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

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ABSTRACT

We briefly summarize the work and discussions that occurred during the Working Group 8 sessions of the EAAC 2017, dedicated to advanced and novel accelerators for high energy physics applications.
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1. Introduction

Working Group 8 (WG8), Advanced and Novel Accelerators for High Energy Physics, was created as a result of the Advanced and Novel Accelerators for High Energy Physics Roadmap (ANAR) Workshop 2017 that took place at CERN, April 25–28, 2017 [1]. The workshop was organized at the initiative of the ICFA subpanel on Advanced and Novel Accelerators chaired by B. Cros. The workshop was a first step towards federating the fragmented advanced and novel accelerator (ANA) community, to define an international roadmap towards colliders based on advanced accelerator concepts, including intermediate milestones, and to discuss the needs for international coordination. A preliminary report summarizing the state-of-the-art of ANAs and the proposed future steps can be found at [2].

Working Group 8 was organized in two specific parallel sessions and one joint session with Working Group 1 — Electron beams from plasmas. The WG8 charge was to examine key challenges, discuss suitable concepts, and identify topics for future R&D or innovation, including electron and positron sources, damping rings, optics between stages, acceleration of positrons, luminosity goals, final focus, and overall efficiency.

2. General discussion

The work started with a general discussion led by A. Seryi who emphasized the need for our ANA community to take advantage of the vast knowledge of the conventional accelerators community. That community has built working accelerators, but has also developed Conceptual Design Reports (CDRs) and Technical Design Reports (TDRs) for future colliders that are ready to be built, such as the International Linear Collider (ILC) and the Compact Linear Collider (CLIC).

In the ILC case, the enterprise started with a group of motivated scientists who produced more and more refined designs that were periodically and critically reviewed by the community over many years. These designs were organized around systems (injector, damping rings, linac, beam dynamics, beam delivery system, etc.). Each system was analyzed, and for each system issues were identified and ranked. Required R&D programs relevant to collider criteria such as feasibility, reliability, production, and technical and cost optimization were defined and carried out. The work started with a number of options for each system, e.g., warm and superconducting technology for the linac. From the many designs that were generated (Tesla, JLC, NLC, etc.), one was eventually selected to become the ILC.

The ILC process towards a collider could serve as model for the design of an ANA-based advanced linear collider (ALC). Indeed, at this time the community includes four major ANA R&D efforts: Laser-driven plasma wakefield accelerators (LWFA), particle-driven plasma wakefield accelerators (PWFA), structure wakefield accelerators (SWFA), and dielectric laser accelerators (DLA), all with potentials and challenges, as summarized, for example, in the ANAR report [2].

This discussion helped define the structure of the next workshop organized by ICFA-ANA and the ALEGRO (Advanced LinEar collider

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study GROup) group [3], to be hosted by the University of Oxford and the John Adams Institute March 26–29, 2018. The upcoming ALEGRO workshop will have seven main working groups: Physics Case (PC), Collider machine design/definitions (CMD), Theory, Modeling, Simulations (TMS), LWFA, PWFA, SWFA, DLA, and a joint sub-WG on positron acceleration (PAC).

3. Plasma-based ANAs

In this section, we report on the conclusions of the presentations discussing acceleration in plasma.

In plasma-based ANAs operating in the bubble regime, the transverse fields are of the same order as longitudinal fields. Whereas it can be seen as an advantage to channel bunches over long distances, it also means that the particles emit betatron radiation. The radiated power depends on the particle energy and amplitude of oscillation about the beam axis. Calculations performed by V. Shpakov show that, per unit length, the radiation loss is always smaller than the energy gain and betatron radiation loss is therefore not a limitation to energy gain. As expected, emission betatron radiation together with acceleration lead to some cooling of the bunch emittance. However, radiation loss causes increase of the energy spread, which decreases the overall quality of the accelerated bunch.

Under-dense plasma lenses have very strong focusing gradients compared to magnetic lenses. The focusing gradient, proportional to the local plasma electron density, can in principle be tailored along the lens. Increasing the focusing gradient *adiabatically* along the length allows for minimization of synchrotron radiation and overcoming of the Oide limit. Calculations, presented by F. Filippi, show that for an experiment at the INFN SPARC-LAB, an exponential increase of the plasma density by a factor of 400 over 6 cm and starting with a density of 5×10^{15} cm^{-3} would be needed to focus a 110 MeV electron bunch from an initial 75 μm radius to $\sim$ 5 μm. Using a capillary discharge with a tapered entrance tube could be used for the density tapering. The size of the focused bunch could be inferred from the spectrum of the radiation emitted by the electrons in the constant density plasma inside the capillary.

Nikolay Andreev discussed external injection and acceleration of short electron bunches in plasma waves generated by intense femtosecond lasers in plasma channels. The dependence of the bunch length and energy spread was studied as a function of the phase of the plasma wave in the quasi-linear regime where the electrons are injected. For the parameters studied, when an electron bunch is injected with a size of the order of 20% the plasma wave length, at the maximum of the wave potential, the energy gain is or the order of 2 GeV over 20 cm of propagation with an rms energy spread smaller than 0.01. This energy spread is achieved for charges of the order of a few pC; for larger charges, beam loading leads to increased energy spread. Mechanisms relevant to multi-stage accelerators, such as the preservation of emittance and spin polarization of electron beams between plasma stages were examined by D. Pugacheva. Multi-stage LWFA was shown to preserve beam polarization, as the theoretical prediction gives 0.02% for depolarization after acceleration up to 1 TeV, which is suitable for high-energy-physics applications.

Driving plasma wakefields with a positively charged particle bunch raises a number of challenges related to the nonlinearity of the transverse forces acting on the bunch when reaching the non-linear regime. Some of the challenges can be overcome by using a hollow plasma channel rather than a uniform plasma. High-energy proton bunches are long, which means that one has to rely on self-modulation to produce a train of bunches that can then drive large amplitude wakefields. However, the self-modulation process operates by de-focusing a large fraction of the protons. Y. Li proposed to deal with these two issues by driving wakefields with a pre-formed train of short proton bunches in a hollow plasma channel. Initial estimates also show that this scheme is relatively weakly sensitive to variations of the plasma channel.

4. DLA

The dielectric laser accelerator (DLA) scheme has shown accelerating gradients exceeding GV/m, however over rather short accelerating distances and with small energy gains (sub-MeV). One of the advantages of the DLA is that optical elements can be used for all the functions necessary for an accelerator (power source, focusing, diagnostics, etc.), potentially allowing for an “on-chip” accelerator. As with other ANA concepts, one of the next steps for DLA is a global concept that includes an injector and a number of acceleration stages to produce high-energy, high-quality bunches. The DLA community, gathered in the ACHIP collaboration, is addressing challenges related to developing a high-energy accelerator on a chip.

J. England summarized the ACHIP program, including issues such as acceleration from rest to relativistic energies, micro-bunching at the laser wavelength scale, powering of multiple structures, compensation of globally de-focusing transverse forces during the weakly-relativistic part of the acceleration process, etc. The results of these studies are continuously integrated into updated versions of the “straw-man” concept collider based on DLA.

5. Simulations

A key component for the progress towards an Advanced Linear Collider based on one of the ANAs is the availability of computationally efficient simulation tools. Simulations are particularly challenging for plasma-based ANAs.

Most simulation codes use explicit particle-in-cell (PIC) algorithms that are particularly consuming in terms of computer memory and time. Reduced models (quasi-static, hybrid, etc.) and numerical methods (boosted frame, azimuthal decomposition, etc.) can provide significant time and memory savings, without loss of physical fidelity. However, at present, the full modeling of a single multi-GeV accelerator stage in 3D remains extremely challenging. J.-L. Vay presented a very ambitious program, a seven-year, exascale modeling project, based on WarpX. The goal of the project aims at a full numerical description (3D) of 100 plasma-based accelerator stages, towards a 1 TeV collider design. The project plan includes modeling of a single plasma accelerator stage with static mesh refinement by 2017, modeling a single GeV-scale plasma accelerator stage by 2018, and modeling of multiple GeV-scale plasma accelerator stages by 2020. WarpX is an up-graded version of the WARP, coupled to the latest adaptive mesh refinement algorithms. WARP is an open-access code, and WarpX is scheduled to be released to the public by 2018. The plans also include visualization tools as well as interfaces for analysis with various programs. This is a very important and welcome initiative.

6. Facilities

During the joint session with Working Group 1 (Electron beams from plasmas) of some of the present and planned ANA experimental facilities were described.

EuPRAXIA is a design study for a 5 GeV electron beam research facility for light source (FEL) and high-energy physics applications. The major goal for EuPRAXIA is to design and, in a second phase, build a compact European advanced accelerator with superior beam quality. P.A. Walker presented a designed and preliminary global parameters of a generic facility that uses ANA technology to drive an FEL. The facility would generate 5 GeV electron beams and include two users areas: one for the FEL and one for high-energy physics applications. The design accommodates options for the electron source (RF-gun with x-band linac, LWFA), and for the accelerator (LWFA, PWFA). Drive lasers and klystrons would be located in an upstairs mezzanine, whereas accelerators, undulators and experimental areas would be located on the ground floor.

At the moment there are five European facilities that could candidate to host the construction of a facility resulting from Eupraxia design study.

M. Ferrario presented plans for a new compact FEL facility at INFN-LNF that would be compatible with the EuPRAXIA design. The plans include all the options envisaged by EuPRAXIA, but also the option to have a 1 GeV x-band linac that could drive the FEL without plasma acceleration. The TDR is expected to be completed by the end of 2017. The facility would be an upgrade of the current SPARC-LAB that already operates with an s- and c-band accelerator to drive an FEL. In addition, the high-power laser FLAME, presently used for LWFA studies, would be upgraded with the aim of externally injecting and accelerating the bunch from the RF-gun. Plasma sources are already available for PWFA and plasma lens studies. Preliminary simulation results indicate that beams produced in the current SPARC-LAB, and thus its upgraded version, from plasma accelerators would lead to lasing of the FEL in the water window.

FLASHForward is the future-oriented wakefield accelerator research and development facility at FLASH, DESY. The main goal of the project is to explore PWFA. At FLASHForward, a PWFA witness bunch can be generated by a plasma cathode or from the FLASH linac. Single bunches can in principle be tailored for large transformer ratio and optimal beam loading experiments. Studies will also focus on the hosing instability, a effect that could disrupt beams in very long acceleration sections. In a second phase (starting 2020), undulators will be added to the beamline to drive an FEL using an electron bunch produced in the PWFA. The work is supported by a strong simulation program, including start-to-end simulations. In his presentation J. Osterhoff described how many of the critical scientific challenges faced by the PWFA, and other ANAs, can be addressed at FLASHForward.

ARES is another facility at DESY studying LWFA and possibly DLA for FELs and other applications. The beam produced by the ARES linac would be injected into the LWFA. Towards this end, simulations including deleterious effects such as CSR, presented by J. Zhu, showed that after compression the ARES bunch could reach sub-fs length, which would make the bunch suitable for injection into an LWFA. These short bunches contained 0.8 pC, with 600 A current. Longer bunches with larger currents can also be produced and, perhaps, are more suitable to drive the FEL. Maintaining a low energy spread suitable for FEL lasing is a challenge, as in all LWFA designs. In the ARES case, simulations showed space charge effectscan limit the bunch current and the beam matching into the plasma.

The MAX IV is a 3 GeV light source storage ring located in Lund (Sweden). The 3 GeV beam from the linac is available for ANA experiments, when not used for filling of the ring. Simulation results presented by O. Lundh show that the 100 pC bunch can be compressed to reach more than 10 kA of peak current. However, in this case emittance growth becomes a serious issue. Less aggressive compression to 1.5 kA produces a bunch with low emittance and relative energy spread. Driving the gun photo-cathode with two laser pulses could lead, after two stages of compression to a drive/witness bunch train that would be very interesting for PWFA experiments. In particular, simulations showed that a loaded accelerating field could reach the 10 GV/m level. Plans for PWFA experiments are awaiting endorsement by the MAX IV Laboratory.

7. Conclusions

Discussions during the working group re-enforced the need for active collaborations, community-gathering behind a global high-energy physics application of ANAs, continuous critical analysis of the various “straw-man” designs for an ALC, and need for leadership in this endeavor. It is clear that there is much to learn from the conventional accelerator community’s experiences building accelerators and developing TDRs for future linear colliders (e.g., CLIC and ILC). It is also clear that there is an urgent need to involve this community in the development of ANAs and also in the development of a global collider concept starting at the injector and ending at the detector and physics case. This model will be used for the up-coming ALEGRO workshop and for the generation of a document as an input for the next European Strategy on High-Energy Physics.

From the scientific point of view, presentations in WG8 showed that significant progress is being made towards high-energy accelerator concepts. The most attractive feature of ANAs remains the large accelerating gradients.

There are now roadmaps for ANA development that have been drawn in the US [4] and in Europe [2]. There is a European facility design study (EuPRAXIA) focusing on a plasma-based ANA to produce high-quality beams. A number of facilities are either operating, coming on-line, in the building phase, or in the planing phase. All of these facilities are geared towards light sources or high-energy physics applications. They will all contribute to addressing the major scientific challenges that have been identified by the community, most recently at the ANAR Workshop. ALEGRO will provide a forum for organizing the global ANA efforts towards producing high-quality and high energy beams, as well as deliver a document for the next European Strategy input and for an ALC.

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