LASER-BASED BEAM INSTRUMENTATION R&D WITHIN LA3NET*

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Abstract

Within LA³NET, Laser Applications for Accelerators are being developed by an international Network of more than 30 partner institutions from across the world. Laser-based beam instrumentation is at the core of this EU-funded project which will train 17 Fellows during its four year project duration. In this contribution, we present the consortium's recent research results in beam diagnostics, ranging from development of a laser velocimeter to measurement of the bunch shape with electro-optical sampling in electron accelerators. We also provide a summary of past training events organized by the consortium and give an overview of future workshops, conferences and schools.

INTRODUCTION

Lasers can be used for the generation of high brightness electron and exotic ion beams, the acceleration of particles with highest accelerating gradients, as well as for the characterization of many complex particle beams by means of laser-based beam diagnostics methods.

Without constant progress in laser technology and close collaboration between laser experts and accelerator scientists, many of today's most advanced experiments would simply be impossible. The LA³NET consortium combines developments in laser technology and sensors with their application at advanced accelerator facilities, providing complex beams ranging from the highest brightness electron beams in fourth generation light sources to high intensity proton beams in spallation sources. This way a very broad, yet closely interconnected, experimental program can be covered that combines many different scientific disciplines, such as for example mechanical and rf engineering, physics, electronics, IT, material sciences, and medical applications. The strong participation of the industry sector within the consortium and their active input during the definition phase of all research projects and along the ongoing training within LA³NET ensures that the transfer of industry-relevant skills is an integral part of all individual research and training projects.

The project started on 1.10.2011 and has a duration of 48 months. With a maximum project budget of up to 4.6 M€, it is one of the very large projects funded within the FP7 Marie Curie Actions ITN scheme [1].

RESEARCH

Research within LA³NET is distributed in five different work packages: Laser-based particle sources, laser-driven particle beam acceleration, lasers for beam instrumentation, system integration and lasers and photon detector technology. Beam diagnostics are of particular importance in this context as sophisticated instrumentation reveals the properties of a beam and how it behaves in a machine. Without an appropriate set of diagnostic elements, it would simply be impossible to operate any accelerator let alone optimize its performance. The DITANET project [2] has pioneered a new approach to researcher training in this field and the concepts developed by this consortium have formed the basis also for LA³NET. The following subsection present some initial research results in beam diagnostics R&D from individual LA³NET Fellows.

Laser Velocimeter

Gas jets have been successfully exploited for beam instrumentation purposes and are, amongst others, a promising way for online monitoring of the 2-dimensional transverse beam profile [3]. For such monitor, it would be highly desirable to have a compact sensor able to record the jet velocity and density profile in order to understand its dynamics in detail. It should be possible to integrate such monitor in a simple way in an existing set-up to provide accurate information about the velocity and density of the gas jet. The sensor would ideally consist of comparably cheap components. A promising option is a velocimeter based on laser self-mixing (SM) which is currently being developed by A. Alexandrova in the QUASAR Group based at the Cockcroft Institute/University of Liverpool, UK.

SM is used to characterize some properties of a moving object by using both, laser light and the cavity where the laser originates from. It is based on the following principle: Laser light is scattered or reflected from a moving target and returned into the laser cavity. The laser plays the rule of a coherent heterodyne receiver and at the same time the amplifier of the signal. The initial radiation interacts with the scattered or reflected radiation and produces a signal in both, the power and frequency spectrum of the laser. It is a system without a complex optical system, based on an in-expensive and compact diode laser, which can be easily installed and used to provide central information about the target, such as velocity, distances of movement and property of the surface (for solid target), density and property of scattered molecules (for liquids and/or gases). SM can be used with any kind of laser as long as the properties of the laser are correctly taken into account in the equations for the electric field and carrier density. In the case of a supersonic gas jet, a laser diode (LD) is going to be used. Such system can be compact, easily integrated into an existing set-up and is very cheap, thereby fulfilling all central requirements on such detector.

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In first experiments the main goal was to investigate ways to receive the right type of signal and how to improve its quality and amplitude. It was found that in order to receive a proper signal, many different things need to be optimized, such as distance to the target, noise in the diode, noise in the amplifier, and collimation. In the regime of weak feedback a neat phase transition and a linear decay following it should be achieved. As a result of the optimization, the measured SM signal became very close to the theoretically expected one, see Fig. 1.

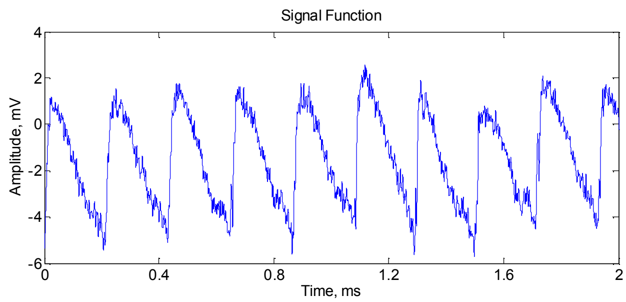

Figure 1: Example signal received from SM with a mirror as target.

The next part of the study was to derive the velocity of a movable stage from SM measurements. For the calculation of the velocity, a signal processing software was written which allows to calculate the velocity of the signal with an accuracy that mainly depends on noises and system instabilities. The signal beats with the Doppler shift frequency and is hence proportional to the velocity. The program for calculating the spectrum was based on FFT with different windows, and fitting the peaks afterwards together with calculating the velocity. It was found that the accuracy is increasing with distance between target and LD, due to a reduction in the feedback strength. Velocities were measured with absolute accuracies of better than 1.5%. After having received good results with a mirror target, similar experiments were carried out with white paper, i.e. a target which scatters the light strongly. Full results can be found in [4].

Electron Bunch Shape Detection

Typically, synchrotron light sources use incoherent light in their experiments. Coherent synchrotron radiation arises when the longitudinal electron bunch length is smaller than the wavelength, which can normally only be achieved for relatively long wavelengths in the (sub-) THz regime. Substructures on the electron bunches (micro-bunching) can then lead to strong «bursting» in the emission of coherent radiation. The physics behind these effects is still poorly understood, mainly because it is rather difficult to measure the bunch profile with sufficient temporal resolution.

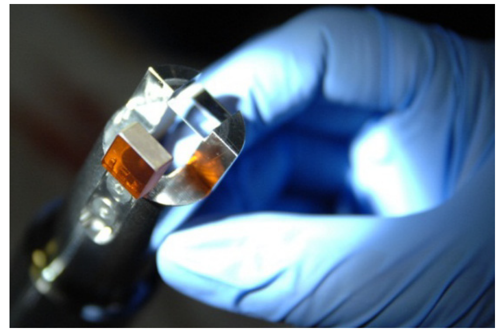

Figure 2: Photograph of an EO GaP crystal, mounted on its support (image courtesy of N. Hiller, KIT).

Electro-optic measurement uses the linear electro-optic or so called «Pockels» effect. This effect – usually a change in polarization, which is turned into a change in optical power at a polarizer – can then be measured with a photo detector yielding the bunch signal. LA³NET Fellow Andrii Borysenko is carrying out a project aiming at the realization and use of a high resolution electron bunch shape detection system at the new linear accelerator FLUTE, currently being designed at KIT, Germany [5]. Within his project he is designing and building up an electro-optic system for FLUTE. For this purpose, a system currently being developed for the ANKA ring shall be adapted. In addition, studies into performance limitations with regard to temporal resolution shall be carried out. Fig. 2 shows a photo of one of the crystals currently under investigation.

EO Bunch Temporal Profile Monitor

Detailed temporal diagnostics of the shortest electron beam bunches in free-electron lasers pose some of the most significant challenges in accelerator beam instrumentation. Electro-optical (EO) methods are a promising approach for the single-shot non-intercepting measurement of electron bunches with a time resolution of better than 50 fs, but new, more reliable methods of measurement require to be developed, and suitable electro-optical materials need to be better understood and carefully studied. These aspects are currently under study in collaboration between the University of Dundee and STFC Daresbury Laboratory, partially supported through the EU-funded LA³NET project.

Current techniques, developed over the last decade by the Dundee-Daresbury Group, are based on either spectral or temporal decoding of the Coulomb field of ultra-relativistic electron beams. The former technique is limited to beam bunches around 1 ps [6], while the latter requires ultra-short-pulse lasers that are expensive and potentially unreliable, making them unsuitable for turn-key accelerator control systems. The Group is currently working with the CERN compact linear collider (CLIC) project, with the intention of measuring the 150 fs CLIC main beam bunches to an accuracy of 15-20 fs, and using relatively simple laser systems, which is better than the current state-of-the-art for such measurements.

This work is also of pivotal importance for future advanced light sources, free-electron lasers and laser plasma wakefield accelerators, all of which share the characteristic of few-femtosecond (and shorter) electron bunches. There is therefore a pressing requirement to devise methods of measuring and optimising such very short electron bunch profiles, which will ultimately extend to the attosecond regime.

All of these techniques rely on the generation of a faithful 'optical replica' of the Coulomb field of the beam. This is generated by a process termed 'spectral upshifting' or 'pulse carving', whereby the Terahertz pulse representing the transverse Coulomb field is upshifted to an optical frequency via sum and difference frequency mixing in a suitable optical detector material placed adjacent to (but not traversed by) the electron beam. This is currently achieved using thin inorganic electro-optic crystals such as GaP and ZnTe, but the optical bandwidth of these materials (a few THz) renders them inefficient at very short bunch lengths, partly due to the onset of transverse optical phonon resonances [7]. Since 2011 the Dundee Group have been investigating a range of alternative materials to substitute for GaP, including $GaSe_2$, organic crystals such as DAST and MBANP, and the development (at Dundee University) of novel "meta materials" tailored to have the appropriate optical characteristics.

The MAPS group specialises in the development of nano materials, and specifically (a) metal-dielectric nano composites (MDNs) such as silver-doped glasses and polymers, and (b) surface-modification of metals and other materials to produce periodic and aperiodic micro- and nano-structures.

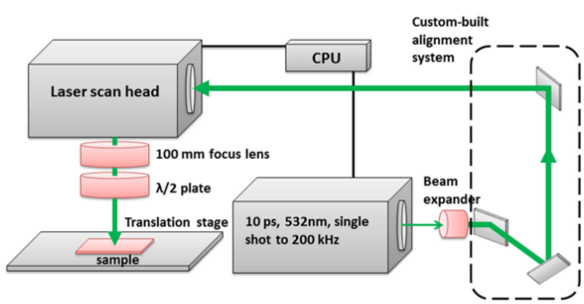

Figure 3: Ultra-short Laser configuration for materials processing.

These modifications are generated by a combination of nanosecond and picosecond pulsed high-power lasers with a range of wavelengths in the UV, visible and IR - facilities unique within the UK. Within the last six months we have made significant progress in the fabrication of silver-doped glass nano composites for EO applications in accelerators, and have demonstrated dichroism and SHG in these materials, a first step towards implementation as an EO detector material, see Fig. 3. LA³NET Fellow Mateusz Tyrk has made a major contribution to this project. He has been responsible for setting up and maintaining the recently-purchased Talisker picosecond laser from Coherent, designed and installed the X-Y scanning system to permit the Talisker to irradiate samples in a controlled pattern with a measured fluence, produced spheroidal nanoparticle distributions within these samples by picosecond-pulse laser irradiation at a wavelength of 532 nm and measured the extinction spectra of such samples, verifying the splitting of the surface plasmon resonance (SPR) into two bands. Moreover, he has verified the dichroism produced by the polarised laser irradiation and has liaised with colleagues at Daresbury Laboratory in the initial measurements of second-harmonic generation from these samples, which is an important precursor for an electro-optic effect.

TRAINING EVENTS

Training of all LA³NET Fellows is mostly through specific project-based research, often carried out in the frame of PhD studies. In addition, the consortium organizes a number of network-wide events for them that are in most cases also open to the wider accelerator and laser communities.

International Schools

A first international School on laser applications at accelerators was held at GANIL in Caen, France between October 15^{th}-19^{th} 2012 [8]. 80 participants from inside and outside the LA³NET Consortium were introduced to the state of the art in this dynamic research area. Lectures covered topics such as introduction to lasers and accelerators, beam shaping, laser ion sources, laser acceleration, laser based beam diagnostics and industrial applications. Several prizes were also awarded during the School. Jurjen Couperus (HZDR, Germany), Kyung Nam Kim (Kongju University, South Korea) and Andrii Borysenko (KIT, Germany) all received prizes for excellent poster contributions.

A second School will be held in September 2014 at CLPU in Salamanca, Spain and will cover advanced laser and accelerator technologies, in particular the combination of different fundamental techniques. Registration for this event will open later in 2013.

In addition to their training through research, all LA³NET Fellows also receive comprehensive training in complementary skills. This shall provide them with a solid basis for their future careers and key skills that are important in both, industry and academic sectors. All LA³NET Fellows descended on Liverpool from their host countries on 17^{th} March for a week-long School. The School covered diverse skills such as presentation techniques, project management, grant applications and peer review. The concept for this School had initially been developed by the DITANET consortium [9], but has since been refined and is now offered to all PGR students in the School of Physical Sciences at the University of Liverpool. Discussions with other UK HEIs are ongoing with the aim to let more students benefit from this successful training scheme which was recently commended as 'success story' by the EU.

Topical Workshops

The first LA³NET Topical Workshop covered laser based particle sources and was held at CERN in February 2013. 10 invited speakers gave 40-minute talks on their current research in this area and an additional 22 delegates delivered shorter oral presentations providing a good balance of talks on the generation of electron and ion beams using laser methods. The following main topics were covered:

- Lasers and photocathodes for 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
- Optimizing selectivity for RILIS
- In-source spectroscopy of rare nuclides.

All contributions to this event can be found in indico [10]. Many more Workshops are already in the planning and will be held over the next two years. The second LA³NET Topical Workshop 'Laser technology and optics design' will be held at ILT Fraunhofer in Aachen, Germany from the 4th-6th November 2013 and is now open for registration [11]. This workshop will cover general optics design, provide an overview of different laser sources and discuss methods to characterize beams in details. Participants will be able to choose from a range of topical areas that go deeper in more specific aspects including tuneable lasers, design of transfer lines, noise sources and their elimination and non-linear optics effects. The format of the workshop will be mainly training-based with the opportunity for discussion on the state of the art in lasers and optics design and future requirements for funding. A tour of the ILT laboratories is also included in the programme. Also, a Workshop on 'Novel Acceleration Schemes', covering high power laser acceleration, dielectric laser acceleration and plasma wakefield acceleration will be held at LA³NET partner HZDR in Dresden, Germany between 28th-30th April 2014. The program is currently being finalized and registration will open soon. Full details and all contributions can be found via the project home page [1].

Conference on Laser Applications

In the last year of LA³NET, a 3-day international Conference on R&D in laser applications at accelerators will be organized on Majorca, with a focus on the methods developed within the network. This event will also serve as a career platform for the network's trainees who will get the opportunity to present the outcomes of their research projects.

Finally, a Symposium open to the general public will be held on 26th June 2015 in Liverpool, UK to promote the project's research outcomes.

CONCLUSION

Within an international consortium of more than 30 institutions, training of 17 Early Stage Researchers has recently started across five thematic work packages. In this paper, first results from investigations into novel beam diagnostics tools were presented. In addition, a summary of past events that LA³NET has organized for the wider community and an outlook on future Schools and Workshops was given.

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