LASER APPLICATIONS AT ACCELERATORS*

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Abstract

The LA³NET consortium has developed advanced laser applications for particle accelerators within an international research and training network. It brought together research centers, universities, and industry partners to carry out collaborative research into all the above areas and jointly train the next generation of researchers. This paper presents selected research highlights from the LA³NET network. It shows how enhanced ionization schemes can provide better ion beams for radioactive beam facilities, results from studies into ultra-compact, fiber optics-based electron accelerators and new radiation sources based on laser-accelerated beams. The paper also provides a brief overview of past and future training events organized by the consortium.

INTRODUCTION

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 network partners provided a cross-sector research and training experience to all Fellows which is expected to serve them as a very good basis for their researcher careers.

The secondary aim was to establish a sustainable network and generate new knowledge through the research carried out by the Fellows. New links and collaborations have been generated through a number of network events and by working together, particularly between the laser and accelerator communities which are usually distinct. Importantly, the active participation of industrial partners has ensured the application of the knowledge generated. Recently the network has decided to carry on collaboration beyond the EC-funded project duration. 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 are given.

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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.

Development of Optimal Ionization Schemes for the Dual Dye - Ti:Sa Laser System of RILIS

The laser ion source (RILIS) of the ISOLDE on-line isotope separator [2] is based on highly selective, multi-step resonant ionization using wavelength-tunable lasers [3]. The aim of the project of T. Goodacre was to improve the efficiency and scope of the RILIS system through the development of ionization schemes that make optimal use of the laser installation. The actual focus of his development work was driven by ISOLDE user requests for new ion beams or specific selectivity improvements.

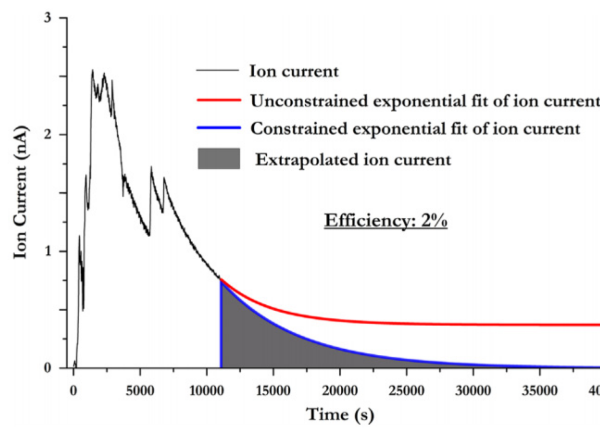

Figure 1: Laser ionized ^{76}Ge ion current against time during the efficiency measurement [4].

The present technologies for wave-length tuning, such as dye lasers, Ti:Sapphire lasers and optical parametric generators were exploited in the course of this project and laser based developments required close links to industry partners. The main objective of the Fellowship was the development of new, optimal, RILIS ionization schemes following a laser upgrade in 2012. Schemes for Hg, Ba, Ba^+, Cr, Ge, Ho, Li and Te were investigated and a total of 8 new scheme were successfully developed. For example a new three-step, two-resonance RILIS scheme for germanium was identified and tested using the ISOLDE RILIS, see Fig. 1 [4]. A laser ionization efficiency of >2% was measured. This efficiency can be increased by the application of an additional first-step to access another thermally populated low-lying atomic energy level, possibly increasing the efficiency of the scheme to >4%. This work extended the range of RILIS ionized beams at ISOLDE to 31 elements. In addition, a new hybrid "VADLIS" ion source was developed which combined the RILIS laser ion source with the ISOLDE VADIS type arc discharge ion source. The new laser ionization scheme for mercury improved the ionization efficiency by a factor of 60. This allowed to measure the isotope shifts and hyperfine structure of ^{180}Hg, ^{179}Hg, ^{178}Hg, ^{177}Hg, ^{207}Hg, and ^{208}Hg for the first time.

Optimization of Dielectric Laser Accelerators

Dielectric Laser-driven Accelerators (DLAs) are a promising way to shrink the size and hence costs of particle accelerators. In this scheme a laser is used to generate an accelerating electric field in a compact channel within a grating structure after passing through a dielectric, see Fig. 2. The longitudinal field varying field is caused by the delay of the wave front when passing through the dielectric and hence a function of the grating geometry and chosen material. These structures can provide access to accelerating gradients of up to several GV/m due to a higher damage threshold of the dielectrics as compared to metals. So far two experiments have successfully demonstrated accelerating gradients of up to 300 MV/m [5] and 690 MV/m [6] for the case of relativistic electrons in fused silica dual-grating structures while accelerating gradients of up to 25 MV/m [7], 220 MV/m [8] and 370 MV/m [9] were observed in fused silica and silicon structures for non-relativistic electrons.

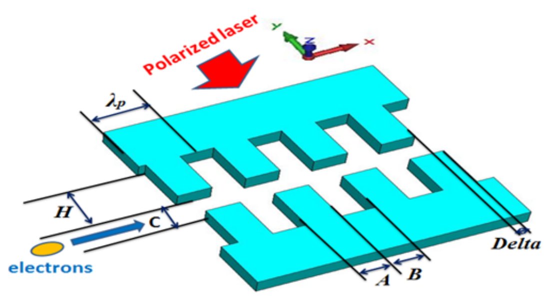

Figure 2: Schematic drawing of a dual-grating structure.

Optimization studies into dual-grating structures have already been performed with the aim to increase accelerating gradient [10-12]. However thus far there have been hardly any simulation studies into the final beam quality that can be obtained in a DLA, although this is obviously one of the key parameters in any particle accelerator. Fellow Y. Wei, based at the Cockcroft Institute/University of Liverpool has investigated into the achievable beam quality of small electron bunches travelling through 100-period dual-grating structures. Specifically, he has studied the expected emittance, energy spread and accelerating gradient in such a structure.

In his simulations, a Gaussian plane wave was assumed to represent the laser impacting on the structure:

$$E = E_p * e^{-\left(\frac{x-LX*0.5}{w_x}\right)^2 - 2*log2*\left(\frac{t-T_d}{\tau}\right)^2} * \cos(2\pi f t) \quad (1)$$

where E_p is the peak laser field and set to 4.0 GV/m, LX is the total length of the structure, T_d is the period of the dielectric and chosen as 122.3 fs so that the electron bunch witnesses the peak field at the centre of the structure.

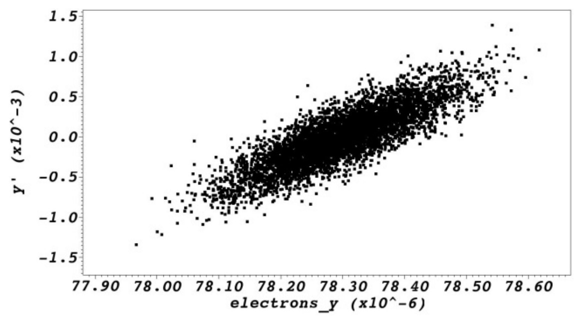

Figure 3: Transverse phase space at the exit of the structure after interaction with the drive laser [13].

Using VSIM simulations [13], a Gaussian electron bunch with a transverse RMS size of 0.05 µm was tracked through a 100-period gratings structure. It was found that after the interaction between the electron bunch and the laser, the emittance of the particle beam increases by 4.20% from 0.1993 nm to 0.2077 nm and its energy spread grows from 0.001 to 0.00576. It was also found that a loaded accelerating gradient of up to 905±45 MV/m can be expected in this case [14].

Bremsstrahlung Gamma-ray Source Based on Laser Wakefield Acceleration

Since the first proposal in the late 1970s [15], laser wakefield accelerators have come a long way from a theoretical concept to a reliable source of highly relativistic electrons. While mostly known for its compactness, resulting from the gigavolt to teravolt per meter field gradients inside a plasma cavity [16], this type of accelerator also inherently provides beams of femtosecond duration [17] and micrometer diameter [18]. It has been shown that high energy radiation can be generated via bremsstrahlung emission in a high-Z material. This technique, analogous to conventional X-ray tubes, was first demonstrated in 2002 [19] and subsequent experiments have demonstrated that the source is suitable for high resolution imaging in non-destructive testing [20, 21]. In his project, Fellow A. Doepp, based at CLPU in Salamanca, Spain and working with LOA, Paris, France, has studied enhanced schemes for Gamma-ray generation [22].

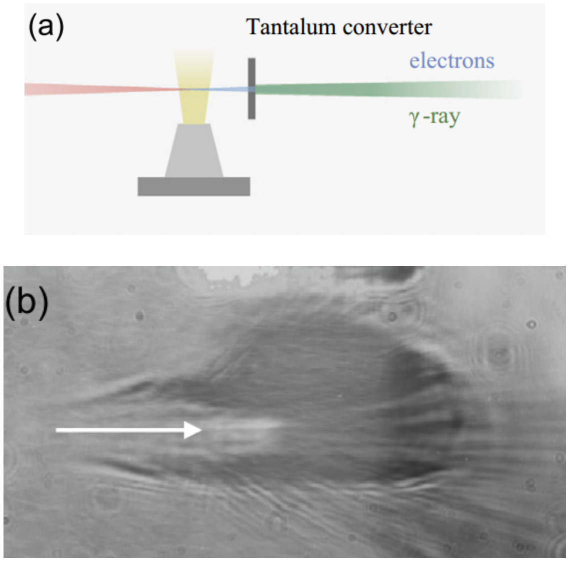

Figure 4: (a) Illustration of the setup; (b) Shadowgraphic image of plasma channel [22].

Multi-TW laser pulses that hit a gas jet of nitrogen or argon were studied, as shown schematically in Fig. 4 (a). During the interaction, inner shell electrons are injected via delayed tunneling ionization into the wake of the pulse and accelerated. Once they exit the gas jet they penetrate a tantalum foil, leading to the emission of bremsstrahlung. This radiation is then detected on an image plate, while the charge and energy of the electron beam (blue) is measured in a calibrated spectrometer. Fig. 4 (b) shows a typical shadowgraph of the plasma channel created by the laser. It was found that the electron beams have a quasi-Maxwellian energy spectrum and exhibit a high beam charge of almost 1 nC at 1 J pulse energy. The shot-to-shot stability was found to be very good for a laser plasma accelerator and the source was in permanent 1 Hz operation over hundreds of shots. Using a tantalum converter, the production of gamma radiation with less than 100 µm source size was demonstrated and it was shown that features of 200 µm size can be resolved on radiographs of image quality indicators. In conjunction with next generation high-rep rate laser systems, this configuration shows great promise as very compact radiation source.

TRAINING EVENTS

LA^{3}NET serves as an example of the benefits of network training built on project-based research within an international consortium of universities, research centers and industry. The fundamental core of the training was a dedicated cutting edge research project for each researcher. Most researchers were in post for the full 36 months and registered in parallel for a PhD. 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.

This included two international Schools on Laser Applications at Accelerators which were held at GANIL, France in 2012 [23] and at the Spanish Pulsed Lasers Centre (CLPU) in Salamanca, Spain [24]. Each school attracted more than 70 participants and all course material remains available via the event indico page.

In addition, LA^{3}NET 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. Fellows were given the opportunity to give talks about their individual projects and invited research leaders complemented the program of each event.Workshop topics included for example laser based particle sources, laser technology and applications, as well as beam diagnostics. The network will continue this activity and will organize Topical Workshops on 'Novel Accelerators', as well as on 'Laser Ion Sources', between 24 - 26 October 2016 in Paris, France. Full details about both events can be obtained via [1]. The network also held an international Conference on Laser Applications at Accelerators on Mallorca, Spain [25]. The conference included sessions on all research aspects within the network. 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 available as an online resource, including videos of the talks that were given [26]. The Symposium also showcased the LA^{3}NET 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.

SUMMARY

The LA^{3}NET project is one of the largest Marie Curie initial training networks ever funded by the European Union. It has successfully trained 19 early stage researchers in an interdisciplinary area and organized numerous events for the wider scientific community. This paper gave examples of research results by LA^{3}NET Fellows. Stretching across beam generation, acceleration and diagnostics, the network provided a unique framework for international cooperation across sectors. Whilst the project has formally ended in 2015, the consortium has decided to continue a number of key activities, including communication of research outcomes and the organization of events for the wider scientific community.

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REFERENCES

[1] http://www.la3net.eu

[2] E. Kugler, *Hyperfine Interactions* 129 (1/4) (2000) 23.

[3] V.N. Fedosseev, et al., *Rev. Sci. Instr*. 83 (2) (2012) 02A903.

[4] T. Day Goodacre, et al., "Laser resonance ionization scheme development for tellurium and germanium at the dual Ti:Sa–Dye ISOLDE RILIS", *Nucl. Instr. Meth*. A (2015).

[5] E. A. Peralta, K. Soong, et al., *Nature* 503,91(2013).

[6] K. P. Wootton, Z. Wu, et al., "Demonstration of acceleration of relativistic electrons at a dielectric microstructure using femtosecond laser pulses", *Opt. Lett*., *accepted* (2016).

[7] J. Breuer and P. Hommelhoff, *Phys. Rev. Lett.* 111, 134803 (2013).

[8] K. J. Leedle, R. F. Pease, R. L. Byer, and J. S. Harris, *Optica* 2, 158 (2015)

[9] K. J. Leedle, A. Ceballos, et al*., Opt. Lett.* 40, 4344 (2015)

[10] T. Plettner, P. P. Lu, and R. L. Byer, *Phys. Rev. STAB* 9, 111301 (2006).

[11] A. Aimidula et al., *Physics of Plasmas* 21, 023110 (2014).

[12] A. Aimidula, et al., *Nucl. Instr. Meth.* A 740, 108 (2014).

[13] VSIM

[14] Y. Wei, et al., "Beam Dynamics Studies into Grating-based Dielectric Laser Accelerators", *these proceedings*.

[15] T. Tajima, J.M. Dawson, *Physical Review Letters* 43 (4) (1979) 267.

[16] E. Esarey, C.B. Schroeder, W.P. Leemans, *Reviews of Modern Physics* 81 (3) (2009) 1229.

[17] O. Lundh, et al, *Nature Physics* 7 (3) (2011) 219.

[18] S. Kneip, et al., *Phys. Rev. STAB* 15 (2) (2012) 021302.

[19] R. Edwards, et al., *Applied Physics Letters* 80 (12) (2002) 2129.

[20] Y. Glinec, et al., *Physical Review Letters* 94 (2) (2005) 025003.

[21 A. Ben-Ismail, et al., *Applied Physics Letters* 98 (26) (2011) 264101.

[22] A. Doepp, et al., *Nucl. Instr. Meth.* A (2016).

[23] indico.cern.ch/conferenceDisplay.py?confId=177701.

[24] indico.cern.ch/conferenceDisplay.py?confId=285698.

[25] indico.cern.ch/conferenceDisplay.py?confId=340153.

[26] indico.cern.ch/conferenceDisplay.py?confId=368273.