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Summary of WG5: High gradient plasma structures and advanced beam diagnostics

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ABSTRACT

We briefly summarize the presentations and discussions from working group 5 (WG5), dedicated to high gradient plasma structures and advanced beam diagnostics, which occurred during the third edition of the European Advanced Accelerator Concepts Workshop (EAAC 2017).

1. Introduction

Working group 5 (WG5), "High gradient plasma structures and advanced beam diagnostics", occurred during four parallel sessions of the third edition of the European Advanced Accelerator Concepts Workshop (EAAC 2017). The working group covered several topics related to recent developments of laser- and beam-driven plasma accelerators, including plasma sources, advanced beam diagnostics, laser guiding and particle beam transport. In many ways, WG5 complemented other working groups focusing on more fundamental studies, notably WG1 "Electron beams from plasmas". In WG5, delicate technical problems and sophisticated engineering solutions were often central. It became evident that as many groups strive to promote plasma accelerators from being "promising" to being "useful", the various subsystems (e.g. plasma sources and beam diagnostics) are becoming increasingly more advanced and precise.

There were in total 20 talks and 4 sessions. The sessions turned out to be rather popular and we are grateful to those who accepted to sit on the floor or standing in the back when all the seats were taken. There was a creative atmosphere with many good discussions and helpful comments. During two afternoons, there were 2 sessions on "Advanced beam diagnostics", one session on "High-gradient structures and components" and one session on "Plasma lenses and laser waveguides". In the following, we summarize the talks according to these themes.

2. Advanced beam diagnostics

This section is dedicated to contributions about novel methods to measure characteristic beam parameters of electron bunches from plasma acceleration. The knowledge of these parameters is crucial for the understanding and optimization of the acceleration process in view of applications of plasma accelerated bunches for radiation sources like undulator radiators or Free Electron Lasers.

Plasma accelerated electron bunches are characterized by very short bunch lengths of the order few micrometer. Measurement and control on such short time scales requires refined diagnostic techniques. One possibility is the spectroscopy of coherent transition radiation produced by the bunches when passing a boundary between media of different refractive index. *O. Zarini et al.* presented a multi-stage spectrometer covering wavelengths from the UV to about 18 μm. The set-up consists of four individual spectrometer stages with specific dispersion and detection technologies. Great efforts have been taken to cross-calibrate the sensitivity over the full wavelength range. First measurements of LWFA accelerated electrons of 300 MeV showed bunch lengths of about 20 fs with substructures in the 1–2 fs range.

At SPARC-Lab, a single shot technique to measure the emittance of plasma accelerated electrons has been developed and was presented by *F.G. Bisesto et al.* . The method is based on the sensitivity of the angular distribution of incoherent transition radiation to the divergence of the beam. In combination with a microlens array in the image plane, an optical pepper-pot measurement of the emittance should be possible. First results show good agreement with Zeemax calculations of the optics.

Direct time domain measurements of the electron bunch profile with femtosecond resolution is possible using strong X-Band transverse deflecting structures (TDS). A novel concept of such a device with variable polarization was presented by *D. Marx et al.* . The device, which

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is at present under development in a collaboration between CERN, DESY and PSI, would enable to streak the bunches in arbitrary planes, allowing for a tomographic reconstruction of the 3D charge profile. In combination with a dispersive section, slice energy distribution could be measured for a final 6-D reconstruction of the phase space distribution. Extensive Elegant simulations demonstrated the diagnostic power of such an instrument.

One idea to overcome the resolution limitations of transverse deflecting structures was presented by *M. Weikum et al.* . In a first step, the bunch passes an undulator together with a strong, resonant laser field. The intense electric field of a CO2 laser imprints a strong horizontal momentum transfer with a periodicity of about 30 fs. The resulting ambiguity for bunches longer than that, can be resolved by using a subsequent vertical streak from a conventional RF-TDS. Like in en etalon spectrometer, this technique combines very high resolution on the sub-fs level with large dynamic range up to picoseconds. A first proof-of-principle experiment at Brookhaven, still limited by the available laser power, demonstrated the expected cross-play between laser streaking and RF-streaking.

For beam-driven plasma acceleration using external injection schemes based on laser ionization, the precise synchronization between the laser and the electron beam are of crucial importance. *P. Scherkl et al.* presented results from an experiment at FACET to solve this problem in a new way. A fraction of the laser to be synchronized is used to create a thin plasma “filament” perpendicular to the electron beam. When the electron bunch passes this filament, the recombination light of the filament is enhanced. The total time integrated light output increases by a factor of 50 compared to the case where the bunch passes the filament region before the laser pulse. This quite strong effect leads to a steep increase of light intensity vs. arrival time which can be used to measure the relative timing with fs precision. In addition, the small dimension of the filament with an r.m.s. width of about 60 μm allows to also measure and optimize the lateral position of the electron beam.

Charge diagnostics especially for small bunch charges is an essential asset for all plasma acceleration experiments. *S. Bohlen et al.* presented a cross calibration of different charge measuring devices done with LWFA electrons from the FLASHForward test set-up at DESY. A variety of DRZ screens where used together with two electronic devices, an ICT from Bergoz and a DaMon (DarkCurrentMonitor) developed at DESY. The DZR screens showed a nearly linear response over three orders of magnitude in charge from 50 pC to 50 nC. The ‘DRZ High’material showed a very high light output, 13 times higher than conventional ’Lanex Fine‘. The DaMon detector uses the TM01 mode excited by the bunch in a resonant cavity to measure the total charge. It is an extremely sensitive device capable to span a range of 7 orders of magnitude from 100 nC down to 10 fC with reasonable sensitivity. In addition, due to its very narrow frequency response, it is highly insensitive to EMP from the plasma or other sources.

3. High-gradient structures and components

In laser- and beam-driven plasma accelerators, it is essential to know and to precisely control the plasma parameters. The plasma source will usually need to be well-defined in terms of its spatial extent, density, uniformity, and composition. The plasma frequency scales with the square root of the plasma density, which means that density variations lead to phase-variations of the accelerating field with respect to the accelerating particles. This can be detrimental unless the density profile is precisely controlled, but it could also be harnessed through controlled phase-variations. These aspects, and others, were considered and discussed in the working group.

The world’s first proton-driven plasma wakefield accelerator experiments AWAKE at CERN started at the end of 2016. For the first stage of the experiments, self-modulation-instability (SMI) is studied. SMI develops as the 12 cm long 400 GeV proton bunch gets transversely modulated over 10 m by the transverse forces in the plasma. *S. Gessner et al.* presented results from the AWAKE experiment, in which a terawatt-class laser is used to ionize a ten meter long Rb vapor during or before the transit of a 400 GeV proton beam. The proton beam is modulated by the plasma through the SMI process and the modulation occurs at the plasma frequency, which is proportional to the square root of the plasma density. In the experiment, the laser timing with respect to proton beam was scanned from zero (coincident with the beam) to tens of microseconds ahead of the beam. At each point, the modulation frequency on the proton beam was measured and used to deduce the plasma density. It was found that for delays $\gtrsim 1\,\mu s$, the plasma density decreased significantly. From this information, the authors were able to extract a decay constant for the plasma.

In the second phase of the AWAKE experiment, electrons will be injected and accelerated into the large scale resonant wakefield created by the micro-bunches formed as a result of SMI. Plasma density variation as small as 0.2% can disrupt the injection and acceleration process. Therefore a unique plasma source was built to meet this requirement. The plasma source was presented in detail by *E. Oz et al.* , with both measurements and simulations. It is a Rb vapor confined in a 10 m heat exchanger tube. The valence electron of the Rb atoms is laser field-ionized to create a 2 mm diameter 10^{14}–10^{15} cm^{-3} density plasma. Two reservoirs located at the ends continuously flow Rb vapor into the open 10 m tube. Precise temperature control of the reservoirs allows generating positive or negative density gradients while the density is measured at both ends with a Mach–Zehnder interferometer with 0.1% accuracy.

In a plasma wakefield, the beam is typically located at the slope of the accelerating field (i.e. off-crest acceleration), such that it is simultaneously accelerated and focused by the plasma fields. However, this choice of accelerating phase also imprints a longitudinal energy correlation (chirp) onto the bunch, an intrinsic feature of virtually all plasma-acceleration schemes, and a major source of the undesired energy spread growth. *M. Kirchen et al.* presented an interesting scheme, to mitigate the chirp accumulation in the linear regime of plasma acceleration, based on a periodically modulated plasma density profile. By modulating the plasma density, the bunch periodically experiences accelerating fields with opposite slope, which effectively suppresses the chirp evolution, while the periodic focusing and defocusing can be controlled for stable beam transport.

Multi-stage laser-wakefield acceleration is planned for the CILEX/Apollon projects, and, as presented by *T. Audet et al.* , several gas cells are being tested as prototypes of the future electron injector in the 50–200 MeV range. Measurements in one of the gas cells using a Mach–Zehnder interferometer showed that, as expected, the neutral gas density in the cell depends linearly on the backing pressure. The measurements were combined with fluid simulations in OpenFOAM to determine the absolute density profile in a wide range of experimental parameters.

An interesting concept for miniaturized accelerator components which is not based on plasma, was presented by *T. Feurer et al.* and *M. Hayati et al.* . The concept is based in plasmon- or phonon-polaritons excited at plane or structured interfaces in sub-wavelength resonators by strong THz pulses. Often these structures show either electric or magnetic near-field enhancement alleviating the need for a strong driving THz source. Today laser-driven THz sources can produce single-cycle pulses with field strengths between 10 to 100 MV/m (electric) and around several Tesla (magnetic); they can be easily synchronized to a gun laser or any other laser in the accelerator chain and the THz free-space wavelength or the plasmon wavelength are well matched to a typical transverse electron bunch size on the order of 100 μm. Several types of miniaturized components were presented, including deflecting structures for electron streaking diagnostics, accelerating structures, and also miniaturized undulator structures.

4. Plasma lenses and laser waveguides

Capillary discharges can be used as plasma lenses due to the strong axial current in medium transparent to the beam. In contrast to quadrupoles, the azimuthal magnetic field leads to focussing forces in both perpendicular planes. Field gradients of up to 1000 T/m have been reported. Another interesting application of plasma channels is the guiding of a laser field due to a radially dependent plasma density.

At the former CLIC test facility at CERN, now transformed into the R&D test facility CLEAR (CERN Linear Accelerator for Research), a plasma lens experiment is being set up as reported by *C.A. Lindstrøm et al.* A 15 mm long, 1 mm diameter sapphire capillary from DESY is powered by a compact Marx-Bank developed at Oxford University. First tests in September 2017 demonstrated the successful beam transport through the capillary. Experiments are planned for Oct 2017 to mid 2018, the main goals are measuring the radial non-uniformity of the plasma with high resolution and evaluate first steps towards a multi-plasma apochromatic lattice.

Results from an experimental campaign using the 855 MeV electron beam from the Mainz Microtron were presented by *J.H. Röckemann*. The radial dependence of the magnetic field gradient was measured with excellent resolution, the results confirmed predictions from MHD and particle tracking simulations. The experiments demonstrated the high reproducibility of the plasma lens from shot to shot. The measured emittance degradation of the beam could be fully explained by the non-linear radial field dependence. Further studies to reduce this non-linearity are planned.

R. Shalloo et al. presented an extensive study on the possibility to guide high-power laser pulses through a plasma channel. Hydrodynamic expansion of the plasma channel creates an parabolic density profile in the plasma and thus a radial dependence of the refracting index. In contrast to collisional heating, heating by optical field ionization as used here, allows for lower central plasma densities which are desirable for acceleration up to the 10 GeV regime. Using a 25 mJ, 50 fs laser focussed into the plasma by an axicon lens, the authors successfully demonstrated the expected shock-front expansion and resulting electron density profile.

The idea of guiding the long laser pulse trains in a plasma with steep radial density gradient was further investigated by *R. Walczak et a.*. They demonstrated with EPOCH 2D PIC simulations that a train of 10 laser pulses with a total energy of 800 mJ could be propagated over 25 cm. This would enable multi-pulse laser wakefield acceleration up to several GeV.

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