Summary of Working Group 8: Advanced and Novel Accelerators for High Energy Physics

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Abstract. We summarize the conclusions from Working Group 8 of the European Advanced Accelerator Concepts workshop in 2019 (EAAC2019) on the suitability and prospects for using advanced and novel accelerator (ANA) technology for future high-energy physics (HEP) applications. We identify the key technology gaps remaining for the main ANA approaches for building future e^+/e^- linear colliders and estimate the time scales needed to close them. We also identify synergistic development paths that can be leveraged to achieve key technology demonstration steps through non-HEP applications and through non-lepton-collider HEP applications.

1. Introduction

Working Group 8 (WG8), Advanced and Novel Accelerators for High Energy Physics, was originated at the EAAC2017 workshop largely to continue the momentum in this topic from the Advanced and Novel Accelerators for High Energy Physics Roadmap (ANAR) Workshop in 2017 [1]. The focus of the EAAC2017 WG8 was to help outline the technical and planning path forward to achieving an Advanced Linear International Collider (ALIC) based on advanced and novel accelerator (ANA) technologies. The focus of this workshop's WG8 has been to evaluate the progress toward developing an ALIC, and its conclusions are summarized in this report.

Tajima and Dawson's landmark 1979 paper on laser wakefield acceleration (LWFA) in a plasma [2] opened up the field of ANA by noting that gradients of hundreds of GV/m are possible in plasma waves excited by an intense laser. Now, the ANA field has expanded to include at least four different acceleration concepts. These approaches either use lasers as a driver (LWFA and dielectric laser acceleration (DLA)) or an intense particle beam as a driver (plasma wakefield acceleration (PWFA) in a plasma and dielectric wakefield acceleration (DWFA) in a vacuum structure), and either use a plasma as the medium (LWFA and PWFA) or a vacuum structure as the medium (DLA or DWFA). All four approaches have demonstrated GV/m-class gradients, with LPAs and PWAs as high as many tens of GV/m.

The impact of these technologies to high-energy physics (HEP) was immediately recognized. The first workshop on the application of ANAs to HEP missions was held in January 1982 [3] which subsequently evolved into the Advanced Accelerator Concept (AAC) workshop series. The newer European AAC (EAAC) workshop series also reflects this vision.

While conventional normal conducting RF (NCRF), limited to a few tens of MV/m gradients, could address existing and near-term HEP needs with limited energy reach, higher energies would require prohibitively long and expensive accelerators. This is also true for superconducting RF (SRF) technologies. Specifically, positron/electron (e^+/e^-) colliders are needed for precision studies at ~ ½ TeV energies in the short term, which have been proposed both with linear topologies (e.g., the International Linear Collider (ILC) and CERN's Compact Linear Collider (CLIC)) and with circular topologies (e.g., the Chinese Circular Electron Positron Collider (CEPC) and CERN's FCC-ee). After a probable discovery-oriented 100-TeV-class circular proton collider, future HEP plans include a yet higher energy lepton collider at a few TeV energies; the only current proposal is CLIC at 3 TeV. In the even longer term, ~10 TeV lepton colliders can be envisaged. ANA technologies may be necessary to reduce the cost of e+/e- 3-TeV colliders and very likely will be needed for energies beyond that.

1.1. WG8 charge

The charge to WG8 at EAAC2019 was to evaluate ANAs for HEP. Specifically, we were to:

- Examine key challenges
- Discuss suitable concepts and identify topics for future R&D or innovation including electron and positron sources, acceleration of positrons, luminosity, final focus, damping ring and efficiency

In addition, we have evaluated the state of ANA for HEP applications and estimated when ANA technologies will be ready for non-HEP and HEP applications.

Steinar Stapnes in his plenary talk pointed out that accelerator luminosities will need to be $> 10^{35}$ cm^{-2} sec^{-1} and their overall efficiencies will need to be 10% or greater to be practical. With nominal currents of 10 μA, a 10 TeV accelerator will have a 100 MW beam, and, with 10% efficiency, about a GW of wall-plug power will be needed. This is consistent with guidance from the US Department of Energy/ Office of High Energy Physics, which has indicated that 300 MW would be the upper acceptable bound for a 3-TeV e^+/e^- collider [4].

Importantly, recent advances in NCRF technology indicate that it too may be reconsidered as a credible alternative technology for HEP applications even reaching beyond 3 TeV. James Rosenzweig in his plenary talk showed that gradients of a few hundred MV/m have been achieved in copper RF structures cooled to 45K . While the promise of cryogenic NCRF technology is not yet clear, it is likely to reach maturity before any of the four main ANA technologies. At the least, it might serve as a stepping stone for mid-term HEP machines or for providing a low-risk baseline while the other technologies mature, and possibly be combined with higher gradient ANA technologies in hybrid approaches for higher energy accelerators in the longer term.

We will focus on the development of ANA technologies for HEP applications in the following sections. First, in Section 2, we will outline the key technological gaps that need to be addressed. We will refer to published technology roadmaps and recent results reported at EAAC2019 to estimate the time scales for closing these gaps. In Section 3, we review the recent progress on these issues presented at EAAC2019, including plans for the first multi-stage technology prototypes. In Section 4, we consider future steps for these technologies, including their first applications to upcoming HEP accelerators. We also consider how they can enable non-HEP missions that would both serve to demonstrate the maturity of these technologies and, importantly, help motivate other science communities to share in ANA development costs.

2. ANA technology gaps

2.1. Technology roadmaps

The US HEP program has developed technology development roadmaps for LWFA, PWFA, DWFA, and NCRF/SRF technologies [5] to address outstanding technology gaps. These roadmaps outline when requirements for beam stability and control, brightness preservation, stageability, high average power, and eventually positron acceleration will be addressed. The US roadmaps all include multi-stage prototypes that will be used to inform a down-select to a higher energy demonstration machine as a step to a multi-TeV e^+/e^- collider, ensuring the technology has matured to support the construction of such a multi-TeV collider in the future. A similar DLA technology roadmap has been developed by the ANA community at the ANAR2017 meeting [1]. An international study group of ANA technologies, the Advanced LinEar collider study GROup (ALEGRO) [6], is further refining and updating these roadmaps based on ongoing technology developments and community input.

The core roadmap steps are

I. Conduct research on current and next-generation R&D facilities to continue to close all technology gaps.
II. Demonstrate key technology capabilities with multi-stage, multi-GeV prototypes (which may also serve as drivers for other applications such as X-ray light sources).
III. Develop a high-energy demonstration facility based upon one or more downselected acceleration technologies. This demonstration facility needs to be on a scale that gives the confidence that a multi-TeV e^+/e^- collider can be built.

Current status summary

ANA technologies are currently in Step I above, but with Step II on the horizon. We summarize the current status of the key technology gaps for the different ANA technologies in Table 1 and estimate the time needed to achieve the maturity required for Step II development. “Near term” means within 5 years, “Mid term” means 5-10 years, and “Long term” will likely take more than 10 years. Additionally, “Done” means already demonstrated, “Ongoing” means currently being demonstrated, and “Ready” means the technology gap is considered closed and is ready to be demonstrated.

Table 1. Time scales to close critical ANA technology gaps.

Technology issue	**LWFA**	**PWFA**	**DWFA**	**DLA**	**NCRF**
Gradient limit	100 GV/m	100 GV/m	10 GV/m	1 GV/m	½ GV/m
Wallplug efficiency	Mid term	Near term	Near term	Mid term	Done
Transformer ratio	-	Near term	Near term	-	-
Average power	Near term	Near term	Ready	Near term	Ready
Energy spread	Near term	Near term	Near term	Near term	Done
Emittance and transport	Near term	Near term	Near term	Mid term	Done
Positron	Long-term	Long-term	Ready	Ready	Done
Staging	Ongoing	Ready	Ongoing	Long-term	Done

The following are notes on Table 1.

- Dielectrics can sustain fields up to about 10 GV/m and thus the gradient limit for DLA may be in fact several to ten GV/m, similar to DWFA. Likewise, ongoing materials research for NCRF may increase that technology’s limit to ~ GV/m.
- Considerations for wallplug efficiency are different for the different technologies. Concepts with laser drives require improved laser efficiencies, which may have a decadal time scale. Beam drives can rely on existing accelerator technologies to be very efficient in producing the wakes. All concepts require efficient transfer of the wake or laser power to the main beam, which appears to be near term. Finally, demonstrations of large transformer ratios for beam-driven concepts are ongoing with already promising results.
- For achieving high average beam powers with LWFA, demonstration of lasers with kHz rep rates are predicted to happen within 5 years (e.g., KALDERA). Lasers needed for high average power DLAs are different (lower pulse energies but higher repetition rates) but are also near the horizon. Plasma devices need to refresh the plasmas at high repetition rates, which should be demonstrated soon. While room temperature NCRF technology has certainly demonstrated high average beam powers, it still needs to be verified for cyrocooled NCRF.

- Energy spread (for plasma concepts) and emittance preservation (for all but NCRF) have traditionally been seen as the main weaknesses of ANA technologies. However, recent results presented at EAAC2019 show that very low energy spreads are now possible. Ongoing work demonstrating emittance preservation is promising but some additional work is needed. Beam transport may be especially challenging for DLAs, which may suffer from wakefields, beam breakup, halo and beam collimation, and intrabeam scattering, and will require sub-micron alignments over km distances [7]. It is important to note that DLA development has lagged relative to the other technologies due to a lack of sustained funding for HEP goals.
- Developing schemes to accelerate positrons in plasma devices remains the largest outstanding problem as plasmas are inherently asymmetric (the negatively charged part is mobile but the positively charged part is not). Carl Lindstrom in his plenary talk pointed out that while a new concept for accelerating positrons is needed, it may likely be based on either linear wakes, nonlinear wakes, wake inversion, or hollow channels.

3. Recent progress

In this section, we summary some of the most relevant technology developments to HEP machines presented at EAAC2019 and which support the conclusions in Table 1.

3.1. Average power

Current plans to increase the average power of LWA laser systems include the development of a 10-kW average power laser system at FLASHForward at DESY by 2025, starting with the 3-kW, 1-kHz rep rate KALDERA laser by 2023, presented by Wim Leemans in his plenary talk.

3.2. Energy spread

Two remarkable approaches to low electron bunch energy spread were presented. First, Jianfei Hua presented results from a plasma dechirper, demonstrating energy spreads as low as 0.13%. Also, Ángel Ferran Pousa presented simulations of an energy-spread compensator, where the final whole-bunch energy spread reached 0.12%, with slice energy spreads as low as 0.028%. The compensator is a simple chicane between two plasma acceleration stages. The momentum compaction of the chicane is adjusted so the energy chirp from the first stage longitudinally flips the beam and the chirp from the second stage counters the original chirp. The chicane will need to scale with increasing beam energy, and may become very laser for a multi-TeV collider. However, it is also likely that the separation between chicane stages may become very large at high energy and that the overall additional length will be acceptable.

3.3. Generation and preservation of low emittances

Several new approaches for improving emittance preservation were presented that show continued progress in this field. These include active plasma lenses (Vladimir Shpakov), hosing stabilization by bunched-induced ion motion (Weiming An and Carlo Benedetti), co-axial hollow plasma channels for TeV acceleration (Alexander Pukhov), and using channeling radiation for beam control (Sultan Dabagov). Importantly, there are no fundamental limitations to preserving high brightness beams in ANA technologies.

3.4. Accelerating positrons

This is a very active research area. Denys Bondar presented simulation results for conditions for uniform focusing for a train of positron bunches and Severin Diederichs presented on positron transport and acceleration in beam-driven, pre-ionized, finite plasma column. Siyi Yu presented results on improved transport and efficiency for positron acceleration in a quasilinear PWA. Spencer Gessner’s van der Meer Award talk discussed promising results using a hollow channel plasma accelerator. Importantly, positron acceleration does not need to be solved immediately to continue progress for future HEP colliders as Step II applications don’t need positrons.

3.5. Plans for LWFA and DWFA multi-stage prototypes

Anthony Gonsalves presented in his plenary talk plans at the Lawrence Berkeley National Laboratory (LBNL) for the BELLA-PW driven multi-stage prototype. The BELLA-PW staging design indicates that 100% bunch capture and acceleration will be achievable. John Power presented a DWFA multi-stage prototype plan in his talk. Ongoing work at Argonne's Advanced Wakefield Accelerator (AWA) has shown significant improvements in the DWFA transformer ratio. A photonic band-gap accelerating structure may be used to eliminate higher-order modes from the wakefields. The AWA multi-stage demonstration would have a counter-propagating drive and main beam, with two stages of two extractors/accelerators each, showing the ability to provide complex phasing and control.

4. Future steps

This is an exciting time for ANA research. Solutions (and even multiple solutions) are appearing for all the main issues listed on Table 1. With the advances described in Section 3, near-term applications of ANA technology are within reach, both for non-HEP application and to support HEP activities.

With their promise of 100-GV/m-class gradients, plasma sources will probably be required for 10-TeV-scale energies, but the positron acceleration problem will likely impact their ability to be the first ANA technologies used for e^+/e^- colliders. NCRF and possibly DWFA technologies are ready now or very soon, including for building lower-energy HEP colliders. But due to their lower potential gradients, it is likely these technologies will be limited to lower-energy and mid-term (multi-TeV) stepping stones. It is important to also note that plasma accelerators will be available soon for non-HEP and certain HEP applications that do not required positrons. Finally, questions remain about the ability for DLA technology to accelerate 10-μA beams up to 30-MW of average power. These questions can only be answered once DLA funding approaches level of the other ANA technologies.

4.1. Lower energy applications

Upcoming light sources will help drive ANA technologies forward. EuPRAXIA, the UCLA compact XFEL, and the LANL MaRIE XFEL have all been proposed in the context of ANA technologies (LWFA for EuPRAXIA and cyrocooled NCRF for the other two). Importantly, and within the mid-term (20025-2027), DESY is proposing using an LWFA injector system for PETRA-IV based on KALDERA.

ANA technologies are already being considered to support HEP projects in the short term as an injector for the Chinese Circular Electron Positron Collider (CEPC) and as an afterburner for ILC and/or CLIC. Specifically, Jianfei Hua presented a plan for using a high transformer ratio (up to 6-12 for cascaded stages) PWFA for the CEPC injector. Aggressively, the plans include using a hollow plasma channel (with transformer ratio of unity) for positron acceleration. The beams will be externally injected and a plasma dechirper will be used to minimize the beams' energy spreads. Also, Erik Adli presented an upgrade path for CLIC. By modifying the CLIC Drive-Beam Complex, appropriately spaced drive beams for a PWFA can be generated. With 1 GV/m acceleration, an upgraded CLIC would produce beams of up to 3.5 TeV. The crossing angle of 20 mrad is optimal for 3 TeV center-of-mass energy collisions and is even compatible with high-energy gamma-gamma collisions. In addition, a plasma afterburner can be considered for ILC or CLIC to double the energy.

4.2. Higher energy HEP machines

High energy non-perturbative QED colliders (discussed by Vitaly Yakimenko and Gianluca Sarri) and gamma-gamma colliders (discussed by Erik Adli) don't need to accelerate positrons, so they can be considered as HEP alternatives, especially if progress with positron acceleration remains elusive. They can also be considered as an intermediate HEP step.

A non-perturbative QED collider is parameterized by the ratio of the electric field in particle's rest frame normalized to a critical field, about 10^{16} V/cm and where the electric field in the rest frame is the externally applied field (~ GV/m) boosted by the relativistic mass factor. High ratios denote a fully non-perturbative regime where the perturbative treatment of the radiation field completely breaks down and can be achieved with colliding 100-pC electron bunches at 100 GeV. Gianluca Sarri pointed out planned experiments at FACET-II can take a first look at non-perturbative QED physics.

5. Summary

Using the same notation as Table 1 ("Near" means within 5 years, "Mid" means 5-10 years, and "Long" will likely take more than 10 years; "Longer" indicates multiple decades), the WG8 conclusions are summarized in Table. 2.

Table 2. Time scales to apply ANA technologies to HEP accelerators.

Application	**LWFA**	**PWFA**	**DFWA**	**DLA**	**Cyro NCRF**
Light sources	Near to mid	Near to mid	Near	Mid to long	Near
HEP add-ons	Near to mid	Near to mid	Near	Unknown	Near
e- only HEP	Mid to long	Mid to long	Near to mid	Unknown	Near
Multi-TeV ALIC	Long	Long	Mid	Unknown	Near to Mid
10-TeV ALIC	Longer	Longer	Not suitable	Unknown	Not suitable

The following are notes on Table 2. Importantly, these estimates only refer to the acceleration technology and not to other critical collider elements common to all these technologies (i.e., such as those required for gamma-gamma colliders).

- "Light sources" is meant to also include any synergistic application for demonstrating a multi-GeV, multi-stage prototype.
- "HEP add-ons" includes a plasma injector for CEPC or a plasma afterburner for ILC/CLIC.
- "e- only HEP" indicates a relatively high beam energy HEP application that does not require positrons, such as a nonperturbative QED or gamma-gamma collider.
- "Multi-TeV ALIC" indicates the start of a high power demonstrator and assumes that the multi-GeV, multi-stage prototype has already been successful.

Importantly, the 3-TeV CLIC option with room temperature NCRF shows that even a moderate gradient NCRF approach can be considered feasible. Moreover, cyrocooled NCRF or DWFA technology could be used for a low-risk baseline design for future machines with the possibility of LWFA or PWFA insertion if there is sufficient maturation of those technologies. In addition, several hybrid approaches are possible where, for example, a cyrocooled NCRF accelerator is used to accelerate an electron or positron beam to a relatively high energy where a plasma accelerator takes over. The DLA concept needs significant additional and focused investment before its feasibility as an ANA driver for the applications in Table 2 can be evaluated. Finally, for all these ANA technologies, it will be important to stay on the technology development roadmap and to start with small demonstrations leading to successively larger demonstrations to build enthusiasm with non-HEP users and sponsors.

References

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