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DANIEL JOSEPH BRADLEY
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Elected FRS 1976
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BY J. ROY TAYLOR*

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Dan Bradley was a pioneer of laser physics and technology. He was internationally distinguished for his seminal work on broad-band, wavelength-tuneable lasers, the generation of ultra-short pulses, and the development of the technology that allowed the only direct temporal characterization of optical pulses with sub-picosecond resolution. He was responsible for the creation of two major UK university laser research centres and was a leading proponent for the formation of the UK Central Laser Facility, establishing the foundations of a vivacious living legacy in UK laser physics.

FAMILY BACKGROUND, EARLY LIFE AND EDUCATION

The Bradley family have their roots to the south side of the walls of the city of Londonderry/Derry in what is now Northern Ireland, residing at various locations bounded by Bishop Street and the River Foyle. Dan’s paternal grandfather, William John Bradley, was the Head Postman for the Derry postal area. He was also notably an alderman, between 1920 and 1923, in the Derry Corporation, at a time when the city had its first Catholic majority council and mayor. Following the division of Ireland in 1921, with a Catholic majority in Derry and before the later effects of gerrymandering, a nationalist council was elected which pledged allegiance to Ireland, leading to local unrest. While civil war raged in the South, religious discrimination and sectarian violence escalated in Northern Ireland, such that, in the

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early 1920s, 1500 troops had to be stationed in Derry, a city of only some 40,000 people. As everywhere at this time, life was hard, but it was particularly difficult in Northern Ireland. Unemployment was widespread throughout the country and one imagines that the security of a senior role in the Post Office was very attractive. Alderman Bradley, aware of the plight of others, voluntarily ran a savings scheme, making weekly collections so as to build up credits to enable the poor to have funds available for Christmas and other special occasions.

Dan’s father, John Columba Bradley, who was one of five children, also joined the Post Office, after completing his schooling at St Columb’s College. During the First World War, he volunteered for the Royal Engineers and was seriously injured at the Somme while laying communication cables over a bridge. He was evacuated to St Helens in Lancashire and his mother was given travel tickets to attend the hospital there, owing to concern that he might not survive. Two of his four sisters subsequently died in the Spanish flu epidemic.

Dan’s mother, Margaret, was of farming stock, one of ten daughters born to Daniel Keating near Cashel in Tipperary, who had moved to Derry in the 1920s to seek employment. Dan himself was one of four surviving children, with an elder sister, Elizabeth, and two younger brothers, John and Patrick. A second sister, born immediately after Dan, died as a result of a measles epidemic, an unfortunately common occurrence in the 1930s in Ireland. The family home was in Ewing Street, once again on the south side of the city, near the river.

Throughout Dan’s later school years, during the Second World War, Lough Foyle, with its natural harbour and easily protected narrow entrance, was to play a major role as the base for the vital Atlantic convoy escorts. Base One Europe, later renamed US Naval Operating Base Londonderry, was the main American convoy base in Europe and the largest in the British Isles. Centred at Lisahally, it had been constructed using American ‘civilian technicians’ six months before America’s entry into the war in December 1941. There were also numerous camps at Springtown, Creevagh and Clooney, as well as the air field at Eglinton and others nearby, and the Royal Naval base, HMS Ferret. As a consequence, the population of Derry multiplied with the influx of Americans, Canadians, Free French and other allies. The additional strategic positioning of the city – its closeness to the border of neutral Ireland – gave rise to an active and lucrative smuggling trade. As rationing did not exist in neutral Ireland, meat, dairy produce and other foodstuffs became widely available, as required, at a price. Venturing into Donegal by bicycle with his father, Dan would often return with butter and tea for the family. The demand for fresh food also inspired him into his first – more legal – entrepreneurship, organizing a cooperative that sold the produce grown on local allotments and in neighbourhood gardens to the large US bases.

In 1943 and 1944 Dan undertook the Technical School Examinations in Electrical Engineering. He obtained a pass in the first year and a distinction in the second year. He was always keen to point out to his research students, the majority of whom were physicists, that he had actually obtained this qualification in engineering. However, he never revealed that he had not completed the third year of the course! Dan had instead entered the communications industry, obtaining a temporary job as a telegraph boy, a precursor to following the family line into the Post Office. Entry was contingent on passing the clerkship examination but the results were not favourable and the 1945 academic year saw him enrolled instead as a pupil at St Columb’s College, then on Bishop Street in the building that is now the home of Lumen Christi High School, near to the family home. His father used to say, later, that Dan was not smart enough to be a postal clerk but was stupid enough to be a professor of physics! Perhaps the distractions of his entrepreneurial activities had played a role, but by the summer
of 1945 the academic focus had returned and he duly obtained his Secondary School Senior Certificate, with passes in Irish (Subsidiary), algebra and trigonometry, a credit in Irish (Main) and distinctions in English, geography, maths, additional maths, chemistry and art (Group II). Quite surprisingly, Dan had not studied physics and he had taken art as the alternative. Such grades met the requirement for the award of a university scholarship; however, the scholarship did not cover all the costs and for financial reasons Dan was therefore unable to take up a place at the Queen’s University in Belfast. Better news arrived in September 1945, when he was informed by the Minister of Education for Northern Ireland that, following a successful interview, he had been awarded a King’s Scholarship that would provide the financial support to allow him to enrol later that month at St Mary’s Teacher Training College on the Falls Road in Belfast.

Teacher training was a two-year programme at St Mary’s; in 1947, aged 19, Dan left with a qualification permitting him to teach in public elementary (primary) schools or the preparatory department of secondary schools in Northern Ireland. He obtained an overall Outstanding Merit in his teaching certification and, in addition to excelling in the practice and methods of teaching – an area where he would later come into his own – he shone in mathematics and woodwork. Dan had very good hands and later showed great empathy for the engineering aspects and, in particular, the construction of scientific instrumentation. In contrast, it should be no surprise to those who knew him that the practical and theoretical aspects of physical education were his least favoured subjects.

On graduation, Dan immediately returned to Derry, where between 1947 and 1953 he taught at primary school level. His first post was in the Long Tower Primary School on the fringes of the Bogside. The school was noted for its tough pupils and shortly after he arrived the headmaster asked him to take over a class of older boys whom the incumbent teacher found too difficult to control; Dan was able to handle the situation. He enjoyed various activities outside teaching, including tennis, fishing, rowing, debating and chess. His tennis was played at a club that was noted for an all-white tennis clothing policy but Dan insisted on wearing black socks, a forerunner perhaps of turning up to his son Ronan’s wedding in a pair of bright red socks that were spectacularly revealed in the (seated) wedding photos.

During this period Dan also registered with the University of London and studied privately part-time for a BSc special degree in Mathematics, which was awarded in 1953. While in Derry, he also put his mathematical skills to good use in financially beneficial extracurricular activity. Football pools were in operation, but were very local in nature compared to their subsequent nationwide successors. The problem in Derry was that the organizers of the scheme were very slow in determining the winners, who were quite often not informed of their success until late on the Monday following the Saturday matches. Dan was asked to assist and, with his mathematical approach based on the possible permutations, had the winning results out to the local punters by Saturday evening.

With his BSc qualification in mathematics Dan could teach at secondary level, which he duly did, moving to London, where he acted as a supply teacher in various schools throughout the capital, initially teaching science and mathematics at an independent grammar school. In July 1955, at which time he was teaching at the Henry Compton School (now Fulham College Boys’ School), he received notification from the London County Council that he had satisfactorily completed his probation and was appointed as an assistant teacher by the Council. Although he had been in London since 1953, when he was 25, he had not been liable for National Service (as were most males under 26), since he had not been resident for
the obligatory two years and National Service was not compulsory for residents of Northern Ireland.

Teaching in London allowed Dan the opportunity to apply to Birkbeck College to study for the BSc Special Physics degree. The application process was well underway by September 1953. In a letter sent to the Bradley home in Ewing Street, which appears to have been a second follow-up on Dan's enquiry about taking the course, the Registrar Douglas Dakin, somewhat frustratedly enquired, 'Have you done any Physics?' He requested that Dan confirm whether he had studied physics up to Intermediate standard (equivalent to a low A-level) and pointed out that, if not, he would have to spend the first year of the Special Physics course doing only Intermediate Physics. It is not known whether Dan ever replied to this or if his first year was spent doing the Intermediate module. We do, of course, know that at that time he had never studied physics at any level; however, by October 1953 he had commenced the Special Physics degree. He was a Ravenscroft Exhibitioner from 1954 to 1957 and a College Exhibitioner in 1956, clearly indicating meritorious performance.

The first part of the course was undertaken part-time while Dan taught at various schools in London, eventually teaching mathematics up to Cambridge Scholarship level. However, the last five terms of the course were full time and in 1956 Dan was also the student president of Connaught Hall, a London University Inter-collegiate Men's Hall of Residence. He completed Part I of the course in June 1955 but was prevented from carrying out Part II in 1956 because of illness. Like many in the UK in the 1950s, Dan contracted tuberculosis and was hospitalized, albeit on a scholars' ward where attempts were made to continue with his education. The following year he completed Part II, carrying out a research project to investigate the A line (39.85 kev) of thorium using a high-resolution β-ray spectroscope. He undertook a further project on spherical aberration patterns of an optical system of fourfold symmetry, specifically crossed cylinders, the results of which he submitted for publication some five years later. Not only did Dan graduate with first class honours but he did so at the top of the class in the overall University of London examinations. John Enderby, later Physical Sciences Secretary of the Royal Society, was in second place.

ROYAL HOLLOWAY COLLEGE AND PhD STUDIES

With an eye to postgraduate research and a PhD, Dan had applied to Royal Holloway College for an assistant lecturer's post just before the completion of his Part II studies. He had asked the then Master of Birkbeck College, Professor John F. Lockwood, to act as a referee on his behalf. At that stage, he had little indication that Lockwood would have further indirect influence on his future career decisions, as the author of the somewhat infamous Lockwood Report, published in February 1965 on the future of higher education in Northern Ireland, which primarily dealt with the timing, nature and location of a second university in the province. By early July, Dan had received the offer of an assistant lectureship in Physics, from the then Principal of Royal Holloway College, Edith C. Batho, conditional on him satisfactorily passing his Part II, though Batho added that she knew this would not be a problem. Dan commenced on a salary of £700 per annum on a one-year contract in the first instance, but renewable annually for up to four years.

The decision to accept the offer from Royal Holloway College was to shape Dan's future life in more than science. It was there that he met Winefride O'Connor, a botany graduate from
Liverpool University in 1951 who had joined Royal Holloway College as an assistant lecturer in 1955, having been a research student and research fellow at Liverpool. Dan and Winefride married in 1958. They had five children, Sean born in 1959, Mairead in 1960, Donal in 1962, Ronan in 1965 and Martin in 1972.

Dan’s supervisor for his PhD studies was Professor Sam Tolansky FRS. Tolansky had been appointed to a chair in physics at Royal Holloway College in 1947, holding it until his death in 1973. He was distinguished for his experimental contributions to the measurement of the fine structure of spectral lines, with particular relevance to the determination of nuclear spin. Dan’s chosen area of research was the application of the Fabry–Perot etalon for high-resolution spectral measurement, specifically the design and application of a new type of Fabry–Perot – a rapidly scanning device. Early manifestations of the Fabry–Perot were effectively fixed-gap, consisting of a transparent plate with highly parallel and highly reflecting surfaces (an etalon) or with two highly reflecting mirrors placed parallel with an air spacing (an interferometer) which had a fixed-gap dimension varying in range from microns to many centimetres. The transmission of the device is a function of the wavelength of light, exhibiting transmissive spectral peaks produced by optical path interference as the light resonates between the reflecting surfaces. A circular interference pattern is observed, which is generally recorded photographically, and in which the spectral coverage or free spectral range (FSR) between transmission peaks is a function of the wavelength $\lambda$ and plate separation $d$ (FSR= $\lambda^2/2nd$, where $n$ is the refractive index of the medium between the reflective plates), while the spectral resolution is dependent on the reflectivity of the mirror set (the finesse), improving as the reflectivity increases.

When Dan joined Holloway in 1957, however, Tolansky had suggested a totally different project, which Dan alluded to in 1977 when he gave the Tolansky Memorial Lecture to the Royal Society of Arts. He had proposed that Dan repeat an experiment that he had previously carried out – where he had placed a long-gap Fabry–Perot interferometer inside a vacuum chamber and had pumped out the chamber until it was possible to excite a discharge in the space between the plates. Tolansky had previously noticed that there was a strong enhancement in the intensity of the radiation emitted by the discharge as a result of the placement within the Fabry–Perot. This, of course, could have been interpreted as a simple nitrogen laser resonator, which operates in the pulsed regime. In their classic paper of 1958, Schawlow and Townes proposed both solid state and alkali vapour as potential laser media but it was not until 1963 (Mathias and Parker) that a pulsed molecular nitrogen laser was demonstrated. Dan told the audience at the Tolansky Lecture that he went as far as to have an experimental chamber constructed, but was distracted by his work on the design and construction of the rapid-scanning Fabry–Perot. This was probably a good call by him, as, with relatively short gain length and under continuous wave (cw) excitation, any potential laser action would have been practically impossible. It did however illustrate the ‘feel’ that Dan had for picking the right and more fruitful research topic, which he was to demonstrate throughout his career, much to the amazement and frustration of his colleagues and competitors respectively.

In the late 1950s there had been a flurry of activity in scanning techniques for Fabry–Perot interferometers in order to add versatility and to simplify the recording of spectra. Many of these approaches were slow, cumbersome and resulted in reduced finesse and resolution. The techniques had employed manual micrometer screw motion, pressure and temperature scanning, as well as early investigations of piezo scanning, which is now quite extensively
deployed. Dan developed a simple mechanical oscillation scheme, where one plate of the interferometer was fixed and the other moved. The moving plate was mounted on a brass tube that moved parallel to itself on springs. Although a similar scheme had been previously used by others (Gobert 1958), the Bradley system exhibited superior finesse, resolution and scanning rate. This was another trait that Dan exhibited: he could pick something that another researcher had introduced and make changes that immediately improved the performance and impact. In addition, photomultiplier detection was utilized, enhancing the linearity and sensitivity and, with the potential of scanning rates of up to 1 kHz, the output could be displayed directly on an oscilloscope. The initial performance of the device was first reported by Dan in a joint paper with Tolansky, ‘An oscillating Fabry–Perot interferometer’ (1)*, at the Symposium on Interferometry held at the National Physical Laboratory in June 1959. The lineshape of the 546.1 nm emission of a mercury lamp was recorded directly and, on application of a magnetic field of about 1500 Oersteds, the Zeeman splitting of the line was clearly resolvable and stably displayed.

Dan submitted his thesis, ‘A high resolution interference spectroscope’, in August 1961, presenting a comprehensive theoretical and experimental review of the device. He also pointed to the potential applications in the ultraviolet with an appropriate change in the reflective coatings and noted that, with remote control of the robust oscillating mechanism, possible application to earth satellite observations could be undertaken with a miniaturized version. By the time of his single-author paper in the Proceedings of the Royal Society in 1961, which essentially summarized the highlights of the thesis (2), Dan had already been appointed to a lectureship at Imperial College.

**Imperial College lectureship and Royal Holloway College readership**

Dan joined the Instrument Technology Group (later renamed the Applied Physics Group) at Imperial College, headed by Professor J. D. McGee FRSE, who was internationally renowned for his seminal work in the field of photoelectronics, in particular the development of the Emitron, a result of his research on television camera tubes in the 1930s. In the 1960s and 1970s the group’s development of the cascaded image intensifier also found wide application in astronomical detection.

In his first year at Imperial, Dan submitted six single-author papers primarily on the development and application of the scanning Fabry–Perot, as well as publishing the results of the Part II research project that he had carried out at Birkbeck on spherical aberration diffraction of crossed cylinders. However, 1960 had heralded the laser era, with Maiman’s report of laser action in a pulsed, flashlamp-pumped ruby, and by the end of 1961 McClung and Hellwarth introduced the concept of the Q-switched or Q-spoiled laser, which allowed the controlled generation of high peak powers in pulses of only a few nanoseconds (McClung and Hellwarth 1962). Dan was quick to see the limitation of the scanning Fabry–Perot both in the diagnosis of the dynamic spectral emission of these high peak power Q-switched lasers and also in the spectral characterization of the plasmas they generated on interaction with different target materials. The problem with the scanning Fabry–Perot was that the temporal

* Numbers in this form refer to the bibliography at the end of the text.
and wavelength dispersions were superimposed on the swept image while, irrespectively, the operational scanning rates (\(\sim 1\) kHz) were orders of magnitude too low to resolve time scales of the order of nanoseconds. Dan clearly took early advantage of the expertise in image intensifiers in the Instrument Technology Group by replacing the scanning Fabry–Perot with a fixed-plate device and using electron-optical scanning of the full Fabry–Perot ring interferogram by varying the current in the coils in a magnetically focused single-stage image intensifier (3). Expanding upon the technique, he directly demonstrated the possibility of simultaneous temporal, spatial and spectral resolution of plasma and laser sources (5).

Imperial also gave Dan his first opportunity to supervise postgraduate research students. His first two students, Brian Bates and Sampanna (Shum) Majumdar, helped him extend his research interests to interference spectroscopy in the ultraviolet and to time-resolved electro-optical imaging respectively. Brian and Shum continued their collaborations with Dan long after receipt of their PhD degrees in 1966, moving subsequently with him to Royal Holloway College and then on to the Queen’s University of Belfast. Dan also availed himself of the high-level technological skills in the group at Imperial in the manufacture of image tubes and cascaded image intensifiers. He established a long-term collaboration with Fred Barlow, who later, as the head of Instrument Technology Limited (ITL), worked closely with Dan in the development of the Photochron series of image tubes deployed in pulsed streak cameras that were to exhibit picosecond temporal resolution.

Dan’s research at Imperial could be divided into three principal themes. The first centred on the development of image intensifiers for ultrafast, time-resolved spectroscopy of lasers, for plasma sources and for ultraviolet spectroscopy for space research. The second was the continuation of his broad research interest in Fabry–Perot interferometry, with the programme extended to investigate ultraviolet interference filters and new, efficient, highly reflecting coatings that would allow operation of Fabry–Perot devices in the vacuum ultraviolet. The third centred on how the superior angular dispersion of the Fabry–Perot interferometer and its large gain in luminosity over grating dispersers made it attractive for astronomical spectroscopy from space vehicles. Consequently, Dan initiated a programme in high-resolution solar and stellar spectroscopy to be undertaken from balloons and rockets. He gave invited talks, both nationally and internationally, on all these areas during the four years at Imperial.

In the very early 1960s in the UK, access to lasers was somewhat limited. There were some commercial ruby lasers available, primarily in government laboratories; generally, however, systems had to be home-built, but there was none in the Instrument Technology Group at Imperial. In order to develop his ideas on time-resolved spectral progression in giant-pulse lasers and to characterize them for their suitability as a source for plasma light-scattering application, Dan therefore had to initiate a collaboration with researchers at the UK Atomic Energy Authority (UKAEA) Culham Laboratory, where he had access to one of the first commercial lasers, a Triton Instruments LS-4 ruby laser which was Q-switched using an intra-cavity Kerr cell, generating pulses of about 40 ns. Using various fixed, wide-gap (2–4 cm) Fabry–Perots, he recorded the interference fringes on infrared sensitive film using a framing camera and demonstrated unequivocally and for the first time that the spectral output consisted of several longitudinal modes (4). In development, Dan and his colleagues added electron-optical image detection which could be gated or mechanically swept, but all in-house optimization and characterization were undertaken using conventional mercury lamp sources.
In 1964, Dan was promoted to a University Readership in Experimental Physics at Royal Holloway College, where he moved with students and postdoctoral research assistants and expanded his group. Importantly, at that time he acquired the components for a Q-switched ruby laser system that was built by his postdoctoral research assistant Mike Key, who had originally joined Dan’s group at Imperial College from the Plasma Physics Group. The laser was used in studies of gas breakdown plasmas, which were imaged using a nanosecond electronic framing camera.

At Royal Holloway, Dan also carried out studies of laser-induced optical damage in diamond sheets, looking at surface and bulk damage using a range of peak powers from both giant-pulse and relaxation oscillation pulsed ruby lasers (6). In addition, he investigated self-optical damage in ruby rods, Q-switched using organic dye saturable absorbers, where quasi-mode-locked behaviour led to high peak powers and associated self-focusing, causing permanent damage. In the early days of pulsed and amplified lasers, self-damage was a common occurrence; this was before the shaping of spatial and temporal inhomogeneity that led to self-focusing was fully understood and controlled. Dan also maintained his collaboration with UKAEA Culham, continuing investigations of ruby laser axial mode structure using Fabry–Perots. Over a few years, a comprehensive spectroscopic study of the behaviour of the pulsed ruby laser was carried out, including the detection of single transverse modes of a gain switched system, studies of the intensity-dependent frequency shift, and the characterization of single and multimode pulsed lasers (7, 8), with Dan thus establishing an international reputation in the diagnosis of the ruby laser and its application. As a result, he was appointed as a visiting consultant to the Materials Sciences Centre at the Massachusetts Institute of Technology to advise on the optics of laser light scattering, and he was widely recognized for his expertise in the science and application of the Fabry–Perot interferometer, extending the capability of the device.

Dan had pointed out that, on slightly defocusing a spherical Fabry–Perot by reducing the mirror separation by an appropriate amount from the precise radius of curvature spacing, the resulting fringe pattern had a nearly linear wavenumber dispersion over a considerable annular region outside the central axial fringe and as such was widely applicable to high-resolution spectroscopy, in particular lasers and laser-induced plasma emission (10). Studies of high-resolution interference spectroscopy of solar magnesium II resonance lines from rockets were also extended. In this area, as well as Dan’s improvements made in the optical coatings used for extension to the mid ultraviolet, considerable advance was made by him in the design of fixed narrow-gap Fabry–Perots for space vehicle application. He utilized a novel optically contacted construction (9). A Fabry–Perot acts as a high-performance filter. Simply by rotation of the device, one of the many transmission maxima can be selected. If a wide free spectral range is required, this means that a gap thickness of only 100 microns or less is needed. Such a single polished-glass construction is simply too fragile to handle, to obtain the necessary flatness and to coat. Dan conceived the idea of an optically contacted assembly (with surfaces better than λ/50), where two plates were separated by precisely optically polished and contacted spacers, which were relatively thick. A third element optically contacted to one of the main plates with a thickness approaching that of the spacers allowed narrow-gap devices to be readily constructed from materials of dimensions that were easily workable, with reflection surfaces better than λ/150. These optically contacted Fabry–Perots had the advantage of stability and were robust, as was clearly demonstrated in their application to solar spectroscopy from rockets and balloons. As Dan was later to show, they also played an
important role as the interferometric tuning device in broad-band lasers (19), in both scientific and commercial applications.

With a growing research group and an increasing reputation in laser diagnostics, solar spectroscopy and electron-optical imaging, Dan was ready for his next challenge – one that was to establish his reputation as a true international leader in lasers and ultrafast electron-optical technology.

THE QUEEN’S UNIVERSITY OF BELFAST YEARS

In 1966, Professor K. G. Emeléus, who had been Head of Department and Professor of Physics since 1933 at the Queen’s University of Belfast, retired. Although a new Physics Department building had been designed by John McGeogh in 1955 and work on the construction had commenced by 1958, it was not officially opened until 1962. Set on the corner of the main campus of the university adjacent to the Botanic Gardens, the red brick, four-storey building, with its impressive tower and spiral staircase entrance, had superb laboratory and office space, but the potential of the support facility and the Department had yet to be exploited. This was to change dramatically when Dan was appointed Professor and Head of Department in October 1966 in place of the departing Emeléus.

Dan arrived with his group of postgraduate students and postdoctoral research assistants. In addition, lecturing appointments were made in the laser area. Mike Key, who had a PhD in plasma physics from Imperial and who had been a post-doc with Dan at Imperial and Royal Holloway, was one of the first appointed. In 1967, Geoff New, who had just completed a PhD at Oxford with Professor John Ward and had carried out measurements of non-linear coefficients in crystals as well as reporting the first observations of third harmonic generation in gases, was also appointed to a lectureship. In addition, Dan enlisted extensive technical support. He recruited Roy Morrison, a highly skilled optics technician who had worked at Royal Holloway. Dan was well aware that, in those early days of laser technology, practically all the equipment had to be home-built and that access to in-house skills such as machining of elliptical cavity heads, polishing of laser rods, mirror substrates and manufacturing optically contacted Fabry–Perots to exacting accuracy would give him an unrivalled advantage in the race to improve laser capability. Consequently, the support facilities within the Department received his full attention and he also ensured that all students and post-docs realized and appreciated the vital role that the mechanical workshop technicians, research officers, electronics technicians, chemical laboratory technicians and photographic unit played in the underpinning of the research output and the overall success of the group. Dan was very practical and had a keen appreciation for manual construction, possibly arising from his woodworking days at teacher training college; he thus had a real empathy with those who designed and built the bespoke equipment, and a unique rapport developed between him and the large body of highly skilled and innovative technicians.

In order to fuel the expansion of the research group it was important to recruit postgraduate students. Like most universities in the 1960s, Queen’s University had seen student numbers expand considerably. In addition, students from Northern Ireland tended to go to the local university, while students from the UK mainland also found Belfast attractive, as, although some civil unrest had commenced by 1966, the so-called ‘Troubles’ were still a few years away. As an experienced teacher, Dan knew that lecturing final-year undergraduates was an
assured recruitment route and he taught several courses, including Electromagnetic Radiation: Applications of Quantum Mechanics and Laser Physics, and Non-linear Optics. Many of those who sat through those lectures were simply inspired by Dan’s relaxed approach – making everything seem so simple, clear and exciting, and emphasizing that this new field was so applicable and would underpin everything from communications and entertainment to medicine and defence. How right he was. Most certainly Dan’s lecturing abilities owed a lot to his earlier teaching experience. Lectures were always pitched at the perfect level and pace, and postgraduate numbers in the laser group swelled. Undergraduate recruitment was also targeted and Dan participated in the first major Science Fair to be held in Northern Ireland, which took place at Queen’s in September 1967. An open-house policy allowed up to 4000 attendees to wander around the various departments and research groups, where it was reported that Dan gave a particularly impressive demonstration of the electrical breakdown in air that resulted from a focused Q-switched laser output. Obviously there were no health and safety issues to deal with then, but Dan clearly knew how to impress a young audience and leave his mark on them, once again a definite legacy from his teaching days.

Throughout his time at Queen’s, Dan maintained a steady published research output on improvements and applications of Fabry–Perots. His interests were primarily directed towards the spectral diagnostics of the Q-switched laser, which was becoming somewhat routine, and towards studies of the Solar MgII doublet obtained in rocket flights. In 1965 and 1966, however, two developments in laser physics were to occupy his interests, resulting in him redirecting the major part of his research programmes and leading to a decade and more of international dominance and innovation. The technique of passive mode locking of the ruby laser was reported by Mocker and Collins in 1965 and this was followed the next year by the passive mode locking of the neodymium–glass laser by de Maria et al. A cell of organic dye solution placed in the laser cavity acted as a saturable absorber, an intensity-dependent light gate, in which low-intensity fluctuations were absorbed while high-intensity spikes were preferentially transmitted. This loss introduced to the cavity was periodic, occurring at the round trip time of the cavity as the radiation circulated. This periodicity passively locked the modes of the cavity in synchronism, such that, with a fixed phase between them, the temporal output was nominally the inverse of the lasing bandwidth, although other perturbations in the cavity such as dispersion generally prevented such transform-limited operation initially.

The other major discovery to affect Dan’s research was that of laser action in dyes, which resulted from studies of the intensity-dependent transmission properties of saturable absorbers themselves, which were primarily organic species dissolved in various organic liquids. Sorokin and Lankard (1966) first reported laser operation in the dye chloro-aluminium phthalocyanine, which is really an organometallic compound, but the spectral emission arises from the organic moiety. This was once again rapidly followed by the Schäfer group’s report of laser action in a true organic dye, 3,3’-diethyltricarbocyanine bromide (Schäfer et al. 1966).

Dan quickly realized the importance of these two major achievements: the organic dye laser would allow wavelength selectivity throughout the complete visible spectrum; and by adding wavelength selective filters, Fabry–Perots and gratings, narrow-line tuneability would be achieved to provide a remarkable and unprecedented spectroscopic tool. Additionally, the gain bandwidth of an individual organic dye was large (≥50 nm), quite capable of supporting pulses of ≤12 s around 600 nm.

This work led on to a further question: how, once generated, were such short pulses – the shortest events produced by man at the time – going to be measured? The Bradley group made
Daniel Joseph Bradley

an initial attempt by undertaking the first experiments on the synchronous pumping and mode locking of a transverse-pumped dye laser using a mode-locked ruby laser, which required the precise matching of the pump and slave dye laser cavities to achieve mode-locked output (11). Dan also inserted a Fabry–Perot into a dye laser that was longitudinally pumped by a Q-switched ruby laser, with the dye laser cavity formed by an eschelle diffraction grating and a conventional dielectric mirror reflecting over the gain bandwidth of the dye to allow the generation of 2 MW pulses that were tuneable over 10 nm with a linewidth of less than 0.05 nm (12).

In the first reports of passively mode-locked solid state lasers, the saturable absorber was placed in a dye cuvette simply located within the laser cavity. Dan realized that the positioning of the saturable loss was vital in the pulse formation mechanism, and in a very simple initial assessment one can see that in a linear cavity the saturating pulse encounters the saturable loss twice per round trip, leading to excess loss that will affect the mode-locked laser efficiency. Dan began a comprehensive programme of research into the generation and measurement of picosecond pulses and sub-picosecond structure in pulses from mode-locked ruby and neodymium lasers. One of the most influential innovations and discoveries in a theoretical and experimental study was that mode-locked performance and reliability, in terms of pulse energy and the minimum pulse durations achieved, occurred when thin dye cells (less than 100 μm) were placed in contact with the high-reflecting cavity mirror (14). Qualitatively, the improvement can be visualized by noting that, as the pulse saturates the absorber, it reflects off the mirror, setting up a standing wave pattern. Where nodes exist, there is no electric field and hence no absorption, while the antinodes saturate the transmission and minimize the loss. A short dye-cell length also enables interaction well within the recovery time of the saturable absorber, which is typically in the range of ten to a few hundred picoseconds. The stability and reproducibility of the mode locking ensured the rapid adoption of the contacted dye cell in mode-locked laser systems. Although fixed-gap cells were ultimately used, it should be noted that beautifully engineered, high-precision, variable-gap cells incorporating dye-contacted mirrors were designed and produced in the workshops at Queen’s for the initial optimization studies.

To measure the individual mode-locked pulses, the technique of two-photon fluorescence track photography was used. In this method, a pulse was split into two counter-propagating samples which were made to collide in a cell containing dye which had a ground state (S0) to first excited state (S1) absorption energy that corresponded to twice that of the incident laser photons. After rapid thermalization, fluorescence occurred and this fluorescence was enhanced where the two pulses overlapped in time. Consequently, from a photograph of the fluorescence track and specifically the overlap region, the pulse duration could be inferred. The actual interpretation of the fluorescence profiles was fraught with difficulty and researchers were often wrong or overoptimistic in the evaluation of their generated pulse durations. Dan showed that random phase and amplitude fluctuations in the picosecond pulses generated by mode-locked lasers contributed to this misinterpretation and that often pulses were no more than picosecond envelopes containing sub-picosecond noise structure (15). Reports of femtosecond pulse generation, which generally resulted from the coherence spike of the noise signatures, were subsequently corrected as a result of Dan’s seminal reported work on this.

Dan also discovered quenching effects in two-photon fluorescence (16, 20), which he explained by excited state interactions of the organic dyes employed, for example excited state absorption to non-fluorescing energy levels or to stimulated emission from the S1
fluorescence level, noting that many of the dyes used were conventional laser dyes such as Rhodamine 6G. These processes led to a marked departure of the quadratic dependence of the two-photon fluorescence on intensity. In detailed studies, the two-photon absorption cross-sections of many of the dyes used were characterized and this work definitively explained why experimentalists had difficulty in obtaining the theoretical contrast ratio of 3:1 peak to background signature in two-photon fluorescence measurements. Clearly there had to be a better and more direct technique to measure picosecond pulses and Dan had this underway too, with pulsed streak camera development.

Since his time in Jim McGee’s Instrument Technology Group at Imperial, Dan had maintained a growing interest in ultrafast electron-optic detection. Initially his interest was in gated image tubes for time-resolved spectroscopy in combination with Fabry–Perots. He had extended this into fast imaging of Q-switched laser-produced plasmas and he continued this work at Queen’s, investigating and making improvements on nanosecond-timescale gated imaging and framing tubes. At the 1968 International Quantum Electronics Conference, held in Miami, Dan, who had attended to present a paper on single-frequency dye lasers, had been particularly impressed by Basov’s first report of the observation of neutron emission from a laser-generated plasma employing amplified picosecond pulses from a mode-locked Nd:glass lasers system (Basov et al. 1968). Dan foresaw the absolute necessity of direct picosecond-timescale diagnostics and realized that the electron-optical streak camera could possibly achieve this.

The basic concept of the streak camera is very like a simple, single-sweep early television tube. A picosecond-timescale optical pulse incident on a photocathode produces an instantaneous electron pulse that mimics the optical pulse envelope, which is imaged and accelerated up the image tube, where it encounters a synchronously pulsed, deflecting electric field that sweeps the electron pulse across a phosphor. This directly transfers the time image to a spatial image that can be detected by image intensification and photography. Dan was especially aware of the early work of Zavoisky and Fanchenko, who had proposed that high-speed photography using image converters could achieve temporal resolution of the order of a few tens of femtoseconds. All postgraduate students who joined Dan’s group to carry out research on optical chronoscopy were initially given a copy of Zavoisky and Fanchenko’s 1965 review paper, to ensure that they understood the essential aspects of the technique.

Several factors contribute to the temporal resolution limit of a streak camera. One component, the streak-limited temporal resolution, is essentially the minimum spatial resolution of the image tube divided by the streak velocity, i.e. the time taken to sweep across a resolution element. This can be reduced by improving the imaging quality of the electron lenses and was an active area of research for Dan throughout the Queen’s University years and later at Imperial. Increasing the streak velocity also reduces the streak-limited temporal resolution. In his initial studies, Dan utilized a laser-triggered breakdown in a spark gap to derive the kilovolt deflection voltages that allowed streak velocities of up to $3.5 \times 10^9 \text{ cm s}^{-1}$, but jitter was a problem. In later designs this was replaced by avalanche transistors driving a krytron that allowed reduced jitter operation and 5 kV sweep voltages with deflection velocities in excess of $10^{10} \text{ cm s}^{-1}$. The krytron is a cold-cathode gas-filled four-electrode (anode, cathode, keep-alive and trigger grid) tube, which has a high current capability and fast turn-on time – making it also applicable as a potential trigger of nuclear devices. Zavoisky and Fanchenko had, however, pointed out that the major contribution to the limiting temporal resolution of an image-tube streak camera arose from the transit time spread.
of the photoelectrons in the first stages of the tube. This was caused by the energy spread $\Delta E$ in photoelectrons ejected. As a result of this, by about 1970 the temporal resolution of streak cameras was limited to about 20 ps and they were unable to directly resolve the structure of the few picosecond-timescale pulses being generated by mode-locked solid state lasers.

Dan overcame this limitation by a simple expedient: he modified an English Electric Valve Company P856 image/streak tube by inserting a fine transmissive metal mesh a few millimetres from the photocathode, to which he applied several kilovolts (18). This large field rapidly accelerated the emitted photoelectrons such that the spread in electron energies compared to the mean energy $\Delta E/E$ was insignificant and consequently reduced the transit time spread. Over the years, this configuration was optimized and, with other significant changes to the electron lens and sweep plate design, this eventually led to the direct demonstration of sub-picosecond resolution. It also led to the filing in 1971 of Dan’s first United States patent (no. 3761614), an extremely strong and very successful registration, as this concept was to be deployed in all future families of commercial streak camera tubes.

An important part of the programme in improving the temporal resolution of the single-shot streak camera was the simultaneous development of a reliable and reproducible source of picosecond pulses. Mode locked ruby and neodymium doped silicate-glass systems were generating durations routinely in the 5–20 ps range, while the synchronously pumped dye laser relied upon ultra-precise matching of the pump and slave laser cavity lengths, and the generated pulse durations were comparable to those generated by the solid state systems. With the first reports of the flashlamp-pumped dye laser, Dan was quick to realize that, scientifically, passive mode locking could be achieved using the contacted dye cell (13), that tuneability could be achieved using intra-cavity elements such as the Fabry–Perot etalon, permitting extensive tuneability throughout the complete visible spectrum and that, importantly, such simple devices providing wavelength-selectable picosecond pulses would be commercially attractive.

The group embarked on a comprehensive programme to develop linear flashlamp-pumped dye lasers. This involved all aspects of the device, from flashtube design and optimization to power scaling, laser head construction, power supply construction and studies of the rapid electronic discharges essential for efficient excitation of the organic dyes, which exhibited a relatively short upper-state lifetime, in the order of a few nanoseconds. In the power scaling, work concentrated around the use of ablative wall flashlamps, similar in design to the evacuated Garton tubes used in spectroscopy, which allowed energy dissipation at the kilojoule level. For lower power operation, the group worked in collaboration with commercial manufacturers, putting sealed flashlamps containing xenon typically at a pressure of around 100 Torr through numerous iterations of design optimization and improvement, optimizing the discharge length, tube diameter and ballast region dimensions. Such a comprehensive programme required increased numbers of research personnel and the group expanded rapidly, primarily recruiting postgraduate researchers from the local student population. Figure 1 shows Dan in 1969, centre, with his research group totalling around 80 people, including support staff and an ablative flashlamp-pumped, mode-locked, dye laser, removed from the research laboratory to the undergraduate teaching laboratories for the purposes of the photographic record.

Having established an international reputation as a leader and innovator in the field of pulsed, mode-locked dye lasers, in the four years from 1969 to 1973 Dan carried out a series of investigations that reinforced his group’s reputation as pioneers in the then highly topical
area. Using a streak camera in combination with a Pockels Cell pulse selector, he was able to characterize for the first time the rapid evolution from intra-cavity noise to a single isolated picosecond mode-locked pulse (21). In another series of experiments (22,23), the role of gain saturation in association with saturable absorption as the dominant pulse-shaping mechanism in a mode-locked dye laser (cresyl-violet) was investigated and a direct comparison made with a ruby laser operating at a similar wavelength, where saturable absorption alone was the principal pulse-shaping process. In short, with the low-gain cross-section solid state laser, the ultimate pulse durations were primarily determined by the relaxation time of the saturable absorber employed, while, with the dye laser, the pulse durations obtained were effectively independent of the absorber recovery time, which could be varied by orders of magnitude. In the dye laser, with its large-gain cross-section, gain saturation led to an effective reduction of the rear of the generated pulses, while saturable absorption reduced or removed the front of the pulse and these were the main pulse-shaping processes. In the solid state laser, the saturable absorber recovery time alone effectively defined the generated pulse durations. In pulse formation with the dye laser, it was essential for absorption saturation to take place before gain saturation; hence focusing into the absorber cell was shown to be pivotal in later cw-pumped systems. These crucial experimental findings were formalized theoretically by Geoff New (1974).

Dan also exploited the wavelength tuneability of the dye laser. By incorporating wavelength selective devices intra-cavity and by cascading, for example, several different gap-width
Fabry–Perots, he found that ultra-narrow and single-frequency operation was possible. He utilized this wavelength selectivity and tuneability in numerous spectroscopic investigations, such as the first studies of self-induced transparency in potassium vapour (17) and selective excitation in magnesium. The versatility of the flashlamp-pumped dye laser in operating over extended wavelength ranges, with tuneability and selectable narrow linewidth or alternatively with broad bandwidth and controllable picosecond pulse duration, made it particularly ripe for commercialization.

In reviewing the lasers aspect of the National Physics Exhibition which was held in Alexandra Palace in 1969, Dan drew on the analogy of lasers and children. He pointed out that as the laser entered its second decade it had grown up and was no longer a laboratory toy but was beginning to form the basis of a new and important optoelectronics industry. He did, however, echo Lord Mountbatten’s concern that the United Kingdom did not appear to be entering the field with the vigour and enthusiasm required to ensure that it obtained a fair share of the market, and he complained that the total effort was too small.

In 1970, Dan became a consultant to Electro-Photonics Limited, a small company registered in Shenfield in Essex. As a result of the innovation in pulsed dye laser technology and ultrafast electro-optics measurement systems coming from Dan’s group at Queen’s, the company established large, purpose-built commercial headquarters with extensive laboratory space and manufacturing, with the assistance of the Northern Ireland Development Agency, at the Cutts in Dunmurry, a suburb of Belfast about five miles from the University. The company provided a source of employment for graduates from Dan’s group and a free flow of information and technical knowhow from the university, particularly on flashlamp-pumped dye lasers and the pulsed streak camera, ensured rapid commercial exploitation of the basic research laboratory innovation. Electro-Photonics Limited eventually ceased trading in 1979. By that time, Dan had relocated to Imperial College and the close interplay between the company and the research group had been lost. In addition, the company had failed to package their product to a high commercial standard, with much of it simply looking like what it was: a piece of university-based research equipment. They also failed to take advantage of the advances being made in cw lasers, which were underway in the Bradley group, and to develop new products, although Dan had remained a consultant with the company throughout its lifetime and towards the end had worked tirelessly to find new buyers for the company and prevent it from going into administration.

During the Belfast years, Dan’s reputation internationally was very much in the ascendant and he was widely acknowledged as the leader in ultra-short pulse generation, measurement and applications. This status was best illustrated by the fact that in September 1969, despite escalating civil disorder and terrorist actions in Northern Ireland, the international conference on Non-linear Optics, which Dan and Mike Key organized under the auspices of the Optical Group of the Institute of Physics, attracted more than 250 delegates to Queen’s. The conference was a stunning success, with attendees from more than 15 countries, as reported by the Belfast Telegraph, which also ran a daily update on the week-long conference! More than one third of the papers were presented by American institutions, such as Bell Laboratories, while many of the leading European figures in the laser field were present. Such was Dan’s influence on the importance of this conference that fifteen delegates from the Soviet Union participated, including the maser and laser Nobel Laureates Nikolay Basov and Alexander Prokhorov (see figure 2), who both presented papers. It was remarked that the high academic standard of the conference was also punctuated by exceptional Northern Ireland hospitality.
Dan ensured that an outstanding social programme was also laid on, including a reception
at Stormont, the seat of the Northern Ireland government, while the Conference Dinner held
at Queen’s Elms had the McPeake Family, one of Northern Ireland’s foremost folk groups,
provide a well-received musical interlude.

Not everything, however, was going Dan’s way in 1969, despite his stellar rise, and his
frustration, primarily with science funding in Northern Ireland and to a lesser degree with
Queen’s University, bubbled over in a long letter to the *Belfast Telegraph* on 1 July 1969. Dan
was particularly irked by a statement earlier that week from the Northern Ireland Minister of
Education expressing the hope that local scientists who had emigrated would return to enrich
Northern Ireland’s science base. Dan was quick to point out how ludicrous the statement was
— simply because there was nothing to return to! The Lockwood Report of 1965 had not only
considered the location of a newly proposed university in Northern Ireland but had also had the
remit to make proposals on the future of funding and development of university education in
the province. One recommendation was that a government-supported establishment should be
set up in association with Queen’s University, directed towards research and development. Dan
argued that the blossoming field of lasers and optoelectronics was ripe for this, and reiterated
Lockwood’s point that postgraduate research in universities underpinned and affected
development of industry, such that postgraduate numbers should be increased. He pointed out
that, despite him contributing to more than doubling these numbers at Queen’s and establishing
new postgraduate courses, the promised building expansion had faltered. In the late 1960s, all UK universities were suffering from financial stringency and Queen’s was no exception. Dan, who was always charming and persuasive in his quest for funds, had the support of the Vice-Chancellor, Professor Arthur Vick, a fellow physicist, and buoyed by his scientific successes and burgeoning international recognition had received considerable support from the university. However, he was somewhat irritated by the inability of the university to provide the necessary building to expand his group and underpin future development plans, describing as inadequate the planned extension due for completion in 1972.

In the same letter, Dan pointed out that Northern Ireland had no government research laboratory on the scale either of the National Physical Laboratory or of any of the numerous Ministry of Technology and Atomic Energy laboratories. He had openly discussed the idea of a national laser laboratory being located in the province, to be associated with and to take advantage of the training facilities at Queen’s. He believed that laser fusion had considerable potential but that such a programme was too big an undertaking for a single university laboratory, although he had initially proposed such a project for Queen’s. As a consequence, he had strong hopes that a government facility could be established close to the university site. Some would argue that, in retrospective, the Lockwood Report put an end to such an idea. It has been suggested that the location of the new university at Coleraine contributed substantially to civil unrest, particularly in Derry, where it had long been hoped and proposed that the location of the second university should be. This strife had spilt over the province and, by 1969, civil unrest and terrorist attacks had reached unprecedented levels, which were only to get worse in the 1970s. Along with this unrest vanished any hope of the establishment of a government-supported laser facility. Nevertheless, Dan still maintained the idea for such a facility if not in the same location.

Between 1970 and 1972 there was an explosion in political violence in Northern Ireland. This peaked around 1972, when more than 500 people lost their lives, over half of whom were civilians. With neighbours affected by the violence, Dan became increasingly concerned for the safety of his young family. On the funny side, however, he decided, given that he was travelling extensively to international conferences throughout this period, that a good watch dog would be a sound investment with respect to family safety. Much against the advice of several colleagues in the Physics Department at Queen’s, he decided to get a Kerry Blue Terrier, a breed generally known for their dynamic temperament, exuberance and aggression! Yet when Dan made his mind up, no amount of dissuasion could change it. The dog, however, did not last long. Dan admitted to his initially wary colleagues that, after it had seriously bitten both neighbours and family members, it had to go.

At the end of 1971, Dan had been informed unofficially that Professor David Wright, the Head of the Applied Optics Group at Imperial College, was due to retire in 1973 and it had been suggested to him that he consider applying for the soon-to-be-vacant chair. In January 1972, he wrote to Lord Blackett asking if he would be willing to act as a referee in his formal application for the post, realizing that it would lend enormous credibility. Blackett, who had been the Head of the Department of Physics when Dan had been a lecturer at Imperial, was well aware of Dan’s progress and potential and, after consultation with Paul Matthews FRS, the then Head of Department, he agreed. In March 1972 he wrote in support of Dan to M.A. Baatz, the Registrar at the University of London, expressing his high opinion of Dan and pointing out his remarkable achievements in Belfast in establishing a leading international
laser physics group over such a short period. Dan was subsequently appointed to take up the chair in October 1973.

**The Imperial College Years**

On 12 June 1972, Paul Matthews formally announced internally that Dan would take up the Chair of Applied Optics, in the Physics Department at Imperial College, in October 1973, to enable an expansion in quantum optics and laser physics. This was prior to the opening of the Huxley Building, which was under construction and then designated W2, where it was proposed that much of Dan’s laboratory space would be located. He would initially occupy laboratories becoming available on level 7 of the Physics Department brought about by the retirement of Jim McGee and the phasing out of the Applied Physics effort. Since technical support played a vital part in Dan’s experimental programme it was suggested that he would avail himself of some of the technicians in the Applied Physics group, many of whom he had known from his time as a lecturer in that group.

In the summer of 1972, Dan was one of the principal lecturers at the Science Research Council (SRC) Vacation Course on Lasers and Non-linear Optics held at Swansea University from 17 July to 3 August. Although many of his postgraduate students participated and interacted with postgraduates from Imperial, all were blissfully unaware of the announcement of Dan’s appointment and it was not until September 1972 that Dan officially informed the undeniably surprised members of his group. As Physics at Imperial had somewhat ‘missed the boat’ as regards laser technology, there was no infrastructure to support a major laser development programme. Thus, to ensure a smooth transfer of the research from Queen’s, Dan sent a heavily equipped advance party in January 1973, consisting of five postgraduate students and a postdoctoral research assistant, to set up a suite of laboratories and help establish the infrastructure that was to support the group when he arrived with the remaining members who transferred in October.

Once again, starting from relatively small beginnings, Dan was to build the group at Imperial into one of the leading international groups in the field. Two lectureship appointments were made to support the establishment of the Laser Group: Geoff New, who then concentrated on the theoretical and modelling aspects of ultra-short pulse generation, and Henry Hutchinson, who had obtained his PhD at Queen’s and was a postdoctoral research assistant working with Dan on his new project, direct e-beam pumping of molecular noble gas lasers for vacuum ultraviolet (VUV) generation. Throughout the remainder of his time at Imperial, Dan was to appoint only one other academic staff member to the Laser Group, Dr Wilson Sibbett, as he was well aware of the problems of having too many permanent staff members working in similar research areas but was also mindful of the importance of being seen to operate fairly by the rest of Physics Department.

In 1970, the problems associated with build-up in the triplet state had been negated and the dye laser was demonstrated to operate continuously for the first time by Snavely and colleagues at Kodak laboratories in Rochester. Dan had realized that the passive mode locking of such a system would provide a unique source of high repetition rate pulses that would find wide application in photochemistry, and the group in Belfast had pursued that goal only to be narrowly beaten into second place by Ippen, Shank and Dienes (1972) at Bell Laboratories. At Imperial, the programme continued, and passively, actively and hybridly mode-locked cw dye
Lasers were extensively studied, with the former allowing the first reliable source of pulses of a few hundred femtoseconds to be achieved (26). At various times throughout the 1970s Dan held the record for the shortest pulses generated by a laser.

Improvements carried out after transfer to London in the electron lens design and in the sweep circuitry also allowed pulsed streak cameras to achieve femtosecond timescale resolution (25). However, with the move towards continuously operating mode-locked lasers, Dan concentrated on the development of continuously operating streak cameras driven in synchronism with the cw mode-locked lasers. This so-called family of synchroscan streak cameras (27) was to revolutionize real-time, ultrafast diagnostics. The operation of the synchroscan camera was much the same as that of the single-sweep version, except that the pulses being examined were used to simultaneously derive a sinusoidal signal, initially derived from a tunnel diode oscillator circuit that was amplified to kilovolts and applied to the deflection plates of the camera. This ensured that the signal was swept across the phosphor at the same periodicity as the driving pulses and swept back when no pulse was present, while each sequential swept image was precisely laid on top of the previous one, with picosecond precision. Applicable to all cw mode-locked systems, the accumulative nature of the detection mechanism meant that the cameras were highly sensitive and significantly increased the dynamic range of the device compared to single-sweep systems, while, with improved electronics developed throughout Dan’s Imperial College years, sub-picosecond resolution was achieved. A United States patent (no. 4327285) relating to synchroscan operation was filed by Dan in 1979, adding to his portfolio of streak camera patents. Again, this was a particularly influential patent, and licensing agreements were signed with Instrument Technology Limited, Electro-Photonics Limited, Hamamatsu Limited and Hadland Photonics Limited. At various stages Dan also held consultancies with these companies. The world-leading position of the Bradley group in ultrafast measurement – particularly in synchroscan cameras, in development of new streak camera tube configurations, in reduction of the temporal resolution to the femtosecond regime and in X-ray streak cameras – most certainly influenced the international committee’s decision to locate the XIth International Conference on High-Speed Photography in London, at Imperial College, with Dan as a keynote speaker.

The cw mode-locked laser in combination with the synchroscan streak camera became a powerful tool in the routine measurement of low-level light events, allowing the group to carry out unique and important measurements: investigating the relaxation dynamics of saturable absorbers, carrying out the first real-time measurement of resonant energy transfer between fluorescing and absorbing species (28) and investigating the environmental influence on the fluorescence lifetime of biological probes.

In the first few years at Imperial the group grew rapidly in size to accommodate the expanding research programmes in e-beam excitation of gaseous excimer and exciplex lasers for VUV generation. Pulsed dye laser-amplifier schemes were also developed, generating peak powers in excess of 1 GW (3 mJ in 2 ps) for studies of harmonic generation and frequency mixing in noble gases and alkali metal vapours, primarily for tuneable VUV generation, while a large glass laser system was deployed for XUV generation and the testing of X-ray streak cameras for plasma diagnostics. Dan was also quick to see the potential and application of the mode-locked semiconductor laser and initiated a programme on this in 1978.

As a result of his international leading role in the production, measurement and application of ultra-short pulses, Dan was invited to author numerous review articles in a field that was
making an impact, particularly in its applications. In 1974, along with Geoff New, he published ‘Ultra-short pulse measurements’, a review classic (24). By the mid 1970s, although mode-locking techniques had been deployed for more than a decade and various techniques, both linear and non-linear, had been introduced to measure optical pulses in the picosecond regime, no text book existed on this rapidly expanding area of considerable technological importance. The Bradley–New invited paper was the first to give comprehensive coverage to the physics of short pulse measurement, underpinning the topic for decades and providing the basic material for numerous review articles and research-level text books that followed.

During the early 1970s, Dan was Chairman of the SRC Steering Committee for the Joint Laser Centre. It had become obvious that the scale of laser-driven plasma research, particularly as it related to fusion studies, was beyond the capability of any single university group, both physically and financially, and that a national effort was required. Dan was fully committed to the concept of the national facility, despite the fact that it would be seen to compete for funds with all other aspects of university laser research. While at Queen’s, he had actively promoted Northern Ireland as a suitable location for such a facility but the escalating terrorist activity and political instability undermined any hope of that, with the Rutherford Laboratory eventually emerging as the preferred location. In October 1975, funding of the Central Laser Facility (CLF), with a remit to provide high-power laser facilities for UK-based university research, was approved by the SRC Science Board. Figure 3 shows Dan (second left) at the inauguration of the CLF, along with Professor Alan Gibson FRS, the first head of the CLF, Professor Sam Edwards FRS, the Chairman of the SRC, and Dr Godfrey Stafford FRS, the Director of the Rutherford Appleton Laboratory. Dan fiercely championed the work of the CLF and took considerable pride in the role that he played over several years in bringing the idea to fruition. He subsequently served as Chairman of the SRC Laser Facility Committee (1976–1979) and as a member of the SRC Science Board (1977–1980).
Dan’s role in science administration was to increase further in June 1976, when he formally accepted the invitation of the Rector, Brian Flowers FRS, to become Head of the Department of Physics at Imperial for a five-year period commencing that September. Despite this role, Dan still maintained a relatively high level of contact and an overall control of the on-going research within his group, and it was common for him to wander into the laboratories in the late evening with the question ‘What’s going on?’ This was especially so on those evenings when there was a College function to attend, with him generally filling in the period to the start time perched on a stool in the laboratory, getting up to date with the latest research results and proposing changes and improvements.

In the mid to late 1970s funding was tight, such that expansion and recruitment were severely limited. In particular, UGC funding models restricted senior to junior staff ratios, something that especially irked Dan. He was vociferous in his support for the promotion of junior staff and realized that, in London in particular, it was essential to promote, appoint and retain young blood in all aspects of physics for the future good of the department. Dan of course saw the Physics Department as the premier unit in the College. As the one with the greatest income at that stage, he believed that the Physics Department could and should be treated differently. Notably, he proposed that the limits set on senior to junior staff ratios should be ignored and junior staff should be promoted, while the less affluent departments could restrict their promotions in order that the college-wide ratio was maintained. This, naturally, was met with widespread resentment at the higher levels of College administration and within the other departments. In the late 1970s Dan also attempted to instigate a premature retirement scheme within Physics to encourage senior staff to accept financial inducements to retire and make available senior posts for younger academics. In contrast to Queen’s, where he had experienced widespread support in most aspects of his administration, he was clearly finding Imperial a very different operating system.

Although Dan had arrived at Imperial in October 1973, pressure of work had prevented him from delivering his inaugural lecture immediately. Flowers, who attended these events, had somewhat belatedly proposed that Dan kick off the 1977/8 academic year inaugural lecture series. He had also suggested that Dan break with tradition and, instead of presenting a physics-based lecture, speak on the ‘Management of a large Department of Physics’. The proposed date in October 1977 was once again postponed, with Dan eventually opting for 7 February 1978, but, as in his own words when informing the Rector, he chose the humdrum title ‘Some frontiers in laser physics’. The lecture was in no way humdrum and Dan once again called upon his teacher training experiences, laying on a lecture full of demonstrations and enthralling the audience; the highlight was a live video feed to the lecture theatre from one of his research laboratories of a liquid saturable absorber being poured into the solvent reservoir of a cw dye laser, mode-locking it to produce femtosecond pulses in real time.

Throughout 1979, Dan had become increasingly frustrated by administrative problems, especially those relating to the processes and limits on promotion and appointment of young staff. During that period, too, he had been approached by Brian Henderson, then Head of Department at Trinity College in Dublin, with regard to a new chair of Optical Electronics within the Department of Pure and Applied Physics. Dan of course had a close affinity with Ireland both professionally and personally. For some time he had been assisting the National Board of Science and Technology as an assessor of grant applications and they had approached him to become more actively and directly involved in their activities, with particular emphasis on developing links with European and UK science programmes. He also for many years had
a family holiday home near Ardmore Pier in Cill Chiaráin (Kilkieran), a Gaeltacht area of Galway.

Consequently, on 29 October 1979, after what Dan referred to as a lengthy reappraisal of his plans for when he ceased to be Head of Department at Imperial, in a handwritten letter to Brian Flowers he made formal application to take premature retirement, reiterating his disappointment that fellow senior academics had failed to do so when offered to them. He also stated his firm belief that European scientific collaboration was the only sensible path for the future. He specifically pointed out that in the period of his headship, the younger staff within the Laser Group had effectively been running the group on a day-to-day basis and were successful in bringing in the necessary grant income to sustain the research effort. Dan clearly stated that he now wanted to be more personally involved with research and had formed solid ideas on new research and development areas, but he also wished to be more involved with the public exploitation of science. He suggested April 1981 as a tentative date for retirement, but by February 1980 the Council at Trinity College had received Dan in Dublin and appointed him to the new chair in Optical Electronics, to start in October 1980.

THE TRINITY COLLEGE DUBLIN YEARS

Dan’s plan in establishing a new major research group in Trinity was to address two principal themes: the application of semiconductor laser devices, primarily directed towards optical communications and optical logic; and the application of ultrafast lasers to investigate the dynamics of biological molecular species, in which field he also proposed the broad simultaneous application of synchroscan cameras as a real-time diagnostic – in fact, the only real-time diagnostic, with picosecond resolution. It is interesting to note that, nearly twenty years later, Science Foundation Ireland selected optical communications and the biosciences as the country’s two major development themes and funding avenues. Dan undertook this rebuild and redirection of his research portfolio from small beginnings. Only one postgraduate student had transferred from Imperial and no postdoctoral research assistants. In addition, he left practically all his research equipment at Imperial, although a large proportion of it had been obtained through grants from external research sponsors and overseas agencies.

In his resignation letter to Flowers, Dan had suggested that he could possibly be appointed as a visiting professor in order for both to look after his remaining research students until they had completed their PhD programmes and to continue collaborations with the researchers who remained at Imperial working on projects that he had initiated. In January 1981, he was informed by the University of London that he was to be conferred with the title Emeritus Professor of Optics, in recognition and appreciation of his services to the University and to the subject. Late that month, Ian Butterworth FRS, then Head of Physics at Imperial, contacted John Smith, the College Secretary, requesting that the normal arrangements be followed through and Dan be appointed as a College Senior Research Fellow. To their shame, the Deans did not agree to the Fellowship. In 1991, Tom Kibble FRS as Head of Department also supported Dan’s nomination to a Fellowship of the College, only to be told that the Fellowship Committee did not feel able to recommend the award and that Dan’s name would not be put forward for any future consideration. One can only postulate as to the internal politics of why someone with the international standing and influence that Dan had was not awarded such a Fellowship.
The establishment of the research group in Trinity was difficult. Internally, the funds were simply not available for the laboratory facilities that Dan planned and envisioned and the build-up of the group was initially slow. In order to recruit students, he insisted on teaching in the undergraduate laboratories, where he knew he would come into contact with the complete student population and where his personality, flair and teaching skills would, as it had done in the past, attract potential recruits to his research group. He also procured funds to convert some typical Dublin Georgian houses on Westland Row on the periphery of the Trinity College site into a suite of laboratories. A major achievement was the award of a very substantial British Petroleum Venture Research Grant, aimed at undertaking blue-sky, high-risk research programmes. Dan’s proposal to utilize ultrafast laser technology to investigate reaction pathways and to probe the structure of biomolecules perfectly met such an objective and the proposal ‘Fundamental opto-electronic studies of semiconductors and DNA with ultra-short laser pulses’ was initially funded at the level of IR£150,000. Together with Dr John Kelly, a chemist, and Dr David McConnell, a geneticist, he began establishing a team to carry out this programme. He had a particular interest in using two-photon excitation techniques to analyse base sequences in DNA. This work later led to a very successful broad series of experiments undertaken over many years that were carried out by Kelly and collaborators. Together with other grants and the BP Venture funds, Dan invested in equipping his laboratories and appointing postdoctoral researchers.

In this bid to build and re-establish novel and internationally leading research, it is also no surprise that in 1981 Dan became the Bursar of Trinity College, giving him access to information on College funds and potential internal financing. The botanist Professor W. A. (Bill) Watts, who had become the Provost at Trinity that year, had asked the Board of the College to agree to his nomination of Dan as Bursar. A requirement for the appointment, however, was that the nominee was a Fellow of the College. Consequently, to meet Watts’s request, the immediate assent of the Fellows was required by the Board to elect Dan to a Fellowship. It has been pointed out (Finch 2016) that it is remarkably unusual for such an election not to occur on a Trinity Monday, yet, following the expedited election to Fellowship, Dan was appointed Bursar. The Fellows did voice concerns that there might be undue diversion of Dan’s time from his research activities and he only occupied the post for 18 months as he pursued a punishing schedule to build up his laboratories and re-establish an internationally competitive research reputation in what were new areas for him.

By the end of 1983, the group were publishing on picosecond pulse generation in various semiconductor laser systems and reporting on the effects of ultra-short pulse UV irradiation of DNA (29). Additionally, Dan had sourced funding to appoint several postdoctoral research fellows to accelerate the programmes development. However, on 21 October 1983 he suffered a severe debilitating stroke. One of the recently appointed postdoctoral researchers, Kris Johnson, arrived just days after this tragic event, while another, Lawrence Reekie, was still negotiating his contract. A third, Werner Blau, had arrived just before and was left with the others to work tirelessly in the lab to initiate the novel research programmes.

As a result of the stroke, Dan’s mobility was restricted and his speech was severely impaired; he therefore retired in 1984. He was appointed an Emeritus Fellow of Trinity College and continued to visit the Physics Department, taking an interest in the development of the research within the group he had established. He was a co-author on research outputs until 1986 and participated actively in College life. In 1988, Dr Dan O’Connell, a lecturer in Physics who had interacted closely with Dan, initiated the idea of a conference to honour
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Figure 4. Professor Wilson Sibbett FRS, Dan and Mrs Winefride Bradley, Professor Mikhail Schelev and Professor Geoff New in the grounds of the Europe Hotel in Killarney during the ‘The future of optoelectronics: 1990s and beyond’ conference. (Online version in colour.)

Dan and acknowledge his role in establishing optoelectronics research in Ireland. One of the co-organizers was Dr Aram Mooradian from MIT Lincoln Laboratories, who had been a close friend of Dan for many years. They were joined by Professor John Hegarty, who had been appointed to a Personal Chair in Laser Physics at Trinity in 1986, coming from Bell Laboratories, effectively as an academic replacement for Dan. Hegarty suggested killing two birds with one stone, as he was the leader of a small group of Irish scientists who were planning a national centre for optoelectronics and were trying to convince the Irish Government to provide financial support.

The conference was titled ‘The future of optoelectronics: 1990 and beyond’ and was held for a week commencing on 22 May 1988 at the Europe Hotel, on the shores of the lakes of Killarney, a simply stunning and beautiful setting (see figure 4). The idea was to invite research leaders from academia and industry, specific colleagues of Dan Bradley and key personnel from the Irish Government. The conference was made possible by the exceptionally generous financial support of the Electricity Supply Board of Ireland, the CEO of which, Paddy Moriarty, a visionary who had a deep interest in the future wellbeing of Ireland, was a neighbour of Hegarty’s. The Industrial Development Authority (IDA) and Telecom Eireann also provided financial support. A highlight of the conference was a live video link from Killarney to Stanford University in California, where Professor Tony Siegman gave a tutorial and the participants in Ireland were able to hold a live discussion with him. Naturally,
this impressed the Irish Government delegates, although this was the early days of video-conferencing and such a link was really at the frontier, such that some breakdowns and drop-out were experienced.

The conference was attended by many major international figures, including Professor Bob Byer from Stanford University, Professor Mikhail Schelev from the General Physics Institute, Moscow, Dr Dan Grischkowsky from the IBM Thomas J. Watson Research Centre, Dr Chuck Shank and Dr Herwig Kogelnik of Bell Laboratories, and Professor Wilson Sibbett FRS from St Andrews University. The opening talk was given by Professor Art Schawlow, Nobel Laureate and long-term friend of Dan, who was quoted in the *Irish Times* on 23 May as stating, 'The conference is really a tribute to Dan Bradley, who did so much to set up optoelectronics research'. All the major optoelectronics industrial power players were represented, including Sony, Siemens, Plessey, Thomson SA, Hughes Research, NEC, Naval Research Laboratories and Bell Laboratories. Several attendees were also responsible for remarkable impact on Irish optoelectronics in the short term following the conference. The head of research and development at Hitachi, Dr Takeda, on his first experience of Ireland, was suitably impressed, such that within a year the Hitachi Dublin Laboratory was established. This represented the first significant international corporate investment in research and development in Ireland. Another attendee, Dr Alistair Glass, a friend of Dan’s from Bell Laboratories, ended up back in Ireland in 2000, playing a dominant role in Science Foundation Ireland, the government agency established to fund science and technology at a deep level, which also highlighted biophotonics and optoelectronics as principal themes for development.

Dan was officially honoured at the conference banquet, which was sponsored by the IDA, and it clearly demonstrated the respect and international reputation that he sustained throughout his influential career. Following the conference, the Irish Government decided to support the concept of Optronics Ireland, with research carried out in the following decade in five universities, which also spawned a considerable number of spin-out companies and was unquestionably kick-started by Dan’s optoelectronics programme initiated at Trinity College.

Dan’s independence and spirit, however, did not allow the results of his illness to restrict him and he travelled extensively. He attended numerous national (see figure 5) and international conferences, such as the Conference on Lasers and Electro-Optics, the major conference in the field, in Baltimore in 1989. There he was presented with the C.H. Townes Award, one of the most prestigious awards of the Optical Society of America, in recognition of his pioneering contributions to the fields of non-linear optics, the physics of dye lasers and the generation and detection of ultra-short light pulses.

Dan returned to Imperial College on numerous occasions and in 1993 spent time working with members of the Biophysics Group but primarily with an ex-colleague of the Laser Group, Dr John Vukusic, in an effort to develop a computer-assisted speech synthesis and recognition system to assist in Dan’s communication. During these visits to Imperial, after lunch, Dan often enjoyed a walk into Kensington Gardens and in particular on the path that led to the imposing bronze statue *Physical Energy* by George Frederick Watts. Watts had stated that the statue was ‘a symbol of that restless physical impulse to seek the still unachieved in the domain of physical things’ – how appropriate – and Dan always tried to communicate and demonstrate his admiration for this striking piece. Through time, however, the ravages of his illness restricted his travelling and eventually he was cared for in a residential home in Dublin, where he passed away in February 2010.
Figure 5. At the 9th National Quantum Electronics Conference, held in Oxford, September 1989. Dan (front centre) with ex-colleagues and past students. Back row: Professor W. Sibbett FRS (St Andrews University), Professor T. Glynn (University of Galway), Dr R. Manning (British Telecom Research Laboratories) and Roy Taylor (Imperial College). Middle row: Professor M. Key (Central Laser Facility), Professor T. Morrow (Queen’s University of Belfast) and Dr A. Roddie (National Physical Laboratory). Front row: Professor G. H. C. New (Imperial College), Dr I. Duncan (Queen’s University of Belfast), Professor P. Ewart (University of Oxford), Dr H. Koetser (Halbo Optics) and Dr S. Adrain (Central Electricity Generating Board). (Online version in colour.)

**Dan Bradley’s legacy**

In what has been described by many as a relatively short but stellar career, Dan published approximately 160 papers and co-authored about 200 conference presentations. Apart from the major honours listed below, he was also an elected Fellow of the Institute of Electronic and Electrical Engineers (IEEE), the Optical Society of America (OSA) and the Institute of Physics (InstP). In addition, he was a member of the Royal Irish Academy. He presented numerous named lecture series, including the Tyndall Lectures of the Institute of Physics in Ireland and the prestigious Scott Lectures in Physics at the Cavendish Laboratory at the University of Cambridge in 1977. Dan was exceptionally good at drawing analogies and had an unparalleled ability to pull out a good turn of phase to catch the attention. This was demonstrated in the title he gave to the Scott Lecture series, summarizing the three lectures as ‘The laser: a photon dynamo’, comparing the impact, time scales and early scepticism of Faraday’s experiments on electromagnetic induction and Edison’s commissioning of the Pearl Street power station to the underlying discoveries and developments that led to the laser and the vast potential
Daniel Joseph Bradley

it promised. He reused the analogy later that year in presenting the Tolansky Memorial Lecture.

During his career Dan supervised more than 60 PhD students, with the most common assessment by those students being simply ‘an inspiration’. Many of his students and colleagues went on to occupy senior academic positions, leading their own major research efforts, including Wilson Sibbett at St Andrews University, Professor Henry Hutchinson who headed the CLF, Professor Martin Richardson in the Centre for Research and Education in Lasers and Optics, at the University of Florida, Professor Brian Bates at the Queen’s University of Belfast, Professor Paul Ewart at Oxford University, Professor John McInerney at the University of Cork and many more too numerous to mention. It was often asked at international conferences, ‘Why does UK laser research have such a strong Irish connection?’ The answer was quite simple: Dan Bradley. His influence, particularly notable in the field of ultrafast lasers, extends to the present.

Other students, inspired by Dan’s technological vision and entrepreneurial skills, moved into the commercial world, again too numerous to list, but exemplified by Dr Eugene Arthurs, the Executive Director of SPIE, Dr Steve Adrain at CEGB, Dr Harry Koetser, owner and CEO of Halbo Optics, and Dr Bill Sleat, the Managing Director of Electro-Photonics Limited. What made Dan special? As Bill Sleat stated, ‘The remarkable thing about Dan was how quickly he thought of things and so far ahead of others. He could see what to do, implement it and have two modifications done before anyone else even realized what was important.’

An achievement that Dan was particularly proud of was the role he played in the proposal for and establishment of the UK’s CLF. Over the years, this institution has grown in size and in strength, seeing many changes to the principal laser systems deployed, developing into one of the world’s major research centres in the field of laser-driven fusion studies. Through his establishment of three university research centres – two in the UK and one in Ireland – Dan’s influence in laser research and in the application and detection of ultrafast pulses is still strong, particularly at Imperial College, although the time scales have been reduced, as would be expected, by more than three orders of magnitude.

Dan Bradley was an inspirational teacher, an innovative entrepreneur who was one of the first to see and exploit laser technology and a world-leading researcher in the field of ultrafast lasers and applications. His research innovation was underpinned by an exceptional vision of future technological need. In an example of this, in 1969 he was asked to predict what lay ahead in the near future for photonics. He replied:

Lasers would be used ‘in the not too distant future’ to increase radically the speed of computer operations and facilitate faster and cheaper printing of books and newspapers. By the end of the century, lasers could be used to create displays that would show an up-to-the-minute newspaper or colour magazine on the living room wall, activated by a wave of the hand. Photographic cameras could have a ‘crystal layer’ that would allow high-capacity storage of holographic colour images.

Pretty nearly spot on!

Dan is survived by his wife, Winefride, his daughter, Mairead, and his sons, Sean, Donal, Ronan and Martin. Donal, who was admitted to the Fellowship of the Royal Society in 2004, distinguished for his pioneering work on plastic electronics, was also Head of the Department of Physics at Imperial from 2005 to 2008.
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HONOURS AND AWARDS

1975  Thomas Young Medal and Prize of the Institute of Physics
1976  Fellow of the Royal Society
1983  Royal Medal of the Royal Society
1983  DSc Honoris Causa, University of Ulster
1986  DSc Honoris Causa, The Queen's University of Belfast
1989  C.H. Townes Medal of the Optical Society of America
2002  Cunningham Medal of the Royal Irish Academy

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Figure 1 is courtesy of Professor T. Morrow of the Physics Department, the Queen’s University of Belfast, while figures 3 and 4 are courtesy of Professor Mike Key and Professor Geoff New, respectively. The frontispiece was taken by Godfrey Argent in 1977 and is © Godfrey Argent Studio.

AUTHOR PROFILES

James Roy Taylor

James Roy Taylor was born in Carrickfergus, Northern Ireland on 29 April 1949. Educated at Larne Grammar School, he went up to the Queen’s University of Belfast in 1967 to undertake a BSc in physics. There he encountered Dan Bradley, who lectured to him in his third and fourth years of the degree course. It was listening to those lectures and to Dan’s enthusiasm for the then relatively new field of laser physics which inspired him to a future career in lasers and non-linear optics. Obtaining first class honours, he joined Dan’s research group in 1971, at first working on electron lens design of pulsed streak cameras and then on flashlamp-pumped, mode-locked dye lasers and amplifiers. He was one of the advance party who moved to Imperial College in 1973 prior to Dan being appointed to the Chair in Optics. Obtaining his PhD in 1974, he worked in the Technical University of Munich for two years, before returning to Imperial College, where he has remained since. He has been widely recognized internationally for his seminal works on ultra-short pulse generation, fibre lasers and non-linear optics in fibre, in particular through the receipt of the Carl Zeiss Foundation Research...
Award in 1990, the Thomas Young Medal of the Institute of Physics in 2007 and the Rumford Medal of the Royal Society in 2012, for diverse aspects of his broad research programmes.

REFERENCES TO OTHER AUTHORS


**Bibliography**

The following publications are those referred to directly in the text. A full bibliography is available as electronic supplementary material via http://dx.doi.org/10.1098/rsbm.2017.0012, via https://doi.org/10.6084/m9.figshare.c.3792403 or at https://www.imperial.ac.uk/photronics/about-us/history/.


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