LASER-BASED BEAM DIAGNOSTICS FOR ACCELERATORS AND LIGHT SOURCES*

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Abstract

The Laser Applications at Accelerators network (LA³NET) was selected for funding within the European Union's 7th Framework Programme. During its 4 year duration the project has successfully trained 19 Fellows and organized numerous events that were open to the wider laser and accelerator communities. The network linked research into lasers and accelerators to develop advanced particle sources, new accelerating schemes, and in particular beyond state-of-the-art beam diagnostics. This paper summarizes the research results in laser-based beam diagnostics for accelerators and light sources. It discusses the achievable resolution of laser-based velocimeters to measure the velocity of particle beams, the resolution limits of bunch shape measurements using electro-optical crystals, position resolution of laser wire scanners, and limits in energy measurements using Compton backscattering at synchrotron light sources. Finally, it also provides a summary of events organized by the network and shows how an interdisciplinary research program can provide comprehensive training to a cohort of early career researchers.

OVERVIEW

The primary aim of the LA³NET project [1] was to train 19 early stage researcher within a multidisciplinary network of academic and research-focused organizations across Europe. The network was awarded 4.6 M€ by the European Commission in 2011 and joined more than 30 institutions from around the world. The secondary aim was to establish a sustainable network and generate new knowledge through the research carried out by the Fellows. The LA³NET Fellows were hosted by 11 partner institutions all over Europe and although their work focuses on research, they are provided not only with scientific supervision and opportunities of secondments to other institutions involved in the project, but also complementary training through network-wide events. This includes international schools and topical workshops, as well as a final project conference and numerous outreach events. Through the involvement of almost 30 associated and adjunct partners the project gains an interdisciplinary dimension including strong links to industry. In the following section examples of research results from across the consortium in the beam diagnostics work package are given.

RESEARCH

The Fellows carried out research within one out of five thematic work packages. These are particle sources, beam acceleration, beam diagnostics and instrumentation, system integration and detector technology.

Laser Velocimeter

Pencil or curtain-shaped neutral gas jet targets are important for a number of accelerator-based experiments, either as cold targets or for example for diagnostic purposes [2]. However, only very few studies have addressed the optimization of these jets towards their respective application. The development of a laser velocimeter for an in-detail characterization of the gas jet and investigations into the jet dynamics, probing simultaneously its density, velocity, and temperature, was the aim of an ESR project at University of Liverpool [3]. For this purpose, laser self-mixing has been developed by Alexandra Alexandrova. The theoretical and experimental analysis of factors influencing the performance of the self-mixing laser diode sensor was compared. Variables that influence the resulting spectrum were investigated, primarily the velocity of the target, and the concentration of the seeders to assess the performance of the sensor. It has been shown that the spectrum of the signal directly depends on these factors. Experiments have demonstrated the possibility to use the self-mixing technique for measuring the velocity of fluids up to 1.5 m/s with a low level of seeders from 0.03% which would provide sufficient feedback of light. It has also been shown that increasing the target velocity reduces the amplitude of the peak of the spectrum and broadens the peak itself [4]. Analysis of the spectrum allows information to be obtained of the distribution of the velocities within the volume of the flow illuminated by laser light. The outlook of the project focused on characterization of different gas jets, studies into 3D position and motion detection in an UHV environment, using different lasers and benchmarking of numerical studies.

Laser Emittance Meter

The optimum exploitation of the LHC ultimately depends on the quality and availability of the beams prepared in the injector complex. To set up new machine and achieve the best performance, it is important to measure the transverse emittance of the beam as it exits LINAC4 [5, 6]. A new technique has been proposed, based on the "slit & grid" technique, but using a laser beam rather than a physical slit. The project based at CERN was focused on the development of a laser emittance meter and carried out by Thomas Hofmann. Photo-detachment of electrons in an H- ion beam provides an interesting way of non-

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invasive, reliable and maintenance-free diagnostics [7, 8]. 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. He used a 1080 nm laser with 154 µJ pulse energy, 80 ns pulse length (FWHM), 60 kHz repetition frequency and an M² 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. Fig. 1 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.

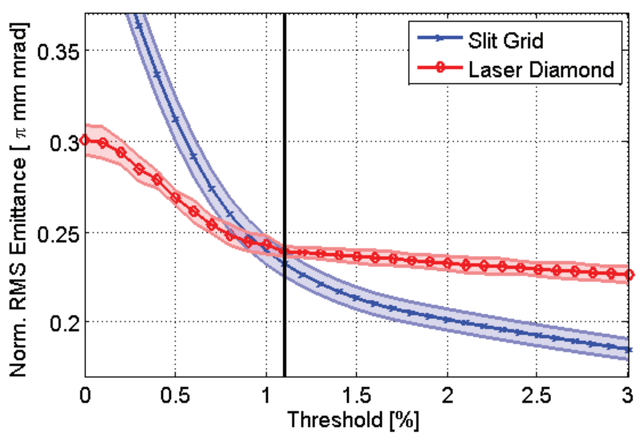

Figure 1: Normalized emittance resulting from both instruments as a function of threshold used for noise suppression.

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. 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 [9]. In preparation for permanent operation the electrode design of the diamond detector and its data acquisition readout chain are being re-designed to provide even higher angular resolution and faster emittance measurements.

Longitudinal Bunch Shape Measurements Using Electro-optical Techniques

To generate highly intense coherent synchrotron radiation in the THz range, the synchrotron ANKA is frequently operated in an optics mode with a reduced momentum compaction factor. The characteristics of the emitted THz radiation depends heavily on the exact length, shape and substructure of the individual electron bunches. A broad research program into the characterization of coherent THz radiation, as well as on the properties of the low alpha mode was established at the ANKA facility, including both, single particle dynamics issues, as well as collective effects. An ESR project at KIT covered the measurement of the bunch shape with electro-optical sampling in an electron accelerator. The linear accelerator FLUTE is currently under construction at KIT and it is expected to have a longitudinal bunch length detection system incorporated. During the development of a bunch profile monitor a set of simulation studies has been performed to make the best possible design for the specific beam parameters of the machine. Within the project, the laser for electro-optical detection system has been assembled at DESY in collaboration with the colleagues from FLUTE. The whole system will be installed at FLUTE to further the understanding of beam dynamics effects.

Electron Beam Energy measurements with Compton-backscattered Laser Photons

The second ESR project at KIT covered the precision determination of the momentum compaction factor with Compton backscattered laser photons at ANKA and was completed by Cheng Chang. 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} [10, 11].

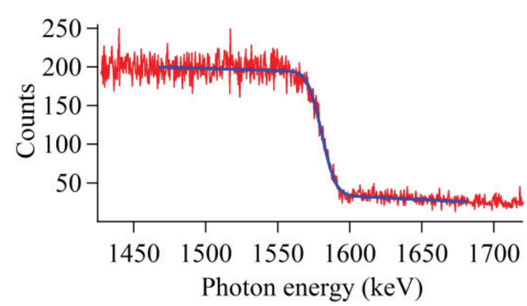

Figure 2: Measured CBS spectrum at 1.3 GeV with fit to determine the Compton edge energy.

Cheng Chang and his co-workers have developed a CBS geometry that applies a transverse configuration (φ=π/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

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either makes measurements and detector calibration easier or enlarges the measurable range of a specific setup. They have used a High Purity Germanium (HPGe) spectrometer to determine the energy of the emitted photons [12]. Fig. 2 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. 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.

Electro-Optics Bunch Time Monitor

An advanced electro-optic bunch time profile monitor for the CERN CLIC Project - development of novel materials and techniques was a project completed by Mateusz Tyrk. This project aimed at pushing the limits of electro-optic (EO) techniques to measure relativistic electron bunches with a time resolution better than 20 femtoseconds. The ability to measure electron bunches with this time resolution have a significant impact on coherent light sources like LCLS or X-FEL, since the generation of coherent X-ray beams from these machines depends critically on maintaining an ultrashort bunch length and direct measurement is not currently feasible. Measurements were carried out in the University of Dundee, with a range of novel nanostructured metamaterials based on metal-glass nanocomposites (MGN). These silver-doped glass nanocomposites were processed using a picosecond laser system in order to change the structure and shape of embedded nanoparticles. This process resulted in a higher efficiency of the nonlinear optical properties of the samples. Tests were also carried out with mechanically stretched MGNs where the shape of previously spherical nanoparticles of silver changed into highly elongated ellipsoids. Measurements at STFC Daresbury Laboratory were performed for further nonlinear optical characterization as well as for EO based characterization of samples, with the conclusion that they could in principle solve many of the problems associated with ‘classical’ materials like ZnTe and GaP.

TRAINING EVENTS

LA³NET serves as an example of the benefits of network training built on project-based research within an international consortium. The fundamental core of the training was a dedicated cutting edge research project for each researcher. The individual research projects were complemented by a series of network-wide events that included external participation and were open to the wider scientific community. Amongst those were two international Schools on Laser Applications at Accelerators which were held at GANIL, France in 2012 [13] and at the Spanish Pulsed Lasers Centre (CLPU) in Salamanca, Spain [14]. Each school attracted more than 70 participants and all course material remains available via the event indico page. In addition, LA³NET has also 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. The network will continue this activity and will organize Topical Workshops on ‘Novel Accelerators’ [15], as well as on ‘Laser Ion Sources’ [16], between 24 - 26 October 2016 in Paris, France. The network also held an international Conference on Laser Applications at Accelerators on Mallorca, Spain [17] and an international Symposium on Lasers and Accelerators for Science & Society with delegates comprising 100 researchers from across Europe and 150 local A-level students and teachers [18].

SUMMARY

LA³NET successfully trained 19 Fellows in an interdisciplinary area and organized numerous events for the wider scientific community. This paper summarized the research results by LA³NET Fellows in the beam diagnostics work package. Whilst the project has formally ended in 2015, the consortium continues a number of key activities, including communication of research outcomes and the organization of events for the wider scientific community.

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