OPTICAL DIAGNOSTICS WITHIN LA3NET*

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Abstract

The Laser Applications at Accelerators network (LA³NET) is a pan-European project that has received 4.6 M€ of funding from the European Union's 7th Framework Programme. It closely links research into lasers and accelerators to develop advanced particle sources, new accelerating schemes, and in particular beyond state-of-the-art beam diagnostics. This contribution summarizes the research achievements in optical beam diagnostics of this 4 year research and training initiative. It presents the achievable resolution of a laser-based velocimeter to measure the velocity of neutral particle beams, results from the measurement of bunch shape using electro-optical crystals with tens of fs resolution, experimental data using a laser wire scanner, and discusses the resolution limits in energy measurements using Compton backscattering at a synchrotron light source. Finally, it also provides a summary of events that have been organized by the LA³NET consortium.

INTRODUCTION

The LA³NET beneficiary partners have recruited 19 Fellows that are hosted by 11 partner institutions all over Europe. Their individual research projects are often carried out within the frame of PhD studies and distributed over the project's different scientific work packages. The largest of these work packages focuses on R&D into advanced beam diagnostics techniques. Furthermore, the consortium organizes a number of international Schools and Topical Workshops, as well as an international conference and numerous outreach events for the wider laser and accelerator communities, as well as the general public.

RESEARCH

Beam diagnostics is one out of the five scientific work packages within the LA³NET project [1]. It is of central importance as the instrumentation developed by the Fellow is crucial in interconnecting research carried out in the other areas of beam generation, acceleration, detectors and power supplies development. The DITANET project [2] pioneered a new approach to researcher training in beam diagnostics and the concepts developed by this consortium have formed the basis also for LA³NET. The following subsection present research results in this work package from individual LA³NET Fellows.

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Electron Bunch Shape Measurements using Electro-Optical Spectral Decoding (EOSD)

FLUTE (Ferninfrarot Linac-Und Test-Experiment – far infrared linac and test experiment) a linac-based light source currently under construction at Karlsruhe Institute of Technology (KIT) is a dedicated accelerator R&D facility. The main R&D goals of FLUTE are to perform systematic bunch compression studies over a wide charge (1 pC - 3 nC) and bunch length (1 fs - 1 ps) range, and to generate THz radiation with high peak fields [3]. The wide range of bunch charges and lengths at a comparatively low energy of 42 MeV requires sophisticated single-shot online-diagnostics. Electro-optical (EO) techniques have proven to be a reliable tool for bunch length measurements at linacs [4, 5]. LA³NET Fellow A. Borysenko had shown previously [6] for a low energy electron beam that longitudinal bunch profile measurements using EO techniques lead to an overestimation of the actual bunch length. This is caused by the electron energy-dependent opening angle of the bunch's Coulomb field that passes the EO crystal during the experiment. The opening angle of the electric field of the bunch is dependent on the electron energy as 1/g due to Lorentz transformation that leads to a longitudinal contraction of the field. Recently, he carried out studies into electro-optical bunch length measurements at beam energies of 40 and 200 MeV at the SwissFEL Injector Test Facility [7], PSI, Switzerland in preparation of measurements at FLUTE.

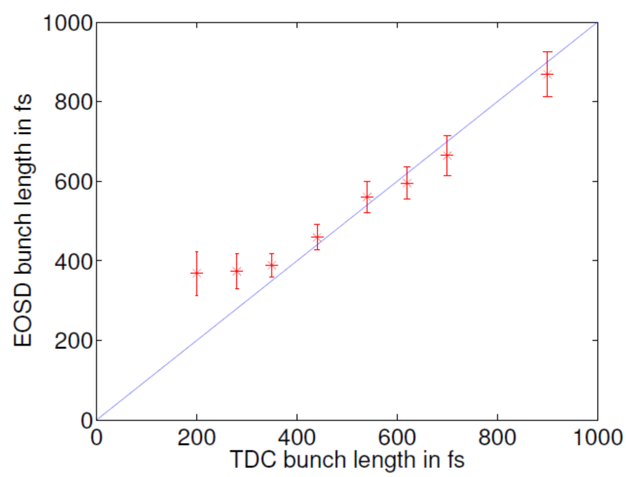

Figure 1: Measurement of bunch profiles using EOSD and a TDC for various electron bunch compressions at a beam energy 200 MeV.

The EO crystal is mounted on a movable arm in a way that the distance to the electron beam can be adjusted during the experiment. The back surface of the crystal has a high reflective coating that reflects the laser pulse. Then it is coupled back into a fibre and transported to the

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experimental station outside of the tunnel for spectral analysis. To record the spectral information of the laser pulse a 512x1-InGaAs photodiode array detector (iDus, Andor) was used that is capable of recording the spectrum of just a single laser pulse. The delay between laser pulse and electron bunch can be adjusted in order to achieve the temporal overlap inside the EO crystal in steps of 188 fs (electronically with a vector modulator) to achieve full temporal overlap inside the EO crystal. Data was compared against measurements using a transverse deflecting cavity (TDC).

The average EOSD bunch profile is depicted together with a single shot EOSD profile in the above Fig. 1. For specified settings of the bunch compressor, each point represents the rms electron bunch length reconstructed from EO measurements and is shown together with the rms bunch length measured with the TDC structure. Each EOSD bunch length is taken as a result of a Gaussian fit for the averaged bunch profile over 300 single shot profiles. The bunch charge was 100 pC. The electron beam energy was set to 40 MeV. The distance between EO crystal and electron beam was set to 1 mm. The EOSD measurement shows good correspondence to the TDC measurement for an electron bunch length longer than 370 fs rms. Moving to a shorter bunch length, the TDC structure is still capable of measuring the bunch length whilst the EOSD system does not measure any shorter than 360-370 fs.

Coulomb Field Strength Measurement by Electro-optic Spectral Decoding

A similar approach has been taken by R. Pan, based at STFC, and co-workers from CERN and the University of Dundee. An EOSD based bunch profile monitor at CTF3 of CERN has been developed and demonstrated [8, 9]. This monitor has a resolution of 1 ps and is suitable for characterizing bunches longer than 3.5 ps with an effective window of 16 ps. The system has a demonstrated single shot signal to noise ratio of 28:1 for a bunch with 0.17 nC charge, 6 ps duration and at a 2 mm offset. Recently, this technique was applied at the CALIFES beam line at CERN's CTF3 facility.

In the measurement the background signal is eliminated by rotation of a λ/2 wave plate. This allows the absolute value of the Coulomb field to be determined and also for the polarity of the field to be observed. All measurements were taken at 0.3 nC bunch charge, 200 MeV beam energy and observed at 2 mm away from the bunches. A laser pulse centred at 780 nm, with 130 fs FWHM initial duration chirped to 13.8 ps FWHM was used. The nonlinear crystal is 4 mm thickness ZnTe.

As can be seen from Fig. 2 there is a small bump following the main peak between 20-30 ps. This bump can be easily mistaken as a bunch structure in the tail within one electron bunch for the crossed polarization detection.

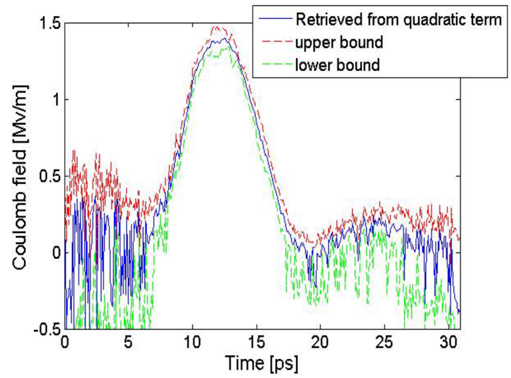

Figure 2: Retrieved Coulomb field from the quadratic term, the 95% confidence intervals determined bounds are shown in red (upper) and green (lower).

However, this bump comes from the negative part of the retrieved Coulomb field, since the cross polarization detection measures the Coulomb field square and represents a measurement of the wakefield of the bunch. The developed analysis techniques and the measured signal-noise characteristics are expected to be of use in the evaluation of the full potential for EO-based beam profile monitors [10].

Beam Characterization using Laser Self-Mixing

The increasing importance of supersonic gas jets for applications at accelerators [11, 12] means that their detailed characterization becomes very important. A sensor that can provide information about the jet's velocity, density and temperature in a least-destructive way would thus be an ideal tool to have. Laser self-mixing (SM) has been investigated as a simple to integrate, compact and cheap device for such purposes by Fellow A. Alexandrova, based at the Cockcroft Institute/University of Liverpool [13].

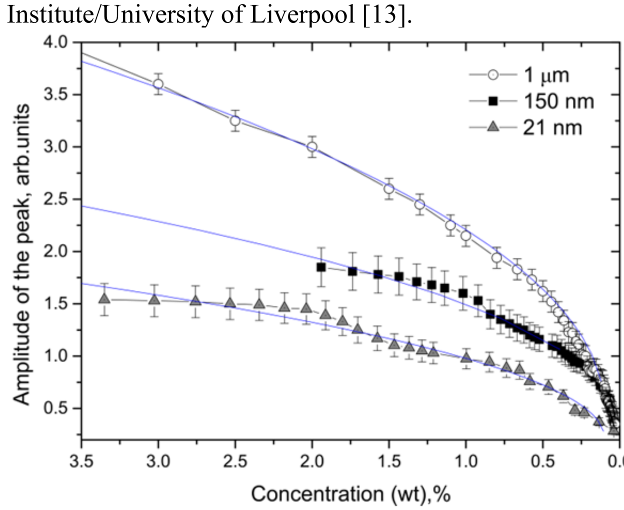

Figure 3: Measured influence of the concentration of TiO_2 seeders in water on the spectrum of the SM signal. Seeder diameter is indicated by different markers.

Laser self-mixing is based on the coupling of laser light reflected or scattered off a moving target back into the cavity. The backscattered light will have experienced a wavelength shift as a result of the Doppler effect. Its

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intensity depends on the detailed characteristics of the target, including velocity, density, optical properties, etc. The interaction between emitted and incoming signal will create a signal determined by a number of important target properties that can be directly derived. Direct measurements on a gas jet traveling at velocities of up to 2,000 m/s, however, are very demanding and hence investigations were started using liquids in combination with different seeder particles [14].

The concentration of the seeders is responsible for the amount of light being backscattered into the cavity. Varying concentrations of different seeder sizes have been studied to understand the influence on both the amplitude of the spectrum peak and its bandwidth. Figure 3 shows the measured amplitude of the peak signal as a function of seeder concentration and for different seeder sizes. The amplitude was averaged over 100 measurements. It can be seen that the overall trend of all plots is identical, irrespective of particle size, but that the amplitude can be changed using different seeders. Future studies will focus on the efficient seeding of gases and extension of the method to even higher velocities.

A Laserwire Emittance Scanner for LINAC4

Photo-detachment of electrons in an H^- ion beam provides an interesting way of non-invasive, reliable and maintenance-free diagnostics [15, 16]. Since the reduction of accelerator downtime is a major target for any accelerator and in particular for high current accelerators this technique can help to maximize machine efficiency. T. Hofmann who is based at CERN has successfully applied this technique at the new LINAC4 facility [17, 18]. He used a 1080 nm laser with 154 µJ pulse energy, 80 ns pulse length (FWHM), 60 kHz repetition frequency and an M^2 of 1.8. Due to its comparatively low pulse energy, the laser can be efficiently delivered to the accelerator by means of a long optical fiber. The laser is focused into the vacuum vessel with a final diameter of approximately 150 µm. Due to the quasi-monomode beam quality the laser diameter remains almost constant when colliding with the millimeter-size particle beam. Vertical scanning of the laser is performed by a remote controlled stage. A CCD camera and a fast photodiode are used to continuously monitor the laser beam quality. To detect the neutralized H^0 atoms a 20 mm x 20 mm polycrystalline diamond detector with 5 strip channels was used.

Figure 4 shows the resulting emittance values, measured with both a laser-diamond detector system, as well as with a ‘classic’ slit/grid reference system as a function of the applied threshold.

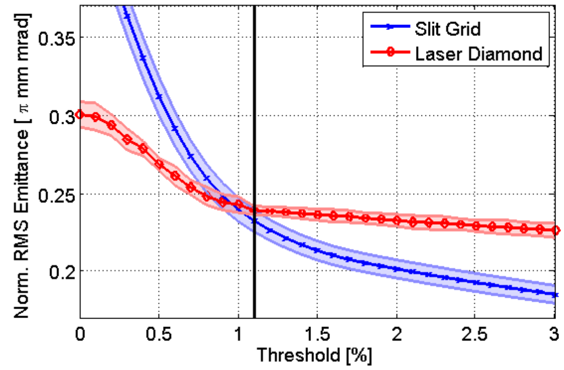

Figure 4: Normalized emittance value resulting from both instruments as a function of threshold used for noise suppression.

The characteristic kink in this curve marks the spot where the noise is largely suppressed and the sampled signal starts to originate from impinging particles. It can be seen that for the laserwire system this point is quite well-defined at 1.1%. The equivalent position for the slit/grid is not so clearly defined but can be marked down in the same region. Assuming the same threshold of 1.1% for both systems the resulting emittance values are 0.232 π mm·mrad for the slit/grid system and 0.239 π mm·mrad for the laserwire. SD represents the uncertainty of the emittance measurements at intervals along the LINAC4 pulse.

It is planned to use a modified version of the instrument during LINAC4 commissioning at 50 MeV and 100 MeV with the aim to measure the detached electrons and reconstruct the beam profile in a non-invasive manner [19]. In preparation for permanent operation the electrode design of the diamond detector and its data acquisition readout chain are in the process of being re-designed to provide even higher angular resolution and faster emittance measurements. Furthermore, it is foreseen to modify the system such that scans in horizontal and vertical planes will be possible.

Energy Measurement using Compton Backscattering at ANKA

Compton Back-Scattering (CBS) has some significant advantages for non-invasive beam energy measurements as compared to other techniques such as spin depolarization, reduced measurement times and that a polarized beam is not required. Several facilities have reported energy measurements based on CBS using a head-on collision geometry with relative accuracies reaching 10^{-4} to a few 10^{-5} [20, 21]. LA³NET Fellow C. Chang who is based at KIT and his co-workers have developed a CBS geometry that applies a transverse configuration ($\varphi=\pi/2$). This setup has several advantages: It is very compact and can therefore be used at rings with restricted space. Furthermore, the transverse setup reduces the energy of Compton edge photons by a factor of two which either makes measurements and detector calibration easier or enlarges the measurable range of a

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specific setup. They have used a High Purity Germanium (HPGe) spectrometer to determine the energy of the emitted photons [22]. Fig. 5 shows a typical spectrum that was acquired from a 1.3 GeV electron beam over 120 seconds. The mechanical centers of two quadrupoles were used as the reference line and the laser direction measured relative to this line with a laser tracker and a camera.

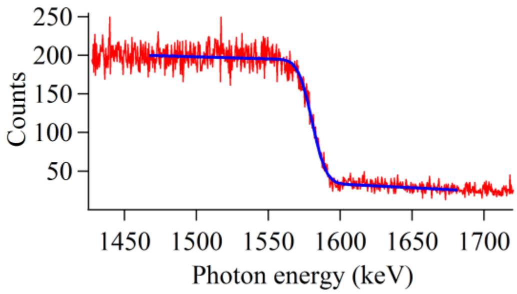

Figure 5: Measured CBS spectrum at 1.3 GeV with fit to determine the Compton edge energy.

The collision angle φ was determined from this measurement and yielded an average value of the beam energy of 1287.0 MeV ± 0.2 MeV. As compared to conventional CBS methods for energy measurement, a compact setup based on a transverse scheme has been successfully tested at ANKA. These measurements have been extended to beam energies of 0.5 GeV, 1.6 GeV and 2.5 GeV and gave promising initial results. It was shown that longer acquisition times can help further reduce statistical uncertainties in the Compton edge and hence beam energy. This might give access to measurements uncertainties to below a few 10^{-5} in the future.

TRAINING EVENTS

The primary training that all Fellows receive is training through their individual research projects. This is complemented by local courses and lecture series that are provided by their host institute or partner university. In addition, a series of network-wide training events has been organized by the consortium. These have brought all Fellows together on a regular basis training them in aspects that significantly stretch beyond their core research projects, thus maximizing their skills and increasing employability.

International Schools

A first international school on laser applications was held at GANIL, France in 2012 [23]. 80 participants from within and outside the LA³NET Consortium were introduced to the state of the art in this dynamic research area. The five day event followed the successful format pioneered earlier in the DITANET project. Renowned lecturers covered topics such as introduction to lasers and accelerators, beam shaping, laser ion sources, laser acceleration, laser based beam diagnostics and industrial applications. In addition to the lectures there were study groups, poster sessions and two evening seminars on major international initiatives in the laser and light sources field. All newly recruited LA³NET fellows joined this school and benefited not only from the excellent lectures, but also from discussions with participants from the wider community.

Between 29 September and 3 October 2014 the consortium held an Advanced School on Laser Applications at Accelerators. This event was hosted by the Spanish Pulsed Lasers Centre (CLPU) in Salamanca, Spain and attracted over 70 participants from all over the world [24]. It started with lectures about an introduction to lasers, the history of accelerator development in Europe, accelerator applications, as well as beam generation, acceleration and diagnostics. Day two included lectures on laser ion sources, photo injectors and Free Electron Lasers (FELs), in addition to a two-hour study session giving delegates a chance for a hands-on look at some of the topics covered. The following days covered more advanced topics in ion and electron acceleration, commonly used simulation codes for accelerator design and optimization, as well as industry applications of accelerators and lasers. Both Schools stimulated many fruitful discussions. In addition, the network has organized two researcher skills schools for all Fellows, covering wider skills, such as presentation, scientific writing, project management and CV writing in the first and final year of the project. The training scheme that was developed for the network's Fellows was specifically praised by a number of bodies, including the REA, HEA and UKRO and has since been implemented for many additional student cohorts at partner universities.

Topical Workshops

In order to stimulate knowledge exchange and help the Fellows in building up an international contact network LA³NET has organized a number of targeted scientific workshops at venues across Europe. These lasted 2-3 days and focused on expert topics within the network's scientific work packages. Fellows were given the opportunity to give talks about their individual projects and invited research leaders complemented the program of each event.

The first Topical Workshop covered laser based particle sources and was held at CERN in February 2013 [25]. It covered photocathodes for the production of high brightness electron beams, RF and DC photo injectors, hot cavity and gas cell ion sources for radioactive ion beam facilities, laser systems for efficient resonance ionization, as well as in-source spectroscopy of rare nuclides. A second workshop on laser technology and applications was hosted by the ILT in Aachen in 2013 [26] and included session on optics and laser design. The third workshop focused on novel acceleration techniques and was held in Dresden in 2014 [27]. It covered laser and particle beam plasma wakefield acceleration, as well as dielectric laser acceleration. A "Scientists Go Industry" workshop hosted by the Helmholtz Association in Berlin provided the Fellows and external delegates with an insight into the full range of job opportunities available for them outside of academia [28]. Finally, a Workshop

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on Beam Diagnostics was held in 2015 on Mallorca and included presentations about the state of the art in optical diagnostics, beam profile and emittance measurements and the use of optical techniques for ultra-short bunch diagnostics. On the second day longitudinal measurements of ultra-short Bunches, novel sensors and technologies and advanced diagnostics technologies were covered [29].

Conference on Laser Applications and Outreach Symposium

In March 2015 the network held a Conference on Laser Applications at Accelerators on Mallorca, Spain [30]. Following an introductory overview, methods for particle beam generation including laser ion sources and photoinjectors were presented. In the afternoon laser-based ion acceleration and dielectric laser acceleration were the focus as two examples of novel acceleration techniques with demonstrated performance gains. The conference also included sessions on electron acceleration and industrial applications including a seminar about the new Extreme Light Infrastructure (ELI). Finally, beam diagnostics methods were covered, linking to the efforts in the other work packages and indicating how existing and future facilities can be further optimized.

As the final project event an international Symposium on Lasers and Accelerators for Science & Society took place on the 26th of June in the Liverpool Arena Convention Centre. The event was a sell out with delegates comprising 100 researchers from across Europe and 150 local A-level students and teachers. The aim was to inspire youngsters about science and the application of lasers and accelerators in particular. All presentations are now available as an online resource, including videos of the talks that were given [31]. The Symposium also showcased the LA³NET projects through an interactive poster session with Q&A, giving young people the opportunity to see how scientists just a few years older than themselves are pushing back the boundaries of knowledge.

CONCLUSION AND OUTLOOK

Over the past four years, the LA³NET consortium has successfully trained 19 researchers and organized a large number of scientific events for the laser and accelerator communities. The network has established new training schemes that promote international collaboration. This paper described the progress made in the beam diagnostics work package and the results obtained by the project's Fellows.

In its last meeting the LA³NET Steering Committee decided to continue promoting the activities of the network's Fellows beyond the original project duration via various communication channels and to also continue organizing events for the wider research community. Details will be announced via the network's social media channels, website and quarterly newsletter.

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