LASER-PLASMA ACCELERATION – TOWARDS A COMPACT X-RAY LIGHT SOURCE AND FEL

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Abstract

Advances in many scientific and technical fields depend on availability of instruments, which can probe the structure of materials or molecules on unprecedented levels of spatial or temporal resolution. Many of such instruments are based on accelerators of charged particles, with particular examples of synchrotron radiation light sources and coherent X-ray Free Electron Lasers. The high cost of such facilities, however, preclude wide spread of such instruments. Modern accelerator science witnesses emergence of a new direction – compact x-ray sources are coming to the scene, enabled by the synergy of accelerators and lasers, where high gradient laser-plasma acceleration can significantly reduce the size and cost of the facilities. Compact x-ray sources will be developed in the nearest future and will share their scientific and market niche with large national scale x-ray facilities. The compact sources will in particular be suitable for placement in universities and medical or technological centres. The compact x-ray light sources are being developed by many centres in UK. Development of compact x-ray FEL is a promising topic for scientific and technological collaboration between UK and Russia, where expertise of partners will cross-fertilize their ability to solve scientific and technological challenges.

ACCELERATOR SCIENCE AND TECHNOLOGICAL PROGRESS

Science is a driver for the economy. This is a commonly accepted statement —however, the mechanisms of the impact are complicated and their analysis is necessary not only from a philosophical point of view, but also in order to optimize research priorities and define the strategy for technological innovation.

Particle accelerators have already impacted many areas of our lives via their medical and industrial use, and in research instruments. Tens of millions of patients receive accelerator-based diagnoses and treatment each year around the world, and the total annual market value for all products that are treated or inspected by accelerators is more than US$500B [1]. Approximately 30% of the Nobel Prizes in physics, as well as many in other areas, are directly connected to the use of accelerators [2].

The ideas that enabled use of accelerators in everyday life and industry were developed decades ago; therefore, new ideas will be essential for ensuring the future impact of this field. Analysis of the mechanisms how accelerator science affects the economy and technological progress is needed in order to make predictions and optimise the future directions of research. In the text presented below in this section, we follow the approach and views expressed by the author earlier in [3], [4] and [5].

One of the attempts to analyze the model for research and technology transfer was done by the famous Vannevar Bush, who, during the WWII, was instrumental in reorganizing the research and science community according to the needs of that difficult time. Vannevar Bush's post-war report, "Science, the Endless Frontier", prepared for the USA President, has defined the post-war scientific policy in the USA and in many other countries for decades to come.

In this report, Bush describes what will later be called a one-dimensional or linear model for research and technology transfer. In this report, Bush, in particular, claims that research that is more basic is less applied and vice versa. According to Bush, applied research invariably drives out pure if the two are mixed, and therefore basic research must be completely isolated from considerations of use.

Correspondingly, the dynamic linear model of technology transfer looks like a pipeline wherein government funding stimulates basic research, which then in turn feeds to applied research, which then results in technology and product development, with eventual benefits for the society.

These views of the relationship between basic science and technological innovation have since then been analyzed, criticized, and a new model has been developed.

The contradiction between these linear models and practice can be illustrated via the example of accelerator science and technology. The invention of the so-called "strong focusing" in the fifties was a revolutionary change in accelerator technology. It enabled numerous applications. This invention may have come about as a result of pure fundamental interest— however it was developed as a result of the pursuit of a certain concrete goal, and was made possible due to certain technologies available at that time.

A new model of research and technology transfer was suggested by Donald Stokes, who worked on the Advisory Committee on Research for the USA National Science Foundation. In his report to NSF, and in the book he subsequently published [6], Donald Stokes argued against Bush's linear model and introduced the notion of use-inspired research, of "research with consideration to use", which redefined the paradigm of the relationship between basic science and technological innovation.

To illustrate his views, Donald Stokes suggested considering research on a two-dimensional plane, where the axis are fundamental knowledge impact and consideration of use.

A characteristic example of a purely fundamental scientific pursuit is the research works of Niels Bohr on the structure of nuclei, while the other examples are

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Thomas Edison's development works. The quantitative assessments of these examples — or other research placed on this two dimensional diagram — can be done by the number of either academic papers or patents, resulting from a particular research.

Donald Stokes suggested, however, that an optimized approach should balance the fundamental pursuit of knowledge with consideration of use, which is illustrated by the works of Louis Pasteur.

In the field of modern accelerator science and technology, characteristic examples can be colliders aimed at exploration of fundamental properties of elementary particles on one axis, and accelerator-based devices for homeland security and medical applications on the other axis.

The criteria suggested by Donald Stokes are universal and applicable to any scientific and technological area. Applying these criteria to accelerator science and technology, we can conclude that the preferred direction — which balances best the fundamental pursuit of knowledge with consideration to use — will be the direction of novel light sources or neutron sources. These could potentially produce scientific instruments applicable to the investigation of protein structures or materials, which may be almost directly applicable to the creation of new medicines or metals with controllable properties.

This analysis also shows that, as many other disciplines, accelerator science and technology can truly span the entire range of directions from pure fundamental science to pure applied development.

The research and technology innovation model is indeed not just linear, but at least two-dimensional, as Donald Stokes outlined in his revised dynamic model.

In the 21st century, the driving forces of technological innovation — as well as the global compact between science and society — are different now than they were in the middle of the last century. The revised criteria — as illustrated in this article via the example of accelerator science — are universal, and can be applied to any discipline, which can help us to optimize the impact of our research investments on our economy and society.

COMPACT LIGHT SOURCES AS TECHNOLOGY DRIVERS

Armed with the general understanding expressed in the above section, we can now consider a particular area of accelerator science – the compact light sources, and discuss how their development can help the technological progress of our society.

Conventional accelerators, no matter how advanced, are primarily based on the acceleration of particles in cavities – metal vessels shaped to resonate and create accelerating fields. The ability of metals to tolerate high electromagnetic fields is intrinsically limited. However, an accelerating wave can be created when gas is ionised and exited by an intense beam of particles or by a laser pulse, becoming plasma – an indestructible medium able to withstand a thousand-times higher accelerating gradient.

The promise of plasma acceleration, indicated by theory and the first pilot experiments, is actively being explored. Many laser and accelerator laboratories around the world have launched plasma acceleration research. In California, the FACET and BELLA projects were begun in SLAC and LBNL to study beam-driven or laser-driven plasma acceleration.

Advanced studies for laser, beam and plasma interaction are being pursued in many countries of Europe and Asia. Many universities and research teams in particular in the UK have made pioneering contributions to this field and continue to be at the forefront of the developments.

Accelerator science and technology is on the edge of a breakthrough enabled by synergy with laser and plasma physics. The most immediate outcome that this synergy will enable is the creation of novel, compact X-ray lasers and light sources. The direct collision of beam and laser light also opens another opportunity for the creation of X-ray sources via use of the Compton effect (when visible light photons are reflected from a relativistic electron beam and thereby decrease their wavelength down to Angstrom level).

Science is indeed the driver of our civilisation's progress. However, the path from ideas and experimental demonstrations to widespread commercial applications is difficult. Various studies performed in different countries have all found a gap, a so-called 'valley of death' in technology transfer. It is difficult to bridge the middle range of the technological readiness of ideas. On one side, the research institutions are usually not positioned to develop ideas into commercial applications, while on the other side, the risk is often too high for industry to pick up ideas that are too fresh and undeveloped.

The challenge originates from different motivations, methods and timescales of three key players: academic institutions, industry and investors. Their corresponding aims and motivations – the front end fundamental scientific results, development of commercial devices in foreseeable future, and optimisation of investments versus risk/return factors – are often incompatible.

Crossing the 'valley of death' of technology transfer is a challenge that often requires a nationwide, coherent initiative to create both the necessary infrastructure and a system that stimulates research organisations, industry and investors while also managing risk.

Accelerators in synergy with lasers and plasma may in fact offer a solution for the academia-industry-investor puzzle via simultaneous, parallel work on a portfolio of three different types of compact X-ray light sources.

The first type, Compton X-ray sources, is now actively being developed and is a lower-risk investment for industrial use. Yet a more challenging, but promising, Compton source requires superconducting acceleration to allow for a much higher electron beam current and X-ray brightness. This second option is placed in the middle of the range for both the projected availability and

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risk/return. The most challenging, but also the most promising one, is an X-ray source based on laser-plasma acceleration – a free electron laser (FEL) that nevertheless may be less than a decade from realisation.

Properly scheduling the relative progression of the different stages of research and development of these three types of X-ray sources, one can balance the typical risks associated with development of innovative products, and the opportunities they offer.

UK research institutions have the necessary expertise and the aspiration to lead – in collaboration with each other, with industrial partners and with world leading centres – the work on this portfolio of compact X-ray sources. This cooperation and technology transfer will enable widespread use of compact X-ray lasers. Every university lab will aspire to have and will eventually be able to obtain an X-ray laser, which will revolutionise future science and technology yet again – not unlike how the spread of near-visible light lasers impacted science and industry in the 20th Century.

COLLABORATION ON LASER-PLASMA BASED COMPACT LIGHTS SOURCES

The Advances in many scientific and technical fields depend on availability of instruments, which can probe the structure of materials or molecules on unprecedented levels of spatial or temporal resolution.

Many of such instruments are based on accelerators of charged particles, with particular examples of synchrotron radiation light sources and coherent X-ray Free Electron Lasers. The high cost of such facilities, however, preclude wide spread of such instruments.

Following trends in accelerator science shows that a new direction is emerging – compact x-ray sources are coming to the scene, enabled by the synergy of accelerators and lasers, where high gradient laser-plasma acceleration can significantly reduce the size and cost of the facilities.

Compact x-ray sources will be developed in the nearest future and will share their scientific and market niche with large national scale x-ray facilities. The compact sources will in particular be suitable for placement in universities and medical or technological centres.

The compact x-ray light sources are being developed by many centres in UK. Some of the major milestones in laser-plasma acceleration have been achieved by UK scientists.

Many scientific centres in Russia have capabilities to contribute significantly to the development of laser-plasma based compact x-ray sources.

Development of compact x-ray FEL is a promising topic for scientific and technological collaboration between UK and Russia, where expertise of partners will cross-fertilize their ability to solve scientific and technological challenges.

Joint UK-Russia activity has recently been initiated for development of compact x-ray light sources, to be performed by coordinated efforts of several centres in the two countries.

The aim of the project under planning is to create new knowledge and new infrastructure, aiming to make several working compact x-ray light sources, in the UK and in Russia, and to develop a design that can be reproduced for installation in many locations.

The project will be carried out by a collaboration of UK and Russia science centres, where the partners are: the John Adams Institute for Accelerator Science, an Institute of the University of Oxford, Royal Holloway University of London and Imperial College London (UK), the Institute of Applied Physics (Nizhny Novgorod, Russia), the Joint Institute of Nuclear Research and the JINR University Centre (Dubna, Russia), Budker Institute of Nuclear Physics (Novosibirsk, Russia), Joint Institute for High Temperatures RAS (Moscow, Russia) and Skolkovo Nuclear Cluster (Russia).

The collaborative project will engage PhD students, postdocs and researchers from the participating institutions, working on experimental facilities enhanced and enabled by this activity.

The proposed project is aimed at solution of scientific and technological challenges that haven't been solved to this moment. Search for solutions requires investigations on many fronts, and also requires development of a new paradigm in research and training – when knowledge of three disciplines, lasers, plasma, and accelerators, will be combined. To this moment, experts were trained in each of these fields separately.

Realisation of the collaborative project will result in creation of the new scientific experimental infrastructure in the participating institutions, in creation of new knowledge, training of young researchers, development of the exchange programme for young researchers, and development of designs of X-ray source suitable for reproduction and commercialisation.

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REFERENCES

[1] Accelerators for America's Future, DOE, 2009.
[2] A. Chao et al, Physics in Perspective, 2010.
[3] A. Seryi, "Accelerating Progress" Public Service Review: UK Science & Technology: issue 6, 2012.
[4] A. Seryi "An X-ray Vision" Public Service Review: UK Science & Technology: issue 4, 2011, p.18-19.
[5] A. Seryi, G. Blair, Z. Najmudin, P. Burrows, "Accelerators Everywhere" Public Service Review: UK Science & Technology: issue 4, 2011, p.20-21.
[6] Donald E. Stokes, "Pasteur's Quadrant - Basic Science and Technological Innovation", Brookings Institution Press 1997.

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