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Progress Report
1999 - 2000

Editor: Marie Holmdahl-Svensson

Lund Reports on Atomic Physics
LRAP-270

Division of Atomic Physics
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Introduction

The Division of Atomic Physics, Lund Institute of Technology (LTH), is responsible for basic physics teaching in all engineering disciplines and for specialised teaching in optics, atomic physics, spectroscopy, laser physics and applications of these disciplines. Research activities at the Division are mainly carried out in the fields of basic and applied spectroscopy, largely based on the use of lasers. The Division is also one of nine divisions comprising the Department of Physics, Lund University. Since 1980, biennial progress reports have been issued within the series *Lund Reports on Atomic Physics (LRAP).* Our latest report, covering 1997-98 was *LRAP-244*, preceded by the reports *LRAP-20*, *LRAP-43*, *LRAP-85*, *LRAP-90*, *LRAP-119*, *LRAP-144*, *LRAP-172* and *LRAP-228*. The present report describes the activities of our division during the calendar years 1999 and 2000.

A highlight of the period was the well-deserved promotion to professor of Stefan Andersson-Engels, Lars Engström, Stefan Kröll and Claes-Göran Wahlström. We congratulate them on their promotion.

Research at the Division of Atomic Physics takes place in a multi-disciplinary atmosphere, in which informal collaboration with external scientists and industry forms an important part. The Division is part of the Lund Laser Centre (LLC) which, based on a long informal existence, was officially established at Lund University on March 28, 1995, directly under the Rectorate of Lund University. Other members are the Division of Combustion Physics (Prof. Marcus Aldén), the Division of Atomic Spectroscopy (Profs I. Martinson/Se. Johansson) and the Division of Chemical Physics at the Chemical Centre (Prof. Villy Sundström). The Lund University Medical Laser Centre is also part of the LLC, and two other umbrella organisations, the Combustion Centre and The Centre for Environmental Measurement Techniques are associated members. The Board of the LLC includes members from the Technical, Natural Sciences and Medical Faculties of Lund University. The chairman of the board, Prof. Bengt E.Y. Svensson, is appointed by the vice-chancellor of Lund University as is the director of the LLC, S. Svanberg.

The EC provides funding for visiting researchers to the LLC by European research groups within the Access to Large-Scale Infrastructures Scheme. The Division has benefited considerably from this programme, which has resulted in many joint projects. The LLC is part of a cluster of Large-Scale Infrastructures, which also includes LENS - University of Florence, LOA - Ecole Polytechnique, Palaiseau, the Max-Born Institute, Berlin, the Amsterdam Laser Centre, and ULF-Forth, Heraklion. The interaction with our sister facilities, especially within the FIRE programme for high-power laser development, has also strengthened our European links.

At the High-Power Laser Facility, which is operated by the Division of Atomic Physics, a vigorous research programme is being pursued, co-ordinated by Prof. Claes-Göran Wahlström. The facility was inaugurated at the end of 1992 and the equipment, spearheaded by a multi-terawatt, chirped-pulse amplification titanium-sapphire system, is successively being upgraded. A new grant of sek 5 million, adding to the previous SEK 22 million obtained from the Knut and Alice Wallenberg Foundation, is instrumental in maintaining the facility at the technical frontier. The facility is the main experimental resource for our basic atomic physics research programme, and is also used for applications. High harmonics have been studied extensively. Optimisation of generation with regard to the atomic response and phase-matching has been pursued, and coherence properties have been investigated. Schemes for attosecond pulse formation are being studied. The experimental programme is complemented by theoretical studies on the description of the phenomena, headed by Prof. Anne L´Huillier, who is also coordinating a European research network on attosecond research.

Another aspect of the high-power laser/matter interaction programme is the generation of broadband X-rays by focusing terawatt radiation pulses on rotating solid targets. The properties of the radiation are being studied with regard to spectral content and temporal evolution. Collaboration with the Friedrich Schiller Universtät Jena in the field of hard X-ray crystal spectroscopy, as part of an EC-funded TMR Research Network, has been a valuable aspect. Radiological applications are being investigated, including gated X-ray imaging for suppression of scattered radiation. The temporal behaviour of softer X-ray pulses has been studied with time-resolved X-ray diffraction studies in mind. Dr Jörgen Larsson is heading this programme, which also includes the use of fast synchrotron radiation pulses, for example, at ESRF, Grenoble. A very close link has been established with the MAX-lab facility in Lund.

Extensive research activities concerning time-resolved laser spectroscopy in the VUV and XUV spectral regions have also been pursued. In a ns-pulse set-up, four-wave mixing or Raman shifting is used in the generation process, while a ps system utilizes low-harmonic generation. Rydberg sequences in free atoms have been investigated, as well as resonance lines in atoms and ions, observed by the Hubble Space Telescope. A laser-induced plasma has been used in many experiments to produce atoms and ions, also in metastable states. Rare-earth atoms, refractory atoms and iron are mostly being investigated. During the period it was possible to extend the studies, even to three-fold ionized atoms. XUV spectroscopy has included studies of astrophysically interesting molecular lifetimes and excited-state photo-ionisation experiments on the fundamental atom helium.

Photon echoes are being used for the investigation of relaxation processes in rare-earth-ion-doped crystals at liquid-helium temperatures and are being tested as a means of optical storage and processing. Different all-optical operations are being implemented using photon-echo techniques. This programme, headed by Prof. Stefan Kröll, also includes basic quantum optics studies of photon self-interference.

Applied molecular spectroscopy at the Division of Atomic Physics is headed by Dr Hans Edner, and includes atmospheric remote sensing using differential absorption lidar monitoring of atmospheric pollutants and fluorescence lidar studies of vegetation and historical monuments. Apart from monitoring of industrial effluents, the atmospheric work is focused on geophysical gas emissions from mining, geothermal and volcanic activities. In the summer of 2000, a fourth campaign of seaborne experiments to study Italian volcanic effluents was performed in collaboration with the Italian Research Council. During the last two years, techniques for IR differential absorption lidar have been further developed for hydrocarbon monitoring. Optical parametric oscillator technology is being employed and extensive control and steering systems have been constructed. Diode laser spectroscopy for applied gas monitoring is being pursued with the frequency modulation technique. The available wavelength region has been strongly augmented by the use of blue GaN lasers and by using sum-frequency mixing techniques. A new method for measurements of gases dispersed in strongly scattering media was introduced, allowing concentration, pressure and diffusion studies in previously inaccessible media. Passive IR gas correlation imaging of gas leaks has been developed with spectacular visualisation of, for instance hydrocarbons. Fluoresence lidar studies have been continued with an investigation of the facades of the Parma Cathedral and Baptistry.

The research activities within the Lund University Medical Laser Centre have further developed during the last two years. An important part of the research deals with malignant tumour detection and treatment. A core group consisting of 10 or more physicists and physicians is located together at the Department of Physics, ensuring close and daily interaction. The activity is headed by Prof. Stefan Andersson-Engels (physics) and Dr Katarina Svanberg (medicine). Members of this group also participate in a large number of projects at other departments and clinics. Particularly active clinical departments in this collaboration are Oncology, Dermatology, ENT, Surgery, Urology, Radiology and Pathology at the Lund University Hospital. Fluorescence diagnostics is widely used, while Raman and near-IR spectroscopy are being developed as alternative diagnostic techniques, in particular for cardiovascular diseases. Photodynamic treatment is firmly established in Lund with the treatment of hundreds of tumours. The use of the haem precursor ALA, applied topically to the lesion or administered orally, has meant a breakthrough in the clinical application. Apart form assessing the therapeutical results, fluorescence and Doppler perfusion imaging have been used to gain insight into the processes involved. Advanced equipment for fluorescence and Raman diagnostics as well as for interactive, interstitial tumour treatment are being developed. A project supported by the Swedish Foundation for Strategic Research is particularly focused on the latter aspect. In order to detect deeper lesions we are developing techniques for tissue transillumination. The long-term goal of this research is to achieve an optical mammographic method for screening without the use of ionising radiation. Promising results have been obtained with techniques

varying from terawatt laser-induced, white-light illumination to diode-laser, time-resolved spectroscopy.

Fluorescence and scattering spectroscopy are being employed for the characterisation of paper and pulp in an industrially oriented programme headed by Adjunct Professor Lennart Malmqvist. Optical and laser techniques are also being utilised in another industrial project, in which the insulators for main grid applications are being studied.

In our report series, *Lund Reports on Atomic Physics* (*LRAP*), material which is not published in international journals is presented. The reports include Master´s dissertations, doctoral theses and special investigations. So far, about 265 papers have appeared in this series. At the end of the period covered by this Progress Report the staff of the Division of Atomic Physics totalled 67. It is through the dedicated work of all the research, teaching and support staff that the accomplishments reported here have been made possible.

The Division is responsible for an extensive teaching programme ranging from the basic physics courses in the various branches of the Engineering School, to advanced elective courses, aimed mainly at Engineering Physics students, who constitute the major recruitment base for our research programme. Elective courses, given by the Division include *Atomic and Molecular Spectroscopy, Advanced Optical Techniques, Laser Physics, Optical Quantum Electronics, Non-linear Optics, Tissue Optics, and Multi-spectral imaging.*

We are very grateful for the support of a large number of funding agencies, in particular the European Commission, the Swedish Natural Science Research Council (NFR), the Swedish Research Council for the Engineering Sciences (TFR), the Swedish Foundation for Strategic Research, the Swedish Board for Technical and Industrial Development (NUTEK), the Swedish Space Board (RS), the Swedish Cancer Society (RmC), the Swedish Medical Research Council (MFR), the Knut and Alice Wallenberg Foundation (KAW) and the Crafoord Foundation.

Special thanks are due to Marie Holmdahl-Svensson and Laila Lewin for their efforts in collecting and editing the material for this report.

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Head of the Atomic Physics Division

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Ph.D. Theses

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Claire Lyngå	99-11-19	High-order harmonics – Characterisation, optimisation and applications LRAP-248
Charlotta Eker	99-12-03	Optical characterization of tissue for medical diagnostics LRAP-249
Ulf Gustafsson	00-04-28	Diode laser spectroscopy in extended wavelength ranges LRAP-253
Jonas Sandsten	00-09-22	Development of infrared spectroscopy techniques for environmental monitoring LRAP-257
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DIVISION OF ATOMIC PHYSICS
LUND INSTITUTE OF TECHNOLOGY
Head: S. Svanberg
Deputy head: C.-G. Wahlström

Research Programme				
Basic Atomic Physics	**Quantum Electronics, Quantum Optics and Applied Optics**	**Applied Molecular Spectroscopy**	**Medical Applications**	**Paper Physics**
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D. Descamps	A. Larsson	J. Sandsten	Ch. Eker	C.M. Nilsson
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A. Basic Atomic Physics

Most of our research in basic atomic physics has been directed towards ultra-intense laser-matter interactions, and laser spectroscopy in the VUV and XUV spectral regions. Experimental research is carried out at the Lund High-Power Laser Facility, which is part of the Atomic Physics Division. The main system is the *10 Hz femtosecond terawatt laser*. It is based on chirped-pulse amplification in titanium-doped sapphire, and provides 50 fs pulses of terawatt power. It operates with two separate laser beams; one with peak power of about 2 TW, propagating in air, and the other approaching 20 TW, with pulse compression and subsequent beam propagation in vacuum. The *kilohertz laser system* with a peak power of 0.1 TW, delivers even shorter pulses, about 30 fs in duration. It is also a titanium-sapphire-based system but operates at 1 kHz repetition rate. Our *XUV laser system* is based on a mode-locked picosecond Nd:YAG laser, pumping a short-pulse dye laser, followed by a solid-state power amplifier. In combination with high-order harmonic generation in gas jets, this system provides tuneable short-pulse radiation in the XUV spectral range. Finally, the *VUV system* is a narrow-bandwidth, tuneable system with pulse duration in the nanosecond range. It is designed for pulsed laser spectroscopy in the UV and VUV spectral ranges.

Our research using the femtosecond terawatt lasers is mainly devoted to the generation, characterisation and application of high-order harmonic radiation (Section A1) and of laser-produced X-rays (Sections A3-A4). A new research programme, on relativistic laser matter interactions, is described in Section A5. Time-resolved laser spectroscopy in the short-wavelength region (UV/VUV/XUV), using picosecond- and nanosecond lasers, is discussed in Section A6. Most of these spectroscopic investigations are of astrophysical interest and some are directly linked to observations made with the Hubble Space Telescope. Finally, our theoretical work, devoted to the study of atoms in strong laser fields, and in particular, high-order harmonic generation, is presented in Section A2.

During the period of this progress report, three MSc projects [A1-A3, A6] and two PhD theses [A4, A5] have been completed and successfully defended.

A1. High-order harmonic generation

High-order harmonic generation in gases, using short-pulse, high-intensity lasers, is one of our main areas of research. We have recently performed studies on the temporal coherence of the generated radiation [A7,A8], and explored ways to increase the generation efficiency by optimising the length of the non-linear medium or by manipulating the focusing geometry of the laser beam [A9-A12]. During the past two years, however, efforts have been directed towards experiments demonstrating that high-order harmonic radiation is a novel source of coherent radiation for advanced applications in the extreme ultraviolet spectral range. In

March 2000, we arranged a workshop in Lund, together with the European Science Foundation, on “Applications of High-Order Harmonics”.
Below, we present three successful applications: pump-probe spectroscopy, interferometry and two-photon ionization using high-order harmonics. The possibility of generating attosecond pulses is another promising application of harmonic radiation to which we are devoting considerable effort. A European network *"Generation and characterisation of attosecond pulses in strong laser-atom interactions: A step towards attophysics"*, was formed in 2000 by seven European laser laboratories, and co-ordinated by us, to encourage work and collaboration in this area.

Pump-probe spectroscopy

Dominique Descamps, Johan Norin, Johan Mauritsson, Allan Johansson, Vladimir Lokhnygin, Zhongshan Li, Anne L'Huillier, Michael Meyer, Stéphane Aloise*, Merete Raarup*, Stacey Sorensen*, Olle Björneholm*, Wim Ubachs*, Iavor Veltchev*, Rudiger Lang*, Dolores Gauyacq*, Valerie Blanchet*, Betrand Girard* and Sébastien Zamith**
**Visiting scientists*

The short pulse duration of the harmonic source makes it an interesting tool for time-resolved studies of atoms and molecules in the VUV and XUV range. In addition, it can easily be synchronised with another colour, in the infrared, visible or ultraviolet range. Several two-colour, pump-probe experiments have been performed during the past two years, in collaboration with international and Swedish scientists.

Firstly, we extended previous measurements of photoionization cross-sections of excited states in helium [A13-A15, A33]. These excited states, $2s^1P$ and $3s^1P$, are prepared by absorbing the 13^{th} or 14^{th} harmonic of our picosecond laser system, tuned to the appropriate wavelength, and are ionized by absorbing a probe pulse at different wavelengths. The influence of the relative polarisation of the pump and probe radiation has been investigated [A16]. Finally, the short-time behaviour of lifetime measurements using a pump-probe technique, governed by resonant two-photon ionization, has been studied in some detail [A17].

In the second experiment, using the same laser system, lifetimes were measured in two electronically excited states of molecular nitrogen; the c4' $^1\Sigma_u^+$, v=0 Rydberg state and the $b^1\Pi_u$, v=1 valence state. This time the 8th harmonic of the laser was used for the resonant excitation [A18, A19]. (The 8th harmonic was produced by frequency-mixing of the fundamental and second harmonic generated in a KDP crystal.) These measurements are of astrophysical interest, since a major fraction of the VUV emission in the Earth's atmosphere, and also in the planetary atmospheres of Titan (Saturn) and Triton (Neptune) originates from these states. (See also [A20] for a recent analysis of data obtained during our previous experiment on CO.)

The final study concerns time-resolved femtosecond spectroscopy of Rydberg states in acetylene and deuterated acetylene. The experimental set-up is shown in Figure A1.

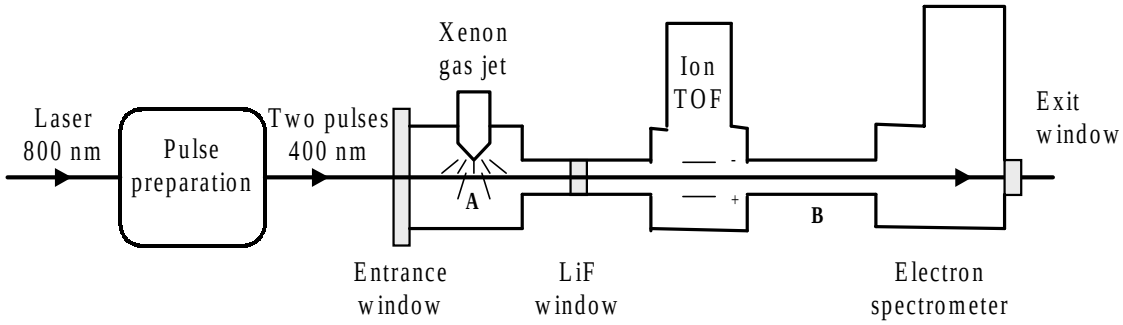

Fig. A1*. Experimental set-up used for femtosecond pump-probe molecular spectroscopy.*

Two frequency-doubled "blue" pulses, one used to generate the high harmonics and the other used as a time-delayed probe pulse, are prepared in an optical setup. The first pulse is focused just under the nozzle of a xenon gas jet (point A in Figure A1), generating harmonics, while the probe pulse is focused at point B in Figure A1. Rydberg states in C_2H_2 and C_2D_2 are excited in the 131-132 nm region by absorbing the third harmonic of the first blue pulse. These ions are probed by the second blue pulse. Both the ion species and the electron spectra are recorded as a function of the time delay between the two pulses. Interesting dynamical effects occurring on a 100 fs time scale have been observed [A21-A24, A33].

In addition, we have theoretically designed a harmonic compressor [A25], using an advanced X-ray tracing code as well as numerical simulations in the time domain. This instrument should be able to select a particular harmonic and to recompress it in time, eliminating any linear chirp. This chirp may be due to the spectral selection using diffractive optics, and/or to the generation process itself. Thus, a single harmonic with a very short pulse duration (down to a few femtoseconds) could, in principle, be produced. However, techniques for measuring the duration of harmonic pulses need to be further improved before the instrument will be constructed.

XUV interferometry

Dominique Descamps, Johan Norin, Anne L'Huillier, Jean-Francois Hergott, Hamed Merdji*, Pascal Salières*, Marco Bellini* and Claes-Göran Wahlström*
** Visiting scientists*

The extension of optical interferometry to the extreme ultraviolet (XUV) spectral region is of great interest in several fields of applied and basic research. In particular, dense plasmas, which are non-transparent to visible radiation, can be probed in the XUV spectral region. However, the lack of compact sources of coherent XUV radiation, and the complexity of XUV beam splitters have made

such applications extremely difficult and scarce. We have demonstrated that harmonic radiation can be used in interferometric applications, eliminating the need for XUV beam splitters. The possibility of creating two phase-locked independent harmonic sources has allowed us to construct an XUV interferometer with a simple optical set-up, where splitting and alignment are performed on light beams in the near infrared (Figure A2). The infrared laser pulse is split into two identical pulses in a set-up resembling a Michelson interferometer. In one arm, a mirror is slightly tilted so that focusing of the laser beams results in two spatially separated foci in a pulsed gas jet. A grating is used to select a given harmonic order and to image the gas jet plane. From this image plane, the two harmonic beams diverge and overlap in the far field, resulting in an interference pattern. This pattern is observed with microchannel plates and a CCD camera.

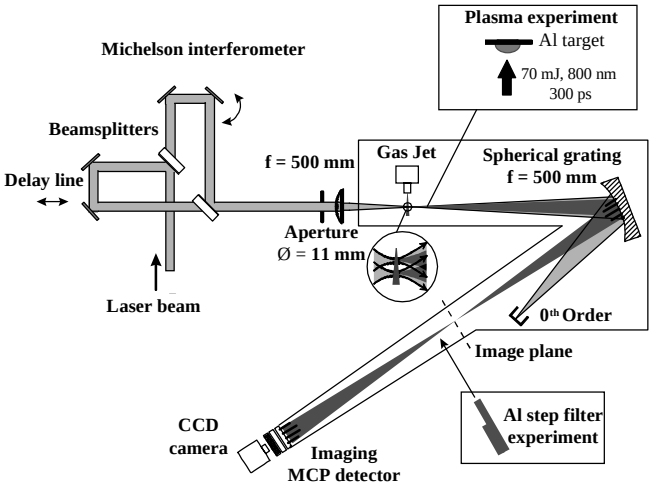

Fig. A2. *XUV interferometer and set-up for the interferometry experiment.*

This set-up has been used to measure the thickness variation in an aluminium step filter (see Figure A3), as well as to determine the density gradient of a laser-produced plasma [A26-A33].

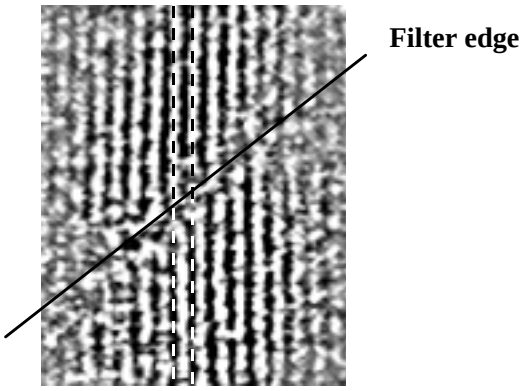

Fig. A3. *Interference pattern with the 13th harmonic through an aluminium step filter. The spatial envelop of the harmonic beam is removed using a Fourier transform technique.*

Two-photon ionization

Dominique Descamps, Lena Roos, Christian Delfin, Anne L'Huillier and Claes-Göran Wahlström

Since the harmonic radiation is of short pulse duration, with good spatial coherence properties and with a relatively high photon number per pulse, a high intensity can be achieved by focusing the harmonic beam using high-quality XUV optics. We have performed an experiment in which we used the fifth harmonic (160 nm) of our 10 Hz terawatt laser to induce two-photon ionization of Xe and Kr as well as three-photon ionization in argon [A34]. Figure A4 shows the experimental set-up. An important prerequisite for this experiment is to eliminate the large background of unwanted ionization processes, mainly due to multiphoton ionization from the intense fundamental beam and one-photon ionization from higher-order harmonics, without decreasing the intensity of the fifth harmonic beam too much. This was achieved by the use of two beam splitters (see Fig. A4), and a quartz plate, absorbing higher-order harmonics. Figure A5 shows the set-up for a measurement of the number of Xe ions produced as a function of the number of fifth harmonic photons on a logarithmic scale. The slope is 2.0 ± 0.2 over more than two orders of magnitude, providing clear evidence that the Xe ions are produced in a second-order process. This experiment is a direct demonstration of the high harmonic intensity. It opens the door to non-linear optics in general in the VUV and XUV, and provides a way of measuring femtosecond and attosecond pulse durations in this wavelength region by autocorrelation.

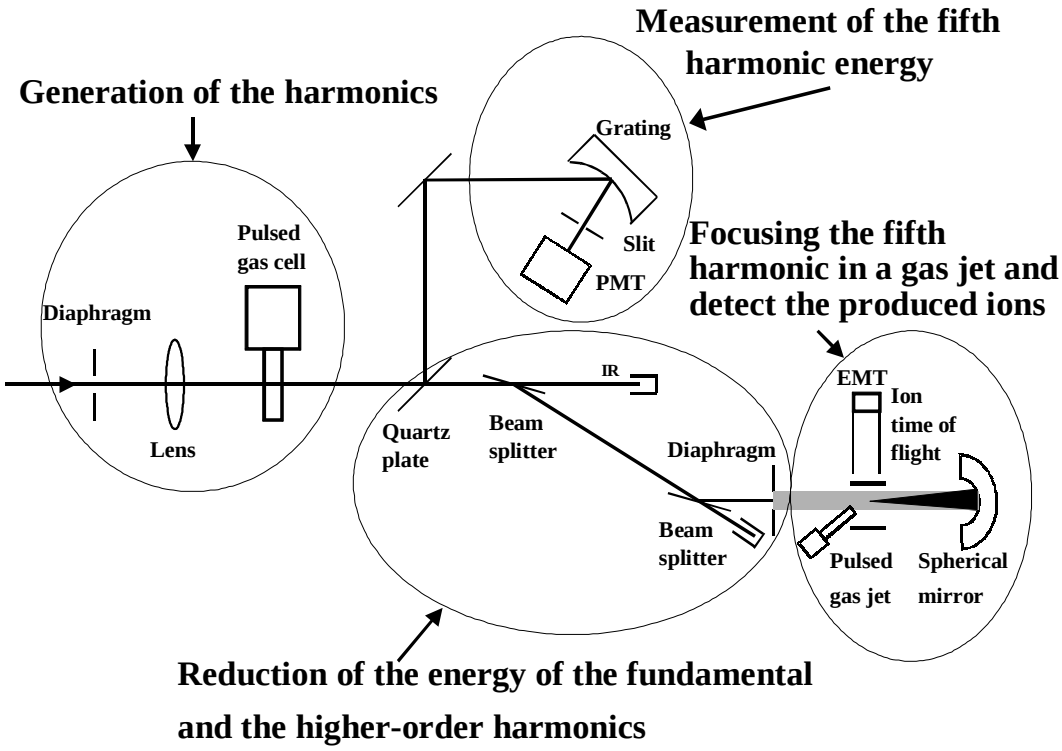

Fig. A4. *Experimental set-up for two-photon ionization of Xe, Kr and Ar with the fifth harmonic.*

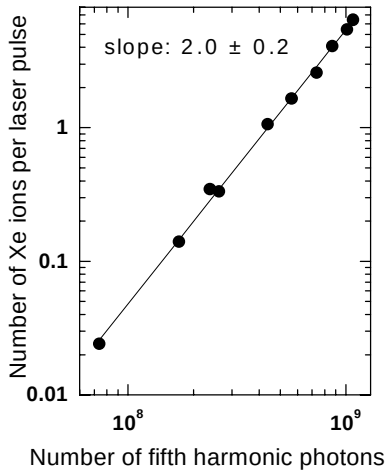

Fig. A5. *The number of Xe ions shows a quadratic dependence on the number of fifth harmonic photons indicating that ionization occurs in a two-photon process.*

A2. Theory of atoms in strong fields

Our theoretical description of the interaction of atoms with strong laser fields is divided into two parts. One part deals with the interaction between a single atom and the intense field, through direct numerical integration of the time-dependent Schrödinger equation, and the other with the macroscopic effects of propagation through a laser focus and phase matching in the non-linear medium. The macroscopic harmonic field is calculated by numerically solving the Maxwell wave equation, using the atomic dipole moment as a source of the non-linear part of the polarisation field. These two approaches in combination allow us to realistically model harmonic generation experiments.

Characterization and optimization of high-order harmonics

Mette B. Gaarde, Lena Roos and Anne L'Huillier

A great deal of effort - both experimental and theoretical - has been put into the development of harmonic radiation as a feasible source of short-pulse XUV radiation. This requires detailed characterization of the harmonic field. We have studied the temporal coherence properties of high-order harmonics through theoretical characterization of their time-frequency behaviour. The harmonics above the ionization threshold all exhibit a strong negative chirp which is caused by the phase behaviour of the single atom dipole moment [A35-A39].

Another important goal in developing high harmonics as an XUV source is to obtain control of the harmonic output. We are currently developing a tool to shape the calculated harmonic field to fit a specific application. We are using an evolutionary algorithm to for instance minimise the spectral bandwidth of the

harmonic profile, or to maximise the number of photons per pulse, by changing the macroscopic phase matching conditions, such as the gas pressure or the size of the laser focus [A40].

Alkali metal atoms interacting with intense mid-infrared laser fields

*Mette B. Gaarde and Kenneth J. Schafer**

**Visiting scientist*

Most strong field studies performed to date - both experimental and theoretical - have been on rare gases exposed to intense near-infrared/visible laser fields, since the large ionization potentials of these systems make them ideal for studying multiphoton dynamics using optical lasers.

The high-power mid-infrared (MIR) laser source recently developed at the Brookhaven National Laboratory (USA) has allowed the study of strong field processes in systems with smaller ionization potentials, such as the alkali metal atoms. Both in collaboration with the experiment and in purely theoretical studies we have found that alkali metals interacting with intense MIR radiation are very rich systems that present a number of striking differences compared with strong field systems studied previously at optical wavelengths [A41-A47].

Figure A6 illustrates our main results with respect to harmonic generation. We have found that in the strong field regime a single multiphoton resonance (in this case either a 3- or 5- photon resonance between the ground 4s and the first excited 4p state in potassium) can enhance many harmonics of the fundamental laser frequency simultaneously. We found that all the harmonics, through at least the 17th, are enhanced over a wide range of intensities, and that the resonance width of the enhanced harmonics is governed by the lifetime of the multiphoton resonance.

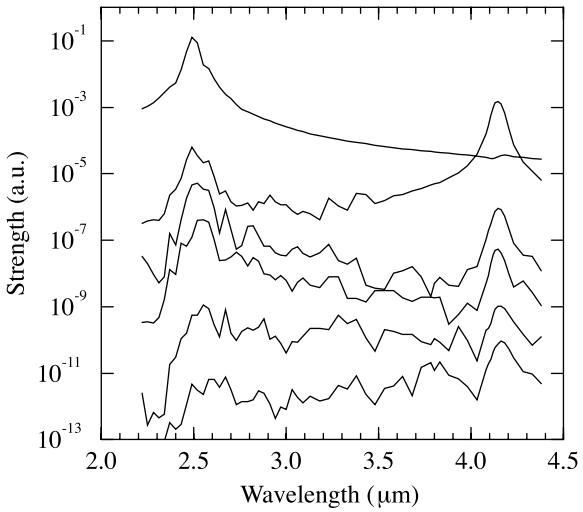

***Fig A6**. Wavelength scans of several harmonics in potassium. From above, on the left, the 3rd, 5th, 7th, 9th, 13th, and 17th harmonics are shown.*

A3. Generation of hard X-rays from laser-produced plasmas

Anders Sjögren, Francois Albert, Claes Olsson, Sune Svanberg and Claes-Göran Wahlström*
**Visiting scientist*

This research project was initiated at our division already in 1992, when the high-power laser facility was established. Since then, we have routinely generated hard X-rays by focusing high-power femtosecond laser pulses tightly with an off-axis parabolic mirror, onto solid metal targets. With peak laser intensities on the target of up to 10^{18} W/cm^2, hot dense plasmas are formed, emitting intense bursts of hard X-rays. The energy of these X-rays depends on several parameters, such as the type of target material. With high-Z materials, such as tantalum, the spectrum can extend up to the MeV region.

Since the beginning of this project, one of our underlying aims has been to investigate the possibility of using laser-produced X-rays for medical imaging. With a laser pulse duration of the order of 100 fs, the X-ray pulses are typically a few picoseconds in duration. We have previously demonstrated that these X-ray pulses have novel properties of interest for medical imaging. Extreme magnification radiography, time-gated scatter suppression and differential imaging are examples of such imaging applications. Overviews of these are given in [A48, A49, A30].

Whether or not laser-generated X-rays become a routine source for medical imaging, depends on several factors. The achievable *average* power of these X-rays (~1 mW) is one such factor. It is clear that the power must be significantly increased to become a realistic tool. However, the advantages of differential absorption and time-gated detection, or a combination of the two, might make these techniques practical, even with a modest increase in the average power. (Standard X-ray tubes can produce an average power of the order of ~1 kW).

During the past two years, we have investigated the possibility of increasing the average power of laser-produced X-rays, by using a laser system with a higher repetition rate, and by manipulating the pre-plasma conditions. We have generated hard X-rays with our new femtosecond kHz laser system, and compared the efficiencies, the spectral content of the X-ray pulses, and the imaging capabilities with our previous results obtained with the 10 Hz terawatt laser. The pulse energy on the target, using the 1 kHz laser system is about a factor of 100 less than with the 10 Hz system. However, with the repetition rate a factor 100 higher, the average laser power is comparable. First, we used image plates (as used at the Lund University Hospital in combination with ordinary X-ray tubes) to demonstrate that hard X-rays are indeed produced even with as little as 1 mJ of laser pulse energy (Figure A7).

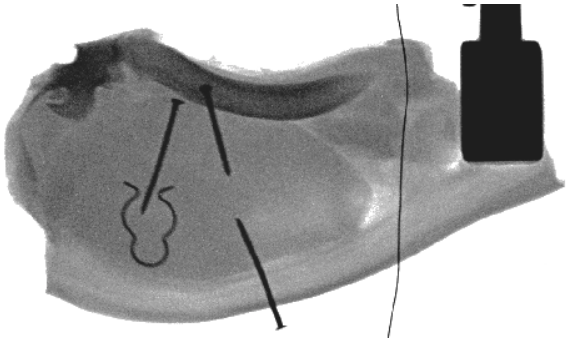

Fig. A7*. An image of pork tissue with bone, acquired during 5 minutes using X-rays produced with 1 mJ, 35 fs laser pulses from a 1 kHz repetition rate laser system.*

Secondly, we have investigated how the pre-pulses from the laser influence the X-ray yield. We studied both the influence of the "intrinsic pre-pulses" originating directly from the laser system, as well as how a specially tailored pre-pulse can be used to enhance the X-ray efficiency. The intensities of these pre-pulses can be high enough to ionize and ablate the target surface, and thereby create a "pre-plasma", with which the main pulses will interact. Following the pre-pulse, the plasma will expand rapidly. Its size and electron density at the time of impact of the main pulse are of the outmost importance, as the X-ray photon number and spectrum depend on these parameters to a high degree. In principle, the plasma condition can be controlled through the pre-pulse intensity and its relative timing to the main pulse. This is one of our current areas of investigation.

Finally, in order to investigate how the spectral content of the radiation is affected by changing between the 10 Hz and the 1 kHz system, and when varying pre-pulse parameters, we used a back-illuminated CCD camera in photon counting mode. Figure A8, illustrates the finding that the number of X-ray photons *per laser pulse* is reduced 10^4 times when moving to the high repetition rate system. The higher repetition rate increases the average number of X-ray photons by a factor of 10^2 [A50, A51]. Adding an artificial pre-pulse result in a few times higher X-ray yield [A52-A54].

The difficulties involved in counting hard X-rays (>20 keV) with a thinned CCD camera have been analysed, and significant effort has been devoted to making the analysis of the raw data more reliable. Finally, we have modified our rotating target mechanism. The target is constantly rotated and manually translated sideways, while being irradiated. The laser pulses will therefore always be focused onto a fresh target surface (all pulses have the same conditions) along a spiral. The motors and the manual control were originally designed for a 10 Hz pulse-repetition rate and were not fast or accurate enough to separate laser pulses at 1 kHz. The system was redesigned and real-time controller software was written.

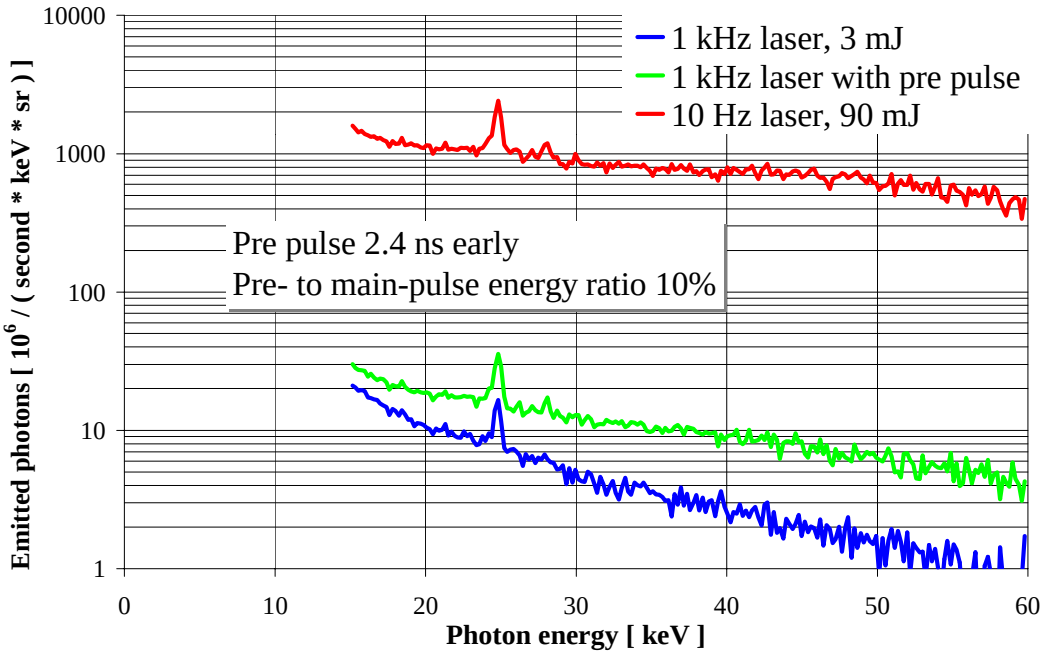

Fig. A8*. X-ray spectra obtained using tin targets. The peaks are the characteristic emission peaks of tin.*

The new system can handle laser-pulse repetition rates from less than 1 Hz to over 1 kHz, depending on the desired spot separation on the target. Figure A9 shows a tantalum target, magnified 20 times. The desired and actual spot-to-spot distance is 40 μm.

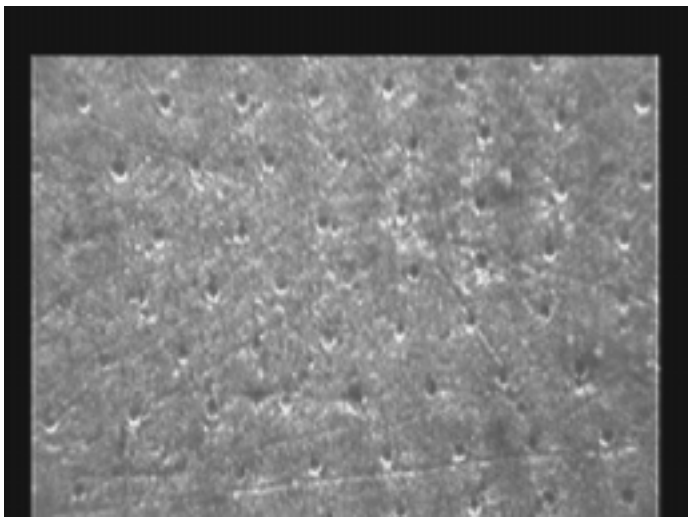

Fig. A9. *Craters from laser focusing on a tantalum target at 20 times magnification. Spot-to-spot distance 40 microns.*

A4. Time-resolved X-ray studies

In 1998, a research programme in the field of time-resolved studies of the structure of matter was initiated [A56,A57] at the Division of Atomic Physics. Recently, we have employed time-resolved X-ray diffraction to study strain propagation in crystals and have developed novel methods for time-resolved X-ray diffraction.

Time-resolved X-ray diffraction using a tilted laser wave front

Ola Synnergren, Thomas Missalla, Michael Harbst, Gergeley Katona, Remco Wouts*, Richard Neutze* and Jörgen Larsson*
**Visiting scientists*

The aim of this investigation was to develop a method for time-resolved X-ray diffraction taking advantage of the divergence of the laser-produced plasma source. This was implemented in an experiment where the temporal dependence of the X-ray reflectivity was recorded by striking the sample with a tilted wave front from the laser. This work is part of a project to improve instrumentation for ultrafast X-ray studies. An alternative approach, using streak cameras is also being pursued [A58].

Figure A10 shows the main set-up. X-ray diffraction is used to study laser-induced strain in the sample. A plasma source generates X-ray pulses with durations of a few picoseconds. The crystal is oriented so that the CCD camera sees the two iron K_α lines. A grating with 1800 groves/mm tilts the laser wave front. This gives a spatial chirp and a varying temporal delay between the laser pulse and the X-rays in the vertical direction.

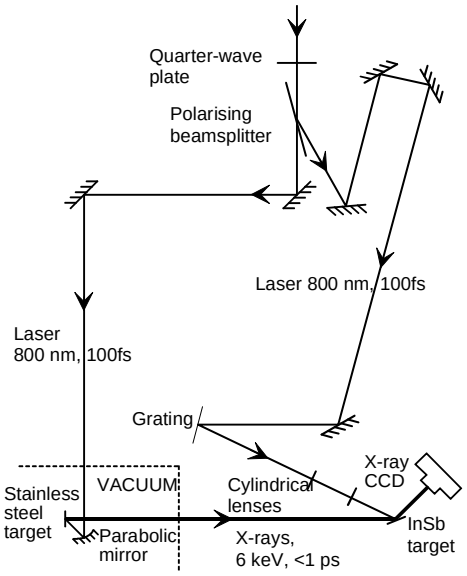

Fig. A10. *Experimental set-up for time-resolved X-ray diffraction.*

A time-dependent effect on the crystal structure was seen. In order to calibrate the time scale we measured the spatial position of the effect as the laser pulse was delayed using a delay line, and found that the time scale was 1.2 ps/pixel.

The advantage of this new method compared with a straightforward pump-probe set-up is that an entire time history can be recorded in a single shot, with high temporal resolution. This eliminates noise due to pulse-to-pulse fluctuations in the X-ray source.

Picosecond diffraction from coherent phonons

*Jörgen Larsson, Thomas Missalla, Anders Sjögren and Justin Wark**
**Visiting Scientist*

Investigations of picosecond diffraction from coherent phonons have been performed. Figure A11 shows the picosecond time-resolved image of the X-ray emission from single electron bunches diffracted from (a) an unperturbed InSb crystal and (b) an InSb crystal within which coherent phonons had been excited by a 100-fs laser. The length of the streak in (a) is the 100 ps electron bunch length, resolved with ~1 ps resolution. The data were recorded on the ID9 sub-picosecond X-ray streak camera. Note the pronounced oscillation in the X-ray signal in (b), directly induced by the effect of the coherent atomic oscillations on the X-ray reflectivity. These are the clearest data yet obtained demonstrating such high-frequency phonon effects with picosecond resolution, and pave the way for a variety of novel experiments aimed at improving our understanding of picosecond ultrasonics, and methods for generating X-ray switching optics on picosecond time scales. In future experiments we fully expect to increase the sensitivity of the intensified picosecond camera even further, which will directly lead to the ability to observe even higher frequency (close to 1 THz) phonons, and other sub-picosecond phenomena such as non-thermal melt. The coherent phonons were observed for a range of energies, and the observed phonon frequencies were in excellent agreement with simulations based on dynamical diffraction theory coupled with a simple hydrodynamic model for the phonon dynamics within the laser-irradiated InSb crystal. Additional work has been performed at the ALS (Berkeley, USA) and APS (Illinois, USA) synchrotrons [A59,A60].

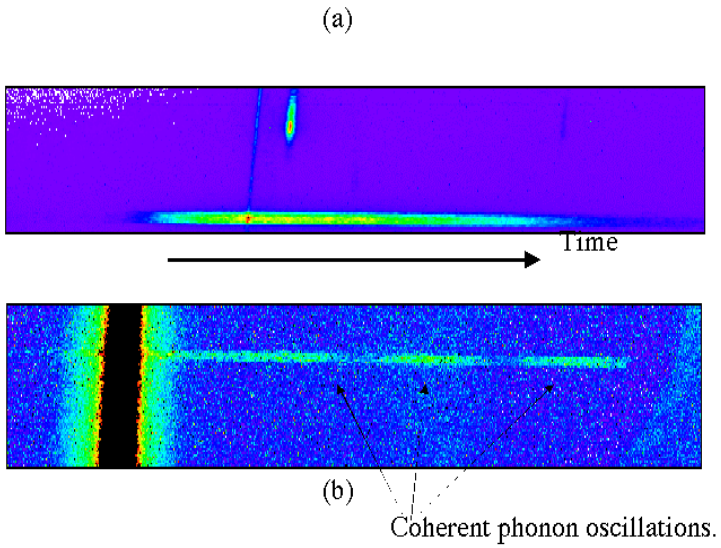

Fig. A11. *Picosecond diffraction from (a) unperturbed InSb crystal and (b) from a crystal within which coherent phonons have been launched by irradiation with a 100 fs laser.*

A5. Relativistic channelling

Christian Delfin, Vladimir Lokhnygin, Anders Sjögren, Johan Mauritsson and Claes-Göran Wahlström

The possibility of generating very intense pulses of fast particles, in particular electrons, by laser acceleration has attracted a great deal of attention lately. During the past two-year period, we have established experimental studies in this area, and obtained our first results. In these experiments, we used the multi-terawatt arm of our 10 Hz femtosecond laser. We focused the laser pulses with a high-quality, off-axis parabolic mirror into a high-pressure helium gas jet. The focused intensity in the gas jet exceeds 10^{18} W/cm^2, and complete ionization occurs during the rise time of the laser pulse. The main part of the laser pulse then interacts with the fully ionized plasma. Wake-field accelerated electrons are detected in the forward direction, and their energies are studied using a magnetic electron spectrometer. Kinetic energies exceeding 10 MeV have been obtained. Such laser-accelerated electrons can be used in new types of novel laser-based experiments, e.g., to induce nuclear reactions or, as we have shown in a collaboration with MPQ, Garching, Germany, to produce short pulses of positrons [A61].

Of particular interest for efficient laser acceleration, is the possibility to accelerate the particles over distances much longer than the length of the laser focus. Since high intensities are required, tight focusing is used with correspondingly short Rayleigh lengths. This problem can be overcome by the use of extended channels formed through relativistic self-focusing. We have investigated the formation of such channels in He plasmas, and the dependence of the channel length on various experimental parameters. In particular, we have investigated how the duration of the laser pulse affects the length of the channel when varying other parameters, such as plasma density, pulse energy, etc. [A62]. An example of a plasma channel formed by relativistic self-focusing is shown in Figure A12.

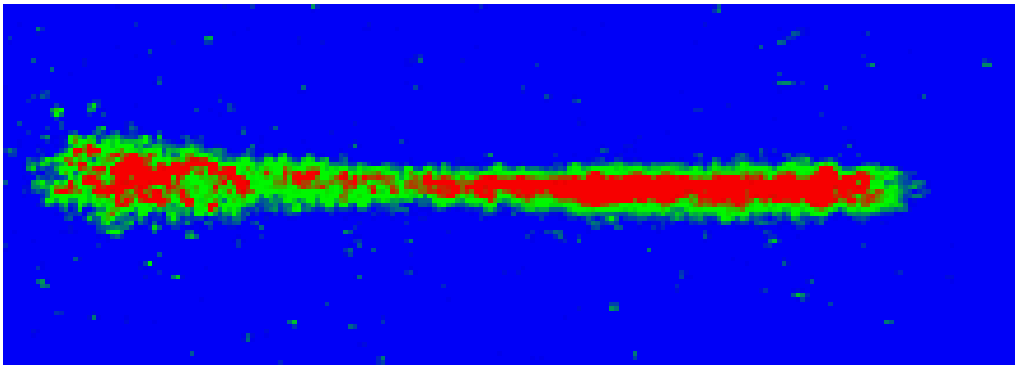

Fig. A12. *Side view of a channel formed by relativistic self-focusing through a He plasma. The length of the channel is 500 μm, whereas the Rayleigh length of the laser focus is about 30 μm.*

A6. Time-resolved laser spectroscopic lifetime measurements of atomic and ionic excited states

Zhongshan Li, Zhiguo Zhang, Hans Lundberg, Vladimir Lokhnygin, Claire Lyngå, Johan Norin, Anders Persson, Claes-Göran Wahlström, Sune Svanberg, Uldis Berzinsh, Per Jönsson*, Sveneric Johansson*, Ulf Litzén*, Glenn Wahlgren*, Hampus Nilsson*, H. Pihlemark*, Carl-Magnus Sikström*, Emile Biémont*, Henri-Pierre Garnir*, Xavier Tordoir*, Pascal Quinet*, Michael Schultz-Johanning* and R. Schnabel*.*
** Visiting scientists*

Time-resolved laser spectroscopy is a powerful method for the determination of excited-state lifetimes in atoms and ions. Experimental data are important in verifying theoretical calculations and for normalising transition probabilities required in astrophysics and plasma physics. With the wealth of new data provided by the Hubble Space Telescope also in the vacuum ultraviolet spectral region, there is a great need to supply the corresponding atomic data. Initial studies were mostly focused on the investigation of free atoms, but it later became possible to study singly ionized atoms using laser ablation production of the species (for an overview up to 1997; see U. Berzinsh, S. Svanberg, *Atomic Radiative Lifetimes Measured by Pulsed Laser Spectroscopy in the UV/VUV Spectral Region,* Adv. Quant. Chem. **30**, 283 (1998)). By refining the techniques it has now become possible to study doubly ionized atoms [A63] and, very recently, also triply ionized atoms, as exemplified by the case of CeIV [A64]. Even refractory elements (MoII, ZrII, WII) constitute no problem when using the laser ablation technique [A65-A67]. Clearly, neutral atoms can also be studied. Experimental lifetime data and theoretical calculations were compared for B, Ge and Pb [A68-A72].

Extensive work has been performed on the rare-earth ions to meet the astronomic need for reliable data. Experimental lifetime determinations have been complemented by theoretical calculations using a relativistic Hartree-Fock method (LaII, LaIII, CeI, CeII, CeIII, CeIV, EuII, EuIII, GdII, GdIII, ErIII, TmIII, YbII, YbIII, LuIII) [A73-A84]. The need for including core polarization effects was frequently very manifest.

The iron spectral lines are very important in astrophysics. Within the FERRUM project we have performed extensive lifetime evaluations for the singly ionized atom [A85-A89]. We have also participated in experiments on lifetime measurements on metastable ions at the CRYRING Facility in Stockholm, regarding Fe^+ [A90] and Ca^+.

The research activities within this programme have been reported at several conferences [A91-A96].

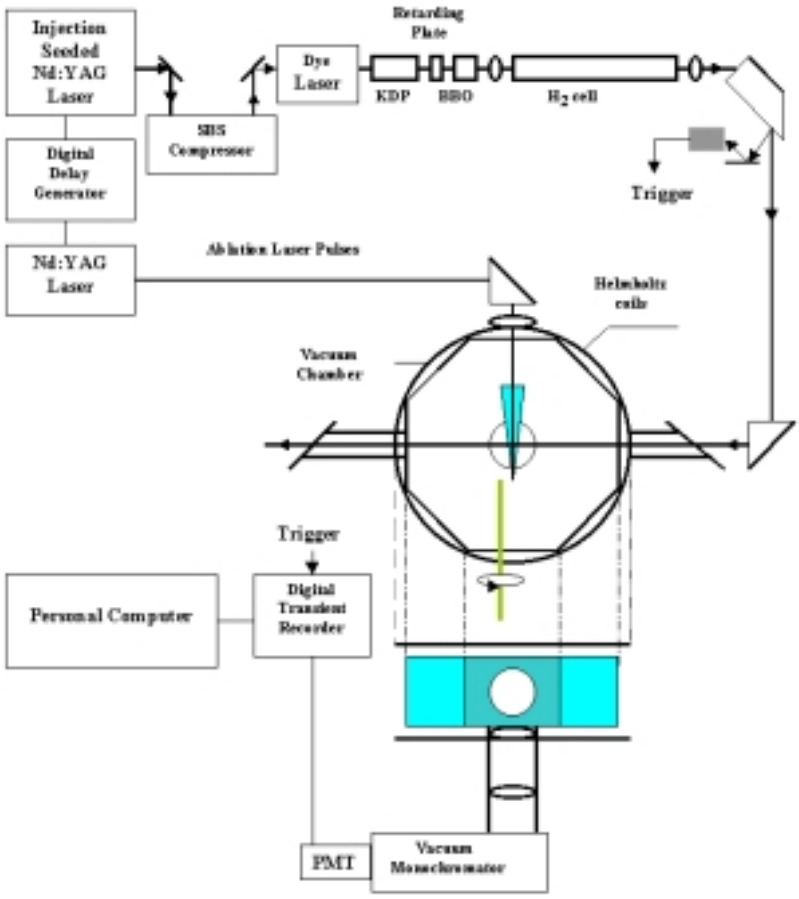

Fig. A13. *Experimental set-up for measurements of lifetimes in atoms and ions produced in a laser-produced plasma.*

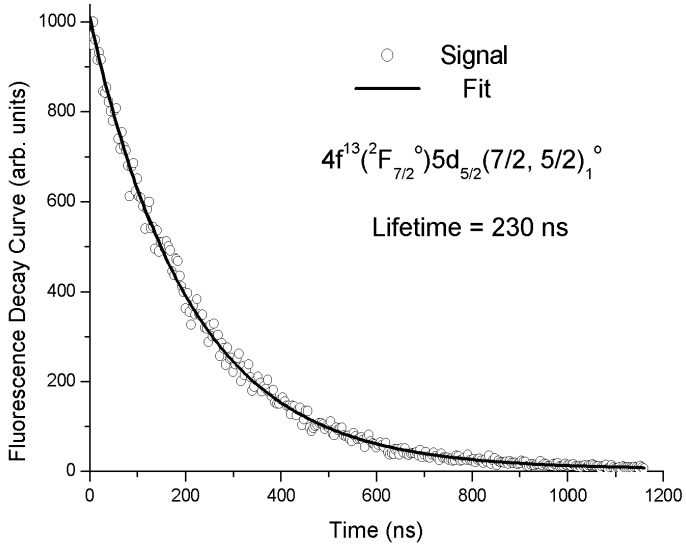

Fig. A14. *Experimental recording of the fluorescence signal from the level at 39720.79 cm^{-1} in doubly ionized Yb. The recorded data points are marked with o while the solid curve shows the exponential fit. The lifetime deduced from the fit is 230 ns.*

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B. Quantum Electronics, Quantum Optics and Solid State Spectroscopy

In this chapter we report from our work on; the use of coherent transient techniques to explore all-optical techniques for data storage and data processing (B1), observing single-photon interference using non-overlapping wave packets (B2), and the first attempts towards quantum computing in rare-earth-ion-doped inorganic crystals (B3). A PhD thesis covering several aspects of the first topic above was presented in January 1999 [B1].

B1. Time-domain optical data storage and processing

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The time-domain optical data storage and processing project is concerned with the physics and the concepts of photon-echo-based techniques for optical storage and processing of information. Optical fibres are replacing electronic transmission lines at increasingly shorter distances and the application of optical switches is continuously increasing. It is clear that the replacement of electronics with optical solutions and devices will continue. Thus, the demand for optical solutions in storage, processing and communication applications will increase.

Data storage densities above Gbits/cm^2, data rates above THz and density bandwidth products of 10,000 Tbits/(cm^{2}s) have been achieved using photon-echo-based techniques, and storage densities >Tbits/cm^2 have been predicted. The projected and demonstrated performance makes photon-echo techniques extremely interesting for future optical storage and processing concepts. Nevertheless, many problems must be addressed and solved in order to make time-domain optical storage and processing competitive with existing technology [B2, B3]. Major long-term objectives in our work include all-optical address recognition and all-optical data-rate conversion, using photon-echo techniques.

In time-domain or photon-echo storage many bits of information can be stored and addressed within a single diffraction-limited point (area) because atoms within this small area absorb at different frequencies. In some rare-earth-ion-doped materials, more than 10^7 different spectral intervals can be addressed within any such single spatial point. This is the basis for the high storage densities that have been achieved and predicted in these materials. In the time-domain or photon-echo approach to data storage and processing in these materials it is the frequency Fourier spectra of temporal wave forms (data streams) that are stored. This makes it possible to perform a variety of all-optical operations on temporal data. For example, temporal pattern recognition, header/address decoding, optical time domain encryption, bit rate conversion, serial-to-parallel and parallel-to-serial conversion.

Amplification of photon-echo data for bit-selective data erasure and for bit-rate conversion

We have been engaged in the issue of how to conveniently implement bit-selective erasure of data stored using photon echoes. We have shown that random phase and frequency fluctuations in the laser sources limit the efficiency of the erasure process (J. Opt. Soc. Am. B**13**, 1905 (1996)). In connection with a visit by two of the group members to Neil Manson's laboratory at the Australian National University in Canberra it was shown that by using phase-sensitive detection of the photon-echo output, the laser phase that is required for the erasure process can readily be determined [B4]. This is a significant step forward in implementing an efficient erasure process. However, we had previously also suggested a self-compensating approach to eliminate laser phase and frequency fluctuations in the erasure process (J. Opt. Soc. Am. B**13**, 1905, 1996), where the idea was to first read out the photon-echo data which are to be erased and then send this photon-echo output signal through an amplifier and direct it into the sample with a 180 degree phase shift. Possible laser phase and frequency fluctuations are now completely irrelevant as we have a true replica of the data and this itself is used for the erasure process. Since the output from a photon-echo process is normally only 0.1-1% of the input it is, however, necessary to amplify the output before it is returned for the erasure process.

We have therefore developed a fibre amplifier that can be operated at the same wavelength (606 nm) as the photon-echo material, Pr^{3+}-doped Y_2SiO_5. This fibre amplifier is capable of providing a single pass gain of a factor of 300. At high gain we demonstrated that when the amplified photon-echo output signals were sent back into the crystal, these could themselves generate new photon echoes [B5-B7]. This was a critical step in terms of being able to realise the erasure process. To further enhance the gain a closed loop configuration operating the fibre amplifier as a regenerative amplifier was tried [B8]. With a suitable arrangement, such regenerative amplifiers can be made to be self-stabilising [B9].

The need for photon echo signal amplification also arises in bit-rate conversion. Bit-rate conversion is of interest, for example, because there is a mismatch between the bandwidth of the optical fibres that transmit signals and the electronics used to generate the signals. By compressing the data generated from opto-electronic devices in time, the data rate can be increased to better match the communication channel, and before the data are read by the electronics at the other end, they can be de-compressed (expanded). One photon-echo process can be used to compress the data and another photon-echo process can be used to expand it. However, again the output signal from the compression process must be amplified to make it strong enough to be used as input in the de-compression process.

Temporal compression of optical photon-echo data pulses and pulse trains was performed in Tm-doped YAG. Single-pulse temporal compression by almost a factor of 500 from 10 μs to 22 ns and pulse train compression by almost a factor of 100 from 20 μs to 212 ns was demonstrated using a high-speed frequency-tuneable

external-cavity diode laser and theoretically analysed [B10-B14]. It is expected that significantly higher compression could be obtained by improved control of the laser frequency and laser frequency chirps.

Development of frequency-agile external-cavity diode lasers for space-based microwave radiation detectors

There are several other interesting aspects of using chirped pulses to generate photon echoes. For example, it is possible to perform a spectral analysis of the stored input signal. Since it is the Fourier spectrum of the input sequence which is stored, individual Fourier frequency components can be read with a chirped input pulse. In a project supported by the European Space Agency (ESA) we are co-operating with Jean-Louis LeGouët´s group at Laboratoire Aimé Cotton, France. The objective of this project is to construct a broadband analyser of microwave signals based on spectral hole-burning/photon-echo materials. This analyser is intended to be carried by satellites on scientific missions. Our task in this project is to construct the first prototype of an external-cavity diode laser which features rapid frequency scanning and good frequency stability, which can be used for spectrally selecting the different microwave signals.

Fig. B1. *External-cavity diode laser developed in the European Space Agency project.*

Such lasers are also required for the bit-rate conversion project. To increase the data rate to high data rates the frequency must be chirped over large frequency intervals. An improved version of our frequency-agile external-cavity diode laser has now

been designed and constructed [B15]. This new device (Fig. B1.) has a 50 GHz single-mode continuous tuning range without mode hops, it can be tuned at rates up to 2 GHz/μs and it has a 1 MHz frequency stability over a 1 ms time scale.

Data storage and data processing

There are several other interesting aspects of using chirped pulses to generate photon echoes. The Fourier spectrum of a stored input sequence can be read with a chirped input pulse. Depending on the chirping rate of the read-out pulse, the recalled Fourier spectra will be more or less distorted. It can be shown [B16] that such a Fourier analysis can be the temporal counterpart to a diffraction process in space, and by changing the chirping rate, a transition of the diffraction in time can occur, which is exactly analogous to the transition from Fraunhofer to Fresnel diffraction for diffraction in space. The existence of a temporal Talbot effect was also predicted for this type of experiment [B16-B17].

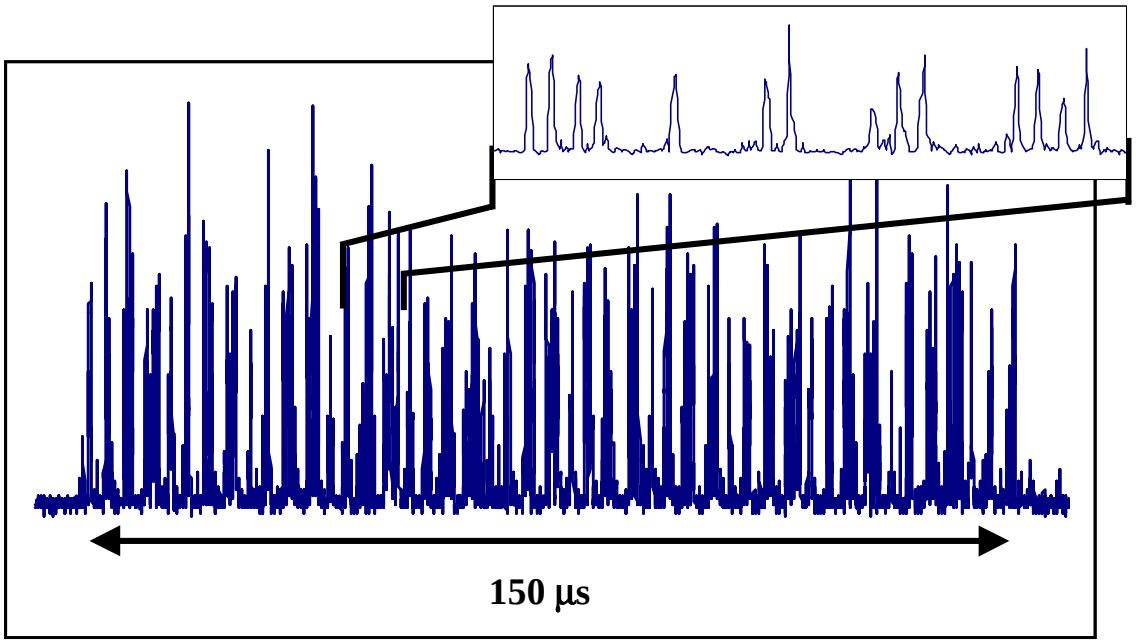

Fig. B2. *Recall of 330 bits of data stored in a single point. The inset is part of the recalled data sequence expanded in time.*

Using our frequency-agile external-cavity diode laser source multiple bit storage at a single spatial location was also demonstrated [B18-B20]. 330 bits were stored at a single spatial location, yielding a storage density of 500 Mbit/cm^2 (see Fig. B2). Further, we believe that this can be significantly improved using the new diode laser shown in Fig. B1 [B15]. In addition, both the bit-rate conversion and the multi-bit storage would benefit from higher laser powers, and laser amplifier based on a broad-area laser diode that can be operated together with the new external-cavity diode laser is now being constructed [B21].

B2. Delayed single-photon interference

Stefan Kröll, R. Krishna Mohan, Serguei Moiseev and Nicklas Ohlsson*
**visiting scientist*

This project concerns basic aspects of the interference of light, as well as basic aspects of the absorption of photons.

The aim is to perform an experiment in which a single-photon wave packet is split into two. The two wave packets take two different routes and are then subsequently made to interact with an atom (or an ensemble of atoms) where the time delay between the two interactions is much longer than the wave-packet coherence time. This experiment is similar to Young's double-slit experiment in which an interference pattern due to single-photon self-interference occurs when the photon probability amplitudes for both paths are simultaneously nonzero at some crossing point. However, in the experiment proposed in this project the probability amplitudes do **not** need to be nonzero simultaneously at the crossing point for interference to be observed. This is distinctly different from the normal Young's double-slit case. The reason why an interference pattern can still be formed is attributed to the fact that the phase of an atomic wave function excited by an electromagnetic field is open to interference with a later field, as long as the time of zero amplitude between the interactions is shorter than the homogeneous dephasing time of the transition. This is generally utilised in photon-echo experiments.

We have analysed an experimental realisation of this idea of delayed single-photon self-interference based on photon echoes using materials with long homogeneous dephasing times. We have calculated the expected photon-echo signal strength using different semiclassical and quantum approaches, and pointed out several unique features of the phenomenon, *e.g.*, single photons are used to carry out what is generally regarded as a multiphoton process, it presents a novel single-photon absorption experiment in the sense that the absorption of a single photon, in this case, can be seen as being separated into two distinctly different moments in time. This in itself raises a number of intriguing questions, *e.g.*, when does absorption actually take place? If the first part of the split single-photon wave packet were to be absorbed by an atom, when and by what mechanism, is this information communicated so that the next packet is also seen only by the same atom? and many more.

Our earlier calculations (Phys. Rev. A**58**, 4348-4358, 1998) have show that the single-photon experiment should be feasible in terms of obtaining a signal of detectable strength if many single-photon events are accumulated before the resulting signal is read out. During the past two years we have been continuously improving our experimental set-up [B22-B26]. Presently, we can detect the signal down to a level where we have about 700 photons in each pulse. Compared with our initial experiments, which required 10^{11} photons per pulse, this is a most significant improvement. So, although we are still rather far from the single-photon case, we are very optimistic about reaching it within the two years left of the project. The experiment described in this section was originally proposed by Dr

Serguei Moiseev at Kazan Physical Technical Institute in Russia, and we are also co-operating with Dr Moiseev concerning a fully quantised theoretical description of these types of phenomenon [B27-B28].

B3. Quantum computing in rare-earth-ion-doped inorganic crystals

Tomas Christiansson, Stefan Kröll, Lars Levin, R. Krishna Mohan, Mattias Nilsson and Nicklas Ohlsson

We have presented a scheme for generating multiple, strongly interacting qubits in rare-earth-ion-doped inorganic crystals at cryogenic temperatures [B29, B30]. The qubits are chosen to be two of the ground state hyperfine levels in these crystals. These hyperfine levels can have lifetimes of hours, and ms or longer decoherence times. Controlled logic between the qubits could be accomplished using the change in permanent dipole moment that occurs in an ion when it makes an optical transition between the ground and excited state. We believe that a system with several interacting qubits could readily be set up using existing techniques and technology.

So far, to date, we have demonstrated the first of the steps required to prepare the system in its initial state. Specifically, we have studied the system Eu:Y_2SiO_5, where we have demonstrated that the ions can be moved between the different hyperfine levels in a well-controlled fashion [B31, B32].

A critical step in the proposed scheme is to make the different qubits interact. As pointed out above, this should occur through dipole-dipole interactions between the permanent dipole moments of the ions in the crystals. We have found that interactions between excited ions in these crystals can be observed although the average distance between the excited ions (assuming randomly distributed dopant atoms in the crystal) is greater than 100 nm [B33, B34]. Although the dipole-dipole interactions might not be the dominant interaction in the Pr-doped crystals that we have investigated, dipole-dipole interactions are expected to dominate in Eu-doped systems. Thus, both from experimental observations and from our calculations [B30] there is good reason to believe that the interaction should be readily observable, and intensive work is in progress at our laboratory to demonstrate a CONTROL-NOT gate in these materials.

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C. Applied Molecular Spectroscopy

Research projects in the field of applied molecular spectroscopy are directed towards the development and application of optical techniques, both laser and non-laser, to measure mainly gases and particles in various environmental studies. Several of the techniques are used for remote sensing over long distances. The method most used in studies of air pollutants is the differential absorption lidar (DIAL) technique, where a mobile DIAL system has been employed in several field campaigns. The lidar system has also been used in the remote monitoring of environmental effects on historical stone buildings and monuments using laser-induced fluorescence techniques (LIF), and special multi-colour imaging methods have been developed for this purpose. The method for imaging of gas flows using an IR camera and gas correlation techniques has been further pursued. The aim here is to develop a method that can produce images of a certain gas at a certain location using only the thermal background radiation. Finally, ultrasensitive gas measurement methods are being developed in a project utilising diode laser spectroscopy and frequency modulation (FM) techniques. During the period, two PhD theses have been completed within the group [C1,C2].

C1. Lidar measurements of atmospheric gases

Hans Edner, Jim Smith, Sune Svanberg and Petter Weibring

Most DIAL measurements are made on single compounds by switching the transmitted beam between two wavelengths. The selection of more than two wavelengths is a mathematical necessity for simultaneous measurement of multiple species, or for resolving interference effects between a compound of interest and a background gas, such as water vapour or carbon dioxide. However, until recently, laser technology has not provided a narrow-linewidth, tunable light source that can switch between wavelengths at the rate that is required for such multiple-wavelength measurements. A multi-wavelength approach is especially important in the mid-IR region, where many hydrocarbon compounds have fundamental rotational-vibrational transitions. For this purpose, a fast tuning lidar transmitter, using all-solid-state technology, has been developed to provide range- and temporally-resolved atmospheric gas concentrations [C3-C5]. The instrument is based on a commercial OPO laser, which has been redesigned with piezoelectric transducers mounted on the wavelength-tuning mirror and on the crystal angle-tuning element in the OPO. A piezoelectric transducer similarly controls the frequency-mixing and doubling stages, which have been implemented to extend system capabilities to the mid-IR and UV regions. The system is able to produce radiation in the wavelength regions of 220-1800 nm and 3000-4000 nm with a linewidth better than 0.2 cm^{-1}, an output power of 1-100 mJ and a shot-to-shot tunability of 70 cm^{-1}. This means, for instance that the fast tuning ability is 75 nm

in the mid-IR wavelength region. The system performance in terms of wavelength, linewidth and power stability is monitored, on a shot-to-shot basis, in real time by a surveillance system consisting of a Fabry-Perot interferometer and reference cells. If the desired requirements are not met for a specific light pulse the system discards the collected data and repeats the measurement until the requirements are fulfilled. The system will extend the monitoring possibilities of the mobile DIAL system for measurements of different pollutant concentrations and fluxes. The new construction allows the system to be tuned to any wavelength, in any order, in the range of the piezoelectric transducers on a shot-to-shot basis. The number and sequence of different wavelengths are easily defined by marking the interesting wavelengths on the computer screen displaying the spectra, as shown in Fig. C1.

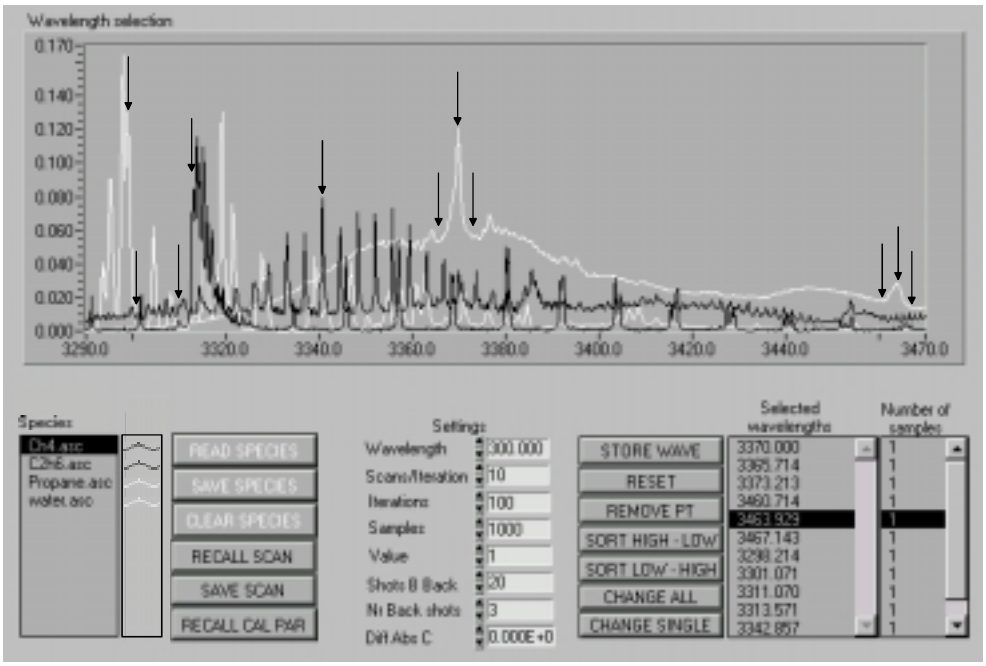

Fig. C1. *The wavelength selection menu showing the mid-IR wavelength region with methane, ethane, propane and water vapour interfering spectrally with each other.*

For quantitative identification of multiple, co-existing compounds we have used multivariate methods commonly used in gas chromatography and near-IR absorption spectroscopy [C6]. In most studies that have been performed to date, the multivariate regression technique of partial least squares (PLS2) has been shown to provide the most accurate predictive models, that are least sensitive to background noise. The use of partial least-squares techniques involves the acquisition of spectra for known gas compositions. A regression model is then constructed, with the important constraint that the model should be based on the individual and combined spectra for all compounds and concentrations that one would be likely to encounter in future measurements of new gas samples.

To determine the ability of remote analysis of a gas mixture an outdoor test cell was used. Long-path absorption measurements were performed by firing through the cell and hitting a topograpic target. In Fig. C2, the mass flow inlet of three gases to the outdoor cell is shown together with the results from the lidar system measurement of the different gases. The diagram shows typical 20 % agreement between the lidar results and the mass flow control signals. The major factor affecting the agreement is probably the weather. The effective absorption path (back and forth through the plume) varies depending on the wind speed and direction. If there is little or no wind the effective absorption length will be longer than during strong side-winds.

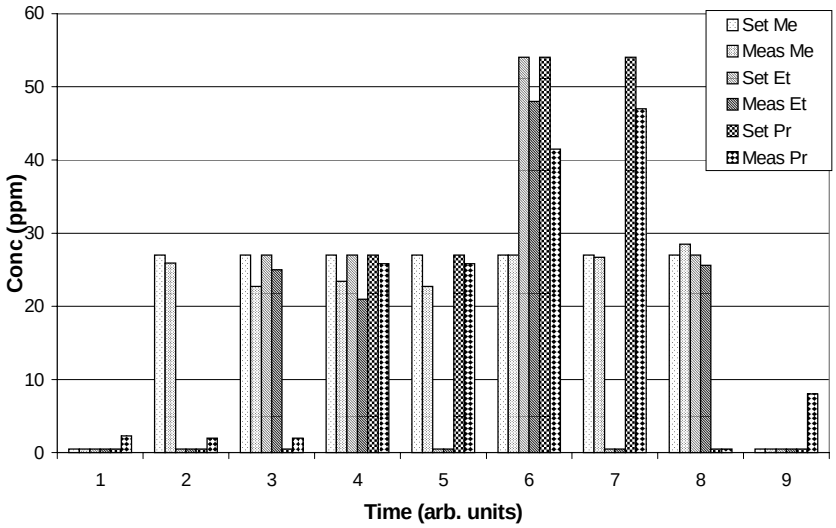

Fig. C2. *Set values for mass flow controllers and lidar system response for methane, ethane and propane.*

The mobile lidar system has once more been employed in studies of the emission of sulphur dioxide from the Italian volcanoes Etna and Stromboli during ship-borne underpasses of the volcanic plumes. Four different optical spectroscopy techniques were used and inter-compared. All the techniques utilise the spectroscopic signature of the gas in the wavelength region around 300 nm. In parallel with active DIAL measurements, a passive DOAS (differential optical absorption spectroscopy) system provided spectrally resolved absorption spectra. In one configuration the absorptive imprint in the sky-light recorded with a vertically looking telescope was studied, while a different DOAS implementation utilised the sun disc as the light source in slant-angle, long-path absorption measurements. Parallel measurements with the customary correlation spectroscopy (COSPEC) method were also performed. The results are compared with special emphasis on systematic effects due to scattering under different conditions.

Some of the DIAL data from the Etna plume measurements have also been used for statistical analysis of different averaging and evaluation schemes, investigated

together with the Division of Mathematical Statistics (Torgny Lindström and Ulla Holst) [C7]. For this purpose, a large number of lidar signals from individual laser pulses were stored, which could later be evaluated in detail. The single-shot measurements were used for better estimates of the variance function, which is important in the analysis since the calculation of optimal bandwidths for the regression relies on it. Local bandwidths are used in the analysis, allowing for locally adapted regression to account for the varying variance function and the curvature of the data. This means that the averaging bandwidth as a function of distance is automatically selected for a minimum of variance and bias in the signal. The data confirmed that the local polynomial variance function estimate performs well, and that the regression gives qualitative measures of the variance and bias of the estimated concentrations. Three different methods for signal averaging were also compared. It was found that the normal averaging method, where the signals at each wavelength are averaged before the ratio and logarithm are calculated, performs best for the weak signals received from the Etna plume altitude.

C2. Fluorescence lidar applications

Hans Edner, Thomas Johansson, Sune Svanberg and Petter Weibring

Historical buildings constitute an important component of our cultural heritage. However, detailed investigations of their status and their conservation can often be a very laborious and time-consuming task. From this point of view, remote-sensing techniques may be an attractive method for quick and truly non-destructive monitoring of building surfaces. Colour photography is one obvious approach; however, fluorescence techniques are known to be capable of revealing aspects that are not evident to the naked eye or photography. Fluorescence lidar techniques make it possible to extend the application of fluorescence spectroscopy to the outdoor environment, where large distances and uncontrollable background light have to be dealt with.

An experiment was performed on Lund Cathedral employing the mobile lidar laboratory, which was adapted for fluorescence monitoring [C8-C10]. The frequency-tripled Nd:YAG laser beam was concentrated to a high-intensity spot on the target, which can be at a considerable distance away, and was observed by the receiving system with a narrow field of view. Typically, the transmitted pulse energy was limited to 30 mJ with an 8-cm diameter laser spot on the target in these experiments. The received fluorescence light was then dispersed by dichroics and bandpass filters or by a spectrometer, using two parallel detection systems. The first one was based on interference filters selected at 438/448 nm and 682/600 nm and photomultipliers. The second system, with a spectrometer and a gated optical multichannel analyser, captured the complete spectrum from 445 nm to 745 nm with a spectral resolution of about 10 nm. Using the computer-controlled folding mirror the lidar was pointed at selected points for spectral data collection, or scanned row by row along the façade for image generation. Daytime measurements

with full spectral resolution were possible through the time-gating technique, with a 100 ns gate matched to the arrival of the fluorescence pulse.

A full fluorescence spectrum was recorded at each of the 6400 points in a scan of the northern portal of the cathedral. The data were then analysed with multivariate statistical methods. Since the chlorophyll signature is very different from other spectral features and is associated with organic biodeteriogens rather than to the building material, it was found useful to perform the spectral analysis in three steps. First, all pixels with a chlorophyll signature were isolated. About 25 per percent of the pixels fulfilled this criterion. In the second step a PCA analysis was performed on the pixels identified in the first step and only including wavelengths longer than 650 nm. Prior to analysis, the individual vegetation-related signals were removed from the sloping stone fluorescence background using the fitting procedure described above. In this way, full “orthogonalization” between vegetation and other materials was achieved. In the third step, a principal-component analysis was performed on the non-vegetation spectra/pixels.

Fig. C3. *False-coloured image of the fluorescence light from the northern portal of Lund Cathedral.*

In Fig. C3 a fully processed colour image of the whole scene is shown. Biodeteriogen invasion has occurred mostly on the cathedral wall behind the portal addition, and is related to the more protected and moist environments found there compared with the exposed portal façade. Small scattered islands of growth at other locations were also found. The vegetation data have been merged into the figure

using three shades of red. Pixels with a sharp peak at 680 nm are shown light red, those with a pronounced double peak at 680 nm in darker red and those with a low signal in this region (only little vegetation colonisation) with very dark red. The violet area featuring iron-ion fluorescence quenching is simple to identify because of the sharply decreasing intensity towards the red. The ornamented 12th century stone arch can at least be partly distinguished from the 19th century portal façade stone. Areas related to these particular spectral signatures are shown in blue/indigo and green. The new technology of remote fluorescence imaging was shown to be technically viable. In particular, the identification and mapping of façade stone treatment and conservation is a field with great promise. Early laboratory work and field monitoring indicate that a considerable potential exists. The work presented establishes a useful baseline from which the new emerging technology can develop. Further measurements have recently been performed in Parma, Italy, as part of a Lund Laser Centre project.

C3. Gas imaging using gas correlation spectroscopy

Hans Edner, Jonas Sandsten, Sune Svanberg and Petter Weibring

Real-time gas imaging is of great interest in many contexts. Inspection of leaks from chemical installations, petrochemical plants, tank farms or pipelines has economical, environmental and safety aspects. Easily deployable surveillance techniques for assessing sites of accidents involving gas tankers or trains are desirable for public safety. We have further developed a method for remote visualisation of gas flows based on infrared absorption or emission and gas-correlation techniques using a sensitive IR camera combined with optical filters and gas cells [C2]. The method relies on simultaneous multi-spectral imaging and computer processing of the data. A suitable IR wavelength window where the gases of interest absorb is chosen by a bandpass filter, but the high-resolution "holistic" filtering is performed by the optically thick gas cell. In a field test, ammonia, ethylene and methane detection was demonstrated in the spectral region 7-13 μm [C11]. When two gases, such as ammonia and ethylene, are absorbing in the same wavelength region it is possible to isolate only one for display with the gas correlation principle. An example of such a measurement, with simulated leaks from a gas tanker, is shown in Fig. C4. The ambient thermal background radiation is the only illumination in these real-time recordings at 15 frames/s. Gas concentration calibration for ammonia was performed by integrating the relative transmittance of the system over wave numbers from 700 to 1100 cm^{-1}, with increasing gas concentrations, and then dividing the decreasing integrated relative transmittance with the integrated relative transmittance without gas. In a practical situation with a thermal background, the self-radiance from the gas has to be taken into account. The gas will selectively radiate at the absorption lines with an intensity of [(1-Transmittance) $\times$ B_G], where B_G is the intensity of a black body radiator at the gas temperature T_G. This will be seen as a higher effective transmittance of the gas, and this effect can be calculated by adding the emitted

intensity of the gas at temperature T_G to the transmitted intensity of the background at temperature T_B.

Fig. C4. *A burned-out gas tank provides the backdrop for imaging pollutant gas leaks. Green pixels highlight areas where ammonia and ethylene gases are leaking. Red shows the selective detection of ammonia with a gas correlation cell.*

In a further measurement campaign gases leaking from a polyethylene plant and a cracker plant were visualised [C2,C12]. Leakage at a high-pressure reactor tank was found and visualised by scanning the camera system over the industrial site. Ethylene escaping from flares due to incomplete or erratic combustion was also monitored. Due to the high frame rate, the gas-imaging technique also has the potential to estimate the flux in a gas plume by combining a wind vector map, derived by cross-correlating the images in time, with a calibrated gas path-integrated concentration image. A wind vector map is derived by cross-correlating a small matrix in an image at time T_0 with a corresponding small matrix in an image at a later time, T_1. The size of the small matrices is chosen by maximising the cross-correlation product. By creating and moving the cross-correlation matrixes over the complete images a resulting time-correlated wind vector map can be produced. The resulting wind vector map merged with the image at time T_0 is shown in Fig. C5. A typical time interval, T_1-T_0, was 1/15 s.

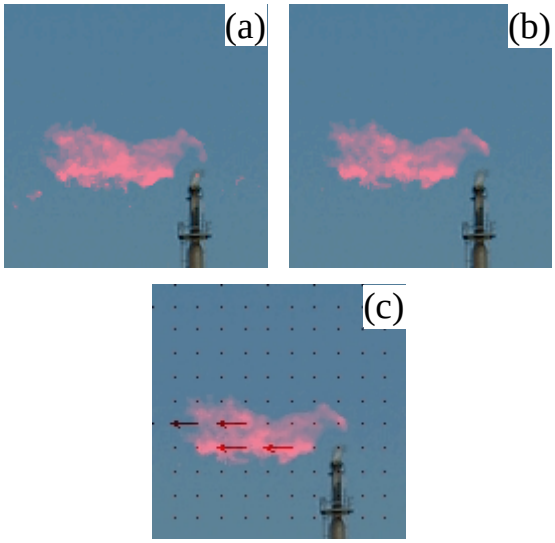

Fig. C5. *(a) Gas-correlated ethylene image at time T_0. (b) Gas-correlated ethylene image at time T_1. (c) Wind vector map derived by cross-correlating the gas-correlated images at time T_0 and T_1. The luminous flare near the exit is filtered out by the image processing.*

C4. Diode laser spectroscopy

Janis Alnis, Hans Edner, Ulf Gustafsson, Jonas Sandsten, Gabriel Somesfalean and Sune Svanberg

Diode lasers have provided many new areas of application for high-resolution laser spectroscopy. For a long time, diode laser action was limited to the infrared, near infrared and red spectral regions. Recently, we have pioneered the spectroscopic use of the new violet and blue continuous-wave diode lasers, which we gained access to under a special agreement with the Nichia Corporation well before the units were released on the open market. The lasers have been used for spectroscopic measurements in the blue region but also to generate short UV laser light, using frequency mixing with the output from near-IR diode lasers. Difference-frequency generation was also utilized to reach the IR region around 3 μm. During the past two years, we have pursued a number of different applications based on these different sources for measurements on mostly gases in laboratory set-ups but also for long-path atmospheric monitoring [C1]. The previously reported development of an aerosol particle sensor using a coupled-cavity diode laser has now been published [C13].

Our first experiments with the new blue diode laser source concerned the resonance lines of potassium at 404.5 and 404.8 nm [C14]. Absorption spectroscopy, as well as fluorescence spectroscopy, was demonstrated on a potassium vapour cell, and opto-galvanic detection was performed on a potassium hollow-cathode lamp. The laser diode was operated both in free-running mode and in a Littrow-type external-

cavity set-up that ensured single-mode operation and lower sensitivity to back reflection.

Laser absorption spectroscopy is a powerful method, especially when combined with frequency-modulation (FM) techniques. The basic concept is to shift the detection band to a high-frequency region, where the noise level is low. Wavelength-modulation spectroscopy (WMS) and two-tone frequency-modulation spectroscopy (TTFMS) were successfully performed for the measurement of the weak second resonance line of potassium at 404.8 nm, as well as for the transition at 405.8 nm in lead, originating from the thermally populated $6p^2\ ^3P_2$ metastable level [C15-C17]. The modulation parameters for the blue diode laser were determined in fits to experimental data. Experimental signal-to-noise ratios at different absorption levels were compared with theoretical signal-to-noise ratios and showed good agreement. Additionally, various noise sources were examined, and we concluded that TTFMS is dominated by RAM noise, whereas both RAM and thermal noise limit WMS. Minimum detectable absorptions of 2×10^{-6} and 5×10^{-6} for wavelength and two-tone frequency modulation spectroscopy, respectively, in a 120-Hz bandwidth were demonstrated.

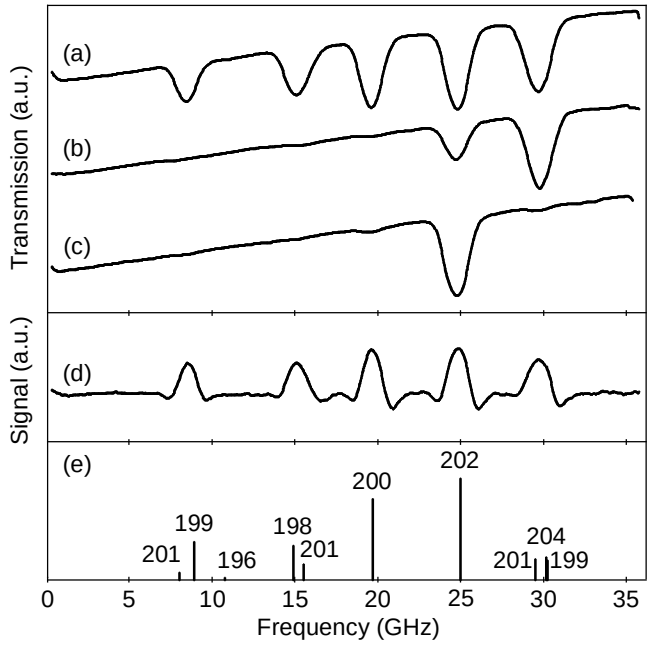

Fig. C6. *Ultraviolet absorption spectra from low-pressure mercury cells containing the natural isotopic mixture of atoms (a) and separated isotopes (b) and (c). The wavelength-modulated spectrum is shown in (d), and (e) gives the designations and relative strengths of natural mercury isotope lines.*

We have demonstrated sum-frequency generation to the 254-nm mercury line by mixing the light from a 404 nm and a 688 nm diode laser in a BBO crystal [C18].

The ultraviolet light power was estimated by photon counting to be 0.9 nW, and a 35 GHz mode-hop-free tuning range was achieved. This is sufficient to perform high-resolution ultraviolet spectroscopy of mercury isotopes, as illustrated in Fig. C6. Mercury is especially interesting, being the only pollutant present as a free atom in the lower atmosphere and having a strong transition at 253.7 nm, which allows detection at low concentrations.

Long-path absorption measurements using sensitive TTFMS spectroscopy were recently performed [C19]. Traffic-generated NO_2 could thus be remotely detected, even at the readily available wavelength 635 nm, which is situated far from any strongly absorbing lines of this gas. Diode lasers have previously been used for NO_2 measurements, mostly in connection with multiple-pass absorption cells and at reduced pressures in order to minimize line broadening. In our scheme, long-path absorption was used at atmospheric pressure. A real-time laser absorption spectrometer was accomplished by repetitively applying a rectangular current pulse to the diode laser DC drive current allowing detection of isolated NO_2 absorption lines. A detection limit of 10 $\mu g/m^3$ for NO_2 at atmospheric pressure with a 160-m absorption path was demonstrated. Continuous monitoring of NO_2 over a road intersection under peak traffic conditions was performed.

An all-diode-laser-based spectrometer was developed for the simultaneous detection of methane, oxygen and water vapour [C20]. This was accomplished using a 760 nm diode laser and a 980 nm diode laser in conjunction with difference-frequency generation to 3.4 μm in a periodically poled lithium niobate crystal. Each of the output wavelengths is resonant with one of the molecular species. Simultaneous recordings over a 15-m open path of laboratory air were made. The recording scheme shows the wide applicability of a diode-laser-based difference-frequency spectrometer for the detection of molecular species in different wavelength ranges. By increasing the frequency of the 760 nm diode laser and decreasing the frequency of the 980 nm diode laser, a maximum continuous tuning range in the mid-infrared of 3.6 cm^{-1} was achieved. This enabled the recording of several methane lines at atmospheric pressure. Pressure dependence studies of methane lineshapes were also performed in an absorption cell. The signal-to-noise ratio in the recorded methane spectra indicates that sub-ppm detection of methane at atmospheric pressure is feasible.

A completely new aspect of gas spectroscopy has been proposed by us for the analysis of gas enclosures in turbid solids and liquids [C21-C23]. Many substances, frequently of organic origin, are porous and contain free gas distributed throughout the material. For instance, wood, plants, cheese, powders, sintered materials, and foams can be considered. The normal method of gas absorption spectroscopy fails for porous media, since the radiation is heavily scattered in the material containing the gas. Thus, there are no well-defined path lengths as required by the Beer-Lambert law, but light emerges diffusely. Gas detection is enabled by the sharp absorptive feature of the free gas molecules in contrast to the slow wavelength dependence of the absorption and scattering cross-sections in solids and liquids.

Thus, embedded gas gives rise to a tiny but narrow signal that can be picked up by sensitive modulation techniques, even in the presence of a high background. In the case of strong scattering, which is the most interesting aspect of the proposed gas-detection technique, a long effective pathlength is achieved, giving rise to a strong gas signature. An absorption sensitivity of 2.5×10^{-4}, corresponding to 1.25 mm of air, was demonstrated in measurements on dispersed molecular oxygen. The spectroscopic measurements were performed at around 760 nm on lines belonging to the oxygen A band. Two measurement geometries are particularly useful for performing basic studies in this new field: transillumination and backscattering monitoring, as shown in Fig. C7. In both cases, optical fibres can be used for injecting the light and for collecting scattered radiation. The absorption and scattering properties of the bulk material have been deduced independently by spatially resolved and time-resolved measurements, providing a direct and independent assessment of the photon history. The mean path length of the impinging photons through the scattering material was estimated, which together with the magnitude of the gas absorption, determines the concentration of the dispersed gas.

This new opportunity of observing free gas in scattering media not only allows static gas assessment but also the study of dynamic processes, *i.e.* how gas is exchanged with the environment. The fields of application of the new technique include medical diagnostics, material technology, geophysical monitoring, etc, where the use of laser absorption spectroscopy provides fast, sensitive, nonintrusive and selective measurements of embedded gases in scattering media.

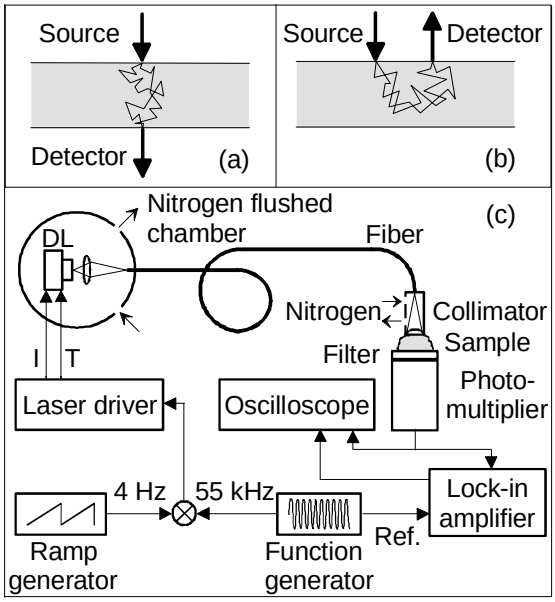

Fig. C7. *(a), (b) Basic geometrical arrangements for monitoring of free gas in scattering media. (c) Experimental set-up of the initial experiments.*

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D. Laser Applications in Medicine and Biology

All research conducted at the Division concerning laser spectroscopy applied to biomedicine is conducted within the framework of the Lund University Medical Laser Centre. The "medical group" at the division can be considered as a core group at the Medical Laser Centre, with a highly interdisciplinary approach to developing and evaluating novel optical tools for both diagnostic and therapeutic purposes. The aim of the Centre is to support multidisciplinary projects using lasers in medical research, to run courses and seminars in related topics, to act as a base for grant applications and to act as a partner in multicentre research studies. The activities within the Centre cover a wide field of interdisciplinary research, involving clinicians from various clinical specialities, physicists and chemists. In our presentation of the personnel involved in the different projects, only people affiliated to the Division of Atomic Physics are listed. A large number of collaborators, within and outside the Medical Laser Centre, also contribute to our work.

The research at the Division of Atomic Physics involves tissue characterization using laser spectroscopic techniques and laser treatment of malignant tumours. The tissue diagnostic research has mainly been directed towards early detection and identification of premalignant and malignant lesions. We are currently participating in four European projects within the field: Laser Assisted Investigations in Cardiology (LAIC), Optical Mammography (OPTIMAMM), Medical Photonics (MedPhot) and Virtual European Laser Institutes (VELI). Below, the different projects are briefly presented with citations to the original publications.

D1. Photodynamic therapy

Photodynamic therapy (PDT) is an treatment modality for various diseases under development and evaluation. The procedure is based on a photochemical reaction in which a photosensitizer absorbs light and reacts with tissue oxygen. The sensitizer is applied to the patient systemically or topically and accumulates selectively in lesion cells. Illumination with light at the wavelength of the absorption peak of the photosensitizer results in the formation of tissue radicals (e.g. $^1O_2$) which lead to immediate tissue necrosis. Secondary effects include vascular damage, induction of apoptosis and inflammatory reactions.

The limitations of the treatment procedure are the selectivity of photosensitizer, the penetration depth of the photosensitizer after topical application, tissue oxygen concentrations and light fluence rate in the different tumour regions. These limit the treatable tumours to superficial lesions of limited thickness. To understand and improve the treatment procedure we have conducted different measurements in

connection with PDT of skin malignancies. Also, by inserting optical fibres into the lesion - interstitial PDT, it is possible to improve the light penetration and to treat thicker lesions.

Superficial PDT

Stefan Andersson-Engels, Inga Karu, Claes af Klinteberg, Sara Pålsson, Katarina Svanberg, Sune Svanberg and Ingrid Wang

One clinical trial has been completed, in which PDT was compared with cryosurgery for the treatment of non-melanoma malignant lesions. The clinical results showed that PDT is comparable to conventional treatment methods in terms of response. PDT causes less scar formation and more normal tissue is saved using PDT compared with cryosurgery. The effect of fractionating the treatment light [1] was studied and also the pain sensation during treatment [2]. The investigations showed that fractionation did not alter the results of the treatment and that some patients felt itching and/or prickling during illumination, but in all cases the patients endured the treatment without local anaesthetic.

We have also performed a small pilot study of PDT (five patients) regarding the treatment of psoriasis. In this case the pain was extremely high, and could not be tolerated by one patient. The clinical results two months after treatments are inconclusive.

Interstitial PDT

Stefan Andersson-Engels, Thomas Johansson, Inga Karu, Claes af Klinteberg, Sara Pålsson, Eva Samsoe, Marcelo Soto Thompson, Maria Stenberg, Katarina Svanberg and Sune Svanberg

To be able to treat thicker lesions and lesions located inside the body, a system for interstitial PDT (IPDT) has been developed [3]. It consists of a beam-splitting unit, which divides the output light from the treatment diode laser beween six individual 400 μm optical fibres. The fibres are inserted into the tumour according to calculations of light fluence. Experimental studies have been performed on rats with tumours on the hind legs, see Figure D1. The results show that volume decrease was found in 85% of the treated tumours [4]. The average tumour volume reduction was 44% with one tumour completely disappearing. Two clinical trials have been performed. More experiments are clearly needed to fully optimize this novel treatment procedure. Experiments using only two fibres inserted into tumour tissue and normal muscle have been performed to measure the contribution from one fibre and investigate the biological variability. The result of treating a tumour with two fibres is shown in Figure D2. A tissue phantom has been constructed for reference measurements. We are also co-operating with researchers from Risø National Laboratory in Denmark, who are developing a fibre-coupled external-cavity diode laser, which may be useful for interstitial PDT.

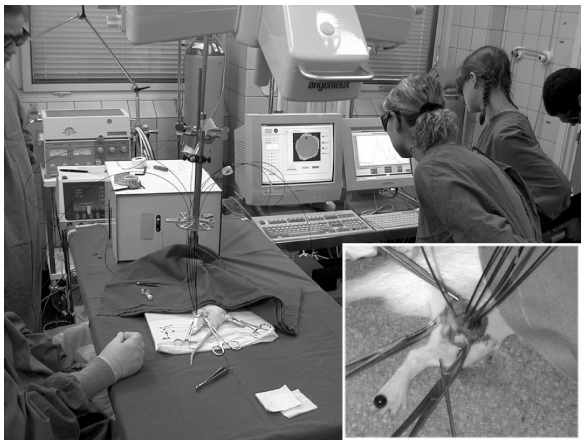

Fig. D1. *Photograph from experimental treatment of a tumour with interstitial PDT.*

Fig. D2. *Slices of a tumour resected three days after IPDT are shown. The lighter areas in the slices indicate tumour necrosis, while the dark areas are due to bleeding.*

Measurements in combination with photodynamic therapy

Stefan Andersson-Engels, Thomas Johansson, Inga Karu, Claes af Klinteberg, Sara Pålsson, Marcelo Soto Thompson, Maria Stenberg, Katarina Svanberg, Sune Svanberg and Ingrid Wang

To improve the understanding of the treatment mechanisms of PDT using δ-amino laevulinic acid (ALA) as sensitizer and optimise the treatment procedure, a number of measurements were performed in connection with the treatment, e.g. laser-induced fluorescence (LIF) spectroscopy, laser-Doppler perfusion measurements and temperature measurements.

The spatial and kinetic production of the PDT-active Protoporphyrin IX (PpIX) has been measured with laser-induced fluorescence spectroscopy [5-6]. Using an esterified sensitizer, it was found that the selectivity and penetration depth could be increased [7].

We have also measured the superficial blood perfusion in the lesions, before and after treatment. The results show that the perfusion increased after application of the sensitizer [7-9]. After PDT, the perfusion was, on average, higher for lesions treated with methyl esterified ALA than those treated with normal ALA. This suggests different treatment mechanisms.

The skin temperature of basal cell carcinomas (BCCs) during PDT was measured using an infrared camera [8]. The temperature was seen to increase a few degrees, but was well below the level of hyperthermia.

D2. Tissue diagnostics

Taking into account the different spectral properties between healthy tissue, slightly lesional and lesional tissue, several studies have been performed in various clinical areas. Much work has also been devoted to the development of methodologies and instrumentation to measure the fundamental optical properties of tissue. Further development of existing treatment modalities, equipment and improvements to the methods of data analysis are of major importance, and have resulted in several theses [10-12].

Fluorescence spectroscopy

Stefan Andersson-Engels, Charlotta Eker, Thomas Johansson, Inga Karu, Claes af Klinteberg, Sara Pålsson, Marcelo Soto Thompson, Maria Stenberg, Katarina Svanberg, Sune Svanberg and Ingrid Wang

Two new fluorosensors have been developed within the group [13-15]. The first is a relatively advanced system using several excitation wavelengths and with the capacity to measure time-resolved fluorescence spectra. The second is a compact fluorosensor, consisting of a blue diode laser, fibre optics and a small, integrated spectrometer. The box is only 22 x 13 x 8 cm^3 and together with a laptop computer. It is easy to transport.

In two different fluorescence studies we have followed the kinetics of PpIX accumulation following the application to ALA cream on patients with BCCs. The first study was concerned with 5 superficial and 10 nodular BCCs on 15 patients [6]. The lesion and adjacent healthy tissue was investigated prior to the application of ALA, 2, 4, and 6 hours post ALA application, immediately after and 2 hours after PDT. The results showed a maximum accumulation of PpIX 6 hours after application of the ALA cream for the superficial lesions, while the nodular lesions exhibited their corresponding maximum 2-4 hours after the application of ALA.

The second study was carried out using essentially the same protocol, but using different types of ALA [7]. In addition to ALA, methyl-esterified ALA (ALA-ME) was also used, the latter being more lipophilic than ALA, possibly resulting in a greater penetration depth. A total of 30 BCCs on 11 patients were included in the LIF part of the study, the results of which indicated a higher and more selective build-up of PpIX in the tumours treated with ALA-ME than those treated with ALA. To improve the statistics of this data, a study is in progress including 50 lesions each with ALA and ALA-ME.

Further, fluorescence imaging studies have been performed on skin lesions [16]. The aim of this study was to investigate the localization of skin tumours after the topical application of ALA, by detecting the PpIX fluorescence either in the spectral or in the time domain. Two fluorescence imaging systems were used to identify BCCs after topical application of ALA. Both systems rely on the

comparison between the exogenous and the endogenous fluorescence. Clear demarcation of skin malignancies was seen *in vivo*, noninvasively, with both fluorescence imaging systems. The two complementary approaches applied in this study show promise for skin tumour detection and delineation based on specific fluorescence features.

In several other studies, fluorescence has been recorded from small suspected lesions in order to evaluate the potential of laser-induced fluorescence as a tool to assist the examining doctor in tumour diagnosis. One study was aimed at estimating the extent and severity of lesions on the vocal fold suspected of being malignant [17].

Fluorescence spectra from colonic mucosa were measured *in vivo*, with and without ALA, in an attempt to differentiate between neoplasia and non-neoplasia in real time during colonoscopy [18]. Thirty-two adenomas, 68 normal sites, and 14 hyperplastic polyps in 41 patients were studied. Twenty-one of the patients had been given a low dose of ALA and light of 337, 405 or 436 nm wavelength was used to induce fluorescence. With 337 nm excitation, 100% sensitivity and 96% specificity was obtained between normal mucosa and adenomas. Seventy-seven per cent of the hyperplastic polyps were classified as non-neoplastic. When using excitation of 405 and 436 nm, the possibility of distinguishing between different types of tissue was considerably better in the ALA patients than in the non-ALA patients. The *in vivo* point measurements indicated that good discrimination could be obtained between normal tissue and adenomatous polyps using LIF. LIF also showed potential for distinguishing adenomatous from hyperplastic polyps.

Measurements on biopsies from patients with transplanted hearts have been performed [19]. The results showed that it is possible to distinguish fibrotic myocardium from normal tissue. However, there seems to be no apparent difference between rejected and normal tissue, but the number of measurements is very low.

A study employing fluorescence spectroscopy in the brain has been initiated together with brain surgeons in Linköping. The aim is to be able to detect infiltrating brain tumours during stereotactic biopsy using fibre optics.

Vibrational spectroscopy

Stefan Andersson-Engels, Bethlehem Araya, Peter Snoer Jensen, Hedda Malm and Sara Pålsson

A Raman spectroscopic system for medical applications was subject of a Master's dissertation in 2000 [20]. The design of the Visionex Raman v1.0 Enviva biomedical fibre was studied and two different detectors were investigated (Andor EEV CCD30-11 and Princeton Instruments L/NCCD-1024-EHRB/1). The dissertation also included estimates of the maximum penetration depth from which

Raman signals could be recorded. Furthermore, a new potential application in measuring the potassium concentration in human bone was assessed.

We are also collaborating with Risø National Laboratory in Denmark, in a project aimed at developing and evaluating FT-IR spectroscopy in the near-infrared and mid-infrared regions for biomedical applications.

Optical properties of tissue

Stefan Andersson-Engels, Claes af Klinteberg, Tuan Pham, Johannes Swartling and Jan Sørensen Dam

Knowledge of the optical properties of tissue forms the fundamental basis in most activities in the field of biomedical optics. For therapeutic applications, such as PDT and laser-induced thermotherapy, it is important to achieve optimal light doses by combining optical properties and light-propagation models to predict the effects of the treatment. For diagnostics, such as laser-induced fluorescence and tissue transillumination, the diagnostic information depends on the optical response of the tissue, which again can only be predicted by the optical properties and suitable light-propagation models. In December 2000, Jan Sørensen Dam defended his doctoral thesis ”Optical analysis of biological media – continuous wave diffuse spectroscopy [21]. His work was closely related to the measurements of the optical properties of tissue.

At the Division, a number of methods of measuring the optical properties of tissue have been developed and investigated. Several permanent systems have been built and are available to support day-to-day research. The properties most often used to describe the optical characteristics of tissue are the absorption coefficient, μ_a, and the scattering coefficient, μ_s. Sometimes, the scattering phase function, which describes the amount of forward scattering by the tissue, is of importance, and is usually expressed as the mean cosine of the scattering angle, denoted g. These properties vary with wavelength, so spectral resolution adds one more degree of freedom.

The general problem of measuring the optical properties is an inverse problem. This means that the response from an illuminated tissue sample is measured using an experimental set-up. The response is then indirectly related to the optical properties by means of a light-propagation model. The problem is non-linear, which means that sophisticated numerical algorithms are necessary.

Several systems are available at the Division for determining the optical properties of tissue. For accurate measurements of the properties of excised tissue samples, the integrating sphere method is ideal (see Figure D3 a). The integrating sphere allows the measurement of the total transmitted as well as total reflected light intensity from thin samples. As a third measurement the collimated transmittance can be measured in a separate set-up to suppress the scattered light.

Another type of method involves spatially resolved diffuse reflectance measurements of the surface of the tissue. The advantage of this method is that it can be applied *in vivo*, *e.g.* directly on the skin of the patient. The surface is illuminated in a spot, and the reflected intensity is measured at different distances from the spot. Two such systems are available at the Division. The first is an imaging Fourier transform spectrometer, which can record multispectral images of the tissue surface [22] (see Figure D3b b). The second is a specially designed fibre probe, developed by Jan Sørensen Dam at Bang & Olufsen Medicom A/S, where diode lasers are used as light sources and optical fibre bundles collect the reflected light[23] (see Figure D3 c).

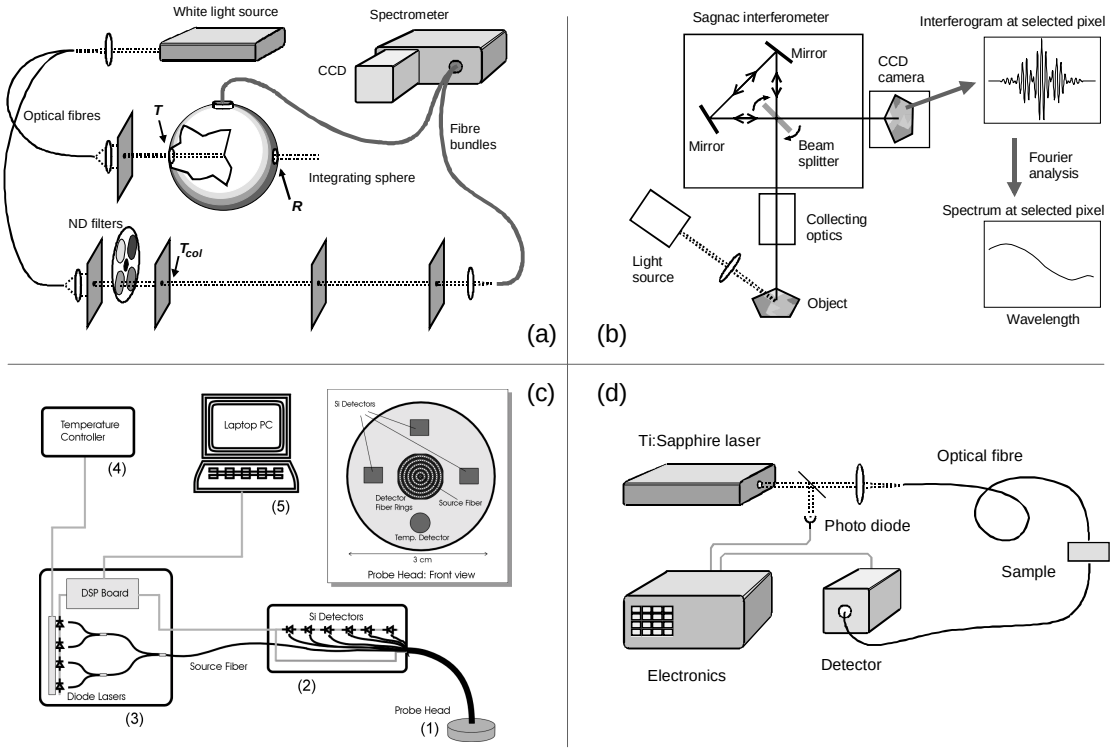

Fig. D3. *Four systems for measurements of the optical properties of tissue are depicted. (a) The optically integrating sphere system. (b) The imaging Fourier transform spectrometer. (c) The Bang & Olufsen fibre probe system. (d) The time-resolved measurement system.*

A third means of extracting optical properties is based on time-resolved measurements of the dispersion of very short laser pulses propagating through the tissue (see Figure D3 d). This method requires slightly more advanced and expensive technology compared with the others, but has several promising benefits. For example, it is suitable for investigating deep into the tissue, and it is possible to perform tomographic reconstruction of the optical properties inside the body. At the Division, both pulsed diode lasers and a mode-locked Ti:Sapphire laser are available as light sources. A time-correlated, single-photon-counting detection instrument is used to obtain the time-resolved data.

White-light, ultra-short high-power pulses can be employed to obtain spectral information from time-resolved measurements. Either the 10 Hz terawatt laser, or the new kHz terawatt laser at the Division, can be focused in a suitable material, such as water, to give femtosecond pulses with a broad spectrum due to non-linear effects. By using a streak camera to detect the light, it is possible to obtain virtually the same information as with the time-resolved system, but for many wavelengths simultaneously.

To extract the optical properties from the measurements, advanced numerical methods have been developed. For the integrating sphere and the diffuse reflectance systems, Monte Carlo simulation is usually employed as the model for light propagation. It is also possible to directly calibrate the system against a set of phantoms with known optical properties. This was done for the fibre probe system. Irrespective of which method is used, the non-linear nature of the problem calls for special care. A powerful method that relies on fitting the results from the light propagation model (or calibration measurements) to multidimensional polynomials has been developed. The optical properties can be determined by comparing the measured data with the polynomials using a generalised Newton-Raphson algorithm [24].

The time-resolved measurements can successfully be modelled using diffusion theory. Since the distance between the light source and detection point is relatively large, and the scattering is high, the propagating light resembles a diffusing ”gas” of photons.

Apart from investigating methods for measuring the optical properties of tissue, one project at the Division has been aimed at measuring the optical properties of flowing blood. Knowledge of the scattering and absorption of blood is important for diagnostic applications, for monitoring parameters such as haemoglobin concentration, oxygenation, and various other constituents of blood. The optical properties were measured in the integrating sphere set-up, and yielded new information on how the scattering from red blood cells changes due to varying flow conditions.

Looking to the future, a new project involving several research groups throughout Europe has started with the aim of developing a new method of detecting breast cancer, based on the time-resolved transillumination technique. The technique was pioneered at the Division a decade ago. The basis of the method, which could provide an alternative to X-ray mammography, is to measure the optical properties of the breast tissue and detect any variation between normal and cancerous tissue. The project will make use of all of the resources for measurements of optical properties of tissue at the Division. A study has been conducted together with University of California, Irvine, to non-invasively determine the blood, water, and fat content in human breast tissue using frequency-domain photon migration spectroscopy [25].

Microscopy

Stefan Andersson-Engels, Jenny Pettersson, Michael Sebesta, Tommy Sjöberg

Several projects are ongoing using the confocal microscopy system at the Division. In one collaborative project between Dr. Clemens Kaminsky at Division of Combustion Physics and the group at Experimental Pathology, we have used the technique of Fluorescence Resonance Energy Transfer (FRET) to measure collocalisation of proteins in human cells. We have also employed fluorescence microscopy to study the localisation of PpIX in biopsies collected from BCCs just before PDT. These studies aim at understand the diffusion properties of ALA and ALA-ME in this type of lesions. In further another project, we have tried to optimise the signals obtained in two-photon microscopy by introducing a pulse-stretcher in the laser beam-line, compensating the dispersion in the optics.

D3. Analytical chemistry

The different detection techniques used in analytical chemistry constitute an interesting area of research. UV absorption and laser-induced fluorescence are the two main techniques used for detection in liquid samples. Collaboration between the Divisions of Atomic Physics and Technical Analytical Chemistry at the Lund Institute of Technology was initiated a few years ago, and several projects are now in progress.

Airborne chemistry in levitated drops

Thomas Johansson

A miniaturized analysis system for the study of living cells and biochemical reactions in microdroplets has been developed [26]. The system consists of an in-house-developed piezoelectric flow-through droplet dispenser for precise reagent supply and an ultrasonic levitator for contactless sample handling. To evaluate the system, a study was performed with living primary adipocytes. 500 nL droplets containing 3-15 individual cells were acoustically levitated. The addition of β-adrenergic agonists into the levitated drop using the droplet dispenser stimulated adipocyte lipolysis, leading to free fatty acid (FFA) release and a consequent pH decrease of the buffer. The addition of insulin antagonised lipolysis and hence also the decrease in pH. The change in pH, *i.e.* the cell response in the drop, was followed using a pH-dependent fluorophore monitored by fluorescence imaging detection. An image analysis computer program was used to calculate the fluorescence intensity of the drops. To counteract drop evaporation, which was found to affect the fluorescence intensity, a separate dispenser is used to continually add water, thus keeping the drop volume constant.

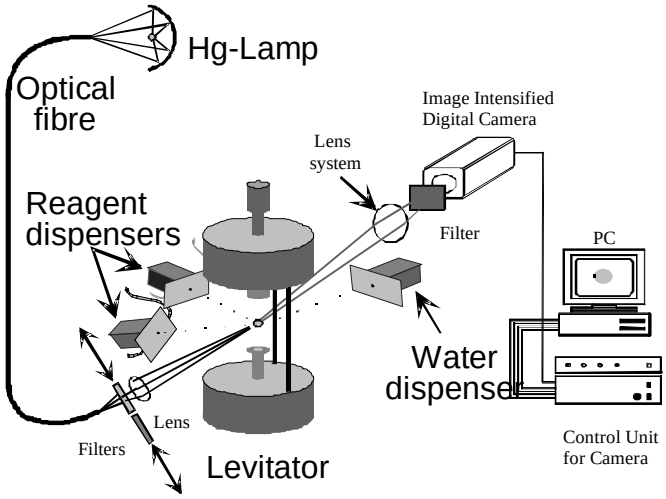

Fig. D4. Instrumental setup for levitated cell experiments using fluorescence imaging detection.

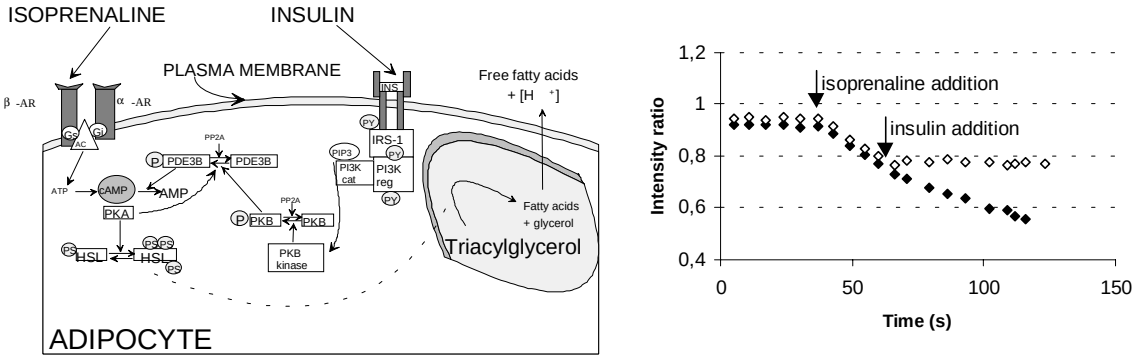

Fig. D5. Left, proposed mechanism for stimulation and inhibition of lipolysis in adipocytes. Right: lipolysis of 12 individual adipocytes in a levitated droplet initiated by the addition of 100 nM isoprenaline, detected using a fluorescence imaging technique. In one of the experiments (◊) the lipolysis was terminated by the addition of 1 nM insulin. In the other (♦), the lipolysis was allowed to continue throughout the experiment.

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E. Optical Diagnostics of Charged Surfaces, Dielectric Materials and Paper

In this chapter we describe the development of techniques for remote non-intrusive optical diagnostics of materials and events of relevance in electrical insulation systems and a programme concerning optical diagnostics paper material that is carried out in co-operation between the Center for Imaging Science and Technologies at Halmstad University and the Division of Atomic Physics at LTH.

E1. Optical diagnostics of charged surfaces and dielectric materials

Magnus Bengtsson, Stefan Kröll and Anders Larsson

Measurement of surface charge

All electrical systems rely on the dielectric strength of their electrical insulation. The electrically weakest point of insulator systems is normally the surface of the insulators. One property of the surface that determines the ability of a surface discharge to propagate is the ability to bind electric charge at the surface. The objective of this project is to develop a non-invasive technique for remote sensing of the charge density on dielectric materials. The primary area of application is the development of new polymeric materials for high-voltage insulators.

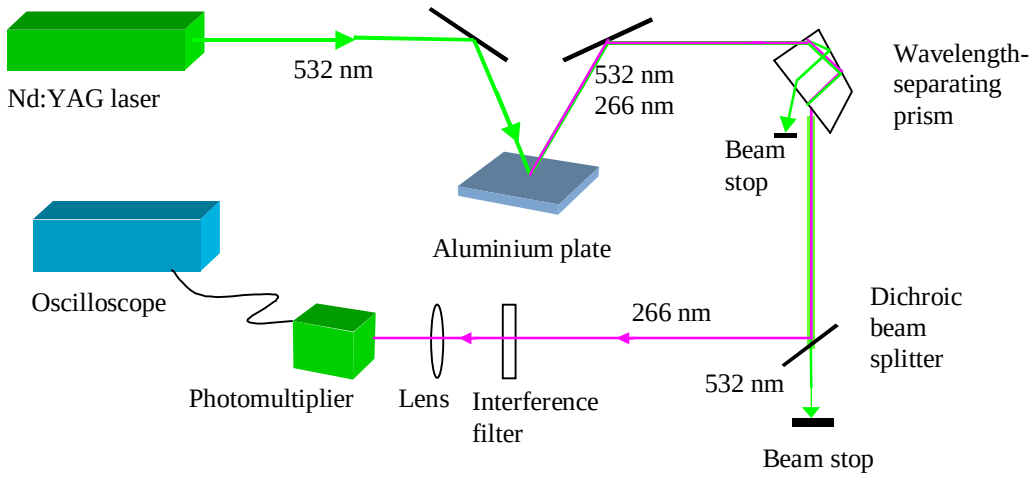

Fig. E1: *Experimental set-up for the measurement of the second harmonic generated at a surface.*

The primary objective will be achieved by utilising non-linear optical processes. When a high-power laser beam is reflected or scattered at an interface, it may be subjected to a non-linear process in which two photons of one frequency are annihilated and one photon of twice the frequency is emitted. This process is called second harmonic generation (SHG). SHG is greatly enhanced in the presence of spatial asymmetry. Surfaces and surface charge are examples of such spatial asymmetries. The project is in its initial stage, and the present status is that the SHG

signal from an aluminium plate has been measured. Current activities are concerned with the theoretical analysis and construction of an experimental set-up for the study of the charge on metal surfaces.

Mid-gap laser-triggered electrical breakdown in dielectric liquids

Pre-breakdown and breakdown phenomena in liquid dielectrics have been studied extensively during recent decades. The understanding of these phenomena has been greatly improved by the advent of new diagnostic tools and techniques. One such new technique is the combination of laser triggering and the laser shadow method, as introduced by researchers at the Division of Atomic Physics. In laser triggering, a laser pulse is focussed in the electrode gap where a plasma is formed in the focal region. The plasma develops into a high-pressure gas-filled cavity that expands and eventually triggers the disruptive discharge. In the laser shadow method (shadowing), the probe volume is illuminated with collimated laser light. An event in the probe volume with a refractive index different from that of the surroundings diverts the collimated light and a shadow appears in the line of sight. The expansion of the cavity and pre-breakdown discharge phenomena in mid-gap laser-triggered dielectric breakdown in transformer oil were imaged using the laser shadow method. The physical mechanisms and the timing sequence of this dielectric breakdown were revealed from the analysis of these measurements [E1], [E2].

Remote and non-intrusive diagnostics of high-voltage insulation materials using laser-induced fluorescence spectroscopy

A new method for remote and non-intrusive diagnostics of high-voltage insulation and insulation materials is under development in collaboration with the Division of High Voltage Engineering at CTH (Göteborg) and the Department of Polymer Technology at KTH (Stockholm). The method is based on laser-induced fluorescence (LIF) spectroscopy of the surfaces of polymeric insulator materials. High-voltage insulators made of polymeric materials are replacing traditional insulators made of porcelain or glass. The new insulators have several advantages, such as having a lower weight, being shatterproof and being easier to work with. However, the main advantage is that insulators made of polymer material have significantly better insulation properties. Their better performance is due to their surface properties; a polymeric surface is highly water-repellant (*i.e.* hydrophobic) whereas water forms a film on a porcelain surface (*i.e.* hydrophilic). Severe environmental conditions can, however, cause permanent or temporary loss of hydrophobicity. High-voltage insulators of polymeric materials with good hydrophobicity are therefore often pessimistically designed for a hydrophilic state. This means that the benefits of using a polymeric material instead of porcelain are not utilised to their full potential. Today, there is still no standardised or widely used technique for inspecting polymeric insulators in the field. However, several techniques, applicable to live insulators, are now being used to assess the state of non-ceramic insulators in service, and to organise and plan maintenance work. These techniques include visual inspection, image intensification (using a night-vision camera), infrared thermography, electric field distribution measurements and

directional wireless acoustic emission. One disadvantage of these techniques is that only large defects can be detected (punctures and cracks) and not deterioration and changes in the hydrophobic properties of housing materials. High-resolution methods, such as *electron spectroscopy for chemical analysis* (ESCA) and *time of flight – secondary ion mass spectroscopy* (ToF-SIMS), give detailed information about the surface, but are intrusive methods. LIF surface spectroscopy is a method that is both non-intrusive and can give detailed information about the properties of the surface under study. Initial measurements have shown a difference between outdoor insulators that have been exposed to different weather conditions [E3], but further work is needed to assess the potential of the approach.

Lightning and aircraft, and electrical breakdown in air

A lightning strike is a natural electrical discharge and lightning strikes to aircraft are frequent and unavoidable events. On average, every civilian airliner is struck by lightning about once per year. Thus, the issue of lightning protection of aircraft is of utmost importance. In response to this need, the European Commission supports the research programme *Methods and Technologies for Aircraft Safety and Protection against Electromagnetic Hazards* (EM-Haz) within their *Fifth RTD Framework Programme*. Office National d'Etudes et de Recherches Aérospatiales (ONERA) is one of the partners in EM-Haz. ONERA and the Divisions of Combustion Physics and Atomic Physics are collaborating in a sub-project within EM-Haz, namely in the analysis of the lightning swept stoke. This work is a continuation of the postdoctoral visit by Anders Larsson at ONERA during 1998-99 [E4-E8].

During the lightning strike to an aircraft in flight, the lightning channel is deformed and displaced along the aircraft, a so-called *swept stroke*. The deformation and the displacement are caused by the interaction between the aerodynamic flow and the plasma properties of the channel together with the properties of the surface. A major part of the lightning current is comprised of a continuous current with a magnitude of hundreds of amperes and a duration of hundreds of milliseconds. High-amplitude current impulses are superimposed on this continuous current. Eventually, the continuous current stops and only high-amplitude current impulses occur separated by zero-current intervals. During the flight of the aircraft, the attachment point of the lightning channel will sweep along the body of the aircraft. The lightning current and the location of the attachment point are potential hazards for flight safety, both in terms of direct effects (thermal or mechanical damage) and of indirect effects (electromagnetic interference with on-board equipment). To be able to correctly determine the different levels of hazards on an aircraft (zoning), the physical behaviour of the lightning swept stroke must be understood.

Further work concerning electrical breakdown in air is being carried out in connection with the High Performance Outdoor Electrical Insulation project (ELIS), which is supported by the Swedish Foundation for Strategic Research (SSF). This includes simulation of streamer discharges [E9, E10], measurements of streamer current [E11] and streamer charge [E12], and laser triggered electric breakdown [E13].

E2. Optical diagnostics of paper

A co-operative research group consisting of scientists from the Divisions of Atomic and Nuclear Physics at LTH and the Center for Imaging Science and Technologies has been formed at Halmstad University. It operates together with four newsprint producing papermills, within the Stora Enso and the Holmen groups, concerning paper physics, printing and print quality evaluation. The research areas are optical methods, nuclear techniques, signal analysis, colour classification and development of fast non-destructive sensor systems.

A red fluorescence sensor for noncontact on-line measurements in paper production

Carl Magnus Nilsson, Lennart Malmqvist and Jörgen Carlsson

A robust sensor has been developed for on-line measurements in paper production [E14]. The sensor is designed for optimal response to lignin in paper. A diode laser operating at 630 nm is used for excitation. The fluorescence light in the wavelength region 660-740 nm is then detected. A compact photomultiplier tube is used for fast detection with a high signal-to-noise ratio. The system can make up to 1.2 million measurements per second. The distance between adjacent measuring points can hence be as short as about 20 μm, even at a paper speed of 25 m per second, as is common with a modern newsprint paper machine. The recording system has the capacity to store data continuously for 45 minutes at this sampling rate. In addition, data from three more sensors can be recorded simultaneously, with the same resolution. With this high-capacity sensor system, the performance of a paper machine can be monitored at much higher temporal and spatial resolution than has traditionally been possible.

Application of optical fluorescence spectroscopy to paper production

Jörgen Carlsson, Lennart Malmqvist, Carl Magnus Nilsson and Willy Persson

Fluorescence light emitted from paper following the absorption of either ultraviolet or visible light has a wavelength distribution determined by the chemical composition of the paper. This can be used for both laboratory measurements of paper characteristics and for on-line monitoring of the paper during production. Such measurements can be performed non-intrusively at sampling rates high enough to give sub-millimetre resolution in the machine direction in a paper machine or rewinder. In this project, two types of fluorescence monitors have been constructed [E15, E16]. They operate at different wavelengths and thus monitor different substances in the paper. The monitors have been tested at newsprint-producing paper mills together with an optical speedometer. The measurements in

the production environment have shown that the equipment is capable of indirectly monitoring paper quality parameters which affect the local abundance of lignin.

Study of paper shrinkage using fluorescence technique

Carl Magnus Nilsson

Non-uniform shrinkage of the paper in the drying section of the paper machine is undesirable. Relaxation of the shrinkage in the printing press can jeopardise the printing quality. The shrinkage of newsprint can be monitored from cross directional profiles using the lignin monitor and a device for scanning the profiles in the laboratory.

Fluorescence measurements at long wavelengths appear to be affected by the local basis weight of wood-containing paper. The spatial resolution of the lignin monitor is limited by the spot size, which can be as small as 0.1 mm. At realistic speeds, the distance between samples can be less than 0.1 mm. The resolution is thus good enough to motivate a search for wire mark information in the lignin signal. The separation of the wire marks can then give information on the shrinkage during drying and on the variation of the shrinkage in the cross direction.

In these shrinkage studies [E17], cross-directional profiles are scanned in the laboratory. The frequency components of the signal can be obtained by applying spectral analysis. Among these frequency components regular patterns in the local abundance of lignin will appear as peaks. In Figure E2 (left) the power spectrum density of a cross-directional profile of 45 g/m^2 newsprint is shown. The two strong peaks in the spectrum are the result of wire marks in the paper. Using precise velocity data the frequency peak at 226 Hz was found to correspond to a distance of 0.43 mm and the peak at 349 Hz to a distance of 0.65 mm. These distances have been matched to the specifications of fabrics used in the paper machine.

In order to obtain the shrinkage profile, the distance between the wire marks at different positions across the web has to be calculated. This can be done using time-frequency analysis. Such a result is illustrated on the right in Figure E2. The horizontal axis represents the distance across the web and the vertical axis the frequency information for each position. The stripes extending across the profile are caused by the wire marks. These stripes are curved, being bent upwards at the edges of the web. This means that the distance between the wire marks is shorter at the edges than at the centre of the web. This can be interpreted as a result the non-uniform drying across the web. The edges shrink more than the centre of the web. It should be remembered that this is a relative shrinkage measurement. In order to obtain the absolute shrinkage profile the deformation of the fabric in the paper machine should also be considered.

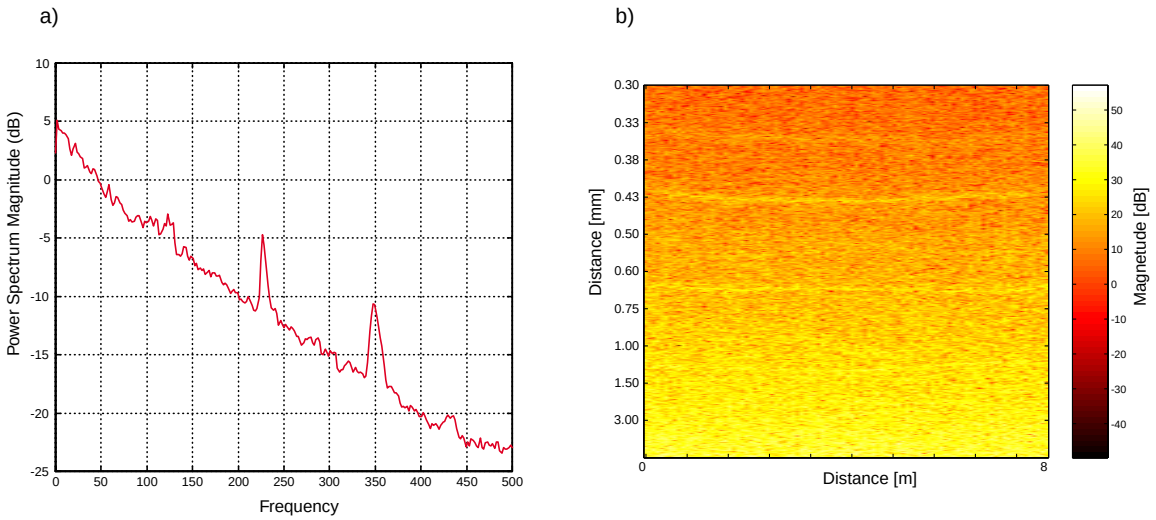

Fig. E2. *Frequency analysis of the cross-directional profile from newsprint (left). The two peaks at 226 and 349 Hz are caused by the wire marks. The shrinkage profile obtained from the time-frequency analysis (right).*

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F. Teaching Programme

Lecturers and physics course representatives: *Stefan Andersson-Engels, Lars Engström, Maria Gerling, Günter Grossmann, Gilbert Jönsson, Göran Jönsson, Gabriele Kalus, Claes af Klinteberg, Stefan Kröll, Jörgen Larsson, Anne L'Huillier, Hans Lundberg, Johan Mauritsson, Daniel Nilsson, Elisabeth Nilsson, Thomas Nilsson, Rolf Petersson, Sven-Göran Pettersson, Nina Reistad, Stacey Ristinmaa-Sörensen, Jonas Sandsten, Ingela Simonsson, Sara Pålsson, Anders Sjögren, Kristina Stenström, Sune Svanberg, Claes-Göran Wahlström, Joachim Walewski.*
Teaching assistants: *About 60 assistants for the laboratory work.*

F1 Undergraduate teaching

The Division of Atomic Physics gives basic physics courses for the Schools of Engineering Physics, Electrical Engineering, Computer Science and Technology, Mechanical Engineering, Civil Engineering, Fire Safety Engineering, Environmental Engineering, Chemical Engineering and Industrial Management and Engineering. Furthermore, specialised courses in *Atomic Physics*, *Laser Physics*, *Laser Technology*, *Advanced Optics*, *Non-linear Optics*, *Optical Quantum Electronics*, *Atomic and Molecular Spectroscopy*, *Multispectral Imaging* and *Medical Optics* are given. Courses not included in the programmes are *Colour Holography*, *Radon* and the *Technical Foundation Year* (a preparatory physics course on a level between upper secondary school and university).

The main purpose of the undergraduate courses is to provide a solid base for "life-long learning", a concept that is becoming increasingly important in the rapidly changing world of science and technology. Basic components in this strategy include underlining the interplay between theory and experiments, emphasizing that there are no absolute truths and that any model is only as accurate as can be verified experimentally. Other important aspects are the design and critical evaluation of models based on physical principles and experimental observations translated and analysed using the language of mathematics. Finally, our courses should develop the students' experimental skills and their ability to plan, execute and critically analyse experimental results. The specialised courses should also provide clear insight into current research projects at Lund University, Department of Physics.

The courses in physics include both theory and experimental work, and are based on lectures, problem-solving sessions and laboratory practicals. Lectures and problem-solving sessions stress the learning of fundamental physical principles and their applications. Whenever possible, the detailed contents of the courses are closely

related to the large variety of basic and applied research projects within the Department of Physics. The laboratory work provides experience in the design of experiments and illustrates the validity and limitations of theoretical models. During laboratory sessions in the basic courses students work in groups of two, and each supervisor teaches 8 students at a time. For the specialised courses the number of students per supervisor is reduced to 4 or 6. In the courses on atomic and molecular spectroscopy and advanced optics, research equipment is used by the students in their experimental work.

A survey of the courses given by the Division of Atomic Physics is given in Table 1.

F2 Basic courses

Students at the School of Engineering Physics take three compulsory courses. *Introductory Physics, Optics,* and *Atomic Physics*. *Introductory Physics* comprises experimental methods, general physics and thermodynamics. An introduction to the research activities at the Department of Physics is also included. *Optics* is a fairly advanced course given at the end of the second year, which allows the students to become well acquainted with physical optics in general, and various optical materials and their properties, as well as spectroscopic techniques utilizing interferometers and gratings in particular. The optics course thus lays the experimental foundation for the study of atomic and molecular spectra, and for specialised laser physics courses. *Atomic Physics* provides students with basic knowledge on the structure and dynamics of atoms and molecules. It also illustrates quantum mechanics as the basis for modern physics.

A basic course in physics is given for students at the School of Electrical Engineering. This comprises general physics, thermodynamics, optics, waves and modern physics combined with laboratory work. From 2001 the contents will be slightly changed.

Students at the School of Computer Science and Technology and the School of Environmental Engineering are also given a basic course in physics. The course covers traditional areas of physics such as experimental methods, mechanics, thermodynamics, heat transfer, optics, and atomic, molecular, atmospheric and nuclear physics. From 2001 the physics course for students in computer science and technology will be changed concerning the contents and the number of credits.

A basic course is also given for students at the School of Mechanical Engineering. This course consists of general physics, optics, waves and atomic physics combined with laboratory practicals.

A course in physics is given for students at the School of Industrial Management and Engineering, which has much the same content as that given at the School of Mechanical Engineering.

For students at the School of Civil Engineering and Fire Safety Engineering basic courses in physics are given. These consist of general physics including thermodynamics, fundamental electricity and measuring techniques, combined with laboratory practicals. For students in their fourth year, courses are given, on *Physical measuring techniques* and on *Radon physics*.

A basic course in physics is also given for students at the School of Chemical Engineering. This consists of fundamental electricity, wave physics, geometrical optics and measuring techniques, combined with laboratory work. The content of this course will, however, be changed next year.

F3 Specialised courses

The specialised courses *Laser Physics* and *Laser Technology* deal with the physical principles of lasers, the most common types of lasers and their applications in research and industry. In laboratory practicals the students learn how to study the fundamental properties of different lasers and to use the laser as a tool in optical measurements.

The specialised course *Atomic and Molecular Spectroscopy* provides knowledge about modern atomic and molecular spectroscopy with special emphasis on technical applications. Together with the laser physics course, this course forms the natural introduction to graduate studies at the Division of Atomic Physics.

The course in *Multispectral Imaging* deals with the extraction of physical and chemical information from images. The course covers imaging using radiation ranging from X-rays to microwaves, and applications from astronomy to microscopy. Four advanced laboratory exercises are included in the course.

A specialised course in *Advanced Optics* has been established at the Division. This course emphasizes Fourier optics, interferometry, fibre optics, holography and phase-conjugation techniques. There is a course in *Medical Optics*, covering light transport in strongly scattering media (such as living tissue) and laser-based therapeutic methods.

The graduate/undergraduate courses in *Non-linear Optics* and *Optical Quantum Electronics* are given in alternate years. These are essentially theoretical courses, which provide the background to non-linear interactions between light and matter and for lasers and laser amplifiers.

Courses in *Holography* are also available to those interested in photography, imaging techniques and optical measurements. The course starts with lectures on geometrical optics and wave optics and, together with laboratory sessions, the fundamentals of holography and related topics are discussed and different types of holograms are produced.

A basic course in physics is given for students in the *Technical Foundation Year* at the School of Engineering in Helsingborg, which is affiliated to LTH. A physics course for engineers, *Production Techniques*, is also given at Helsingborg.

The courses *Radon* and *Radon and Indoor Air Quality* involve measuring techniques, economical, geological and environmental aspects of this radioactive gas, which is present indoors, in the soil and in drinking water.

Course	***School/year***	***No. of students***	***Credit points***
Physics course, E	*E1*	160	9
Physics course, D	*D1*	130	9
Physics course , M	*M3*	140	6
Physics course, I	*I3*	50	6
Physics, basic course, V	*V2*	80	5
Physics, Measuring Practice, V	*V3*	10	3
Physics course, K	*K1*	130	5
Physics course, BI	*BI1*	50	5
Physics course, W	*W1*	60	7
Physics, basic course	*F1*	120	5
Optics	*F2*	90	4
Atomic Physics	*F3*	80	5
Laser Physics	*F4*	30	5
Laser Technology	*F4,E4,D4,M4*	30	3
Non-linear Optics	*F4*	10	5
Optical Quantum Electronics	*F4*	10	5
Advanced Optics	*F4,E4*	10	4
Atomic and Molecular Spectroscopy	*F3*	30	5
Multi-Spectral Imaging	*F4,D4,E4*	20	4
Medical Optics	*F4,D4,E4*	20	5
Radon and Indoor Air Quality	*V4*	10	5
Holography		10	4
Holography with project		10	6
Radon		10	5
Technical Foundation Year		40	16
Physics for Production Techniques		20	3

Table 1. *Courses given by the Division of Atomic Physics, 99/00. The number of student hours is between 10 and 20 per credit point.*

F4 Graduate teaching

Several of the specialised courses in Section F3 are given jointly for graduate and undergraduate students. These include Advanced Optics, Atomic and Molecular Spectroscopy, Laser Physics, Multi-Spectral Imaging, Medical Optics, Non-linear Optics and Optical Quantum Electronics.

In addition a new 5 credit point courses in Quantum Optics was given in 1999 and a new 2 credit point course in Quantum Computing was given in the Spring of 2000.

F5 Master's Projects

Several undergraduate students are performing their Master´s projects within the Atomic Physics Division. Below, those who completed their projects during the present period are listed, together with the title of their dissertations.

Magnus Johansson **Daniel Nilsson**	*Optical sensorsystem for coins,* *LRAP-242*
Fredrik Nordin	*Development of fast wavelength tuning system for OPO-based lidar measurements,* *LRAP-243*
Per Axelsson	*Computer modelling of the temperature distribution in high intensity focused ultrasound thermotherapy,* *LRAP-246*
Johan Mauritsson	*Generation of ultrashort laser pulses using gas-filled hollow waveguides,* *LRAP-247*
Xianjun Wang	*Experiment on optical data compression by using external cavity diode laser equipped with intra-cavity electro-optic crystal,* *LRAP-250*
Mikael Afzelius	*Theoretical modelling of temporal compression of optical pulses and pulse sequences using photon echoes,* *LRAP-251*
Anders Becker	*Development of a zoom probe for spatially resolved diffuse transmittance studies,*

	LRAP-252
Hedda Malm **Betlehem Araya**	*Raman spectroscopy for medical applications,* *LRAP-254*
Lars Borgström	*Construction and testing of a regenerative fibre amplifier based on an optical ring cavity,* *LRAP-255*
Veronica Wänman	*Spectral phase correction of femtosecond laser pulses using a deformable mirror,* *LRAP-258*
Ola Synnergren	*Temporal aspects of reflection and focusing of attosecond pulses,* *LRAP-260*
Lars Levin	*Construction and design of an electro-optically tunable mode-hop free external cavity diode laser,* *LRAP-261*
Mattias Nilsson	*Multi-bit data storage using photon echoes,* *LRAP-263*
Fabian Mellegård	*Development and construction of an automatic calibration unit for a differential absorption Lidar system,* *LRAP-264*
Marcelo Soto Thompson	*Mechanical venous drainage as a treatment for brain oedema.*
Andrea Köble	*A new method for reduction of photomultiplier signal-induced noise in lidar receivers.*
Lotta Gustafsson	*Photodynamic therapy and diagnostic measurements of basal cell carcinomas using esterified and non-esterified 5-aminolevalinic acid.*
Ilgars Schütz **Thomas Teikari**	*Electronic Radon detector. Report Department of Atomic Physics and Department of Applied Electronics 1998-10-19*