Summary of European Advanced Accelerator Workshop (EAAC) Working Group 1: Electron Beams from Plasma.

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Abstract. We summarize oral contributions presented in Working Group (WG) 1 of the European Advanced Accelerator Workshop (EAAC). Working Group 1 is titled 'Electron Beams from Plasma' and included presentations and discussions on the following subjects: laser- and beam-driven plasma wakefield acceleration, recent experimental results and planned experiments, single and multi drive laser pulses (or particle bunches), external and self-injection techniques, staging as well as advanced beam control and manipulation.

1. Introduction
Working group (WG) 1 comprised 29 oral presentations. Each presentation was given a time limit of 15 minutes and had 5 minutes reserved for questions and discussions. There were eight sessions in total, including two joint sessions (8 oral presentations) with WG 5 (Plasma devices, plasma and beam diagnostics) and one joint session (3 oral presentations) with WG 8 (Advanced and novel accelerators for High Energy Physics). We invited three contributions on recent, high impact experimental result:

- A.-M. Bachmann with the title 'Seeded Self-Modulation of a Relativistic Proton Drive Bunch in Plasma';
- F. Habib with the title 'Generation and Acceleration of Electron bunches from a Plasma Photocathode'.
- S. Karsch with the title 'Dual Energy Electron Beams from two Independent Injection Events'.

In this summary article we give a brief overview of the individual oral contributions presented in WG 1. We separated contributions into five categories:

- Towards High Witness Electron Beam Quality;
- Advanced Beam and Plasma Diagnostics;
- Exploring Physics;
- Novel Concepts;
- Facilities and Proposed Experiments.

2. Towards High Witness Electron Beam Quality

Recent progress in plasma-based accelerators features the experimental demonstration of GeV energy gains within cm-scale plasmas at improved pulse-to-pulse witness beam stability. The natural next step will be to control and refine witness beam parameters required for applications. Here an in-depth understanding on the injection and acceleration process as well as precise knowledge on the structural dynamic of plasma accelerators and accelerated beams are keys for the generation of high quality witness beams. Advanced diagnostic tools (discussed in Section 3) with single-shot capability at high spatio-temporal resolution, thus, are essential.

Various electron injection scenarios have been explored in the last decade, departing from rather chaotic nonlinear processes to more control over the spatio-temporal injection point within a certain accelerating phase of plasma wakefield. M. Streeter (I. College) [1] presented the implementation of shock-front injection using a PW-class laser system for the production of almost background-free GeV electron beams with a narrow energy spread. These beam parameters are vital for precision radiation-reaction studies, e.g. comparing semi-classical and fully stochastic QED models. Furthermore, benefiting from high-repetition rate laser system to enable closed-loop stabilization of on-target laser parameters, M. Kirchen (U. Hamburg) [2] demonstrated the generation of narrow energy spread electron beams at improved stability by utilizing a tailored plasma target. A large data set is generated mapping the correlation between the drive laser, plasma target and the accelerated electron beams parameters. S. Karsch (LMU) [3] presented a new concept of combining shock-front and colliding pulse injection for the generation of dual-energy electron bunches. While the parameters of the front bunch remain almost unaltered, by adjusting the collision time, the energy and temporal distance of the trailing bunch can be reliably adjusted. This feature represents an important capability for light source applications. In order to generate high brightness electron beams, beside a short injection time within a small injection volume, the initial bunch needs to have a very small intrinsic emittance. F. Habib (U. Strathclyde) [4] presented the proof-of-concept demonstration of cold-injection in a PWFA stage. Here a spatio-temporally synchronized auxiliary laser was used to release low-momentum spread tunnel-ionized electrons inside an electron beam driven wakefield. A further refinement work is planned in the next experimental campaign at FACET-II facility.

New experimental results regarding the acceleration of an external witness electron beam in a PWFA were reported. G. Andonian (UCLA) [5] showed a novel method to characterize in a single shot nonlinear plasma wakefields, based on emittance exchange and shaping of the drive current profile. In particular, they showed the possibility to achieve electron acceleration with transformer ratio of up to 7.8, as well as to obtain uniform deceleration of the driver by a specific parabolic head shaping, a result published in Phys. Rev. Lett. since the conference [6]. At DESY, K. Poder [7] reported the first electron beam witness acceleration from the FLASHFoward PWFA facility, featuring exquisite stability and showing that, by using the stable drivers from the FLASH superconducting linac, plasma-based acceleration can indeed provide the stability desired for a particle accelerator.

S. Hooker (U. Oxford) [8] discussed the route towards high repetition rate and high average power LWFA, including the use of multi-pulse LWFA, where a train of laser pulses is used to

Journal of Physics: Conference Series **1596** (2020) 012001 doi:10.1088/1742-6596/1596/1/012001

build up the plasma wave. High repetition rate and high average power were also discussed in the context of PWFA by R. D'Arcy (DESY) [9], with FLASHFoward opening the prospect for the ultimate capability of a MHz PWFA, with up to 800 bunches at 1 MHz spacing and at 10 Hz rate, corresponding to a few tens of kW of average power.

The generation and acceleration of high-quality 5 GeV electron beams for FEL application was discussed by A. Rossi (INFN Milano) [10], in the context of EuPRAXIA, with an emphasis on the importance of emittance and energy spread evaluation through a fit and cut procedure, providing much more relevant values in the context of plasma-based acceleration.

For very high quality beams, it is known that the hosing instability and ion motion can be detrimental to the acceleration of a witness beam in the blowout regime. W. An (Beijing Normal University) [11] and C. Benedetti (LBNL) [12] showed through theoretical and numerical PIC results that ion motion can in fact suppress the hosing instability, and that it is possible to limit emittance growth to an acceptable level with a standard linear matching, or even to preserve emittance by the use of a nonlinear, slice-by-slice matching with an equilibrium transverse phase space distribution.

3. Advanced Beam and Plasma Diagnostics

Visualization of plasma accelerator structures in femtosecond timescale is key to access electron injection and acceleration dynamics as well as the physics of relativistic plasma. Transverse synchronized ultrashort probe laser pulses, i.e. shorter than the plasma timescale, can be used to make shadowgraphic snapshots of the electron density modulation of the associated plasma waves. A. Svert (HIJ) [13] deployed such a technique combined with polarimetry to study the evolution of the plasma wave's shape and the induced magnetic fields. It reveals a subtle interplay between the laser pulse evolution and the generated magnetic fields to the injection and acceleration process.

The measurement of the spectral and spatial intensities of transition radiation emitted when an electron bunch tranverses a metal-vacuum interface can potentially be used to extract information on the electron beam structures at sub-femtosecond timescale with micrometer spatial resolution on single-shot basis. O. Zarini (HZDR) [14] presented the realization of multi-octave optical spectrometer together with an advanced phase-retrieval algorithm for the reconstruction of the temporal structure of electron bunches from laser-driven plasma wakefield accelerators. It reveals that the accelerated bunch length depends strongly on the deployed injection mechanism. M. Laberge (U. Texas) [15] imaged the near-field and far-field of the transition radiation, emitted from a foil located directly at a plasma accelerator exit, at multiple narrow bandwidth slices within the visible wavelength range. The data analysis on the beam size, divergence as well as micron-scale sub-structures was presented. Combining these two methods is anticipated to pave the way for a complete three dimensional bunch reconstruction.

Emittance is a key quality parameter of particle beams. Yet, measuring the emittance of plasma accelerated electron beams is far from a trivial task. In order to deduce the phase-space of electron beam at a plasma accelerator exit, P. Winkler (U. Hamburg) [16] deployed a conventional quadrupole scan method where an energy dispersing magnetic dipole was placed in between a set of quadrupoles and a scintillator screen. This configuration enables energy-resolved emittance measurement, thus a chromatic emittance growth during beam propagation in vacuum can be deduced. However this quadrupole scan technique is limited for measuring beam emittance after the accelerator. In order to assess the beam dynamic and emittance evolution of accelerated electron bunches inside plasmas, an x-ray spectroscopy technique on the emitted radiation can be deployed. S. Corde (LOA) [17] presented the correlation of the emitted betatron radiation to the emittance growth during propagation through a plasma in the highly nonlinear regime. Furthermore, when electron beam is filamented as induced by instabilities, the production of bright gamma-ray can be expected.

Chromatic emittance growth during acceleration can be caused by a finite energy spread and/or a finite bunch length. A. Khler (HZDR) [18] presented experimental results showing the correlation between the beam energy spread and divergence, i.e. a minimum energy spread leads to a small beam divergence for a given bunch length. While the beam envelope at the accelerator exit, extracted from betatron spectroscopy, does not change significantly, this effect is attributed to the betatron decoherence process on polychromatic beams. In addition, a proper beam matching during extraction from plasma accelerators to vacuum plays an important role to the final beam quality, mitigating further beam degradation and emittance growth. R. Shalloo (I. College) [19] presented how the variation in plasma scale length at the exit of a GeV class wakefield accelerator affects the quality of the accelerated electron beams. Thus, a properly designed plasma density down-ramp will result to a small divergence beam.

4. Exploring Physics

High-energy proton drive bunches have the potential to drive wakefields that can accelerate a witness beam to very high energies (∼TeV scale) in a single plasma stage. Yet, short and dense proton bunches are currently unavailable. One way to still be able to use available (long) high energy proton bunches is to rely on the 'Seeded-Self Modulation'. This process can transform a long bunch into a train of short bunches that resonantly excites a high amplitude wakefield. A.-M. Bachmann (CERN, MPP) [20] presented an overview of the experimental results on Seeded Proton Bunch Self-Modulation in the context of the Advanced Wakefield Experiment (AWAKE) at CERN. She showed that a proton bunch does self-modulate and that the wakefields driven by this bunch are phase reproducible. She added experimental evidence for seeding self-modulation with the wakefields driven by an electron bunch.

Also in the context of proton drivers and AWAKE, M. Huether (MPP) [21] presented an experimental physics study on the beam-hose instability. He compared measured bunch centroid oscillations with theory and simulations and showed good qualitative and quantitative agreement between the two.

5. Novel Concepts

To advance plasma based acceleration techniques and overcome their limitations, new ideas and concepts are needed. In that context A. Debus (HZDR) [22] presented a simulation study on Traveling-Wave Electron Acceleration (TWEAC). In the TWEAC scheme two pulse front tilted lasers are crossed at an angle, such that the location of the laser peak intensity moves at the speed of light. He showed that the conventional laser dephasing and depletion limit can be overcome. He also presented results of laser pulse energy efficiency optimization studies.

O. Lund (U. of Lund) [23] showed experimental results on X-ray production by electrons propagating in merged wakefields. Lasers and wakefields are merged by small angle crossing and travel in the forward direction. Electrons oscillate in these merged wakefields with an increased radial amplitude. The X-ray yield in the forward direction increased by a factor of three compared to the one created by two separated beams.

Motivated by the prospect of overcoming laser-driven wakefield acceleration (LWFA) inherent limitations, i.e. dephasing, depletion and diffraction, in witness beam energy and quality, a concept of utilizing LWFA electron beams to drive the subsequent beam-driven wakefield acceleration (PWFA) stage was proposed. This platform combines the unique features of each acceleration method in a compact geometry. S. Schbel (HZDR) [24] presented images of LWFA beam-driven plasma waves which were captured at the center of a PWFA stage using the few-cycle shadowgraphy method. It reveals an influence of the drive beam peak current to the shape of the plasma cavity. T. Heinemann (DESY, U. Strathclyde) [25] showed that the witness beam acceleration inside such PWFA stage. Furthermore the witness energy can be further boosted if a plasma enviroment was created prior to the arrival of the drive beam. In this experiment a thin metalic laser-blocker foil was placed in between the two accelerator stages. Beside separating the PWFA process from LWFA, it enables the independent control and optimization required to fully explore the capabilities of laser-based PWFAs. O. Kononenko (LOA) [26] presented the influence of relativistic laser-foil interactions to the emittance growth of the passing electron beams. While multiple scattering is a negligible effect, the high intensity laser induced instabilities becomes a dominant factor for beam quality degradation.

Such a hybrid accelerator was further explored by employing a drive-witness bunch pair generated in the first LWFA stage. This pair prepared with a defined temporal separation is then injected into the subsequent PWFA stage. A. Dpp [27] optimized shock-front injection in the LWFA stage such that a high charge driver is generated and followed by a low charge witness bunch. In the PWFA stage, while the driver excites plasma wakefields and loses its energy, the witness probes the accelerating field, and thus gain an additional energy. J. Svensson (U. Lund) [28] demonstrated that the witness bunch can gain energy higher than the driver's. This process is accompanied by the generation of highly collimated betatron x-ray beams.

6. Facilities and Proposed Experiments

Available research facilities are key to performing experiments and advancing research in the field. R. D'Arcy (DESY) [9] and K. Poder (DESY) [7] presented the status of the FLASHForward facility at DESY. FLASHForward is an extension to the FLASH FEL beamline and is aimed for a next-generation experiment for beam-driven plasma wakefield accelerator research. Proposed experiments include: using plasmas to create high brightness electron witness bunches, demonstrate witness bunch emittance preserveration during acceleration and plasma wakefield acceleration at high average power.

P. Muggli (MPP) [29] presented the path and physics concepts to achieve high-quality electron witness acceleration in the context of AWAKE Run 2, where plasma wakefields are driven by a high-energy self-modulated proton bunch. The goal is to demonstrate sufficient witness bunch quality for first high-energy-physics applications.

FACET-II at SLAC is a test facility to develop advanced acceleration techniques with high-energy electron and positron beams. The following experimental plans were presented: 1) high brightness electron injection based on the Trojan Horse injection scheme from B. Hidding (U. of Strathclyde) [30] and F. Habib (U. of Strathclyde); 2) transverse beam filamentation as well as high efficiency and emittance preservation studies from S. Corde (LOA) [17].

To summarize, three planned/new beam-driven plasma wakefield acceleration research facilities presented their physics goals. FLASHForward already started operation, FACET-II is expected to start in early 2020 and AWAKE Run 2 could start as early as 2021.

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