NIELS BOHR AND THE QUANTUM ATOM

PLASMA AND PLASMONICS
Enter a new world of accuracy, stability and measurement speed

HighFinesse-Ångstrom Wavelength Meters
- Pulsed and cw lasers
- 192 – 11000 nm range
- Auto-calibration
- PID stabilisation and multiplexer
- Control up to 8 lasers simultaneously

High Finesse Laser Systems
- Stabilised laser references (SLR)
  - High accuracy, NIR calibration sources
- Modular CW Titanium: Sapphire technology
  - TS: Precise, narrow linewidth system
  - TS: Fast, high-speed scanning system
Less than 1mm tall,
Narrower than a human hair

This Statue of Liberty has been made using
3D Laser Lithography from Nanoscribe

30μm

The Nanoscribe Photonic Professional is an easy-to-operate, table-top laser lithography system, allowing for true three-dimensional nanostructures in commercially available photoresists. Designed for the high demands of three-dimensional photonic crystal structures, the instrument is suitable for generating three-dimensional scaffolds for biology, micro- and nanofluidic circuitry and more. For more information, contact Warsash Scientific on +61 2 9319 0122.
HF2LI Lock-In Amplifier
50 MHz Frequency

Atomic Force Microscopy, Quantum and Nano-Physics, Laser Spectroscopy, Materials Science, Semiconductors

- 2 independent lock-in units
- 6 harmonics / frequencies
- 120 dB dynamic reserve

Available options: dual PLL, quad PID controller, multi-frequency, AM/FM sideband demodulation.

Australian Sales Partner
Warsash Scientific
sales@warsash.com.au
www.warsash.com.au

www.zhinst.com
Cover
Niels Bohr returning home to Copenhagen in August 1912, after his honeymoon in England and Scotland. See article by Peter Robertson, p156

CONTENTS

150 Editorial
Celebrating centenaries

151 President’s Column
Engagement with Asian Physics

152 Letter to the Editor

153 News & Comment
Hans Bachor receives Harrie Massey Medal
SKA precursor begins operation Outstanding service award to David Jamieson
2013 Eureka Prize for Lloyd Hollenberg & colleagues
13th Asia-Pacific Physics Conference for Brisbane
Vale Peter Pockley

155 Branch News
News for Queensland, ACT and NSW branches

156 Niels Bohr and the Quantum Atom
Peter Robertson describes how Bohr’s quantum theory provided the beginnings of an understanding of phenomena on the atomic scale.

162 Plasma Foundations and Nanoscience: the Plasma-Plasmonics Junction
Amanda Rider, Kostya Ostrikov and Scott Furman explain the connection between plasma and plasmonics.

166 Samplings
Physics news that caught the eye of the editor

170 Conferences

170 Book reviews
Peter Robertson reviews Love, Literature, and the Quantum Atom Niels Bohr’s 1913 Trilogy Revisited by Finn Aaserud and J.L. Heilbron.

173 Obituary
Robert Street 1920-2013

174 Product Reviews
New products from Coherent, Lastek and Warsash.
EDITORSIAL

Celebrating Centenaries

In recent years there has been no shortage of centenaries of significant advances in Physics to celebrate. The International Year of Physics in 2005, recognising Einstein’s 1905 papers, was, of course, an exceptional example. In this issue an article by Peter Robertson (a former editor of Australian Physics) recognises the centenary of the publication of Niels Bohr’s quantum theory, which provided the beginnings of an understanding of phenomena on the atomic scale. This article is based on a talk Peter gave earlier this year at the One Hundred Years of the Bohr Atom conference in Copenhagen and includes photographs from the Niels Bohr archive, some of which have not been published previously. I am very pleased we are able to present this article at a time when we are in the midst of a second quantum revolutions, the outcomes of which, while unpredictable, must surely be as significant as those set under way by Bohr.

Our second article, by Amanda Rider, Kostya Ostrikov and Scott Forman, describes the connections between the relatively new field of plasmonics and classical plasma physics. This article had its origins in a talk Amanda gave at the 2012 AIP Congress and provides an introduction to a field that is at an early stage of finding applications.

Australian Physics is not overwhelmed by letters to the editor, but in this issue we publish one such letter: an author’s rejoinder to a review of his book published in the previous issue, along with a response from the reviewer. Letters to the editor, relating to items published or on any physics-related topic, are most welcome. More information for potential letter writers is proved below the letter and response on page 152.

In this issue we have taken the unusual step of publishing two reviews of the same book, Tesla, Inventor of the Electrical Age by W. Bernard Carlson. Although unlikely to be standard practice, in this case books editor John Macfarlane considered the reviews to be sufficiently different in some respects that both would be of interest to readers.

As always, if you have an idea for an article, particularly if you are volunteering to be an author, please contact me at the address given in the side column.
Engagement with Asian Physics

In July, Vice-President Warrick Couch, 16 other Australian physicists and I attended the 12th Asia-Pacific Physics Conference in Chiba, Japan. In total, we gave two plenary and nine invited talks on topics ranging from galaxy evolution right through to single qubits in silicon. A number of Nobel prize winners spoke and there was a heavier emphasis on particle and accelerator physics, and plasma physics related to fusion energy, than we might find in Australia. The meeting was co-organised with the Asia-European Physics Summit, with the European Physical Society as the counterparty, and a major theme seemed to be whether the Europeans would commit to contributing to the International Linear Collider (successor to the LHC) if it is built in Japan.

The host organisation for the meeting is the Association of Asia-Pacific Physics Societies (AAPPS), of which AIP is a full member. Former AIP President Marc Duldig had represented us in the past, and I was nominated for and elected to join the Council, which meets annually. The next meeting will likely be in Taiwan in January 2014, followed by Canberra in December 2014, in conjunction with our domestic AIP Congress.

During these meetings, I successfully presented the case to hold the next Asia-Pacific Physics Conference in Brisbane in December 2016, in conjunction with that year’s AIP Congress. Brian Schmidt has kindly agreed to act as Honorary Chair, and our bid was supported by University of Queensland, CSIRO, ANSTO and the New Zealand Institute of Physics. So the upshot is that we will hold a combined “13th Asia-Pacific Physics Conference and 22nd Australian Institute of Physics Congress” in Brisbane in December 2016. We are currently strongly engaged with colleagues in Brisbane, particularly Halina Rubinsztein-Dunlop, whom many of you know as Head of the Physics Department at University of Queensland. Indeed Halina will be joining the AIP Executive as a Special Projects Officer. In Chiba, both Warrick and I were struck by the enthusiasm with which our Asian colleagues viewed the prospect of coming to Australia, and Brisbane in particular, for the conference.

In Chiba, there were approximately 1200 attendees, including 250 from outside Japan. The leading non-Japanese presences were from Taiwan, Korea and China. As it happens, we discovered that the Asia-Pacific Physics Conference had in fact been held previously in Australia in 1994, again in Brisbane, and that the AIP was also a foundation member of the Association of Asia-Pacific Physics Societies, right from the beginning.

My own view is that this type of engagement is very important, and that we will have a wonderful opportunity to grow new links and collaborations with our Asian colleagues through hosting the joint meeting.

On a related, but more personal note, I have been asked by the Australian Academy of Science to give a lecture tour in India, and I plan to do so in December of this year. Of course, given my own background and interests, I will primarily emphasise the opportunities for research using synchrotron light (at the Australian Synchrotron in Melbourne) and neutrons (at the OPAL Research Reactor in Sydney). But there is a broader agenda: the Australian Government’s Department of Industry, Innovation, Climate Change, Science, Research and Tertiary Education is funding this (and other activities with India) to increase awareness of Australian research, and develop and facilitate collaborative linkages with Indian researchers and Indian institutions.

Changing subject, I recently had the privilege to attend the premiere of the first all-Australian 3-D IMAX movie “Hidden Universe 3D”, along with my wife and 10-year-old daughter at the Sydney IMAX Theatre in Darling Harbour. Major portions of the movie relied on full 3-D simulations by Swinburne University of Technology in Melbourne, and the movie featured some young researchers from Australian institutions, albeit with North American accents. The director spoke at the preview and he apologised for the fact that the film started with our own sun – but quoted statistics that 45% of Americans are blissfully unaware that our own sun is a star! Anyway, I can strongly recommend “Hidden Universe 3D” to you and your families, if you can get to one of the IMAX theatres in Sydney or Melbourne – it opens commercially in both venues on 1st-September.

Rob Robinson
In his review of my new book (Lessons from Nanoelectronics: A New Perspective on Transport, World Scientific (2012)), Prof. Mukunda Das has raised questions regarding the role of dissipation and the electrochemical potential in nanoscale conductors. These are indeed thought-provoking questions but I would like to point out that they are all addressed in my book and the cited references using an NEGF (Non-Equilibrium Green’s Function)-based approach to quantum transport.

I agree with Prof. Das that “the argument that only elastic conductors dissipate energy is difficult to swallow” but that is not what I argue in my book. What I describe is the well-known Landauer model, widely used in mesoscopic physics, which assumes that the heat associated with a short conductor of resistance $R$ is dissipated primarily in the contacts and not in the conductor.

Furthermore, I present this Landauer model as a useful idealization which provides an intuitive understanding of results that can all be formally obtained using the NEGF method. Part III (Lectures 18-23) of the book is entirely devoted to making this NEGF method accessible to non-specialists, with appropriate examples and caveats. The NEGF method provides a broader framework that allows one to incorporate sophisticated microscopic models for scattering and dissipation as needed.

Consider for example the perceptive questions about the local electrochemical potential raised by Prof. Das. These were addressed using the NEGF method in McLennan et al. (1991) Phys. Rev. B, 43, 13846-13884 which ended by saying that “the main contribution of this work lies in putting the ideas (of Landauer, Buttiker, Imry and others) on a rigorous quantitative footing using a quantum kinetic approach”. The conclusions were summarized in Chapter 2 of my 1995 book. Lecture 20 of the present book incorporates some of these results essentially as homework problems that even beginning students can reproduce.

As the title indicates, the aim is to provide a new perspective, and not a survey of perspectives. I invite readers who care about the “foundational underpinnings of nanoelectronics” to have a look at the book and at the extensive prior work that it builds on. The website https://nanohub.org/groups/lnebook provides answers to questions like those raised by Prof. Das and will be updated as requested by interested readers.

Supriyo Datta
Purdue University, West Lafayette, Indiana
9 September 2013

Professor Das replies:
Professor Datta concurs that dissipation and electrochemical potentials are thought provoking, and claims to have addressed these questions.

But his book only revisits earlier materials that failed to do so. In the exiguous space conceded, I present further serious questions about his claims.

Datta agrees: “that only elastic conductors dissipate energy, is hard to swallow”. Yet in the same sweep he invokes the purely elastic “Landauer” model, assuming dissipation deep in the contacts [Lecture 3, “The elastic resistor” (sic)]. Such assumptions are not rigorous until quantified.

NEGF in the present context has a serious handicap: ad-hoc, it dissects a Hamiltonian into disjoint parts (two leads plus channel). Dismemberment, of an inherently physically unified system, is adopted free of any critique of appropriateness or limitations. In none of Datta’s publications are these ever examined.


I disagree with Datta on novelty. The current book surveys older perspectives in his style. In today’s science, texts are flooding an unprecedentedly noisy publishing industry; should one not refrain from advertising to lessen general confusion?

Mukunda Das
The Australian National University, Canberra
18 September 2013

Letters to the editor, relating to items published or on any physics-related topic, are most welcome.
In general letters should be less than 300 words, and could include an image if appropriate.
Letters should be sent to the editor Brian James, at brian.james@sydney.edu.au
Hans Bachor receives the Harrie Massey Medal

Prof. Hans Bachor was presented with the Harrie Massey Medal for 2010 during a reception at the IOP’s London centre on 10 July. The medal, which is awarded jointly by the IOP and the Australian Institute of Physics, was presented by the IOP’s president, Prof. Sir Peter Knight. Prof. Bachor received the medal for his pre-eminent work in the field of quantum optics, “in particular his research on the squeezing of light and quantum noise suppression, and for his commitment to the development of the teaching and public understanding of physics”.

Prof. Bachor was awarded the medal in 2010, but plans to present it at the 19th AIP Congress in Melbourne were thwarted by a strike that prevented Prof Jocelyn Bell, representing the IOP, from attending. Prof. Knight said the reception, following a public lecture was chosen for the presentation “while we have influential people around to recognise Hans’s contribution”.

Prof. Bachor had been an undergraduate at Imperial College London’s Blackett Laboratory before having a stellar career in Germany, then in Australia, where he helped to establish the country’s first national facility for quantum optics, Prof. Knight said.

SKA precursor begins operation

The Murchison Widefield Array (MWA), the most powerful low-frequency radio telescope in the southern hemisphere, has started its search for signals from the first billion years of the universe, known as the era of reionisation.

The MWA is located at the Murchison Radio-Astronomy Observatory in a remote, radio-quiet region of Western Australia, and is the first of three Square Kilometre Array (SKA) precursor telescopes to be operational.

The MWA has 128 aperture arrays, each consisting of 16 antennas, and is spread across an area of seven square kilometres. It detects signals between 80 and 300 MHz and has a field of view of thousands of square degrees that will enable it to rapidly image the entire southern sky. The MWA’s launch is the culmination of nine years of development by an international consortium of 13 institutions in four countries.

The MWA, which has no moving parts, can be controlled remotely and data from the telescope will be transmitted 800 km to Perth via a dedicated optical-fibre data link for processing at the Pawsey Centre for supercomputing, which will also provide computing facilities for another SKA precursor, the Australian Square Kilometre Array Pathfinder (ASKAP).

One of nine inaugural research programmes is a search for the radio signature of hydrogen emitted during the era of reionisation. The first stars and galaxies formed during this time, but it remains largely unexplored. “This is one of the hottest topics in global astrophysics,” says Steven Tingay, director of the MWA and an astronomer at Curtin University. In another project, Martin Bell, at the University of Sydney, is leading a survey that will use monthly snapshots to observe the dynamic behaviour of supermassive black holes in the southern sky and look out for new, previously undetected classes of objects. The first results from the new telescope are expected by the end of the year.

Outstanding service award to David Jamieson

In the presence of the AIP executive on Monday 5 August, AIP President Rob Robinson had the pleasure of presenting an Outstanding Service to Physics Award to Prof. David Jamieson. David’s citation reads: “For outstanding service to the Discipline of Physics over many years, including contributions to outreach, physics education, research and leadership, particularly in the Einstein Year of Physics and development of the Decadal Plan for Physics. David has a
longstanding and well demonstrated passion for Physics and has supported its advancement both as an outstanding professional scientist and also as a tireless advocate for the support and study of Physics.”

Eureka Prizes 2013

Professor Lloyd Hollenberg, School of Physics, University of Melbourne, and his colleagues in the Quantum Bio-probes team won the 2013 University of New South Wales Eureka Prize for Interdisciplinary Scientific Research. The group developed nano-scale diamond sensors that can light up the inside of cells. This allows researchers to examine activity inside a living cell in greater detail, which may help improve drug delivery in future. The annual Australian Museum Eureka Prizes celebrate the best in Australian science, innovation, leadership, research and science journalism.

13th Asia-Pacific Physics Conference in Brisbane

AIP President Rob Robinson and AIP Vice-President Warrick Couch attended meetings of the Association of Asia-Pacific Physics Societies (AAPPS), and Rob was duly elected to a term on its council. The AIP won its bid to hold the 13th Asia-Pacific Physics Conference in Brisbane in December 2016, in conjunction with the 2016 AIP Congress. Rob thanks the New Zealand Institute of Physics, University of Queensland, CSIRO and ANSTO for their support.

Vale Peter Pockley

Peter Pockley, the science journalist who founded the ABC’s Science unit in 1964, died in Sydney on 11 August at the age of 78. Pockley was the first scientist to work as a full-time science reporter in Australia and became one of Australia’s most recognised science journalists. At the ABC he established Insight which is now known as Ockham’s Razor, and The World Tomorrow, predecessor of The Science Show. He was the producer and on-air host of the ABC’s coverage of the Apollo missions, most notably, the Apollo 11 moon walk in 1969. After leaving the ABC in 1973, Pockley was a columnist for The Sun-Herald, and a freelance contributor to Nature, Search, and Australasian Science. He ran science journalism courses at The University of Technology Sydney.

He studied at the University of Melbourne where he obtained first class honours, winning the Exhibition in Chemistry in his Bachelor of Science degree and also gained first class honours in his Diploma of Education. He taught science at Melbourne Grammar School before going to the University of Oxford on a Shell Postgraduate Scholarship. He completed his Doctorate of Philosophy in the Geology Department with research on lead isotopes and geochronology (1961).

One of the science journalists he mentored was the current presenter of The Science Show, Robyn Williams, who paid tribute to his colleague.

“What he was pioneering was science everywhere for everybody,” Williams said.

“He used plain language, and despite the fact he had higher standards academically, you nonetheless were able to have material that every single Australian and people around the world could understand. Among many honours, in 2010 Dr Pockley was the first and only journalist to be awarded the Academy Medal of the Australian Academy of Science.
This is QUIC! – the 2013 AIP Queensland Youth Physics Lecture Tour

Professor Christian Langton has just completed his Youth Physics Lecture Tour of Queensland, visiting Hervey Bay, Toowoomba, Rockhampton, Cairns, Townville, Mt Isa, Brisbane and Sunshine Coast. Christian has spoken to almost 600 students from over 20 schools, travelling over 6,000 km in the process.

His topic was QUIC, or quantitative ultrasound imaging and characterisation, which is used in medical diagnosis and treatment of osteoporosis and cancer.

Christian says, “I was delighted and honoured to be invited to deliver the 2013 Queensland Youth Physics Lecture Tour designed to promote physics to senior high school students and science teachers. I strongly believe that university academics have a responsibility to share their passion for research and the tremendous enjoyment it provides; and to enthuse the current generation of school students who have the potential to become Australia’s future scientists and engineers.”

In his talks, Christian described his journey in science—as a student, researcher and academic—and his move to Australia from the UK in 2008, which has gone as far as now supporting the Australian cricket team!

He reports on his talk: “By taking along our portable clinical scanner, I was able to demonstrate real-time ultrasound imaging of myself, as well as my lack of detailed anatomical knowledge! My description of how ultrasound is excellent at differentiating a fluid-filled cyst from a solid tumour took on a whole new significance when a student came up to me at the end of one of my lectures and explained, with tears in her eyes, how ultrasound had saved her life when she had an ovarian cyst.”

Following his descriptions of how his osteoporosis assessment techniques became used worldwide in detecting fracture risk in thoroughbred racehorses and new developments in scanning, Christian leaves his student audience with a few ‘Langton’s Philosophies’ including the importance of ‘grasping fortuitous opportunities’, ‘being your best’ and ‘enjoying what you do’.

Christian concludes, “Each Queensland Youth Physics Lecture Tour is only possible through the dedication of the local organisers, particularly the engagement teams at the ‘local’ universities. I also wish to thank the AIP, and in particular the Queensland Branch, for providing the financial support to facilitate the Lecture Tour”.

ACT

The 2013 Women in Physics lecture series came to the ACT on Thursday 5 September, 2013. The 2013 WiP lecture, Professor Elisabetta Barberio of the University of Melbourne and formerly with CERN made three presentations in Canberra to enthusiastic audiences. A joint AIP/ RSPE Director’s colloquium was held at 12.00 noon in the Huxley lecture theatre at the ANU. This talk entitled The Higgs boson at the Large Hadron Collider was well received by a large attendance of ACT branch members and ANU staff. Elisabetta also talked to students at the Canberra Girls Grammar School and presented a public lecture that evening at the ANU, Big question, big facilities: The discovery of the origin of mass.

NSW

The theme for the NSW Branch’s 2013 Physics in Industry Day is The Future of Aerospace. To be Held at the CSIRO and NMI site at Lindfield on Thursday 7 November, the event includes speakers with a wealth of experience across research and industry representing Boeing, GE, CSIRO, the Royal Aeronautical Engineers Society and the CRC for Advanced Composite Systems. This annual AIP event is co-organised this year with SADIG (Sydney Aerospace and Defence Interest Group), the Royal Aeronautical Engineers Society (RAES) and Regional Development Australia (RDA) Sydney. The traditional CSIRO & NMI lunchtime laboratory tours are in the program again and the Ken Doolan Poster Prize for physics-based projects by high school, undergraduate or postgraduate students will be judged and awarded. For more information see http://physics-industry.com/2013AIPIndustryDayPoster.pdf
Introduction
This year marks the centenary of the revolutionary theory of the atom put forward in 1913 by the young Danish physicist Niels Bohr. The theory built upon a discovery by Ernest Rutherford and his group that the atom consists of a tiny positively charged nucleus surrounded by a cloud of negatively charged electrons. Bohr introduced the concept of energy quanta, pioneered by Max Planck and Albert Einstein, and showed that the concept was fundamental in determining the structure of atoms and how they absorb and emit radiation. Bohr’s theory opened the way to understanding the physical and chemical properties of atoms and molecules and led directly to the birth of quantum mechanics in the mid 1920s. Bohr was awarded the Nobel Prize for physics in 1922 in recognition of his achievements (see [1–3, 7] for detailed accounts of his life and work).

Early life
Niels Henrik David Bohr was born on 7 October 1885 into a well-to-do academic family in Copenhagen. His father, Christian Bohr, was a professor of physiology at the University of Copenhagen, a liberal thinker who with his wife Ellen (née Adler) encouraged a close relationship between home life and the intellectual milieu of the university. This no doubt encouraged the young Niels along in an academic direction. Similarly, his younger brother Harald showed even greater promise as a student and later became a distinguished mathematician.

In 1903 Bohr entered the University of Copenhagen where he studied astronomy, chemistry and mathematics, before going on to major in physics under the guidance of the professor of physics, Christian Christiansen, a close friend of Bohr’s father. In 1905 he demonstrated his scientific talent by being awarded a gold medal by the Royal Danish Academy of Sciences for a study on the surface tension of liquids. Niels carried out the experimental work in his father’s laboratory and constructed most of the equipment himself, learning the delicate art of glass blowing in the process.

In 1911 Bohr completed his doctorate on the electron theory of metals. Following a common practice in Denmark he decided to seek further experience abroad on a one-year fellowship funded by the Carlsberg Foundation. For two reasons Niels elected to go to the Cavendish Laboratory at Cambridge University, the most prestigious institution in British physics. First, he hoped to interest J. J. Thomson, the discoverer of the electron, in some of his ideas and, second, he wanted to publish an English trans-
lation of his thesis so that it would reach a wider audience. However, the first few months at the Cavendish were not a happy time for the shy and rather awkward Dane. As head of the Cavendish, Thomson had become increasingly involved in public affairs and no longer had the time to discuss the ideas of only one of many young physicists in the laboratory. Bohr felt equally discouraged by his unsuccessful attempts to interest an English publisher in his thesis.

“Although a consummate experimentalist, Rutherford was impressed by Bohr’s theoretical knowledge”....

Manchester bound

Bohr’s fortunes took a turn for the better in 1911 during a visit to a family friend in Manchester. Bohr was introduced to the New Zealand born physicist Ernest Rutherford and the two struck up an immediate rapport. Although a consummate experimentalist, Rutherford was impressed by Bohr’s theoretical knowledge and invited him to spend time in his laboratory at the University of Manchester. Although Rutherford was 14 years older than Bohr, it was the start of a close friendship that lasted until Rutherford’s death in 1937.

Ernest Rutherford at McGill University, Montreal, in 1907, shortly before he took up a professorship at the University of Manchester (pastel by R. G. Matthews).

The Manchester laboratory had been established and largely financed by the wealthy physicist Arthur Schuster, who had then willingly stepped down from his position as professor in 1907 in order to bring Rutherford back to England from McGill University in Canada. Together Schuster and Rutherford built up a flourishing research school of about twenty physicists. Although the Cavendish Laboratory had more prestige, the real action in British physics was happening in Manchester. The group made one important discovery after another on the nature of the atom and radioactivity using simple ‘string and sealing wax’ equipment. Most of the research was however experimental and there were few in the Manchester group who thought about the theoretical implications of these discoveries.

After his arrival in April 1912 Bohr began by taking a course on experimental methods in radioactivity, but it was not long before he turned to speculating about a discovery made the year before. Under Rutherford’s guidance, Ernest Marsden (a fellow Kiwi) and Hans Geiger investigated the scattering of a beam of alpha particles fired at a thin gold foil. As expected, most of the alpha particles passed through the foil with little or no deviation, but occasionally an alpha would scatter at large angles and in some cases bounce straight back. Rutherford was astonished by the result and, in an oft-quoted remark, likened it to firing a naval shell at a piece of paper and having the shell bounce right back [4].

At the time the commonly accepted picture of the atom was the so-called ‘plum pudding’ model put forward in 1904 by J. J. Thomson. Here the electrons (the plums) were thought to be embedded in a sphere of positive charge (the pudding), with the electrons accounting for most of the atomic mass. In Rutherford’s view, the alpha-particle experiment implied that nearly all the mass was concentrated in a tiny positively charged central nucleus, surrounded by the electrons which took up almost all of the atom’s volume. There were, however, major objections to Rutherford’s model. The most serious was that, according to the well-established laws of electrodynamics, the orbiting electrons would radiate their energy and immediately spiral into the nucleus.

Part of a memorandum Bohr wrote to Rutherford in July 1912 showing the possible structures of some simple molecules. Bohr soon abandoned this ‘pancake’ model of electron rings.
Towards the trilogy

It was on this last point that Bohr made a decisive break with classical physics. To account for the obvious stability of atoms, he assumed that the electrons can exist in certain orbits around the nucleus, which he called stationary states, and that as long as an electron remains in one of these states it will not emit radiation. This was Bohr's first postulate. His second postulate stated that radiation will only be emitted when an electron 'jumps' from a stationary state of higher energy to another of lower energy. The radiation will consist of a quantum of energy equal to the difference between the energies of the two stationary states, given by the simple equation

$$E_2 - E_1 = h\nu$$

where \(E_2\) and \(E_1\) are the energies of the upper and lower states respectively, \(h\) is Planck's constant and \(\nu\) is the frequency of the radiation emitted. By an inverse process, an atom can absorb a quantum of radiation which sees an electron make a transition to higher energy state.

Bohr returned to Denmark in the summer of 1912 and married his fiancée Margrethe Nørlund. The extensive correspondence between the two during Bohr's post-doctoral year in England reveals much about his progress towards the quantum atom. (The Bohr family recently released this correspondence as part of the centenary celebrations – see the book by Finn Aaserud and John Heilbron [5].) At this time Bohr was appointed to a lectureship at the University of Copenhagen, following the retirement of his former supervisor, Christian Christiansen. Although the position involved a heavy teaching load, Bohr had enough time over the next 12 months to develop his ideas from Manchester.

By introducing the concept of energy quanta into his theory, Bohr had made a direct connection to the work of Max Planck (1900) on blackbody radiation and Albert Einstein (1905) on the photoelectric effect in metals. Their revolutionary studies had shown that the interaction of radiation and matter involves an exchange of energy in finite bundles or quanta, a process that cannot be explained by classical physics. In addition, the two postulates at the heart of Bohr's theory provided the key to understanding the field of spectroscopy. For decades physicists had been amassing data on the discrete frequencies emitted when an element is exposed to radiation. Earlier atomic models such as Thomson's plum pudding had assumed that the frequencies characterising each element correspond to the vibrational frequencies of the electrons. Bohr argued that these frequencies correspond to transitions between the electron orbits and not to the orbits themselves.

“...the two postulates at the heart of Bohr’s theory provided the key to understanding the field of spectroscopy”
The three parts of his paper ‘On the Constitution of Atoms and Molecules’ appeared in rapid succession in the Philosophical Magazine, with each part communicated to the journal by Rutherford [6]. Part 1 considered the binding of electrons by positive nuclei, part 2 considered systems containing only a single nucleus, while part 3 examined molecular systems containing several nuclei. In part 1 Bohr presented two results which had an immediate impact on the acceptance of the new theory. His first triumph was to derive from first principles the equation to describe a series of spectral lines in hydrogen, first observed in 1885 by the Swiss spectroscopist Johann Balmer.

To describe the spacings of the hydrogen lines, Balmer had empirically derived

\[ \frac{1}{\lambda} = R_H \left( \frac{1}{2^2} - \frac{1}{n^2} \right), \quad n = 3, 4, 5, K \]

where \( R_H \) is Rydberg’s constant for hydrogen, but the physics behind the equation remained a complete mystery for nearly 30 years.

Using the postulate of stationary states Bohr could derive the closely related equation for the frequency

\[ v = B \left( \frac{1}{m^2} - \frac{1}{n^2} \right) \]

where \( m, n \) are integers and \( n \geq m+1 \), with the constant

\[ B = \frac{2\pi^2 m^2 e^4}{h^3} \]

where \( m \) is the electron mass, \( e \) the electron charge and \( h \) Planck’s constant. Bohr could easily show that \( m = 2 \) reproduced the Balmer series and, for good measure, that \( m = 3 \) accounted for the series in the infrared observed by Friedrich Paschen in 1908.

Bohr’s second achievement was to calculate the constant \( R_H = B/c \), where \( c \) is the speed of light. His value of \( B = 3.10 \times 10^{15} \text{s}^{-1} \) differed somewhat from the experimental value of \( 3.29 \times 10^{15} \text{s}^{-1} \), obtained by the Swedish physicist Janne Rydberg in 1888, but was well within the errors in the fundamental constants.

Impact of the quantum atom

The initial response to Bohr’s theory in England was mixed, and in some circles on the Continent the reaction was decidedly cool. There was a feeling that some of the successes, in particular the calculation of the Rydberg constant, had been the result of a fortuitous playing with numbers. Even Rutherford had his doubts, as he wrote in March 1913: ‘There appears to me one grave difficulty in your hypothesis, which I have no doubt you fully realise, namely, how does an electron decide what frequency it is going to vibrate at when it passes from one stationary state to the other? It seems to me that you would have to assume that the electron knows beforehand where it is going to stop.’ [7]
Most doubts were soon swept aside with the dramatic confirmation of another of Bohr's predictions. In addition to the Balmer and Paschen series, the Harvard astronomer Edward Pickering had detected another series of lines in the spectrum of a nearby star. Next the spectroscopist Alfred Fowler discovered yet a further series of lines in experiments with a vacuum tube containing a mixture of hydrogen and helium. Bohr realised that the two series did not in fact belong to hydrogen, as Pickering and Fowler believed, but to singly ionised helium He⁺. In September 1913 one of Rutherford's graduate students, E. J. Evans, confirmed the prediction in the Manchester lab using a vacuum tube filled with pure helium.

After only a year lecturing in Copenhagen, Bohr accepted an invitation from Rutherford to take up a two-year position in Manchester. His arrival in August 1914 coincided with the outbreak of war, which brought physics to a virtual standstill in the Manchester lab. Many of the senior staff such as Rutherford became involved in war-related research, while most younger staff enlisted in the army (the death of Harry Moseley at Gallipoli in 1915 was one tragic consequence). Bohr spent much of the next two years working on his atomic theory in relative isolation.

Physics in Germany also largely ground to a halt, though there were two notable exceptions. In 1915 Einstein published his theory of general relativity, which would catapult him to international fame in the 1920s. In the same year another breakthrough was made by Arnold Sommerfeld in Munich. By introducing elliptical orbits and additional quantum conditions, Sommerfeld was able to generalise the simpler Bohr model and achieve a better understanding of more complex atomic systems. The Bohr–Sommerfeld theory became the standard atomic model until it was superseded by the introduction of quantum mechanics in 1925.

**The future**

Bohr's theory would win him a place in the history books, but it also marked the start of a remarkable career spanning 50 years. In 1916 Niels returned to Denmark where he was appointed professor of theoretical physics at the University of Copenhagen, a chair created especially for him. He immediately began planning a new institute where he hoped to emulate his mentor Rutherford and create a centre to rival the glory days of pre-war Manchester.

The Institute for Theoretical Physics was inaugurated in 1921 (renamed the Niels Bohr Institute in 1965) and
immediately attracted an international group of young physicists eager to work with Bohr on atomic physics [8]. Most of the principal figures involved in the foundation of quantum mechanics – including Paul Dirac, Werner Heisenberg and Wolfgang Pauli – made extended visits to the Copenhagen institute during the 1920s. One hundred years ago, Niels’ theory of the quantum atom provided the major stepping stone towards the most important revolution in 20th century physics.

Acknowledgments
This article is partly based on a talk given at the conference on ‘One Hundred Years of the Bohr Atom’, held at the Royal Danish Academy of Sciences, Copenhagen, in June 2013. I am grateful to Dr Finn Aaserud, director of the Niels Bohr Archive, and to Felicity Pors for permission to reproduce the images in this article, each of which has been sourced from the archive’s extensive photo collection. I am also grateful to the School of Physics, University of Melbourne for its support.

References

Author Bio

Peter Robertson is an honorary research associate in the School of Physics, University of Melbourne. He is a former editor of the Australian Journal of Physics (1980–2001) and of Australian Physics (2011–12). Peter is currently completing a biography of John Bolton, an early pioneer of radio astronomy and the inaugural director of the Parkes dish in New South Wales.
Aside from etymology [1,2], there are many areas where plasmas and plasmons converge; both are based on the idea of collective electronic oscillations. The most straightforward link is the use of plasmas to make plasmonic nanostructures, i.e. ‘plasmas for plasmonics’. There is also another intersection – ‘plasmas in plasmonics’, i.e. the control and utilization of plasma effects in plasmonics. Before we get too ahead of ourselves and launch into a discussion of the physical ideas linking plasma physics and plasmonics, we will set the scene with a brief historical background (see Fig. 1 for a timeline) of the intersection of the plasma physics and plasmonics.

Historical Background

“Those who don’t know history are destined to repeat it”
-E. Burke

A recent colloquium article [2] featured the subheading – “Everything Old is New Again”. Whilst this line is fitting for research in general as fields intersect and become more and more multidisciplinary (nanoscience and nanotechnology being a prime example), it is particularly apt for plasma physics and plasmonics. Many elements of what we view as cornerstones of modern plasmonics today had their origins in the plasma physics. All we have to do is look at the etymology of the terms ‘plasma’ and ‘plasmon’.
A plasma is a fully or partially ionised gas, and is a major chunk of the known, visible universe. Plasma size spans an astonishing 32 orders of magnitude from nanoscale plasmas (i.e. plasmons) to double radio galaxies! The first person to coin the term ‘plasma’ (in relation to gaseous discharges) was Irving Langmuir in 1928 [3]. In a letter to Nature, years later, H. Mott Smith (who himself derived an expression for the plasma frequency – another cornerstone for plasmonics) recalled that Langmuir decided on the term ‘plasma’ as the behaviour of the discharge reminded him of “the way blood plasma carries around red and white corpuscles and germs” [4] (an interesting side note, the use of ‘plasma’ to denote the fluid in which blood cells propagate dates back to 1845, with ‘plasma’ coming from the Greek meaning “something moulded or created” [5]). Fast forward 28 years to 1956 when Pines coined the term ‘plasmon’ to describe collective oscillations in a metal slab upon excitation by electromagnetic radiation as “the valence electron collective oscillations resemble closely the electronic plasma oscillations observed in gaseous discharges” [1]. Jump further still to the late ‘90s and we’ve come full circle with plasmons in action in a surface plasmon resonance biosensor examining concentrations of heparin in blood plasma [6]. It all has a rather nice symmetry about it.

“All that glisters is not gold”
- Shakespeare

Modern plasmonics as we know it arguably began with Faraday in 1857 who, in the Bakerian lecture [7], described the synthesis of colloidal gold. Small particles of gold have formed some of the easiest systems used to model physical behaviour – for example, Maxwell Garnett [8], Mie [9] and Gans [10] all used it as the basis for their description of how light interacts with small particles.

“Pines coined the term ‘plasmon’ to describe collective oscillations in a metal slab upon excitation by electromagnetic radiation”...

Whilst gold is a very useful model system, it is not the only option for plasmonic nanostructures. The main requirement for a good plasmonic material is the presence of free electrons [11]. The plasmonic response is also heavily influenced by the size, shape and composition of the nanostructure. The traditional choices for plasmonic nanostructures are the noble metals, i.e. gold, silver and sometimes (but very infrequently) copper. However, these materials are chosen more as a matter of experimental convenience (i.e. they are easier to make and control in terms of size and shape, and hence plasmonic response) than of plasmonic merit. Alternative, but more inconvenient materials include intermetallics, alloys and silicides [11]. Other more recent efforts have focused on the use of graphene as a plasmonic candidate [12, 13]. To control the available free electrons and hence the plasmonic response, one has to be able to control the growth of the nanostructures where these electrons are confined. This brings us to plasma nanoscience or ‘plasmas for plasmonics’.

**Plasmas for Plasmonics: Plasma Nanoscience**

Plasma nanoscience is defined as “a multidisciplinary research field which aims to elucidate the specific roles, purposes, and benefits of the ionised gas (plasma) environment in assembling and processing nanoscale objects in natural, laboratory and technological situations and to find the most effective ways to ultimately bring these plasma-based processes to the deterministic level” [14]. The main benefit of using plasmas in nanofabrication processes is that they are versatile. They can be used in all stages of the fabrication process, from surface preparation, to generation and transport of nanostructure building material, to guided self-assembly into desired nanostructures through to post-growth processing.

“...The main benefit of using plasmas in nanofabrication processes is that they are versatile. They can be used in all stages of the fabrication process”...

![Fig. 2: Microplasma-assisted electrochemical synthesis of Ag nanoparticles](http://example.com/fig2.png) (Reproduced from Huang et al [15] with permission from IOP Publishing, Copyright 2013)

Indeed, plasma nanoscience approaches can be used to produce plasmonic nanostructures, for example Ag nanoparticles via microplasma-assisted electrochemistry [15] (see Fig. 2: incorporating a microplasma injects energy...
into the system which significantly speeds up the growth) as well as plasma-assisted fabrication of hybrid structures such as Au nanoparticle decorated vertical graphene nanosheets [16] (see Fig. 3), which are useful for a range of applications, such as surface-enhanced Raman scattering (SERS)-based sensing platforms.

Plasmas in Plasmonics: Plasma Foundations

In addition to plasmas being used to construct nanoscale objects, it should also be recognised that plasma effects may exist as nanoscale phenomena [17]. The most apparent example of this is a plasmon - effectively, a plasmon is a nanoscale plasma phenomenon. For example, plasmas exhibit charge separation and electronic oscillations, which are two of the major characteristics of a plasmon. However, the plasmons are excited within solids without actually generating (“moulding” or “creating” in Ancient Greek terms) a traditional plasma state of matter [17]. The dispersion equation, both for surface plasmon polaritons in solids and transverse mode propagating surface waves which sustain surface wave gaseous plasmas, is the same:

\[
\omega^2 = \frac{\omega_p^2}{2} + c^2k^2 - \sqrt{\frac{\omega_p^2}{4} + c^4k^4}
\]

where \(\omega_p\) is the plasma frequency, \(k\) is the wavenumber, \(c\) is the speed of light. This shows that the transverse mode propagating surface wave is essentially a macroscopic microwave analogue of a (nanoscale) surface plasmon polariton.

Plasma screening occurs when an electromagnetic wave encounters an interface between a plasma and a dielectric; charge displacement leads to the excitation of forwards and backwards plane waves [18]. The plasma frequency is given by:

\[
\omega_p = \sqrt{\frac{e^2n_e}{\epsilon_0m_e}}
\]

where \(n_e\) is the electron density, \(e\) is the charge on the electron and \(m_e\) is the effective mass of an electron. Depending on the frequency, \(\omega\), of the wave, one of two things can happen:

1. If \(\omega\) is less than \(\omega_p\), destructive interference occurs and an energy gap is created.
2. If \(\omega\) is greater than \(\omega_p\), constructive interference occurs and a transverse bulk plasmon is created.

The plasma frequency is influenced by the number density of electrons in the plasma (or plasma-like media with free electrons), hence being able to control the electron number density, affords control over the band gap and over the frequency of the transverse bulk plasmon. That level of control is important for numerous devices in fields ranging from optoelectronics to biomedicine.

“Plasmons are used in a myriad of applications, from surface plasmon amplification by stimulated emission of radiation (SPASERS) and SERS sensors, to theranostics … and invisibility cloaks”

Common parameters mentioned when discussing gaseous plasmas include (but are not limited to) number density of electrons, electron temperature, pressure (both reactor pressure and partial pressure of the feedstock gases), degree of ionisation and applied power. By varying these parameters, the characteristics of the plasma may be tuned. This is particularly notable when considering the transition between a bulk plasma and a microplasma (at least one dimension of the plasma being on the micrometre scale), specifically at the discharge barriers. The transition between a bulk plasma and microplasma occurs at a critical size determined by the surface to volume ratio of the plasma and the electrode spacing. As these increase and decrease, respectively, the collision rates in the plasma increase (the electron temperature and pressure both having increased), leading to a size-introduced collisionality [2].

Size-introduced collisionality is a topic of interest to both plasma science and plasmonics. In the case of plasmons, this is most evident in the case of nanoshells [19], where the scattering of electrons from a surface results in a blue shift of the resonance, distinct from scattering...
due to geometric effects (i.e., Mie scattering) [2]. If this source of shift is taken into account, greater precision is possible when designing plasmonic particles for applications which require a high degree of specification over the wavelength (e.g. sensors). It is clear that, in order to optimize device performance, one must be able to distinguish between plasma-specific and geometric effects.

Another possible link to consider is the use of emission from a plasma source to excite plasmons from IR to the UV frequencies by simply modifying the plasma parameters and hence the electron energy distribution function (EEDF). This would of course involve some engineering challenges in terms of filtering out undesired wavelengths and is an area currently under investigation. Other interfaces between plasmonic phenomena, plasma physics and laser science have also been discussed at length in the recent literature, e.g. the generation of nano-plasmas around plasmonic nanoparticles [17] and surface plasmon wave excitation using lasers [20].

**But why is all this important?**

“The farther backward you can look, the farther forward you are likely to see” - Winston Churchill

Plasmons are used in a myriad of applications, from surface plasmon amplification by stimulated emission of radiation (SPASERS) and SERS sensors, to theranostics (a portmanteau of therapeutics and diagnostics) and invisibility cloaks. But fundamentally, like other plasma phenomena, they are based on the idea of collective electronic oscillations and exhibit a number of similar effects including, but not limited to charge separation, plasma screening, and size dependant eigenfrequencies and collisionality. By appreciating the essential physical links between the plasma physics and plasmonics from the very origin of the field junctions through to modern plasma nanoscience, one can more meaningfully design efficient growth processes as well as nanoscale plasma-like responses for highly tailored nanostructures for the next-generation of cutting-edge plasmonic applications.

**REFERENCES:**

Radio waves measure atmospheric temperature changes

Very low frequency (VLF) radio waves can be used to measure temperatures at the mesopause – the lower boundary of the upper atmosphere – according to researchers in Israel. This new method offers a cheaper and more comprehensive way of analysing the effects of long-term climate change on the upper atmosphere, as well as more short-term phenomena, such as solar storms or thunderstorms.

At the Earth’s surface, increasing levels of greenhouse gases – such as carbon dioxide – reflect escaping infrared radiation back towards the ground. This results in a warming effect. In the upper atmosphere, however, greater concentrations of these gases have the opposite effect. At these low atmospheric densities, carbon dioxide primarily acts instead to radiate heat out to space – and does so more effectively at these altitudes than oxygen or nitrogen, the other main atmospheric components.

When the upper atmosphere cools, it also gradually shrinks – becoming denser and moving closer to the Earth’s surface. This cooling also alters the propagation paths of radio waves, which pass through the upper atmosphere.

The researchers’ method works, therefore, by measuring the amplitude of VLF radio waves – which originate from navigational beacons – after they have bounced off the ionosphere, which contains the mesopause. The strength of the received signal is affected by the ionospheric density, which is in turn a product of the temperature. The team was able to observe a clear correlation between upper atmosphere temperatures – calculated from emissions from carbon dioxide measured by the TIMED satellite’s SABER instrumentation – and the amplitude of the received radio waves.

Previously, direct studies of mesopause temperatures had been difficult and expensive to undertake – with the region being both too low for in situ measurement by orbital satellites, and yet too high for planes or weather balloons. The team reports that its ground-based apparatus, however, is easy to use and considerably more cost-effective – with each VLF antenna and processing computer only costing around a few thousand dollars. The new method also allows for continuous measuring of a specific region of the upper atmosphere – a task that is not possible even with indirect measurements from orbiting satellites. Their current study used radio stations located in Greece, Israel and New Zealand. In addition, the team is looking into comparing its results with other sources of temperature and solar-indices data. [Journal of Geophysical Research: Atmospheres, 118, 4244–4255 (2013)]

B-mode polarization spotted in cosmic microwave background

The South Pole Telescope (SPT) has made the first detection of a subtle twist in light from the cosmic microwave background (CMB), known as B-mode polarization. The signal, the existence of which has been long predicted, paves the way for a definitive test of inflation – a key theory in the Big Bang model of the universe.

Often called the afterglow of the Big Bang, the CMB is thought to have originated some 380,000 years into the life of the universe when neutral atoms first formed and space became transparent to light. Roughly speaking, it consists of microwaves with a temperature of about three kelvin, but it also contains details that have helped to refine our understanding of the early universe. The most noticeable of these details are variations in temperature of about 100 μK, which reveal density fluctuations in the early universe – the seeds of the stars and galaxies that we see today.

The CMB does not only contain variations in temperature, however. Its radiation was scattered towards us from the universe’s earliest atoms in the same way that blue light is scattered towards us from the atoms in the sky. And in the same way that the blue light from the sky is polarized so too is the light from the CMB polarized. Variations in CMB polarization were first detected in 2002 by the DASI interferometer in Antarctica and helped cosmologists understand the dynamics of the early universe.

These polarization variations were known as E-mode or gradient variations because they describe how the magnitude of polarization changes over the CMB. But there are even subtler variations known as B-mode variations,
which describe the rotation or “curl” of CMB polarization. The majority of B-mode polarization is produced by galaxies acting as gravitational lenses, twisting the E-polarized light on its 14-billion-year journey from the other side of the observable universe. It is incredibly faint, producing temperature variations of about 0.4 μK and accounting for just one part in 10 million in the CMB temperature distribution.

The SPT has managed to detect B-mode polarization largely thanks to improvements in detector technology. With more precision, B-mode signals could help cosmologists place tougher constraints on neutrino masses, which cannot be predicted in the Standard Model of particle physics.

But the biggest prize would be using B-mode signals to uncover evidence of primordial gravitational waves. Such ripples are predicted to have been generated in inflation, a brief period prior to the formation of the CMB when the universe is thought to have undergone rapid expansion and given birth to large-scale structures. [preprint arXiv:1307.5830.]

“Surprisingly, we found an enormous enhancement of mass transport by the wind in the presence of mid-air collisions, compared with the case when such collisions are switched off,” explains Nuno Araújo, one of the researchers at the Eidgenössische Technische Hochschule Zürich.

Unlike previous theories – which argued that saltons could only be formed during a splash – the team’s model revealed that leapers can become saltons through a series of mid-air collisions that gradually increase their altitude. The higher the particles go – as well as the longer they can stay in the air – the greater the acceleration from the wind, which increases the likelihood of saltation formation. [Phys. Rev. Lett. 111, 058001 (2013)]

Nanodiamond thermometer takes temperature of biological cells

A new nanothermometer that could be used to measure temperature variations in living cells has been created by researchers at Harvard University in the US. The device, which is based on diamond nanocrystals and is “injected” into the interior of cells using nanowires, can detect temperature fluctuations as small as 1.8 mK over nanometre length scales. If further improved, it could be used to probe a range of temperature-sensitive phenomena in biological cells, and might even help in the development of “thermoblative” cancer treatments.
In their new work, the researchers, led by Mikhail Lukin of Harvard University, exploited nitrogen vacancy (NV) centres in diamond. NVs are defects that occur when two neighbouring carbon atoms are replaced by a nitrogen atom and an empty lattice site.

The ground state of an NV centre is split into two energy levels. When diamond cools or warms, the NV transition frequency shifts accordingly. The new nanothermometry technique works by accurately measuring this shift – which can be detected using fluorescence spectroscopy – and then using this measurement to calculate the exact temperature of the nanodiamond. And since diamond is a good conductor of heat, it is likely to have the same temperature as its immediate surroundings – in this case a biological cell. The device, which the researchers injected into biological cells during their experiments using nanowire “needles”, can detect temperature variations as small as 1.8 mK (in an ultra-pure bulk-diamond sample) and over distances as short as 200 nm.

In another set of experiments, Lukin and colleagues combined their nanodiamond thermometer with gold nanoparticles that had been excited with laser light and so acted as localized heat sources. This technique allowed the team to both monitor and control the temperature in a biological cell – in one particular case a single human embryonic fibroblast. The heat generated by the gold nanoparticles could also be used to destroy the cell, the researchers found. Indeed, they succeeded in calculating the exact amount of heat required to do this. “We believe that combining such ‘thermoblative’ therapy with our temperature nanosensor could be a powerful tool for selectively identifying and killing malignant tumour cells, for example, without damaging surrounding healthy tissue,” says team member Georg Kucsko. [Nature 500 54–58 (2013) doi:10.1038/nature12373]

**Feeling hot hot hot: temperature control inside living cells**

**Physicists call for €5bn Neutrino Factory**

An international group of physicists has called for the construction of the Neutrino Factory as the next high-intensity neutrino facility in Europe. Taking four years to prepare, the report was written by the EUROnu collaboration, which consists of 15 institutions. The report backs the Neutrino Factory – which is estimated to cost between €4.6bn and €6.5bn – rather than two less-expensive options: the €1.6bn Super-Beam experiment and the €2.3bn Beta Beam facility.

The Neutrino Factory will involve producing neutrinos by firing a high-power proton beam at a target to make pions, which are then captured and allowed to decay into muons. The muons are then accelerated and injected into a storage ring where they decay into neutrinos, which are sent some 2000 km to the Magnetized Iron Neutrino detector, which would be made from 100,000 tonnes of iron.

One possible scenario for the Neutrino Factory is to have the accelerator based at CERN with a detector in Finland, the UK or even the US. The primary aim of this experiment – and other existing and planned experiments that send neutrino beams over long distances – is to study neutrino oscillation. This is the process by which neutrinos of one flavour (muon neutrinos at the Neutrino Factory) can with time change into neutrinos of a different flavour. Making more precise measurements of neutrino oscillations could help solve several important mysteries of physics, including why there is much more matter than antimatter in the universe.

Kenneth Long, an experimental particle physicist at Imperial College London and a member of EUROnu, says that the scientific impact of the Neutrino Factory is “potentially enormous” and has the capacity to solve some of the biggest challenges in physics, such as the nature of dark matter.
BOOK REVIEWS

**Tesla, Inventor of The Electrical Age**
by W. Bernard Carlson
Princeton University Press (2013), 500 pages
ISBN 978-0-691-05776-7 hardback


The title is cringe worthy, as to suggest in any way that Tesla “invented” the electric age is absurd, so I approached this book with some trepidation. But once inside the covers the depth of information on Tesla and his inventions belies the silly title. In a word “Wow”!

The author takes us inside the head of Tesla like no other has done before. He explores Tesla’s social, business, technical, financial and even his sex life. The work is very comprehensive and carefully researched and avoids much of the mythology and hype that characterises most previous works by others. Tesla’s own writings are used extensively to set the scene.

We read that Tesla’s career effectively spanned two decades. The first beginning with his arrival in the US in 1884 saw his most productive work on the development of the induction motors (which oddly are not identified as such by the author who consistently refers to rotating field AC motors). These motors played a major role in the DC/AC generation debates as at that time electricity generation was mainly about sourcing power for electric lights (which were cheaper and safer to run than candles). Commutators are subject to wear and arcing and rely on carbon brushes to supply the power, all of which makes them unreliable. A brushless AC motor is more reliable and cheaper to produce. Tesla and independently Galileo Ferraris of Italy invented the induction motor in 1885. The availability of the induction motor was a deciding factor in the AC/DC generation debates as at that time electricity generation was mainly about sourcing power for electric lights (which were cheaper and safer to run than candles). Commutators are subject to wear and arcing and rely on carbon brushes to supply the power, all of which makes them unreliable. A brushless AC motor is more reliable and cheaper to produce. Tesla and independently Galileo Ferraris of Italy invented the induction motor in 1885. The availability of the induction motor was a deciding factor in the AC/DC generation debates as at that time electricity generation was mainly about sourcing power for electric lights (which were cheaper and safer to run than candles). Commutators are subject to wear and arcing and rely on carbon brushes to supply the power, all of which makes them unreliable. A brushless AC motor is more reliable and cheaper to produce. Tesla and independently Galileo Ferraris of Italy invented the induction motor in 1885. The availability of the induction motor was a deciding factor in the AC/DC generation debates as at that time electricity generation was mainly about sourcing power for electric lights (which were cheaper and safer to run than candles). Commutators are subject to wear and arcing and rely on carbon brushes to supply the power, all of which makes them unreliable. A brushless AC motor is more reliable and cheaper to produce. Tesla and independently Galileo Ferraris of Italy invented the induction motor in 1885. The availability of the induction motor was a deciding factor in the AC/DC generation debates as at that time electricity generation was mainly about sourcing power for electric lights (which were cheaper and safer to run than candles). Commutators are subject to wear and arcing and rely on carbon brushes to supply the power, all of which makes them unreliable. A brushless AC motor is more reliable and cheaper to produce. Tesla and independently Galileo Ferraris of Italy invented the induction motor in 1885. The availability of the induction motor was a deciding factor in the AC/DC generation debates as at that time electricity generation was mainly about sourcing power for electric lights (which were cheaper and safer to run than candles). Commutators are subject to wear and arcing and rely on carbon brushes to supply the power, all of which makes them unreliable. A brushless AC motor is more reliable and cheaper to produce. Tesla and independently Galileo Ferraris of Italy invented the induction motor in 1885. The availability of the induction motor was a deciding factor in the AC/DC generation debates as at that time electricity generation was mainly about sourcing power for electric lights (which were cheaper and safer to run than candles). Commutators are subject to wear and arcing and rely on carbon brushes to supply the power, all of which makes them unreliable. A brushless AC motor is more reliable and cheaper to produce. Tesla and independently Galileo Ferraris of Italy invented the induction motor in 1885. The availability of the induction motor was a deciding factor in the AC/DC generation debates as at that time electricity generation was mainly about sourcing power for electric lights (which were cheaper and safer to run than candles). Commutators are subject to wear and arcing and rely on carbon brushes to supply the power, all of which makes them unreliable. A brushless AC motor is more reliable and cheaper to produce. Tesla and independently Galileo Ferraris of Italy invented the induction motor in 1885. The availability of the induction motor was a deciding factor in the AC/DC generation debates as at that time electricity generation was mainly about sourcing power for electric lights (which were cheaper and safer to run than candles). Commutators are subject to wear and arcing and rely on carbon brushes to supply the power, all of which makes them unreliable. A brushless AC motor is more reliable and cheaper to produce. Tesla and independently Galileo Ferraris of Italy invented the induction motor in 1885. The availability of the induction motor was a deciding factor in the AC/DC generation debates as at that time electricity generation was mainly about sourcing power for electric lights (which were cheaper and safer to run than candles). Commutators are subject to wear and arcing and rely on carbon brushes to supply the power, all of which makes them unreliable. A brushless AC motor is more reliable and cheaper to produce. Tesla and independently Galileo Ferraris of Italy invented the induction motor in 1885.
were sold to Westinghouse. Tesla was an inventor, but he was widely known as the “Wizard” and his greatest skill was his self-promotion. A. P. Trotter, editor of The Electrician describes it thus “[Tesla] did not write or read a paper, nor did he give a lecture, and he was so occupied in waving long glowing electrode-less tubes in the air, and lighting up of ordinary incandescent lamps by a current taken through his body, that he had no time to explain how it was done. Nor do I think could he”. Tesla the Wizard promised more than Tesla the inventor could deliver.

While this book is by far the most comprehensive on the life and work of Tesla it misses out on being the definitive book as Carlson presents all the evidence that not only did Tesla spend the second decade building his power transmitter without success, but that the device did not and could not have worked as Tesla promoted it. There is sufficient evidence also that Tesla deliberately fudged his results (as Carlson indicates) and that his grasp of electrical theory was tenuous at best (something that Carlson glosses over). Carlson allows Tesla to tell us that his transmissions are “loss-less”, and then later that they proceed by way of “standing waves” and still later that “the losses are inversely proportional to distance” (whereas Maxwellian wave losses are inversely proportional to the square of the distance). Carlson fails to alert the reader to these contradictory claims (all of which are false). The evidence of this and much more is all in the book, and Carlson fails to bring it together. The conclusion should have been that Tesla was more crank than genius (as indeed the book reveals was the prevailing opinion of the professionals in his time) - but what an interesting crank!

Review 2: by Dr Lee Weisel, Trinity Anglican College

W. Bernard Carlson’s biography is a journey into the world of an extremely brilliant and yet at times troubled inventor. The nature and volume of Nikola Tesla’s work is astounding. At one time Thomas Edison’s employee, Tesla (1856-1943) became his rival, vying for the crown of Electrical Genius. As Carlson, a historian of technology points out in his biography, Tesla, Inventor of the Electrical Age he has been credited with every innovation of the electronic age and dismissed as a madman. The classic photograph of Tesla seated calmly reading a book in his Colorado laboratory while an electrical storm rages across the gigantic coils around him captures brilliantly the sense of a magus commanding wild forces. In fact, it is his image that he commands here: The photo was a faked double exposure.

This work has many strengths. Carlson does a good job of debunking the conspiracy theorists and instead leaves us to negotiate rather opaque discourses on the merits of alternating-current (AC) versus direct-current (DC) power generation.

Using Tesla’s life story, Carlson draws out many connections between man and invention. Tesla was born in the province of Lika in what is now Croatia on the outskirts of the Austro-Hungarian Empire. The son of an educated priest, he was trying to make flying machines while still at school and was seemingly not destined, as his father hoped, for the priesthood himself. During a rather haphazard training as an engineer in Graz and Prague, Tesla developed a fascination for motors, dynamos and electromagnetism in general. While working in Budapest he was hired by Edison’s branch in Paris and then brought to the Edison Machine Works in New York. Tesla quit soon after when he felt that his contribution to the company’s arc-lighting system went unappreciated.

His breakthrough invention was a motor that ran off AC. It was simpler and without the sparking contacts of DC motors. He sold the patent to George Westinghouse, who collaborated with him to develop AC power—which was easier to transmit over long distances—in America. The construction of Westinghouse’s AC hydroelectric power plant at Niagara Falls in 1895 was arguably Tesla’s greatest and most enduring success. As Carlson explains: “Tesla’s AC inventions were essential to making electricity a service that could be mass-produced and mass-distributed; his inventions set the stage for the ways in which we produce and consume electricity today.”

Like Edison, Tesla was a showman who actively cultivated an impression of wizardry in an age when electromagnetic phenomena still smelled of magic—an association that probably contributed more to Tesla’s status than Mr. Carlson credits. To demonstrate the safety of AC power, he staged public lectures in which he would pass 250,000 volts through his body, creating a glow of ionized air at his fingertips and the ends of his hairs. Despite being prone to depression and odd behavior, he was also, in his heyday, a socialite who could win over tycoons such as Westinghouse, John Jacob Astor and J.P. Morgan.

The work follows Tesla then into obscurity as his popularity wanes. The book is littered with diagrams and explanations of his original inventions as well as stories of his personal struggles. For teaching this book is an invaluable resource.
Niels Bohr ranks with Einstein as one of the most influential physicists of the 20th century. The young Dane burst upon the scene in 1913 with a revolutionary theory of the quantum atom, arguably the most important landmark in the development of atomic physics.

To mark the centenary, Oxford University Press has reproduced a facsimile of the three papers Bohr published in quick succession in the British journal Philosophical Magazine, under the generic title ‘On the Constitution of Atoms and Molecules’. The trilogy opened the door to a new world of phenomena on the atomic scale, a world which could not be understood by classical physics of the 19th century.

After being awarded his PhD on the electron theory of metals in 1911, Bohr spent a postdoctoral year in England, first at the Cavendish Laboratory under J. J. Thomson and then at the Manchester laboratory of Ernest Rutherford. Bohr was strongly influenced by the recent discovery by Rutherford’s group that atoms consist of a tiny positively charged nucleus surrounded by the orbiting electrons. Bohr was able to explain the stability of Rutherford’s model using the concept of stationary states and how the transition of an electron from one stationary state to another leads to the absorption or emission of radiation.

Bohr’s trilogy is introduced by two lengthy essays. The first is by Finn Aaserud, the director of the Niels Bohr Archive in Copenhagen and the leading authority Bohr’s life and work. To mark the centenary, the Bohr family recently released Niel’s personal correspondence from his postdoctoral year in England, much of it consisting of lengthy (and often schmaltzy!) letters to and from his fiancée Margrethe Norlund. Aaserud’s essay reveals Bohr to be rather shy and awkward, who struggled to fit into the culture of the Cavendish Laboratory and who found J. J. Thomson to be aloof and indifferent to his ideas. The young theorist found his feet by moving to Manchester where developed a great admiration for the larger-than-life Rutherford and his style of leadership. It was here, during the first half of 1912, that Bohr developed his seminal ideas on the quantum atom.

The second essay is by the veteran historian of physics John Heilbron, an emeritus professor at Berkeley. His writings on Bohr and the foundation of quantum physics span almost fifty years. Starting around 1900, Heilbron traces the scientific background to Bohr’s trilogy and examines the philosophical and literary influences on the young Niels, who grew up in the well-to-do academic circles of Copenhagen. The essay is aimed at readers with a physics background and Heilbron is not shy in using mathematics to explain how various threads were woven together to form the quantum atom.

Both essays are a delight to read and both are well illustrated with photos and images, many of which are published for the first time. The book was launched at a conference celebrating the centenary of the Bohr atom, held at the Royal Danish Academy of Sciences in June this year. I can highly recommend the book to anyone interested in the history and foundations of modern physics.
After the war he took up a position as Assistant Lecturer in the Physics Department at University College, Nottingham, working with LF Bates. Bates introduced him to the subjects of magnetism and magnetic materials, which formed the basis of his later scientific career. It was here, working with John Woolley in 1948, that Bob and John made the important discovery that magnetisation is a time dependent process. In 1954 he took up a position as Senior Lecturer at Sheffield University.

In 1960, Bob was appointed as Founding Professor of Physics at Monash University. With his wife and two children, Alison and Nick, Bob had made the tremendous leap to the Antipodes. In his new position, Bob was put in charge of a green field site, overseeing the development of undergraduate courses, research fields, research infrastructure and appointment of staff in all areas. Bob fostered a sense of cohesion, co-operation and camaraderie which were the hallmarks of his stewardship at Monash.

Bob was also a pioneer in science education through his involvement in the development of the Victorian physics curriculum; in science communication through an ABC TV science program; in professional development through the Australian Institute of Physics; and in science policy and funding through work with the Australian Atomic Energy Commission, the National Standards Commission (NSC), as chair of the Metric Conversion Board and chair of the ARGC (precursor to the ARC). Bob would later claim that one of his most significant achievements, as part of the NSC, was to require a mark on beer glasses to which the liquid must be filled in order to prevent publicans putting too much head on your beer! In 1974, Bob left Monash to take up the position of Director of the Research School of Physical Sciences at the Australian National University. Under his leadership, the Anglo-Australian telescope was established. In 1978 Bob was appointed as Vice Chancellor of the University of Western Australia, and in 1985 he was honoured by the award of Officer in the Order of Australia (AO) for his service to learning.

Following his retirement in 1986, Bob embarked on a renewal of his research career as an Honorary Research Fellow in the School of Physics, and “gentleman scholar”. He initiated a magnetism research program at UWA, building a well-equipped research laboratory that attracted significant research funding. Over a period of twenty years, Bob supervised 20 PhD students and over 30 honours students. He published 128 papers between 1988 and 2003, and these papers have been cited over 2500 times. During this time Bob loved to come into the lab to talk to the students, and work on any one of a number of scientific questions. He was also passionate in his conviction that physics is important to society and the economy. He oversaw the commercialization of two technological breakthroughs from the lab - techniques for the mass production of nanoparticulate materials (Advanced Nanotechnology Pty Ltd) and a method for non-invasive measurement of liver iron levels (IVB Pty Ltd). Bob served on the Board of Directors of both spin-off companies. As a passionate scientist, a life long mentor, an educator, and a leader, Bob changed the world for many of us.

A more detailed review of Bob’s career is recorded in an interview on the Australian Academy of Science website - http://science.org.au/scientists/interviews/s/street.html

Robert Street AO, FAA

1920 - 2013

Emeritus Professor Robert Street, BSc, MSc, PhD, DSc, (Univ London), DSc Hon (UWA & University Sheffield), FInstP, FAIP, CPhys, CEng, MIEEE, passed away in the early hours of Thursday 4th July 2013, aged 93. To most people who worked with him during his career he was simply known as Bob.

Bob Street had a major impact on science and education in Australia. He was the Founding Professor of Physics at Monash University, became Director of the Research School of Physical Sciences at the Australian National University, and served as Vice Chancellor of The University of Western Australia. He remained an active researcher into his late eighties.

Bob was born in a coal mining district in Yorkshire, England, in 1920. Although his father and both his grandfathers were coal miners, Bob chose a different path. At the age of 12 he had a stated ambition to become a Professor of Physics. This ambition was fostered by his family and his teachers at both junior school and high school.

In 1941, after completing an accelerated BSc degree at King’s College London, Bob joined the Air Defence Research and Development Establishment working on radar research throughout the war. He met his wife Joan during an air raid in Bristol, commenting later “Great unifying events, air raids. You get to talk to people, I suppose to keep your spirits up”. Tim St Pierre, Rob Woodward, Ian McArthur, John Cashion, Michael Morgan and Alison Street

172 AUSTRALIAN PHYSICS

50(5) SEP–OCT 2013
**PRODUCT NEWS**

**COHERENT SCIENTIFIC**

**Vitara UBB : Ultra broad band automated Ti:S Oscillator**

Coherent’s new Vitara UBB provides the widest bandwidth available from a fully integrated Ti:Sapphire oscillator. The bandwidth is adjustable to more than 220nm and supports compressed pulse durations of <8fs. The new laser is designed for maximum ease of use and is fully automated, thus allowing researchers to concentrate on their experiment rather than on the laser.

**Features include:**
- Computer controlled bandwidth (<180nm to >220nm)
- Integrated spectrometer
- <8fs pulsewidth capability (<10fs standard)
- Low noise (<0.1% rms)
- PowerTrack active optimization
- Integrated Verdi-G pump laser
- Compact footprint
- Hands-free operation

**Libra HE+ : Extending Libra performance to >5 mJ**

Coherent’s Libra HE+ extends the pulse energy of the Libra series to >5mJ in an easy to use “one-box” platform. The new specification satisfies the most energy-hungry applications and allows multiple experimental end-stations to be operated simultaneously from a single ultrafast source with a choice of <100fs or <40fs pulse width. The robust design of the Libra family integrates Coherent’s Vitesse or Vitara oscillators and Evolution pump lasers with a compact, regenerative amplifier to provide superb stability and ease-of-use. Full computer control of all sub-systems, plus a range of on-board diagnostics and detectors provide thousands of hours of trouble-free operation. Libra is also compatible with the OPerA Solo and TOPAS OPAs, thus providing tunable ultrafast output with exceptionally low noise and complete computer control of all functions.

Contact your Coherent Scientific ultrafast laser specialist
Dr. Dale Otten
dale.otten@coherent.com.au

Coherent Scientific
116 Sir Donald Bradman Drive
Hilton SA 5033
Ph: (08) 8150 5200 Fax: (08) 8352 2020

**LASTEK**

**PhaseView ZeeScan 3D Imaging**

The ZeeScan is a 3D microscope add-on that attaches to video ports to add 3D imaging capabilities. Using digital wavefront technology, the ZeeScan adds a third dimension to conventional imaging devices, revealing key information:
- 3D topography when light interacts with a reflecting object
- Contrast, 3D structure and aberrations when light passes through low absorption or transparent samples
- Simultaneous Phase & Intensity data for Coherent & Non-Coherent Light

**The ZeeScan is ideal for the following applications:**
- Material Microscopy
- Industrial Quality Control
FIAlab Instruments - Leaders in Flow Injection Technology

FIAlab provides Flow Injection Analysis (FIA) and Sequential Injection Analysis (SIA) instruments for automation of all analytical reagent-based techniques, by using sophisticated microfluidic sample processing.

Flow Injection is an automated method based on injection of a well defined volume of a sample solution into a continuously pumped solution of a carrier. Reagent streams are added at confluence points and a detectable product, often quantified by spectrophotometry, is formed while reactants flow through a coiled reactor and other manifold components into a flow cell.

Sequential Injection, the new generation technique evolved from FI, is based on injection of a sample into a carrier solution, moving in a pre-programmed way. Sample and reagent solutions are selected by means of a multi-position valve and their volumes, on a micro-litre scale and controlled by a syringe pump. Mixing is achieved by flow reversals, and reaction rates may be monitored, while the reacting mixture is held within a flow cell.

Advantages of FIAlab techniques:
- Highly reproducible
- Great reliability
- Low reagent consumption and waste generation
- High sample throughput (50 to 300 samples per hour)
- High degree of flexibility
- Low cost of investment and maintenance

Applications:
- Environmental & Water
- Marine & Ocean
- Agricultural
- Trace Analysis
- Bacterial & Cellular
- Biotech
- Process Control

Raman-AFM Agreement between HORIBA Scientific and AIST-NT

HORIBA Scientific and Lastek are pleased to announce their recent agreement with AIST-NT to distribute a new AFM-Raman system.

AIST-NT is a manufacturer of advanced SPM systems designed specifically for integration with optical spectroscopy. The AIST-NT Scanning Probe Microscope product line implements unique hardware and software features which combined with HORIBA Scientific’s renown spectrometer technology make up the most versatile, powerful and easy-to-use AFM-Raman solution to date.

The exceptional long term stability and speed of the integrated platform bring reliable results both for co-localized measurements and TERS imaging.

HORIBA Scientific’s integrated AFM-Raman solutions with AIST-NT SPM technology will be fully supported by HORIBA Scientific and Lastek.

For more information please contact Lastek at sales@lastek.com.au

Lastek Pty Ltd
Adelaide University - Thebarton Campus
10 Reid St, Thebarton, South Australia
Toll Free: Australia 1800 882 215 ; NZ 0800 441 005
T: +61 8 8443 8668 ; F: +61 8 8443 8427
e-mail: sales@lastek.com.au
web: www.lastek.com.au

WARSASH SCIENTIFIC
20/30 XL UV-VIS-NIR MICRO SPECTROPHOTOMETER

The 20/30 XL™ microspectrophotometer from CRAIC Technologies is designed to non-destructively analyse microscopic features of very large samples when integrated into large scale sample handling machinery. With a spectral range from the deep ultraviolet to the near infrared, analysis of samples can be done by absorbance, reflectance, Raman, luminescence and fluorescence with unparalleled speed and accuracy. The system can also be configured to image microscopic sample areas in the UV and NIR regions in addition to high resolution colour imaging.

Due to its flexible design which gives it the ability to
analyse the largest samples, applications are numerous and include mapping colour and intensity variations of flat panel displays, film thickness measurements across the entire surface of 300mm wafers, scanning the surfaces of hard disks for defects to the analysis of entire paintings with high spatial resolution. With the ability to spectral analyse and image microscopic samples and very large devices, the 20/30 XL microspectrophotometer is the cutting-edge micro-analysis tool for laboratories and manufacturing facilities.

The 20/30 XL microspectrophotometer integrates advanced spectrophotometers with a sophisticated UV-visible-NIR range microscope and powerful, easy-to-use software. By including high-resolution digital imaging, the user is also able to use the instrument as an ultraviolet or infrared microscope.

ULTRA-COMPACT DIODE MODULE LASERS

The Cobolt 06-01 Series lasers, available from Warsash Scientific, consists of high performance fixed wavelength diode laser modules covering a spectral range between 405 and 660nm. The lasers offer optimum beam quality and modulation performance from a small and compact package. Manufacturing using Cobolt’s unique HTCure™ Technology ensures world-class quality reliability and lifetime, as well as unmatched robustness. These high performance diode laser modules have the best extinction ratio on the market (>100 000 000:1) and are available with 12 months warranty (unlimited hours).

Key features:

- Easy-to-integrate compact and powerful laser diode modules
- Wavelengths: 405nm, 445nm, 473nm, 488nm, 515nm, 638nm, 660nm
- Power up to 250mW in a high quality beam
- Direct intensity modulation capability: fast and deep modulation from versatile input signals
- All control electronics fully integrated into laser head
- Ultra-robust design
- Fibre pigtailed option

STANDALONE LOW WAVE NUMBER RAMAN SPECTROSCOPY

Innovative Raman filters from Enspectr ensure spectral range from 7 up to 4000cm⁻¹ with a spectral resolution of 3cm⁻¹ (Stokes component) simultaneously in one shot with spectral range from -1000 to -7cm⁻¹ (anti-Stokes component).

Ultra-low frequency Raman analysis substitutes perfectly well for terahertz spectroscopy, carrying valuable information about long range bonds in polymers, low energy vibrations in complex organic molecules, low frequency phonons in solids and other.

Ultra-low frequency Raman analysis (below 100cm⁻¹) gives a lot of useful information for researchers of important modern materials:

- Radial breathing modes of single- and multi-wall carbon nanotubes exhibit Raman spectral components that depend on the tube diameter and that can be used to determine sample quality and composition
- Folded acoustic modes of multilayer superlattice structures in advanced semiconductor devices show multiple strong signals below 100cm⁻¹
- Heavy atom vibrations in compounds (like halides used in incandescent lights)
- Relaxation mode measurements of various liquids and solutions can help identify their dynamic structure
- Rotational mode measurements of gases can be used to determine bond lengths
- Analysis of low wavenumber shear modes and lattice modes

For more information please contact Warsash Scientific

PO Box 1685
Strawberry Hills NSW 2012
+61 2 9319 0122
sales@warsash.com.au.
New Ultrafast Lasers


Your femtosecond work may range from fundamental research to industrial manufacturing. No matter the goal, day-to-day reliability, lifetime and superior performance are critical to any application.

Coherent’s design and manufacturing expertise now combines all this into one compact unit for Better Ultrafast, Every Day.

Vitara-UBB Broadband Ultrafast Oscillator
Sub-8 fs pulses, computer-controlled and maintenance-free

Libra-HE+ Ultrafast Amplifier
Ultra-stable, 1kHz, 5 mJ, <40 fs, Ti:Sapphire amplifier system

Contact us for Coherent’s latest ultrafast laser systems catalogue

Phone: (08) 8150 5200
Fax: (08) 8352 2020
Email: sales@coherent.com.au
Web: www.coherent.com.au