imaging



Compact muon sources

DARPA

Assessment of Limits Over Last Decade: 15 TeV-class Potential

- Community addressed many potential limits of high-gradient linac technology including
  - Shaped bunches can be used to efficiently accelerate beams without energy spread growth
  - Ion motion induced by dense beams can mitigate transverse hosing instability
  - Scattering in plasma mitigated by strong plasma focusing
  - Energy spread from synchrotron radiation in plasma limited by small beam emittances
  - Laser and beam energy recovery may be used for improved efficiency
  - Supported by experimental results e.g.: 10 GeV class beams, beam loading & efficiency, plasma recovery, staging, high transformer ratio, positrons, and FEL-lasing demonstrating high beam quality

- Concepts for addressing limits need to be developed to integrated collider concepts
  - 100’s of stages: Beam matching / coupling between including efficiency ≥ 99%
  - Small accelerating structures place challenging alignment and jitter tolerances
  - Plasma-based positron stages, beam delivery system and final focus

- Wall-plug power is the apparent limit of energy reach of e+/e- linear colliders based on AAC
  - Beamstrahlung limits bunch charge and luminosity requirements increase required power:
  - Short beams and low emittance could reduce power requirements
  - High gradients could enable practical energy recovery

Collider Potential to 15+ TeV & Re-using Near-Term Facilities

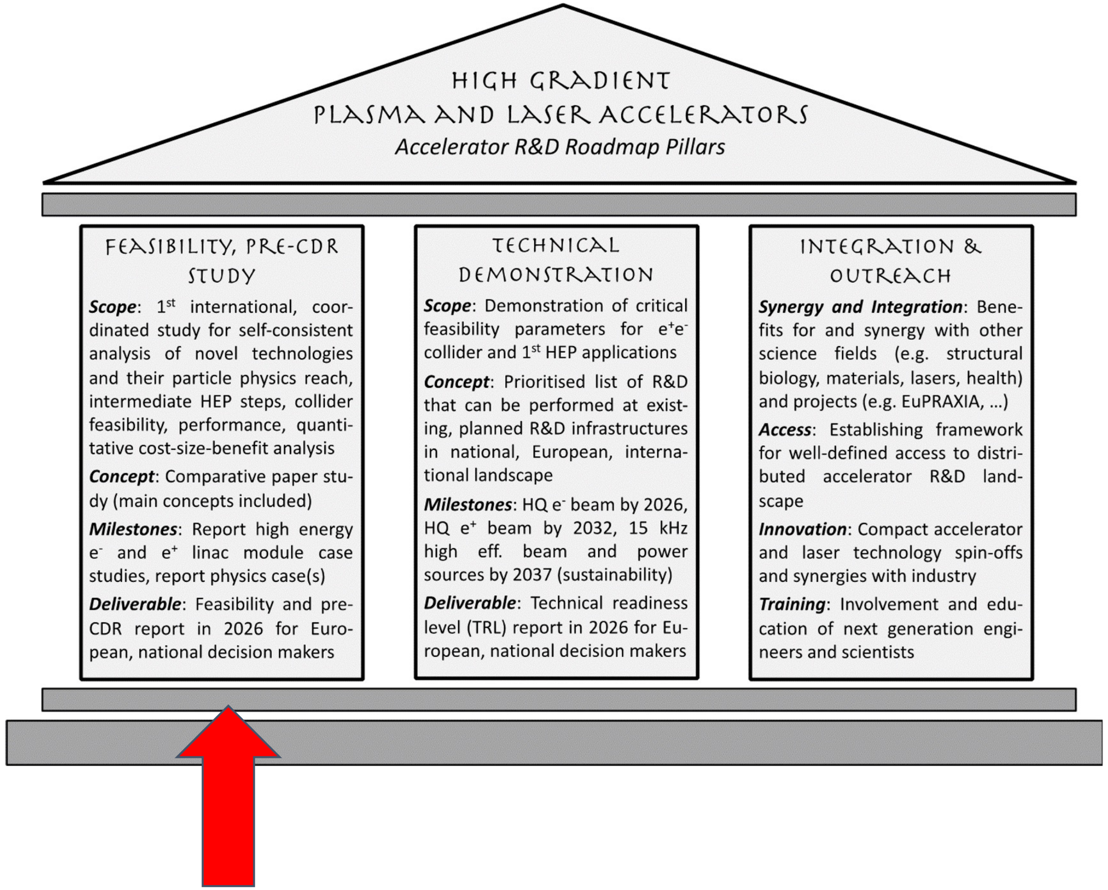
- Similar parameter ranges accessible to each wakefield technology: coordinated example
  - TeV-class established as part of 2016 AARD report, extended to 3 - 15 TeV range
  - **Towards a wakefield collider concept, with technology alternatives (likely to use > 1?)**
  - Potential to re-use infrastructure of nearer-term LC (e.g. ILC, CCC) to enable many TeV
  - Potential injectors, upgrades for conventional colliders & accelerators
- Sequence of collider options available to the 15 TeV class: polarized e+e- or $\gamma\gamma$
  - Coordinated with European Strategy Group, overlapping Snowmass
  - New concepts continue to
- Conceptual parameter sets, based on simulations of components

Example: similar sets for beam driven and structure

Laser-plasma linear e-/e+ collider		3 TeV
Beam energy	TeV	1.5
Particle number (1E9)		1.2
Beam power	MW	13
Luminosity (1E34)	cm-2 s-1	10
Transverse. beam sizes at IP, x/y	nm	10 / 0.5
IP beta function, β*	mm	0.1
RMS bunch length	micron	8.5
Repetition frequency	kHz	47
Time between collisions	microsec	21
Beamstrahlung photons/e-		1.7
Length (2x main linac tunnel)	km	1.3
Facility site power (2 linacs)	MW	315

LWFA parameters: 1 um laser wavelength, 10^{17} cm^{-3} plasma density

Integrated Design Study* is Needed



HIGH GRADIENT
PLASMA AND LASER ACCELERATORS
Accelerator R&D Roadmap Pillars

FEASIBILITY, PRE-CDR STUDY

Scope: 1st international, coordinated study for self-consistent analysis of novel technologies and their particle physics reach, intermediate HEP steps, collider feasibility, performance, quantitative cost-size-benefit analysis

Concept: Comparative paper study (main concepts included)

Milestones: Report high energy e^- and e^+ linac module case studies, report physics case(s)

Deliverable: Feasibility and pre-CDR report in 2026 for European, national decision makers

TECHNICAL DEMONSTRATION

Scope: Demonstration of critical feasibility parameters for e^+e^- collider and 1st HEP applications

Concept: Prioritised list of R&D that can be performed at existing, planned R&D infrastructures in national, European, international landscape

Milestones: HQ e^- beam by 2026, HQ e^+ beam by 2032, 15 kHz high eff. beam and power sources by 2037 (sustainability)

Deliverable: Technical readiness level (TRL) report in 2026 for European, national decision makers

INTEGRATION & OUTREACH

Synergy and Integration: Benefits for and synergy with other science fields (e.g. structural biology, materials, lasers, health) and projects (e.g. EuPRAXIA, …)

Access: Establishing framework for well-defined access to distributed accelerator R&D landscape

Innovation: Compact accelerator and laser technology spin-offs and synergies with industry

Training: Involvement and education of next generation engineers and scientists

European Strategy for Particle Physics Roadmap for Accelerator R&D highlights the need for pre-CDR study

- Develop fully self consistent start-to-end collider designs
  - Includes: alignment and jitter tolerances, stage matching/coupling, BDS and Final focus
- Develop detector and interaction point designs
- Conduct physics studies with Energy & Theory Frontier
- Tech demonstrators, components, collider demo., staged collider E to ≥10TeV
- First steps in Snowmass – critical to build on this

EUROPEAN
PLASMA RESEARCH
ACCELERATOR WITH
EXCELLENCE IN
APPLICATIONS

The EuPRAXIA Preparatory Phase Project

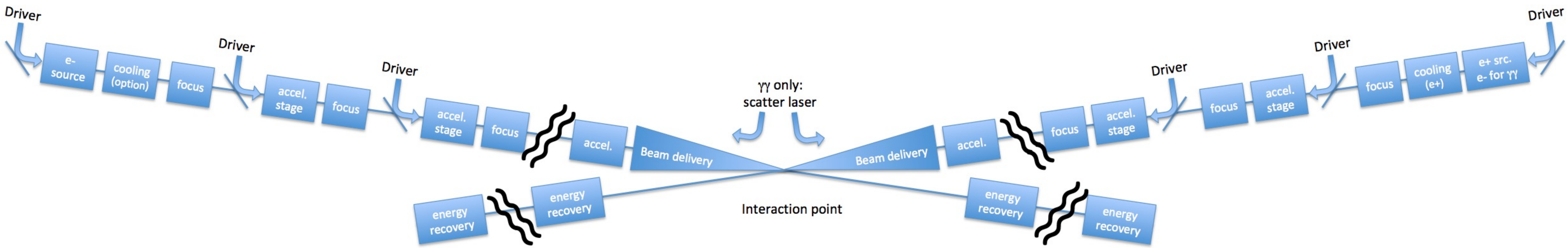
Ralph W. Aßmann, Coordinator EuPRAXIA, DESY & INFN
I.FAST Yearly Meeting 2022 - CERN
4 – 6 May 2022

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 653782.

Strong overlap of AAC with compact light sources

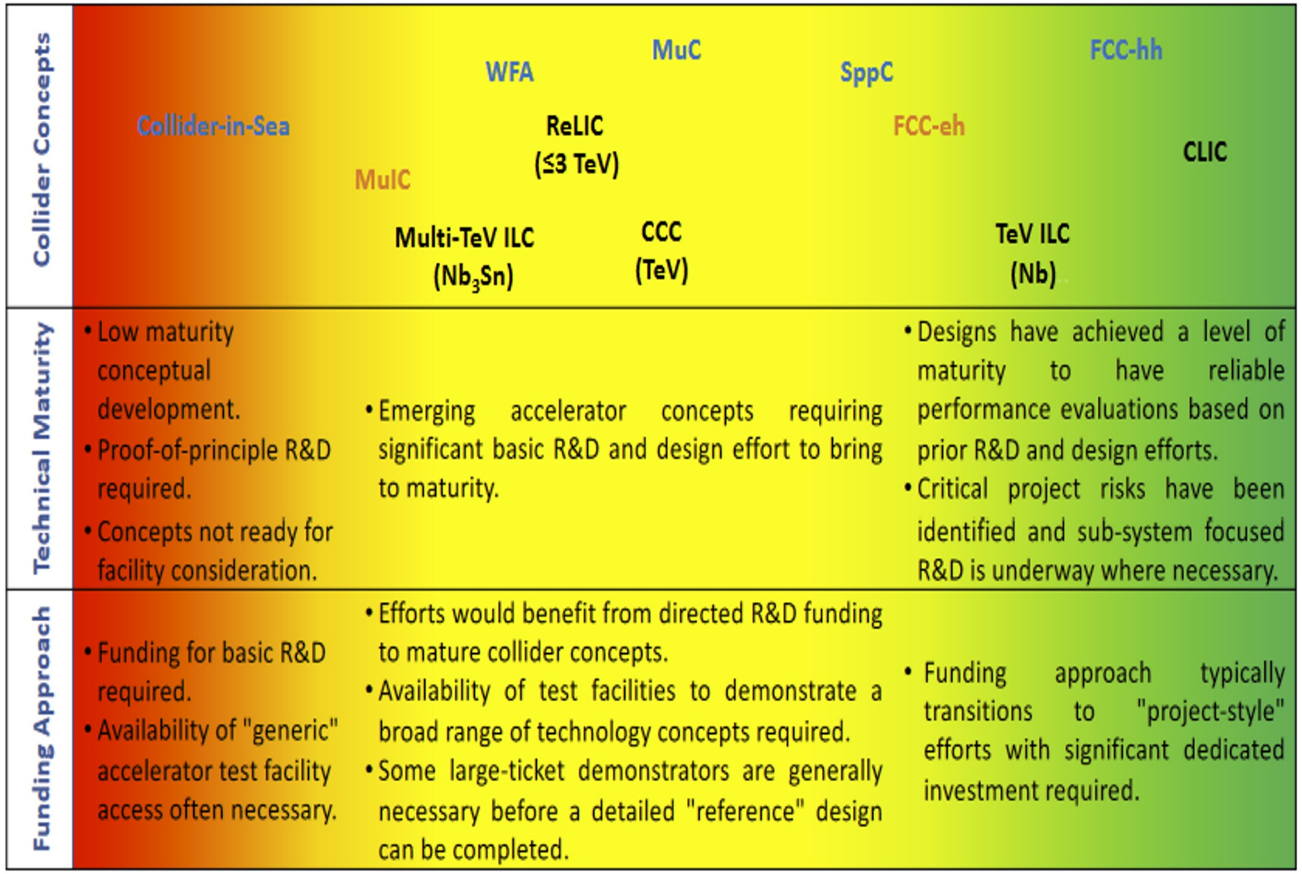
* Also referred to as self consistent design study

AF6 Selected Highlights



- ○ Advanced accelerators in beam and laser driven structures/plasmas offer potential for compact, energy efficient future e-e+/gg colliders to 15 TeV range with few TeV/km geometric gradients
- ○ AF6 key recommendations …vigorous research on advanced accelerators as part of General Accel. R&D
  - ■ A targeted R&D program addressing high energy advanced accelerator-based colliders
  - ■ Recognize near-term applications as essential & providing leverage to colliders-strengthen connections
  - ■ Enhanced driver R&D to develop efficient, high repetition rate high average power… technology
  - ■ Upgrade beam test facilities, continue strong role in workforce, recruiting including high repetition rate facility kBELLA, positrons at FACET-II, integrated SWFA at AWA
  - ■ Pursue 10’s GeV collider demonstration study develop physics experiments at intermediate energy
  - ■ A DOE-HEP sponsored workshop should update and formalize the U.S. Advanced accelerator strategy

AF4 Evaluated Collider Options for Maturity



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.

- 10+ TeV options highlighted in blue
  - Also: novel RF – TeV class + injectors
- Significant R&D required to mature concepts in the yellow shaded area.
- Green maturity level required for decision making and informed comparison.
  - No lepton option in this range yet
  - Advanced accelerators perceived as less mature than alternatives
  - Need for R&D, tech. demonstrations, applications & collider design
  - Interest remains in alternative paths including lepton-ion and γ–γ colliders.

Implementation Task Force

- Key question for Snowmass Accelerator Frontier: performance potential, time and cost scales of potential collider projects
  - 0.25 TeV, 3TeV, and 10-TeV classes

- Implementation Task Force (ITF): broad group of collider and accelerator experts
  - Metrics and process to evaluate proposals and allow a balanced comparison
  - Assessment of schedule and R&D status
  - Associated test facilities and steps

- Expected costs using same process
  - Cost models developed: facilities, sources and cooling, power are major contributors
  - Not always clear smaller is cheaper
  - Collider design requires system approach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Tor Raubenheimer
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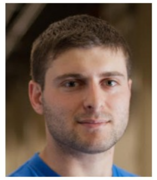
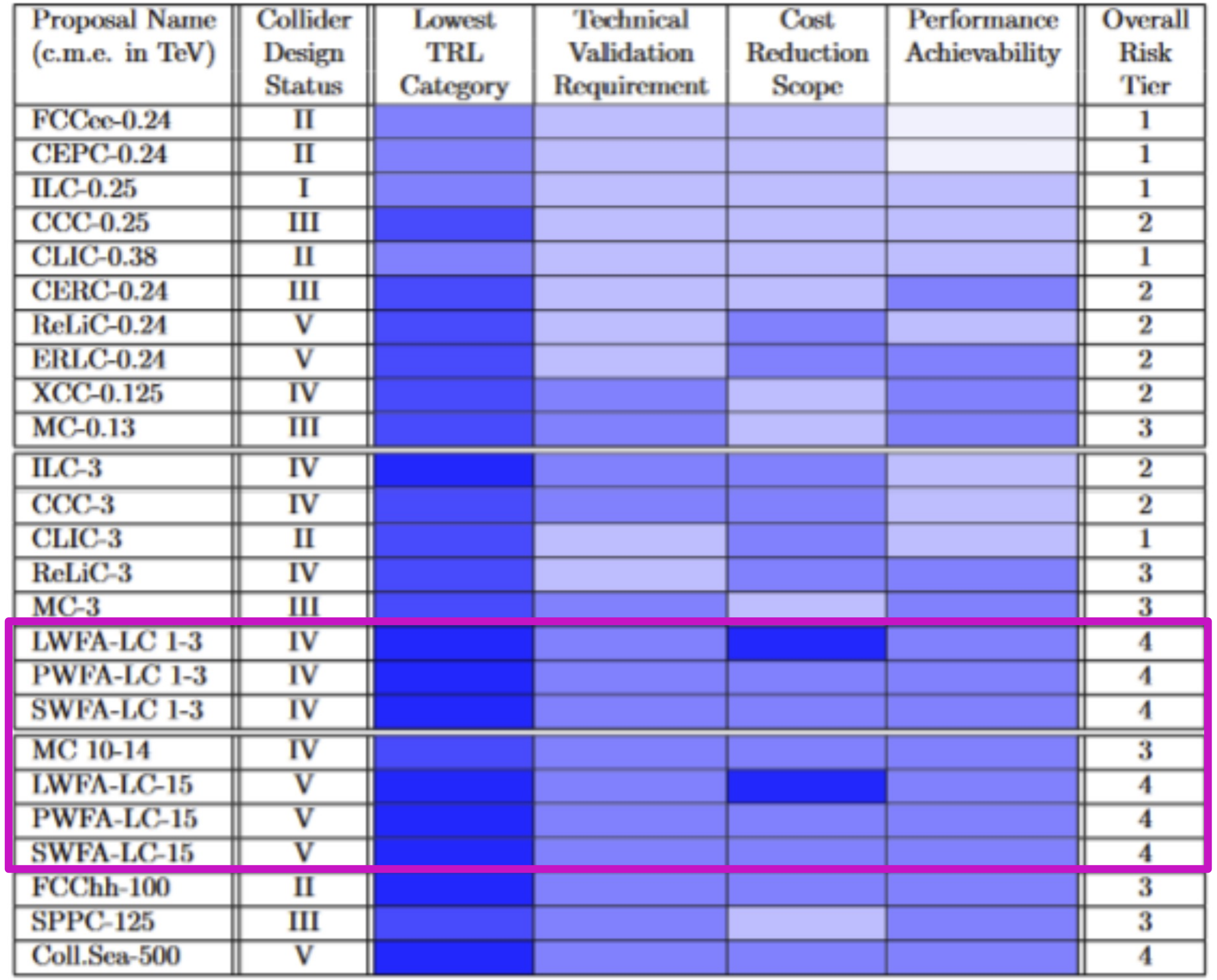
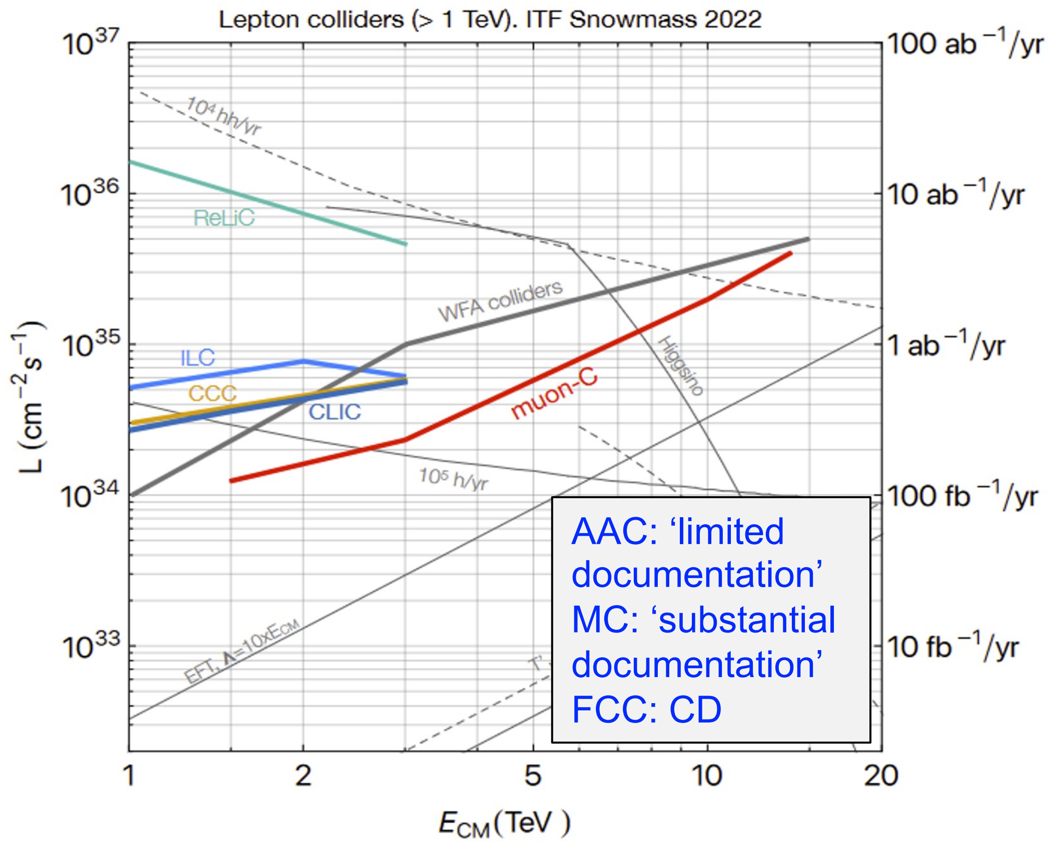

Spencer Gessner
(SLAC)

ITF report: https://arxiv.org/abs/2208.06030
Marlene's talk: https://agenda.infn.it/event/28376/contributions/179407/

ITF Compared Potential Collider Properties



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

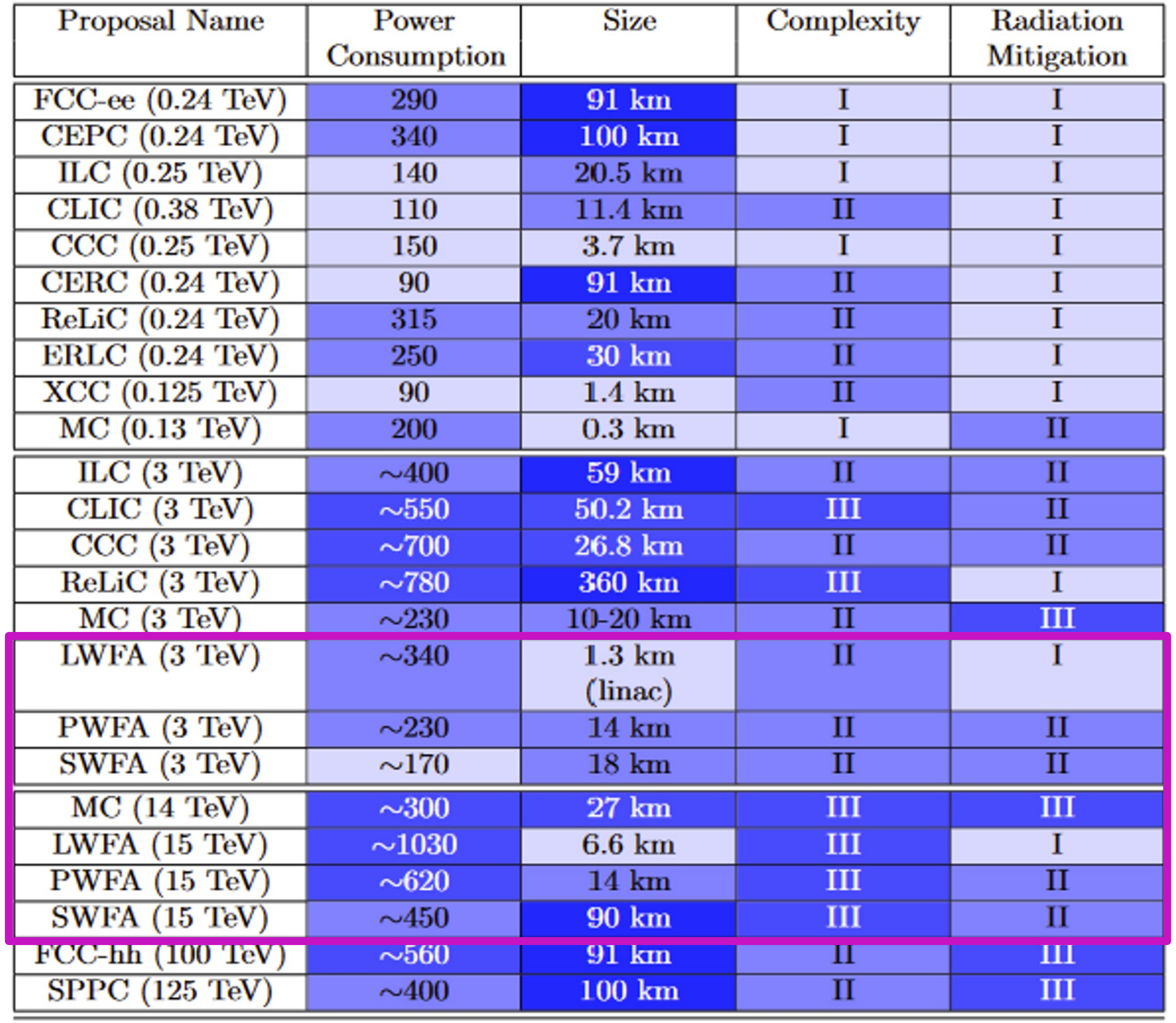


AAC: 'limited documentation'
MC: 'substantial documentation'
FCC: CD

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]

- Potential for interesting parameters and cost, not all at same level of maturity
- AAC goal: ...to reduc[e] the <u>dimensions</u>, <u>CO2 footprint</u> and <u>costs</u> of future high energy physics machines, with the potential to reduce <u>power consump</u>tion and offer e+e- and $\gamma-\gamma$ machines to and beyond 15 TeV energies.

ITF Compared Potential 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

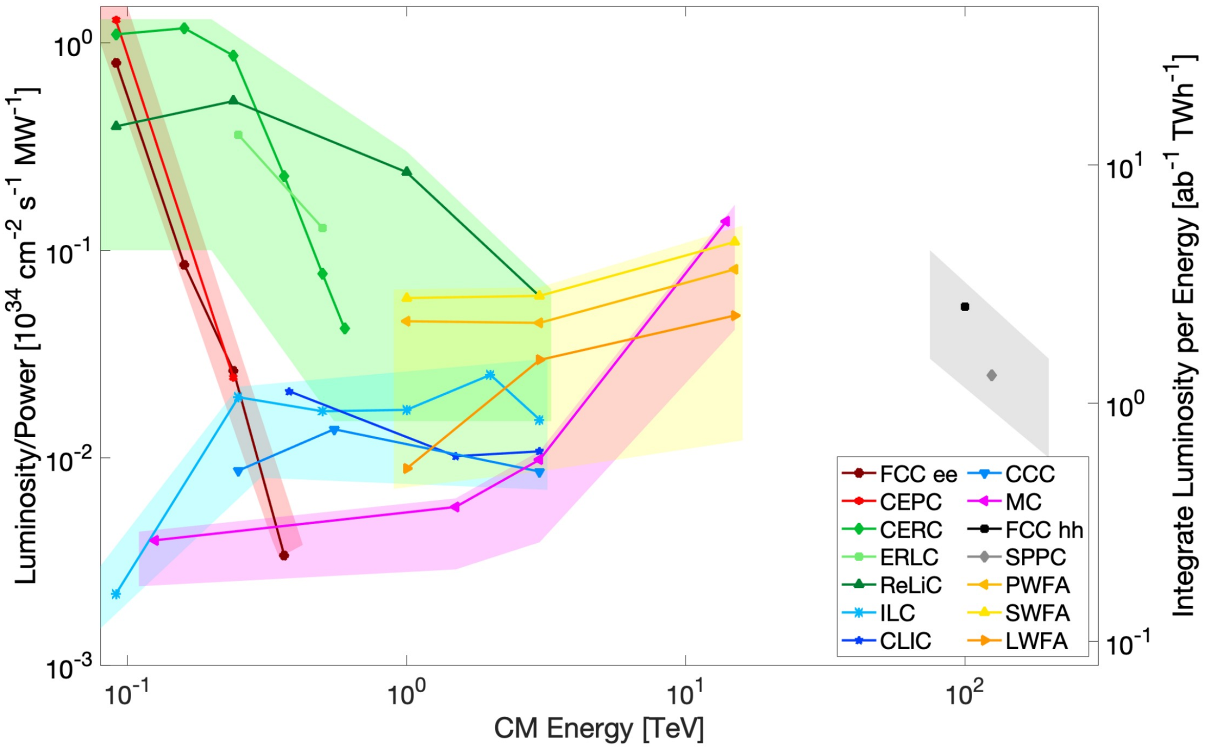


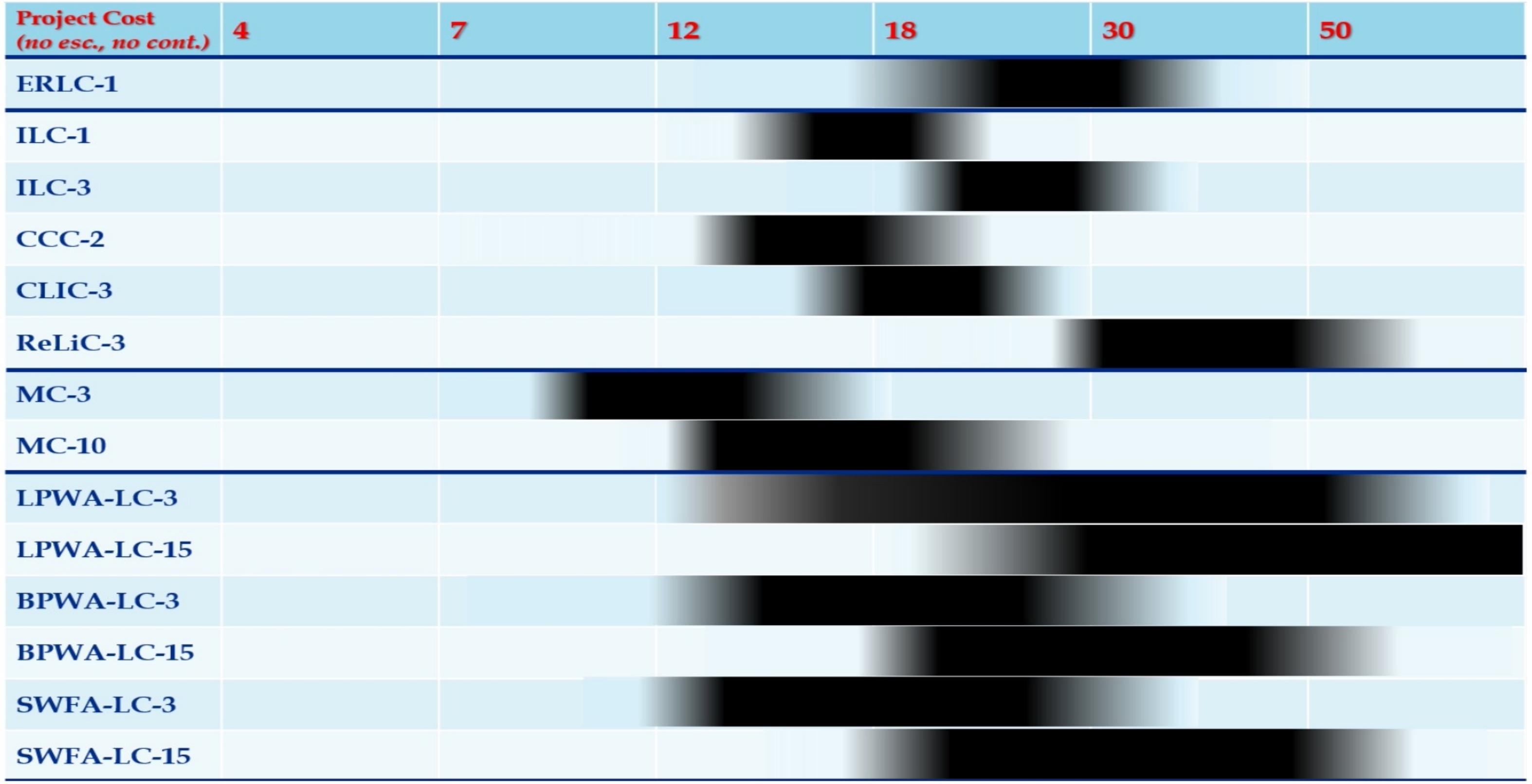
Figure 4: Figure-of-merit Peak Luminosity (per IP) per Input Power and Integrated Luminosity per TWh. Integrated luminosity assumes 10^7 seconds per year. The luminosity is per IP. Data points are provided to the ITF by proponents of the respective machines. The bands around the data points reflect approximate power consumption uncertainty for the different collider concepts.

- Next step for AAC: integrated self consistent parameter sets including tradeoffs to advance evaluation of collider options, and progress to integrated design study
- Proponent performance parameters discussed but not independently calculated

ITF Compared Potential Collider Costs

ITF cost model for 10 TeV class

Note: energies and luminosities not synchronized between technologies

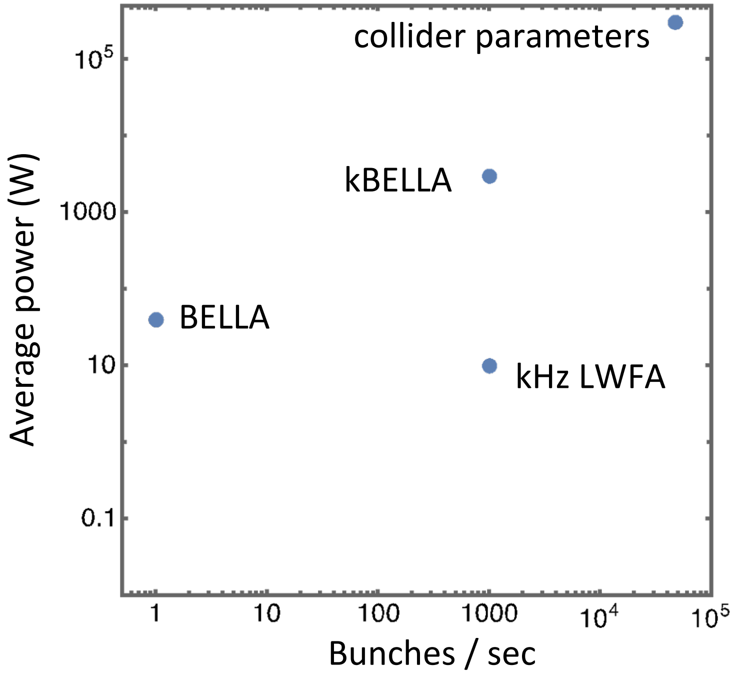


Project Cost *(no esc., no cont.)*	**4**	**7**	**12**	**18**	**30**	**50**
ERLC-1						
ILC-1						
ILC-3						
CCC-2						
CLIC-3						
ReLiC-3						
MC-3						
MC-10						
LPWA-LC-3						
LPWA-LC-15						
BPWA-LC-3						
BPWA-LC-15						
SWFA-LC-3						
SWFA-LC-15						

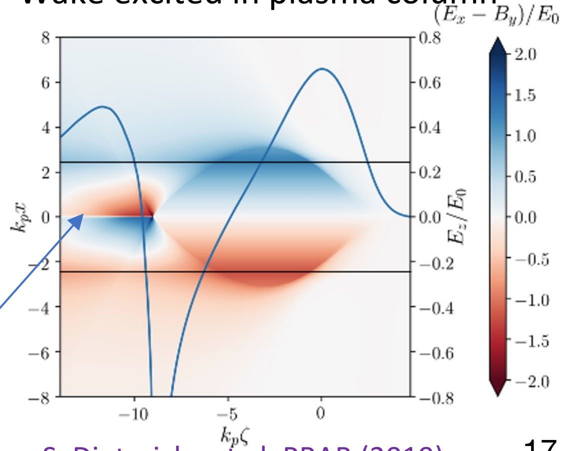
- 30 parameter cost model
- Based on moderate extrapolations of current costs by ITF, with proponent input
- "For future technologies, this cost estimate is likely very conservative and one should expect that the cost for these items can be greatly reduced, maybe by significant factors, through pre-project cost reduction R&D." (pg 47)
- "The laser-power driver costs will dominate to 15 TeV. R&D items needed to reduce technical cost risks are:… lasers , 50 kHz $e+$ bunch production, 50 kHz plasma-cells, and also the final focus system" (pg. 30)

AAC facility next steps will advance technology and test key remaining parameters

- Rapid investment in Europe, Asia, incl. EuPRAXIA
    - US R&D, facility base creates leadership opportunities
- Positron acceleration R&D
    - *Technical challenges:* plasma acceleration of stable, high-quality e+ beams, with high efficiency (comparable to e-)
    - *FACET-II upgrade*: plasma-based positron acceleration experiments/tests (e.g., plasma columns or hollow channels)
- Staging of two modules and multiple-driver/injector beams
    - *BELLA 2nd beamline:* staging; future positrons & injectors
- High-average power and high repetition rate plasma accelerators:
    - *Technical challenges*: targetry at repetition rate, heat deposition and management (~kW/cm), structure durability
    - *kBELLA project*: kHz, J-class laser. Technology available; precision via active feedback, applications on collider roadmap
- Integrated submodule of TeV SWFA design:
    - GW rf power generation and sustainable 0.5GV/m acceleration
    - Over 50% of RF-to-beam efficiency with shaped main beam.
    - 3GeV demonstrator in AWA-II High-Energy Upgrade.



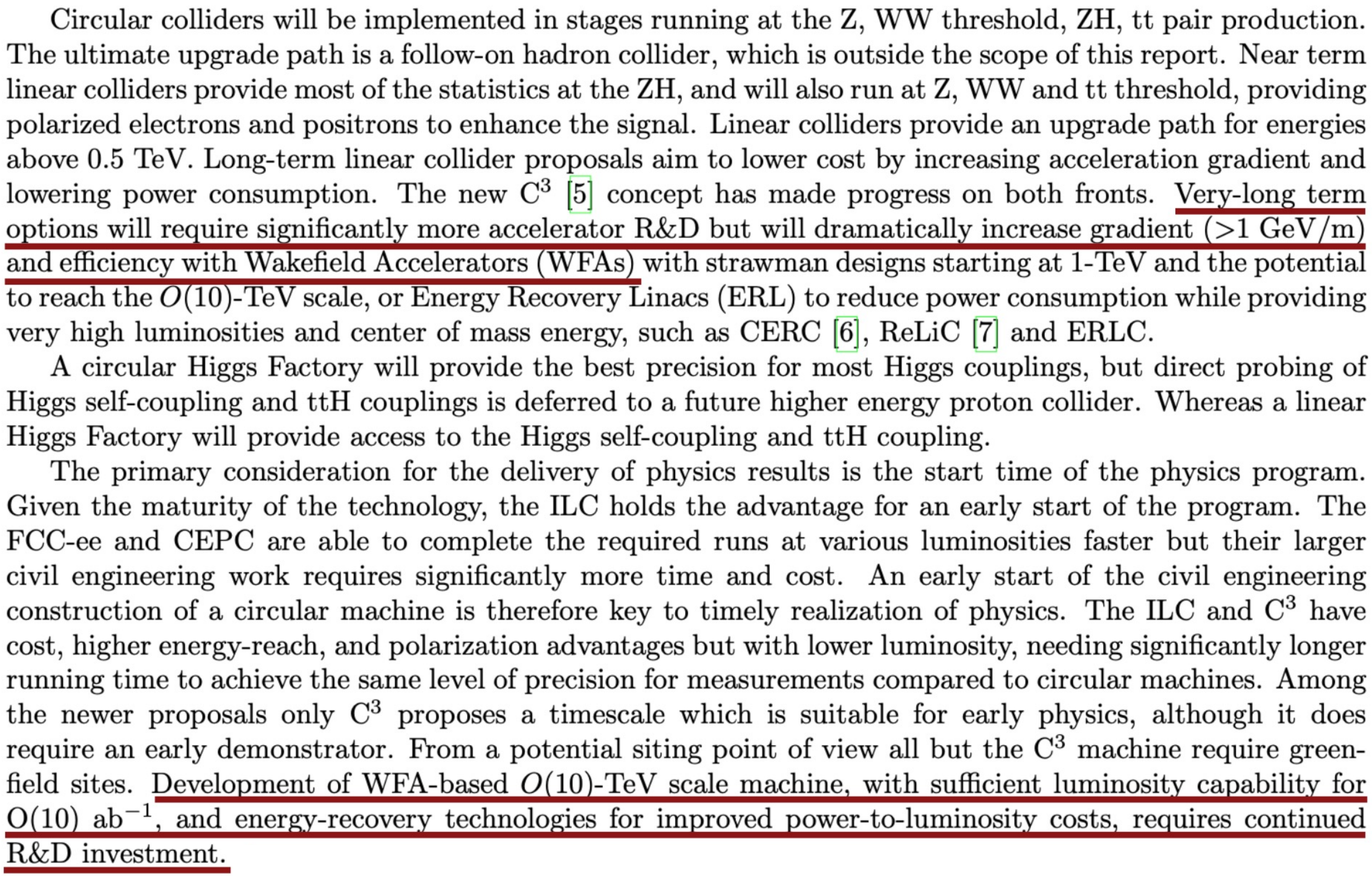
Wake excited in plasma column



e+ focusing and accelerating region

S. Dieterichs et al. PRAB (2019)

e+e- forum



Circular colliders will be implemented in stages running at the Z, WW threshold, ZH, tt pair production. The ultimate upgrade path is a follow-on hadron collider, which is outside the scope of this report. Near term linear colliders provide most of the statistics at the ZH, and will also run at Z, WW and tt threshold, providing polarized electrons and positrons to enhance the signal. Linear colliders provide an upgrade path for energies above 0.5 TeV. Long-term linear collider proposals aim to lower cost by increasing acceleration gradient and lowering power consumption. The new C^3 [5] concept has made progress on both fronts. Very-long term options will require significantly more accelerator R&D but will dramatically increase gradient (>1 GeV/m) and efficiency with Wakefield Accelerators (WFAs) with strawman designs starting at 1-TeV and the potential to reach the $O(10)$-TeV scale, or Energy Recovery Linacs (ERL) to reduce power consumption while providing very high luminosities and center of mass energy, such as CERC [6], ReLiC [7] and ERLC.

A circular Higgs Factory will provide the best precision for most Higgs couplings, but direct probing of Higgs self-coupling and ttH couplings is deferred to a future higher energy proton collider. Whereas a linear Higgs Factory will provide access to the Higgs self-coupling and ttH coupling.

The primary consideration for the delivery of physics results is the start time of the physics program. Given the maturity of the technology, the ILC holds the advantage for an early start of the program. The FCC-ee and CEPC are able to complete the required runs at various luminosities faster but their larger civil engineering work requires significantly more time and cost. An early start of the civil engineering construction of a circular machine is therefore key to timely realization of physics. The ILC and C^3 have cost, higher energy-reach, and polarization advantages but with lower luminosity, needing significantly longer running time to achieve the same level of precision for measurements compared to circular machines. Among the newer proposals only C^3 proposes a timescale which is suitable for early physics, although it does require an early demonstrator. From a potential siting point of view all but the C^3 machine require green-field sites. Development of WFA-based $O(10)$-TeV scale machine, with sufficient luminosity capability for $O(10)$ ab^{-1}, and energy-recovery technologies for improved power-to-luminosity costs, requires continued R&D investment.

- ○ AAC based colliders require ongoing R&D
- ○ Potential recognized
- ○ Viewed as very long term
- ○ Less analysis by energy and theory frontier

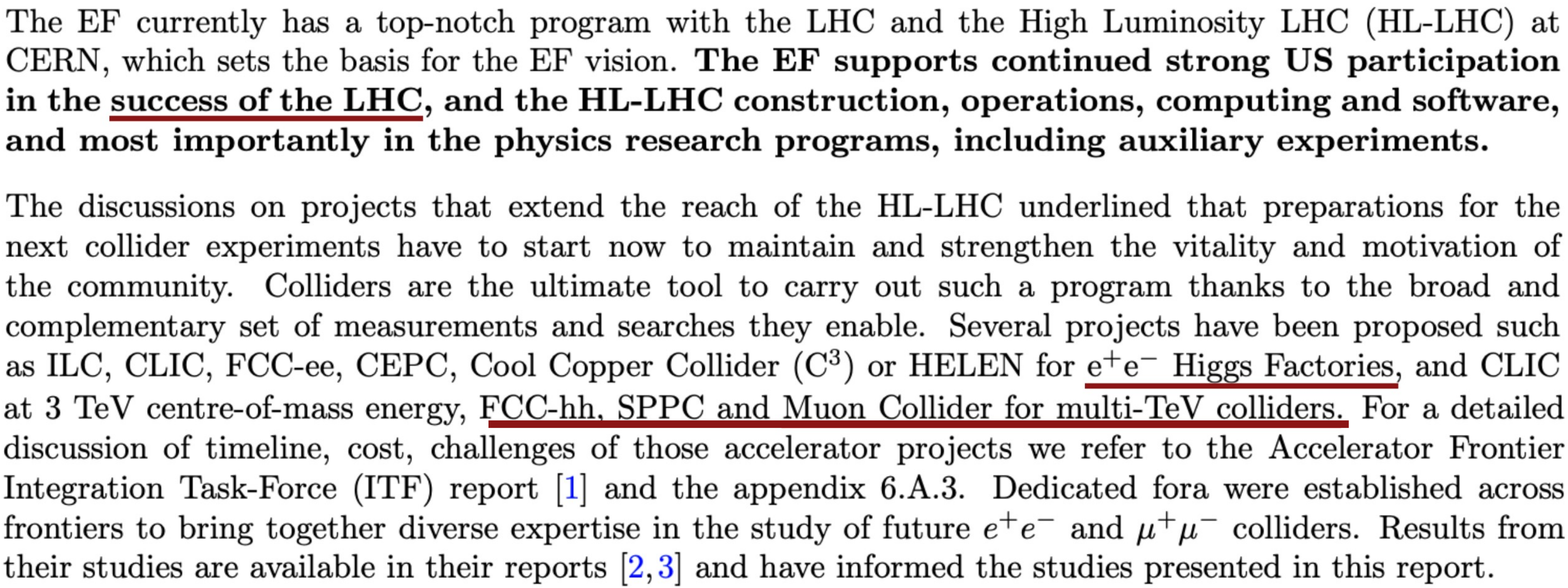
e+e- collider forum report: https://arxiv.org/abs/2209.03472

Accelerator Frontier Summary

- …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. This is an important change that will refocus some of the accelerator R&D programs.
- '… discovery machines such as O(10 TeV c.m.e.) muon colliders have rapidly gained significant momentum… R&D is in progress on other concepts such as wakefield based e +e – or $\gamma\gamma$ systems which may present additional future options… will reduce the dimensions and thus potentially reduce the costs and power consumption of future high energy physics machines
  - 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.)
  - in accelerator and beam physics – [focus on] acceleration and control of high intensity/high brightness beams, high performance computer modeling and AI/ML approaches, and design integration… 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.
  - Strengthen and expand capabilities of the US accelerator beam test facilities

AF Report: https://arxiv.org/abs/arXiv:2209.14136

Energy Frontier Summary



The EF currently has a top-notch program with the LHC and the High Luminosity LHC (HL-LHC) at CERN, which sets the basis for the EF vision. **The EF supports continued strong US participation in the success of the LHC, and the HL-LHC construction, operations, computing and software, and most importantly in the physics research programs, including auxiliary experiments.**

The discussions on projects that extend the reach of the HL-LHC underlined that preparations for the next collider experiments have to start now to maintain and strengthen the vitality and motivation of the community. Colliders are the ultimate tool to carry out such a program thanks to the broad and complementary set of measurements and searches they enable. Several projects have been proposed such as ILC, CLIC, FCC-ee, CEPC, Cool Copper Collider (C^3) or HELEN for $\mathrm{e}^+\mathrm{e}^-$ Higgs Factories, and CLIC at 3 TeV centre-of-mass energy, FCC-hh, SPPC and Muon Collider for multi-TeV colliders. For a detailed discussion of timeline, cost, challenges of those accelerator projects we refer to the Accelerator Frontier Integration Task-Force (ITF) report [1] and the appendix 6.A.3. Dedicated fora were established across frontiers to bring together diverse expertise in the study of future e^+e^- and $\mu^+\mu^-$ colliders. Results from their studies are available in their reports [2,3] and have informed the studies presented in this report.

- Emphasis on muon collider path to 10 TeV scale, AAC not analyzed in detail

EF Report: https://arxiv.org/abs/2211.11084

Energy Frontier Key Thrusts

The EF community proposes several parallel investigations over a time period of ten years or more for pursuing its most prominent scientific goals, namely

1. **supporting the full (3 - 4.5 ab1) HL-LHC physics program**
2. **proceeding with a Higgs factory**
3. **planning for multi-TeV colliders at the energy frontier**

The proposed plans in five year periods starting 2025 are given below.

For the five year period starting in 2025:

1. Prioritize the HL-LHC physics program, including auxiliary experiments
2. Establish a targeted e+e Higgs factory detector R&D program
3. Develop an initial design for a first stage TeV-scale Muon Collider in the US
4. Support critical detector R&D towards EF multi-TeV colliders

For the five year period starting in 2030:

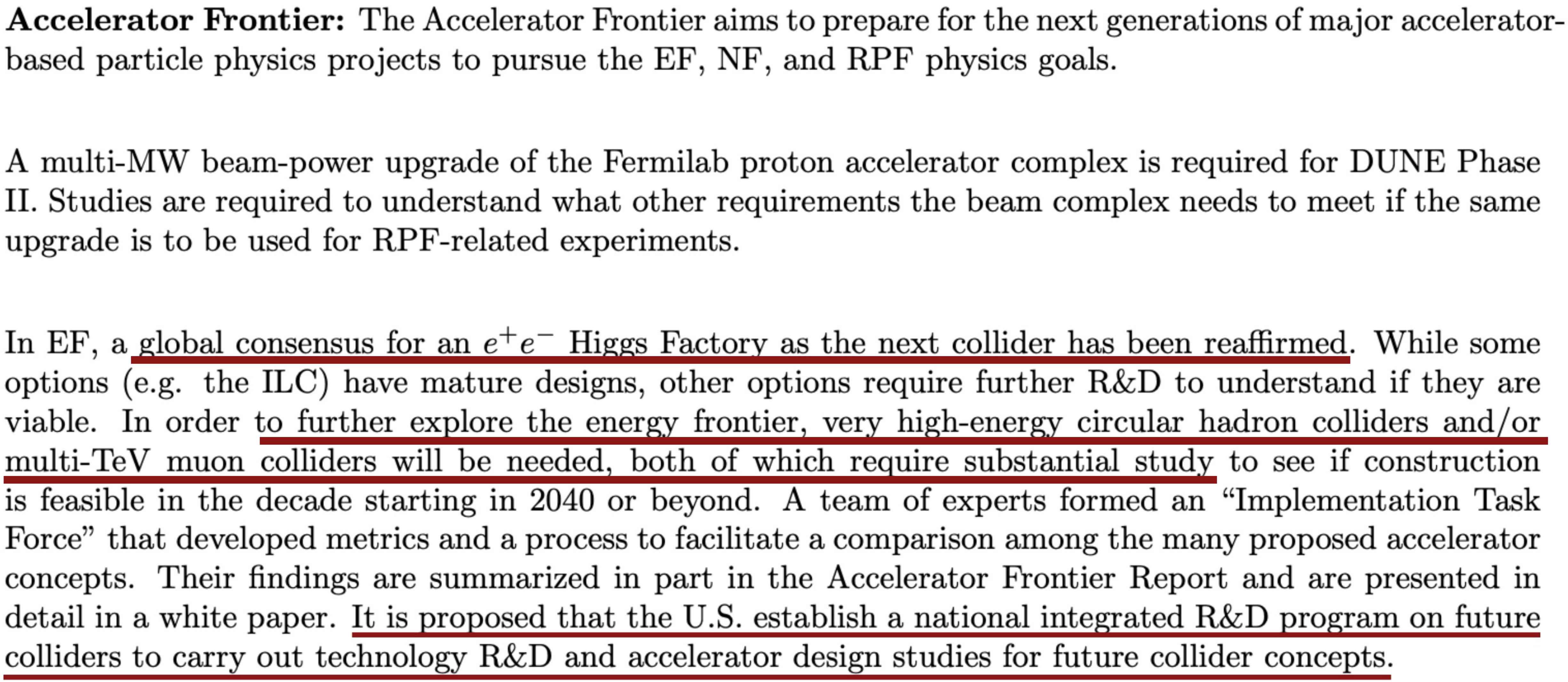
1. Continue strong support for the HL-LHC physics program
2. Support construction of an e+e Higgs factory
3. Demonstrate principal risk mitigation for a first stage TeV-scale Muon Collider

Plan after 2035:

1. Continuing support of the HL-LHC physics program to the conclusion of archival measurements
2. Support completing construction and establishing the physics program of the Higgs factory
3. Demonstrate readiness to construct a first-stage TeV-scale Muon Collider
4. Ramp up funding support for detector R&D for energy frontier multi-TeV colliders.

- Stronger AAC engagement with energy and theory colleagues is needed

Snowmass Summary – Highest Level



Accelerator Frontier: The Accelerator Frontier aims to prepare for the next generations of major accelerator-based particle physics projects to pursue the EF, NF, and RPF physics goals.

A multi-MW beam-power upgrade of the Fermilab proton accelerator complex is required for DUNE Phase II. Studies are required to understand what other requirements the beam complex needs to meet if the same upgrade is to be used for RPF-related experiments.

In EF, a global consensus for an e^+e^- Higgs Factory as the next collider has been reaffirmed. While some options (e.g. the ILC) have mature designs, other options require further R&D to understand if they are viable. In order to further explore the energy frontier, very high-energy circular hadron colliders and/or multi-TeV muon colliders will be needed, both of which require substantial study to see if construction is feasible in the decade starting in 2040 or beyond. A team of experts formed an "Implementation Task Force" that developed metrics and a process to facilitate a comparison among the many proposed accelerator concepts. Their findings are summarized in part in the Accelerator Frontier Report and are presented in detail in a white paper. It is proposed that the U.S. establish a national integrated R&D program on future colliders to carry out technology R&D and accelerator design studies for future collider concepts.

- AAC engagement with the conventional collider community is essential, including strong participation at meetings outside the AAC community and design engagement

Particle Physics Project Prioritization Panel Follows Snowmass

- Resource limited 10 year plan with 20 year vision for the field
  - Context of Snowmass reports
  - Projects and R&D
  - Town halls and events collect community input
  - Panel discussions confidential, no content in this talk
- Broad portfolio includes collider, neutrino, cosmic and other areas
- Report at HEPAP meeting Dec 7-8
  - https://science.osti.gov/hep/hepap/Meetings

Panel Members

Shoji Asai (University of Tokyo)
Tulika Bose (Wisconsin)
Francis-Yan Cyr-Racine (New Mexico)
Cameron Geddes (LBNL)
Karsten Heeger (Yale) - Deputy Chair
JoAnne Hewett (SLAC) - HEPAP chair, ex officio until May 2023
Rachel Mandelbaum (Carnegie Mellon)
Petra Merkel (Fermilab)
Hitoshi Murayama (Berkeley) - Chair
Mark Palmer (Brookhaven)
Mayly Sanchez (Florida State)
Sally Seidel (UNM) – interim HEPAP chair, ex officio
Jesse Thaler (MIT)
Abigail Vieregg (Chicago)
Lindley Winslow (MIT)
Bob Zwaska (Fermilab)
Amalia Ballarino (CERN)
Kyle Cranmer (Wisconsin)
Sarah Demers (Yale)
Yuri Gershtein (Rutgers)
Beate Heinemann (DESY)
Patrick Huber (Virginia Tech)
Kendall Mahn (Michigan State)
Jelena Maricic (Hawaii)
Christopher Monahan (William & Mary)
Peter Onyisi (Texas Austin)
Tor Raubenheimer (SLAC)
Richard Schnee (South Dakota School of Mines and Technology)
Seon-Hee (Sunny) Seo (IBS Center for Underground Physics)
Christos Touramanis (Liverpool)
Amanda Weinstein (Iowa State)
Tien-Tien Yu (Oregon)

P5 site: https://www.usparticlephysics.org/p5/
Hitoshi's talk at HEPAP: https://science.osti.gov/-/media/hep/hepap/pdf/202308/P5_HEPAP_202308.pdf

Snowmass Takeaway Messages

- Interest shifted from the TeV range to emphasize 10+ TeV/parton energies, after a Higgs factory
- Strong AAC progress assessing limits and demonstrating technologies continues motivation
  - Experimental results: 10 GeV class beams, beam loading & efficiency, plasma recovery, staging, high transformer ratio, positrons, and FEL-lasing demonstrating high beam quality
  - Concepts addressing: ion motion, synchrotron radiation, scattering, hosing and positron acceleration
  - Collider conceptual parameter sets developed based on component simulations and models
  - Strengthening R&D and test facilities while leveraging near term applications are important.
- Snowmass science study engaged across the particle physics community and informs the P5 plan
  - Advanced accelerators offer potential for compact, energy efficient future e-e+/gg colliders
  - Viewed as longer term than other options by colleagues outside of AAC
  - Accelerator Frontier and other emphasize the need for designs with documented self-consistent parameter sets and identified technology gaps to guide and assess R&D
  - Engagement with broad accelerator and particle physics communities is needed to advance design and consideration as a collider option, while there has been a strong surge of interest in muon collider

Snowmass Takeaway Messages

- Next steps towards consideration as future collider options include moving towards integrated design, starting with self consistent parameter sets (muon collider success in the last decade)
    - Integrating: injection, cooling alignment and jitter effects and tolerances, matching/coupling between many stages, BDS and Final focus
    - Engaging: the detector, high energy physics and conventional collider communities, & internationally
    - Frame a common wakefield collider concept with techniques offering technical risk mitigation
- Engage particle and detector physicists – there are unique issues with WFA detectors e.g. short bunches. Relaying parameters so they can have to something to calculate with is very important.
- Participate strongly in non-AAC meetings and workshops, learn from and work with muon collider and conventional collider colleagues: IPAC, IMCC meetings, LCWS, APS April meeting…
- Frame the benefit of AAC technologies as injectors or upgrades for other machines such as a linear Higgs factory upgrade to 10 TeV in engagement with ILC and CLIC, as well as light sources
- Leverage near term applications to advance collider path and reduce cost and risk, working across funding agencies

Acknowledgement

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