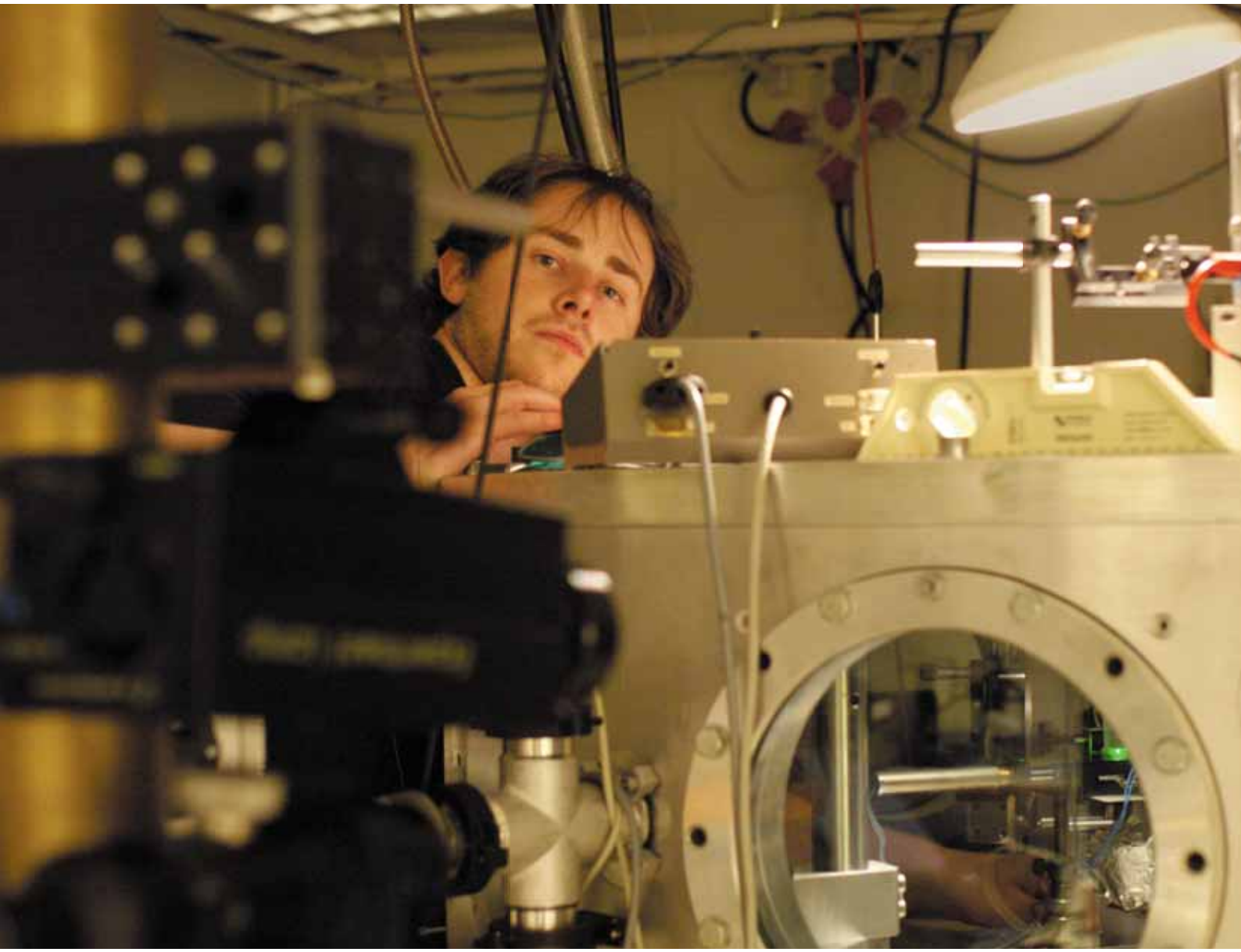
Lund Laser Centre

Lund University, Sweden



Lund
Laser Centre

Lund University

- Founded in 1666 in Lund, southern Sweden, now a city with 100,000 inhabitants
- 4 200 teachers and researchers
- Approximately 40 000 students
- Approximately 140 undergraduate and doctoral degree programmes

Lund Laser Centre – LLC

-
- A European Large-Scale Facility and partner in LASERLAB-EUROPE
-
-

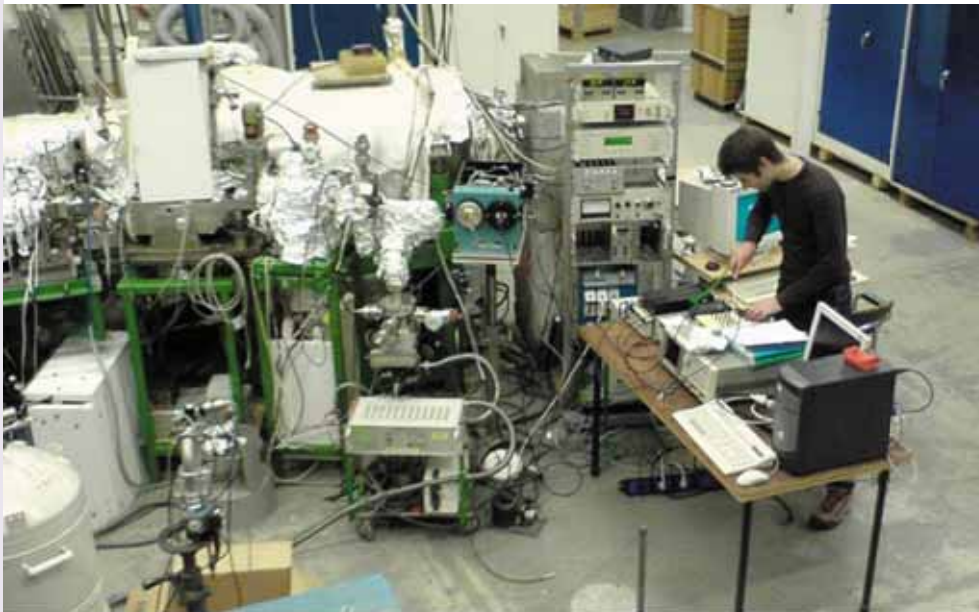
The following research divisions are members of the Centre:

- **Atomic Astrophysics**
  www.astro.lu.se
- **Atomic Physics**
  www.atomic.physics.lu.se
- **Chemical Physics**
  www.chemphys.lu.se
- **Combustion Physics**
  www.forbrf.lth.se
- **Lund University Medical Laser Centre**
  www.mlc.lu.se
- **MAX-lab Synchrotron Radiation Facility**
  www.maxlab.lu.se

$$\frac{n}{N_0} = \frac{1}{(m_1+c_1)^2} - \frac{1}{(m_2+c_2)^2}$$

Lund, home of the Rydberg Formula

Linnaeus Grant 2006-2016



Lund Laser Centre

Standing on tradition – advancing towards the future

LLC – The basis for research and teaching in optics, lasers and spectroscopy at Lund University

Lund has had a tradition in atomic physics and spectroscopy since the 1880s, when Prof. J. Rydberg published his famous formula describing the wavelengths of spectral lines. Since then, atomic spectroscopy, which is strongly affiliated to the field of astrophysics, has been a speciality at Lund, and is now being pursued using modern interferometers and lasers. The range of current research activities is very broad, from basic studies to applications in analysis and diagnostics.

LLC – A Linnaeus Centre

In 2006, the LLC was chosen as one of Sweden's 18 Linnaeus Centres in strong national competition. This long-term support has been awarded for the project, "Exploring and Controlling the States of Matter with Light – Multidisciplinary Laser Spectroscopy within the Lund Laser Centre".

The Linnaeus funding programme was initiated by the Swedish Government to commemorate the 300th anniversary of the birth of one of Sweden's best-known scientists, Carl Linnaeus.

LLC – A partner in LASERLAB-EUROPE

Since its inauguration in 1995, the LLC has been part of constellations of European Large-Scale Installations, funded by the European Union. The number of partner laboratories has grown substantially over the years, including those in new member countries. The constellation LASERLAB-EUROPE now includes 26 laser research facilities in 16 EU member states. Like the LLC, most of these facilities provide access to other European research groups within the LASERLAB-EUROPE consortium.

Content

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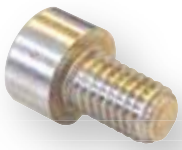

FACTS

The laser system
- 2 kHz line width

Quantum computers
- > 90 % arbitrary single-qubit operation fidelity
- > 97 % state-to-state transfer efficiency

Quantum memories
- 25 % single-photon storage and recall efficiency

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Quantum information

Quantum information processing and communication can be regarded as one of today's most important challenges in the basic science underlying the field of computing and communication. The LLC Quantum Information Group develops quantum hardware based on inorganic crystals doped with rare-earth ions, for use in quantum computing and quantum memories. Quantum systems with long coherence times simplify the development of techniques for controlling and mastering the phase of the wave function. Rare-earth-doped systems offer unique opportunities in this respect, as they have coherence times that range from milliseconds up to minutes.

Quantum computing

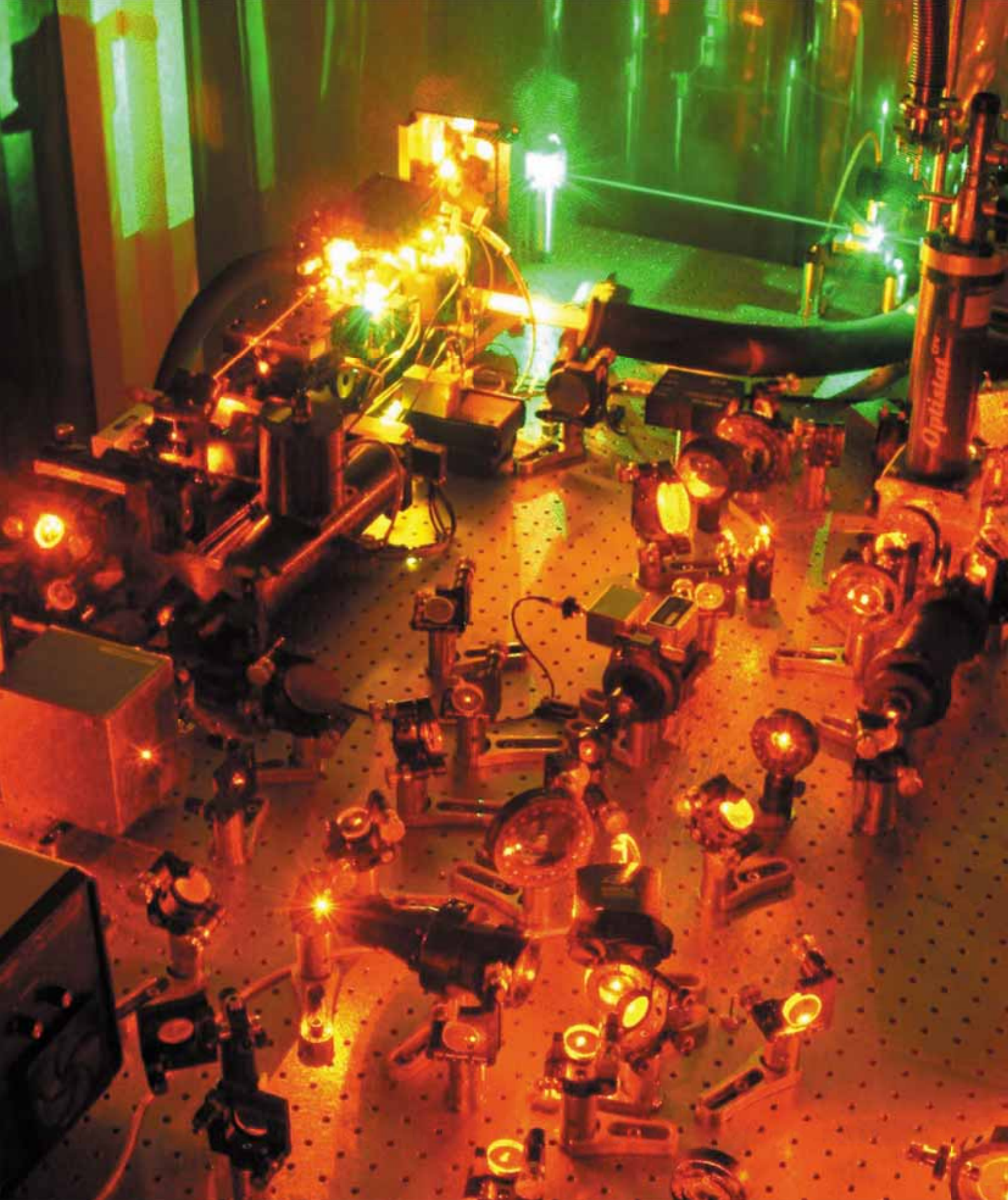
Carefully crafted light pulses and specially designed laser–matter interaction schemes are used to manipulate and fully control the wave functions of quantum mechanical systems. Our quantum hardware, rare-earth-ion-doped crystals, is kept at cryogenic temperatures (2 K). *Qubits*, or quantum bits, are prepared in defined initial states; the qubit state-to-state transfer efficiency is > 97 %, and arbitrary qubit operations can be carried out with a fidelity above 90 %, as determined by full quantum state tomography. Ongoing work is focused on developing two-qubit gates and implementing schemes with improved scalability.

Quantum memories

Quantum memories are being developed for quantum repeaters for long-distance quantum cryptography. The approach employed at the LLC is to control the quantum state of the storage medium such that the absorption process is effectively time reversed, and the stored quantum state is emitted into a selected mode. LLC researchers have recently demonstrated a storage and recall efficiency of 34 %.

The laser system

Developing the hardware required for studies of quantum information is a highly challenging and inspiring task. Controlling and mastering the phase of the wave function is key to utilizing the full power of quantum mechanical systems for applications in information science, as well as in other areas. Controlling the phase of the wave function requires a laser system with a coherence time that is preferably on a par with that of the atomic medium. At the LLC, a dye-laser system has been stabilized to a coherence time of about 100 μs, and a fully computerized light pulse amplitude and phase control system has been developed.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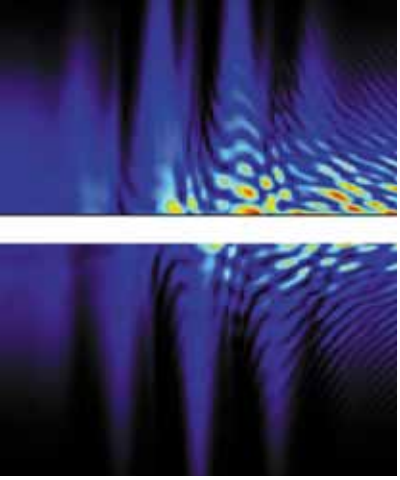
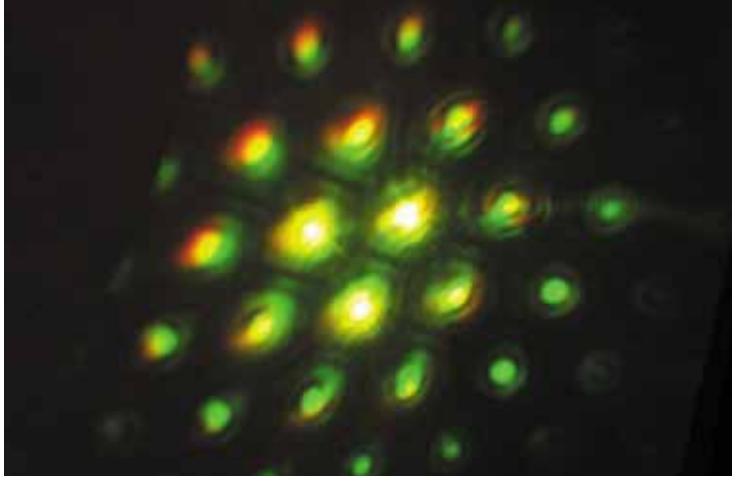
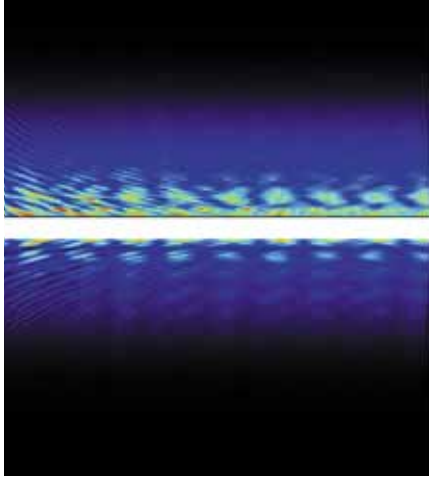
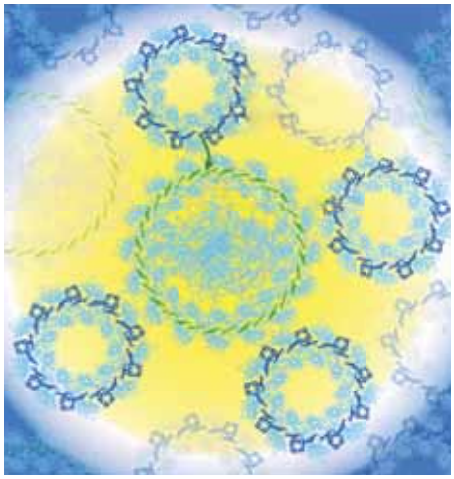
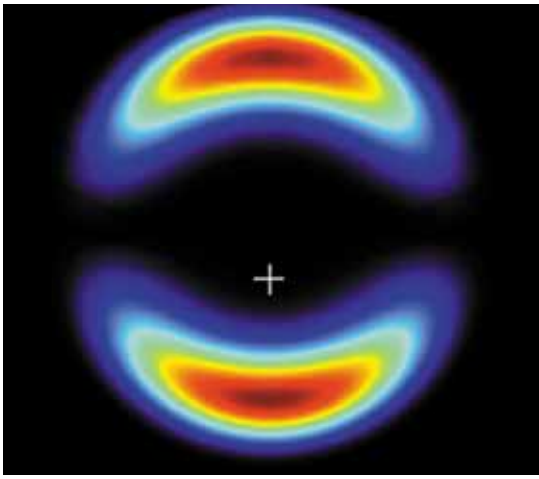
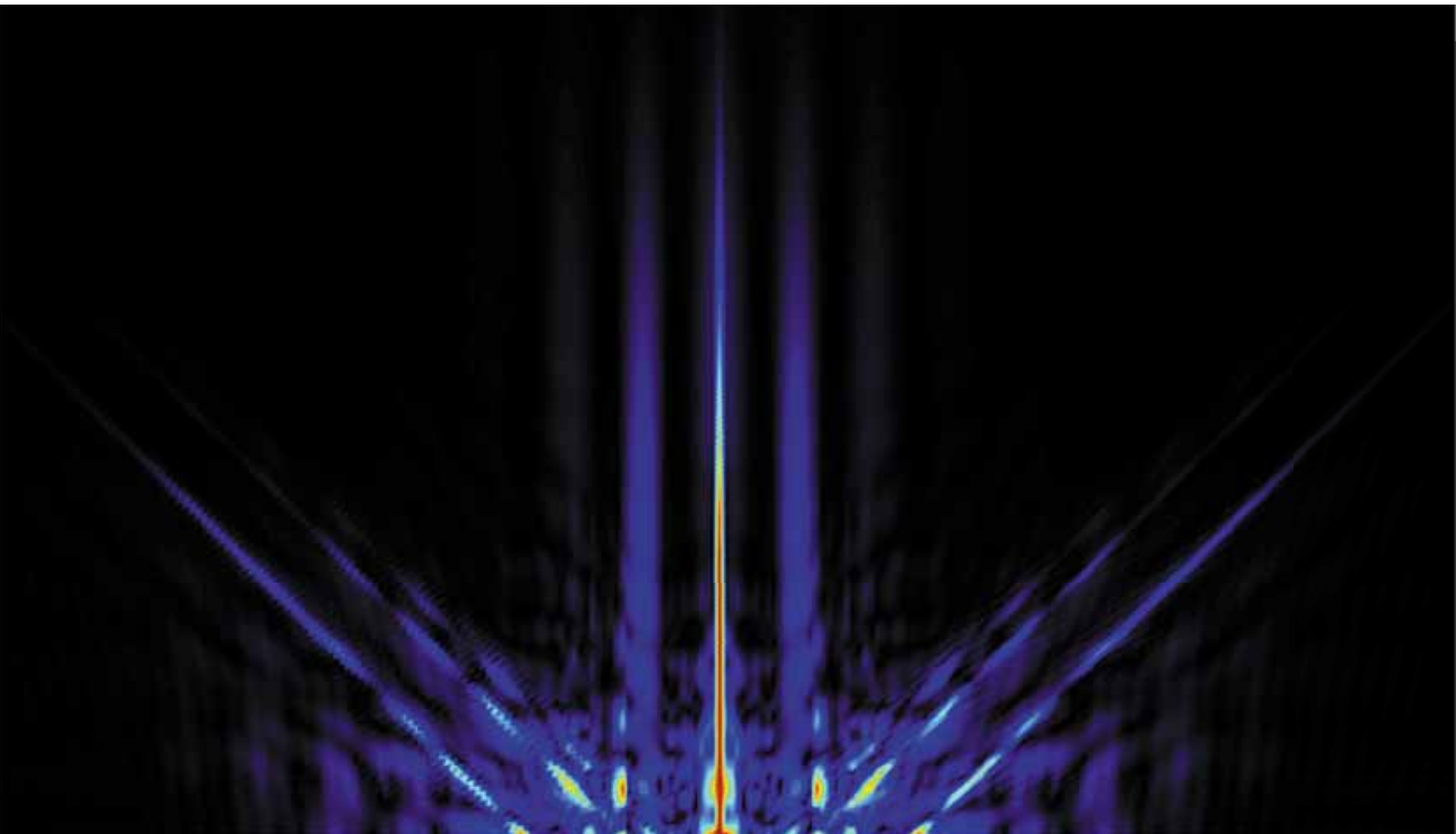




Femtochemistry and attophysics

Photosynthesis and solar energy conversion

Learning from Nature is a well-known concept that is exploited in our studies of the elementary processes in photosynthetic pigments and novel materials for solar cells and solar fuel production. The application of ultrafast spectroscopic methods to these materials allows us to obtain detailed knowledge about the processes determining the function and efficiency of solar-energy-converting materials.

Coherent multidimensional spectroscopy

Recent developments in laser technology have enabled novel, ultrafast multi-pulse experiments, which are analogous to multi-dimensional nuclear magnetic resonance spectroscopy, to be carried out. Femtosecond, coherent multi-dimensional laser spectroscopy is capable of resolving structural and electronic dynamics on a truly molecular timescale.

Coherent control

Coherent control enables the course of a chemical reaction to be altered as a result of multiple interactions of the reacting species with appropriately shaped ultrashort laser pulses. The light field can force the system to take a thermodynamically improbable or even almost forbidden reaction pathway, instead of the conventional pathway of minimum potential energy.

Single-molecule spectroscopy

Single-molecule spectroscopy is the "ultimate" spectroscopy technique, dealing with the fluorescence and absorption spectral properties of only one molecule of interest. By measuring the fluorescence spectrum and the time-resolved dynamics of a single chromophore, we can understand the fundamental physics and chemistry underlying the optical and electronic properties of materials.

Attophysics

Shorter pulses, in the attosecond range, allow us to reach the timescale of electron motion in atoms and molecules. The first applications consisted of measuring the phase of electron wave functions, and controlling and recording the motion of a free electron wave packet in a laser field. Applications are being extended to molecular systems, as well as surfaces, using advanced techniques such as velocity-map imaging spectroscopy and photoelectron emission microscopy. One goal is to extend attosecond physics to the nonlinear regime.

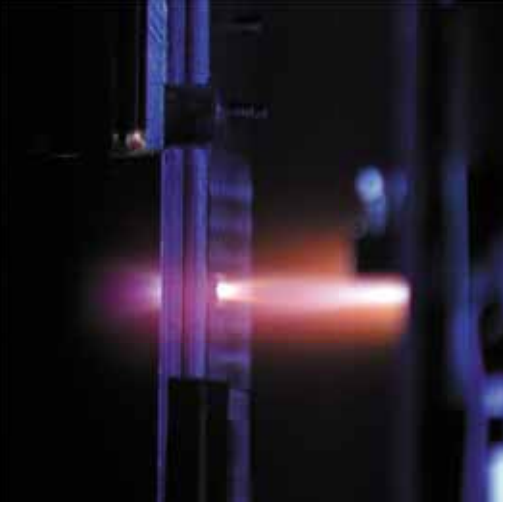
FACTS

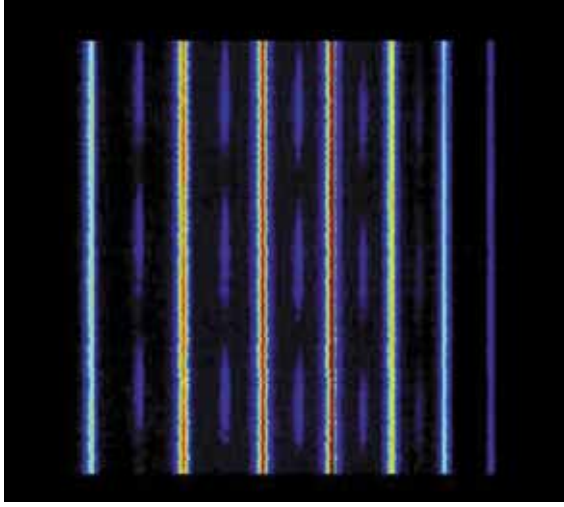
Femtochemistry techniques

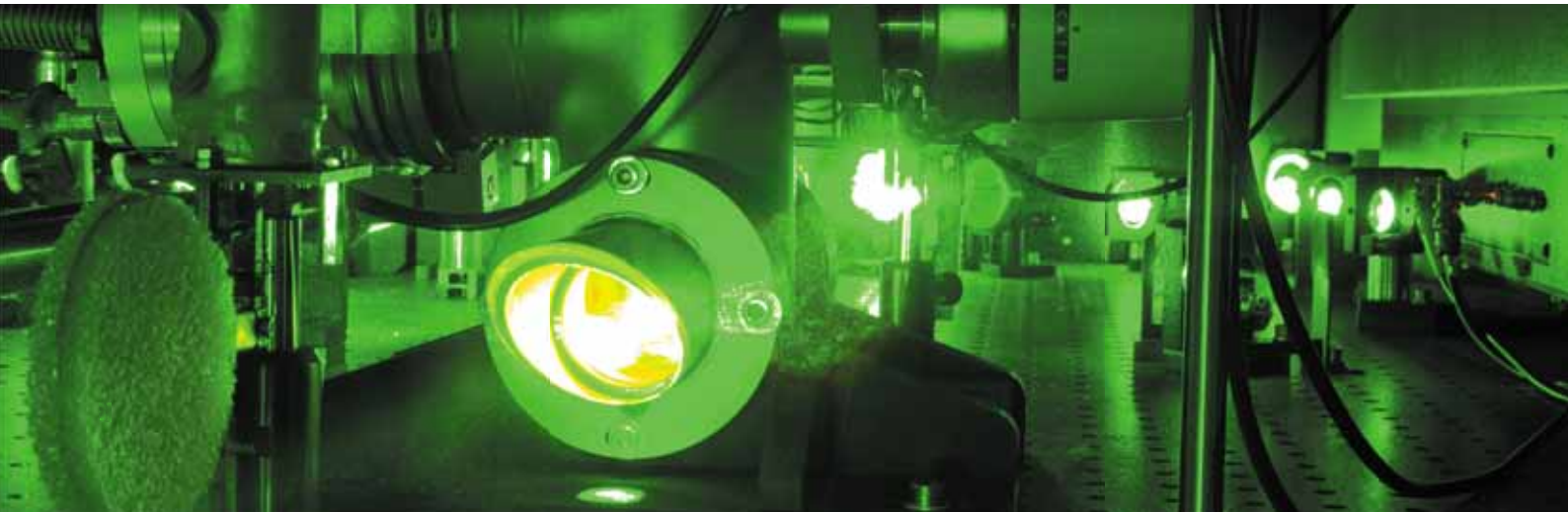
- Transient absorption
- Time-resolved fluorescence
- Photon echo
- Transient grating
- 2D electronic spectroscopy
- Coherent-control single-molecule spectroscopy

Accessible spectral range

- Far infrared (THz) to hard X-rays







The high-power laser facility

Extreme optical physics

The Lund High-Power Laser Facility is an installation within the LLC used for research in high-power, high-intensity and ultrashort-pulse optical physics. Since it was established in 1992, it has been continually upgraded, and has thereby maintained its position as an international state-of-the-art facility. Optical pulses of exceptionally high intensities, where light–matter interactions are strongly influenced by relativistic effects, and ultrashort optical pulses in the attosecond regime are produced. This allows optical physics to be pursued at the extremes.

Advanced lasers

The main laser is a multi-terawatt system providing optical pulses with a peak power reaching 40 terawatts. It delivers laser pulses to two different experimental areas, where a wide range of research topics are being pursued. A separate laser system, operating at 1 kHz, is devoted to the generation of attosecond pulses, for attophysics, while a third system is optimized for time-resolved laser spectroscopy on atoms and ions in the short-wavelength spectral region.

Harmonics

High-order harmonics, with order sometimes exceeding 100, are produced, studied and optimized. The resulting coherent radiation in the extreme ultraviolet (XUV) spectral region is used in applications such as XUV holography, interferometry and spectroscopy.

Relativistic laser-plasma interactions

Exceptionally high intensities can be obtained by tightly focusing the laser pulses from the multi-terawatt laser. Laser–matter interactions at these intensities lead to extreme conditions in terms of temperature and pressure, together with gigantic electric and magnetic fields. This allows research on fundamental plasma physics, laser-driven plasma acceleration of energetic electrons and ions, collimated beams of intense X-ray pulses, laser-induced nuclear reactions, etc.

Spectroscopy for astrophysics

The short pulses and large wavelength range of our spectroscopic system combine to provide a world-leading facility for the measurement of atomic parameters, which are crucial for fundamental atomic physics and accurate interpretation of radiation processes in astrophysical objects.

FACTS

Multi terawatt system

- Peak power 40 TW
- Repetition rate 10 Hz
- Pulse duration 35 fs
- Wavelength 800 nm

Attosecond system

- Repetition rate 1 kHz
- Pulse duration 35 fs
-
- Wavelength 800 nm

Spectroscopy system

-
- Pulse duration 1 ns
- Wavelength 115 - 1000 nm

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FACTS

Attosecond pulses
- Duration 100 - 300 attoseconds
- Central energy 20 - 90 eV

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New radiation sources

MAX-lab and MAX IV

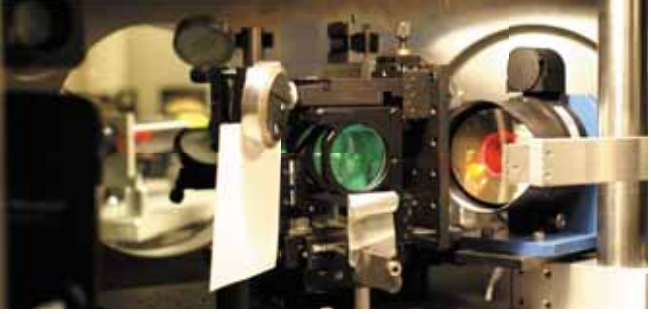
In addition to a completely new state-of-the-art facility for synchrotron radiation, the MAX IV project also includes a short-pulse facility (SPF) and the possibility of constructing a free electron laser (FEL). The SPF will generate intense incoherent X-ray pulses in the 100 fs range, while a future FEL will provide a coherent source with equally short pulses in the soft X-ray range. Developments of techniques are in progress at the test FEL at MAX-lab.

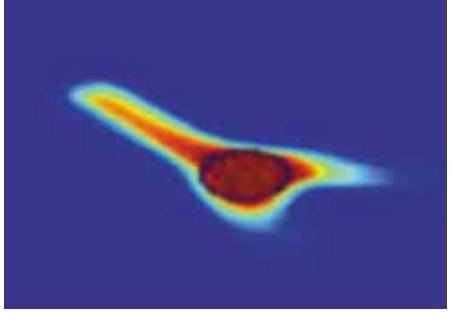
Seeding with harmonics

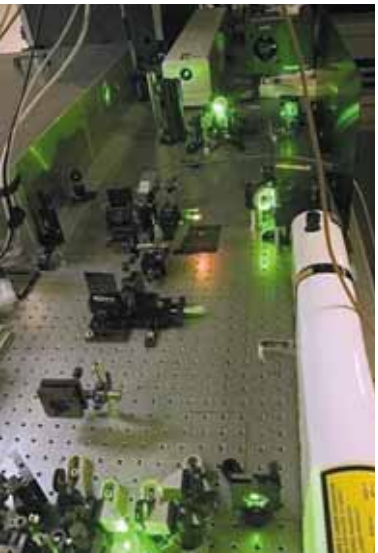
The FEL process can be seeded by an external laser, and the harmonics amplified and extracted. To achieve short wavelengths, a short-wavelength seed laser is needed. The use of high harmonic generation (HHG) in a gas jet for seeding is being explored at the LLC. The aim is seeding at around 30 nm and the extraction of coherent amplified harmonics at 10, 6 and 4 nm. HHG seeding at 100 nm is currently being studied at the test FEL at MAX-lab.

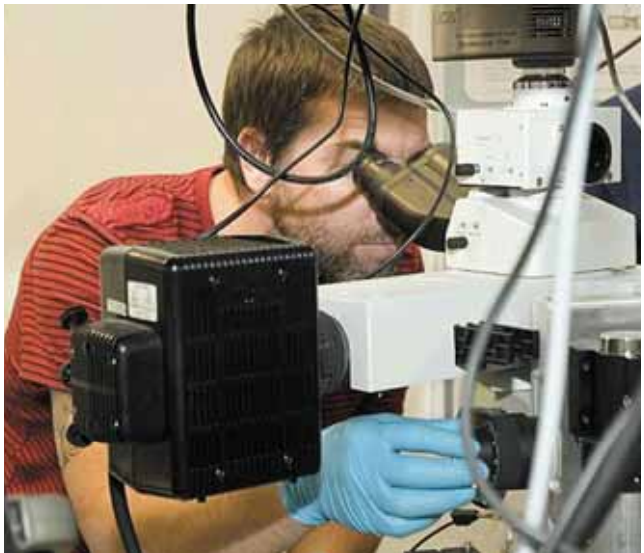
Attosecond pulses

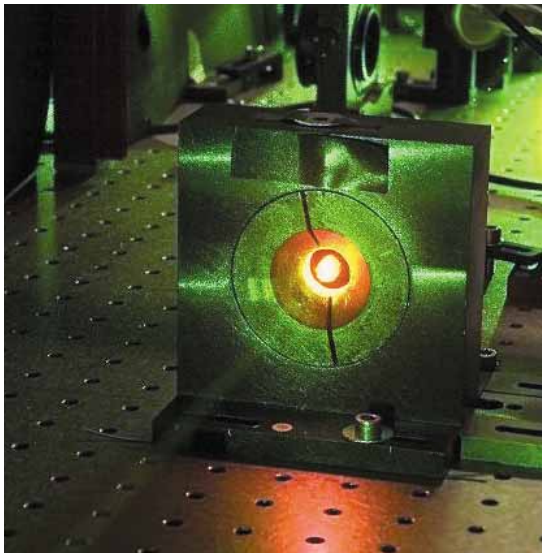
When an intense laser pulse interacts with a gas of atoms or molecules, very high order harmonics are created. If the harmonics are emitted in phase, i.e. they are phase-locked, the temporal structure of the radiation emitted consists of a “train” of attosecond pulses. Thin metallic films are used to select a given spectral range and to synchronize up to ten consecutive harmonics, thus achieving short attosecond pulses, down to 130 as. The separation between the pulses in the train can be chosen to equal a half or a full laser period (2.7 fs). Current research is focused on producing versatile trains of pulses, including isolated attosecond pulses.

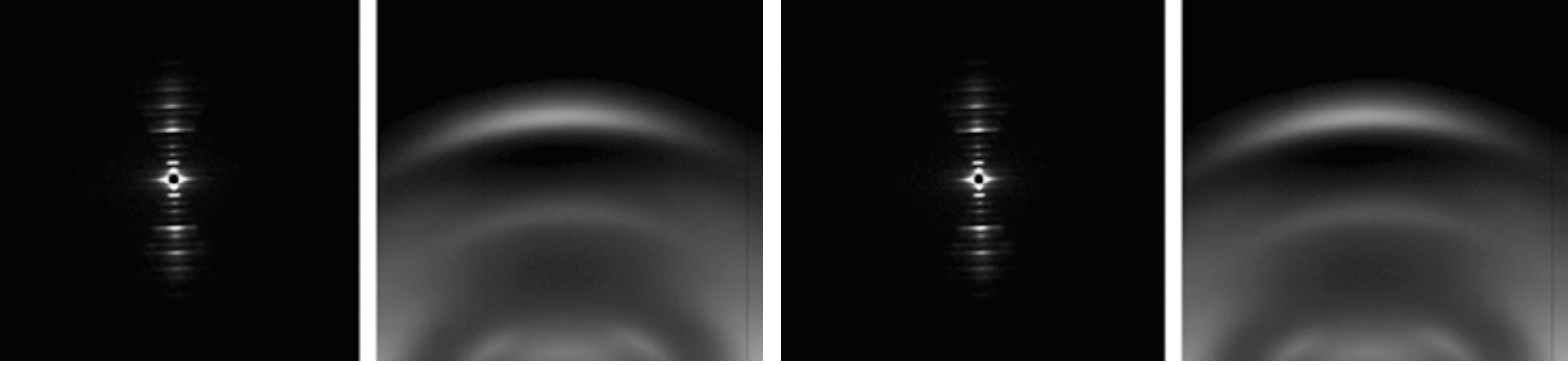


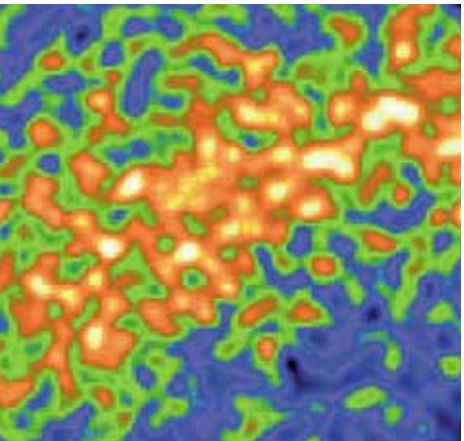


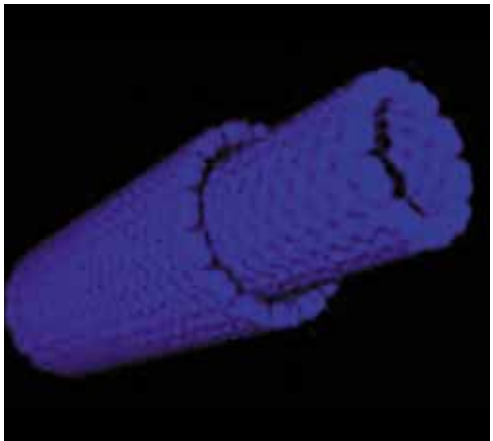












X-ray studies

X-ray generation

X-ray radiation has been a powerful tool for the investigation of the structure of matter since its discovery. At the LLC, high-intensity lasers are used to create sub-picosecond bursts of X-rays. Ultrashort laser pulses interacting with a solid or liquid target can generate "hot" electrons with sufficient energy for efficient bremsstrahlung X-ray production. Laser-accelerated, ultra-relativistic electrons from a gas jet target can be forced to "wiggle" in an undulator or in a laser-produced plasma, and thus emit collimated beams of femtosecond X-ray pulses.

Ultrafast structural dynamics

Function of a molecular or material system implies change of geometrical and/or electronic structure and the timescale for such changes ranges from femtoseconds to seconds or even longer. Ultrashort X-ray pulses can be used to directly record such dynamics via X-ray diffraction or X-ray spectroscopy. Researchers at the LLC are using laser-based femtosecond X-ray sources and synchrotron radiation to study ultrafast structural dynamics. Research is also being conducted to design and exploit a bright, femtosecond hard X-ray source, to be built at MAX IV.

Time-resolved methods

Time-resolved X-ray absorption spectroscopy (TR-XAS) and time-resolved X-ray diffraction (TR-XRD) are two complementary methods used at the LLC to probe ultrafast structural dynamics initiated by a short laser pulse. The TR-XAS spectrum of a selected atom provides information about the local environment around the probe atom and is sensitive to changes in the chemical state. TR-XRD, on the other hand, is sensitive to long-range effects i.e. phonons and phase transitions. Wide-angle X-ray scattering (WAXS) is used to study liquid dynamics. Ultrashort X-ray pulses generated with a table-top laser system are used to investigate chemical structural dynamics on the molecular timescale via TR-XAS, while TR-XRD studies of solid and liquid matter are mainly pursued at accelerator-based sources.

FACTS

- Design specifications for the SPF at MAX IV: 100 fs pulse duration, > 10 photons/s in 1 % bandwidth
- Streak camera time resolution in the hard X-ray regime: 500 fs.

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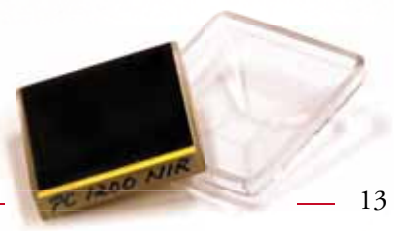

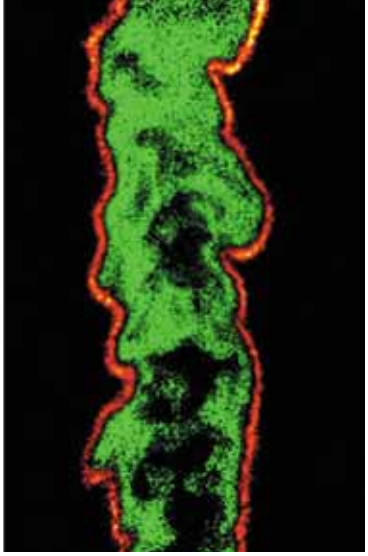

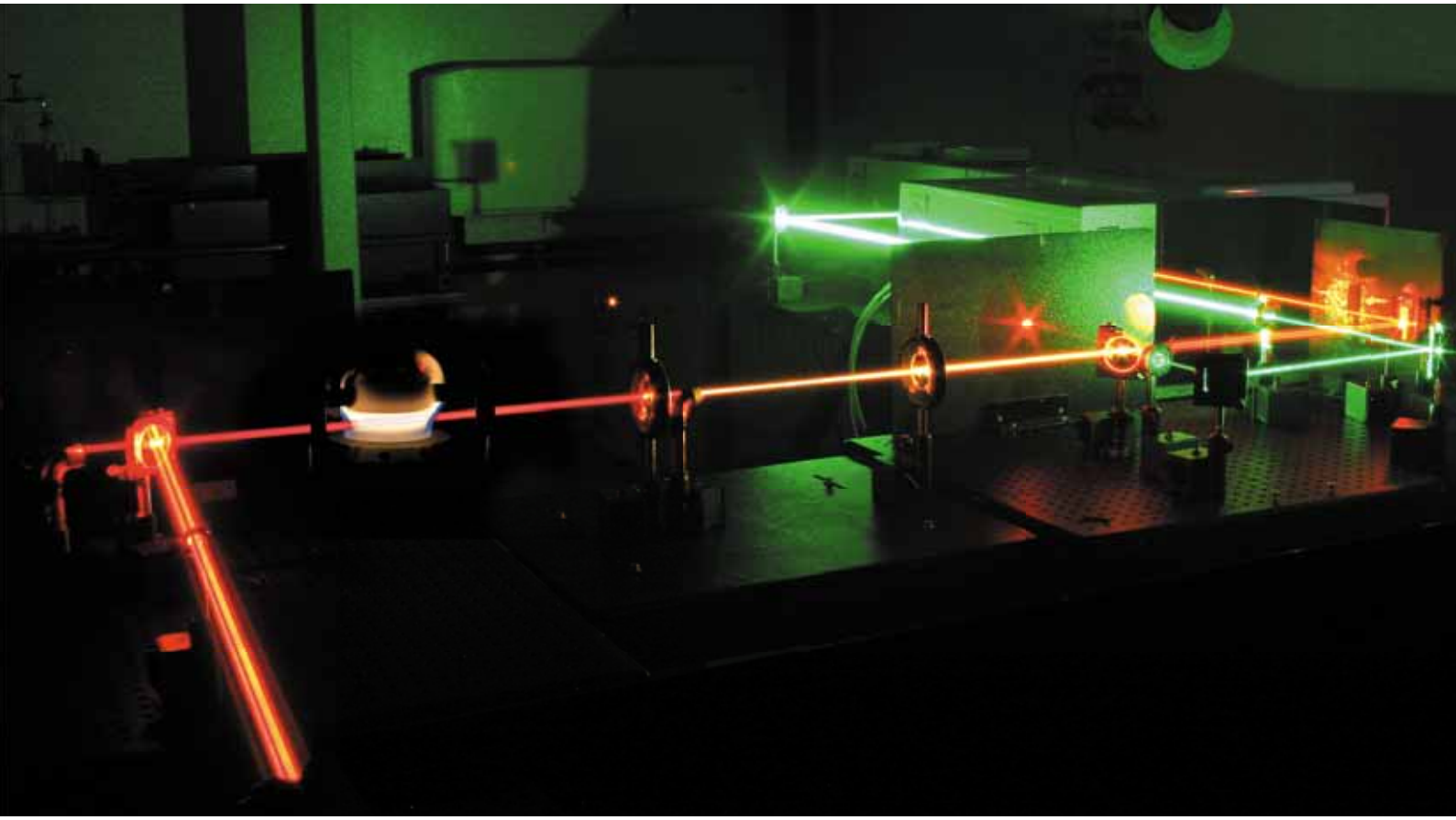

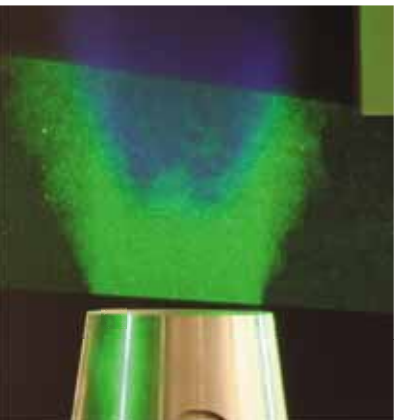

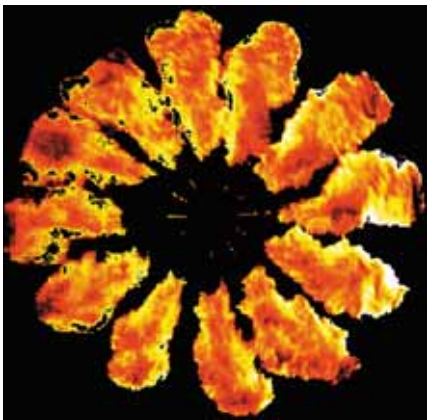

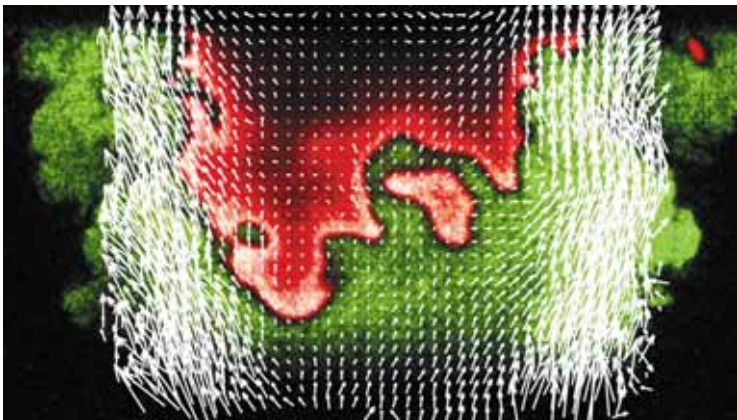

Combustion diagnostics

Research goals

One of the activities within the LLC is the study of combustion processes using optical diagnostic techniques, the majority of which are based on lasers. Combustion is of central importance in today's society, mainly for heat and power production, industrial processing, and transportation. Since fossil fuels are not renewable, and pollutants from their combustion contribute to environmental problems such as acid rain, smog and the greenhouse effect, there are clear reasons to decrease their use. Additionally, the increasing use of renewable fuels has introduced new challenges for emission reduction. Research and development in combustion are very important to obtain a fundamental understanding of the underlying processes. With this knowledge higher efficiency, lower fuel consumption, and reduced emissions of pollutants can be reached.

Optical diagnostics

When a laser beam is transmitted through a region of interest during a combustion process, the interaction between the laser photons and the molecules or particles results in scattering or fluorescence, providing information on quantities such as flame temperature and species concentration. As laser-based optical techniques rely on the small-scale interactions between light and matter, the larger-scale phenomena like flow field and combustion chemistry are unaffected, making these techniques non-intrusive. A large number of techniques are being developed and applied. These include laser-induced fluorescence (LIF) for measurements of species concentrations, coherent anti-Stokes Raman spectroscopy (CARS) for gas temperature determination, thermographic phosphors for surface temperature measurements, ballistic imaging for spray characterization, and laser-induced incandescence (LII) for the characterization of soot particles.

Fundamental and applied research

The research being carried out covers both technique development and applications in combustion. Some studies are oriented towards phenomenological investigations of combustion pr cesses and cold flows, while others are of a more applied nature, involving the study of the same processes in combustion devices, such as internal combustion engines and gas turbines. Measurements are regularly carried out to validate models of both flame chemistry and flow fields.

FACTS

High-pressure combustor rig
- Preheating temperature up to 1000 K
- Pressure up to 16 bar
- Airflow up to 1.3 kg/s

High speed laser/detector visualization system
- Eight full images in less than 50 µs

Framing camera
- 50 million images per second

Alexandrite laser
- Tunable single mode 720 - 800 nm
- 100 ns pulses ~ 400 mJ/pulse

Picosecond Nd: YAG laser
- 30 ps pulses at 532 nm, ~ 55 mJ/pulse
- 70 ps pulses ~ 500 mJ/pulse

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Environmental monitoring and remote sensing

The Applied Molecular Spectroscopy and Remote Sensing Group at the LLC is pursuing a diversified programme of research, based on about 30 years of experience in the field.

LIDAR

In atmospheric lidar applications we are using the DIAL (DIfferential Absorption Lidar) technique to measure concentrations and fluxes of pollutants. Urban, industrial and volcanic emissions of e.g. sulphur dioxide and atomic mercury are being studied.

In fluorescence lidar, ultraviolet laser pulses are directed towards a solid target where fluorescence is induced. Multivariate analysis methods are used to generate false-coloured images displaying features not normally visible. Study objects include the Cathedral in Lund and the Coliseum in Rome. Laser-induced breakdown spectroscopy (LIBS) lidar can even visualize the elemental distributions in the target.

Diode laser and light-emitting diode spectroscopy

The introduction of diode lasers makes the implementation of robust, low-cost spectroscopic techniques possible. Diode lasers can easily be tuned by current or temperature control. By using different combinations of semiconductor compounds, a wide range of wavelengths can be covered, which can be further extended by frequency mixing techniques. The use of multiple light-emitting diodes (LEDs) provides spectroscopy at a very low cost, creating realistic opportunities for applied spectroscopy also in developing countries.

GASMAS

A new aspect of gas spectroscopy, called gas in scattering media absorption spectroscopy (GASMAS) has been proposed and developed at the LLC. It provides unique information on gases enclosed in turbid liquids and solids. Many substances, frequently of organic origin, are porous and free gas is distributed throughout the material. There are many examples of this, including building materials, paper, powder, sintered materials, catalysts, foams and liquids containing gas bubbles. Other examples of the diversity of this method are food packaging control and medical diagnostics of sinus cavity inflammation.

FACTS

LLC mobile lidar system
- 10 tons Volvo bus
- Nd: YAG/OPO laser transmitter
- 40 cm receiving telescope
- Roof-top scanner dome
- Scattering, fluorescence and Raman analysis
- Analysis of atmosphere, water, vegetation and historical monuments

Long-path absorption monitoring
- Diode laser frequency-modulated spectroscopy
- Gas correlation spectroscopy

GASMAS
- Medical diagnostics
- Food inspection
- Materials science

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Biophotonics

Lasers in medical diagnostics

The Biophotonics Group has been working on an interdisciplinary research programme at Lund University since 1982, with the aim of developing and evaluating new diagnostic and therapeutic modalities in biomedicine. The diagnostic techniques developed are mainly based on fluorescence and diffuse reflectance spectroscopy. In fluorescence diagnostics, both endogenous and exogenous molecules are utilized as markers for diseased tissue. Fluorescence has mostly been employed for the diagnosis of skin malignancies, but has also been applied in other parts of the body such as the gastro-intestinal and laryngeal tracts, and in clinical specialties such as urology and neurosurgery. Fluorescence tomography is also being developed to allow longitudinal, small-animal imaging studies, as well as novel nanoparticle-based agents for marking diseased tissue.

Time-of-flight spectroscopy is another technique being developed for *in vivo* characterization of tissue. In this technique, the propagation times of individual photons are recorded. This provides a means of determining the absorption and scattering properties of the tissue probed.

Photodynamic therapy

The group was first to introduce photodynamic therapy (PDT) in Scandinavia in the late 1980s. Many skin malignancies have since been treated with PDT. More recently, we have been exploring how the advantages of this therapeutic modality can be extended to thicker and more deeply located lesions. Interstitial light delivery is used to enable the treatment of large tissue volumes. The group has been developing a system for interstitial PDT with online feedback to allow individualized and better controlled dosimetry. In this system, the laser fluence, and the concentrations of photosensitizer and oxygen, can be estimated by spectroscopic measurements between neighbouring fibres. The system is CE certified and is being tested in clinical trials.

Pharmaceutical spectroscopy

Research is also being performed to improve optical spectroscopy for pharmaceutical science beyond conventional NIR spectroscopy. Time-of-flight and tunable laser spectroscopy instruments are employed for this. These techniques can be used to quantify active substances and for optical porosimetry measurements.

Tissue optics

Novel models for light propagation in highly scattering media are being developed, including accelerated Monte Carlo techniques. Improved models that describe light propagation in porous materials are currently being developed, as conventional techniques based on transport theory are inadequate.

FACTS

Time-of-flight spectroscopy
- Spectral: 650 - 1400 nm, 8 nm resolution
- 50 ps resolution
- 1.5 mW/nm

IPDT
- 18 bare-end treatment fibres
- 200 mW/channel
- IDOSE feedback dosimetry software

Fluorescence tomography
- Peltier cooled CCD camera
- Excitation wavelengths:

473 nm	~	100 mW
532 nm	~	100 mW
633 nm	~	5 mW
660 nm	~	20 mW
785 nm	~	100 mW
980 nm	~	100 mW

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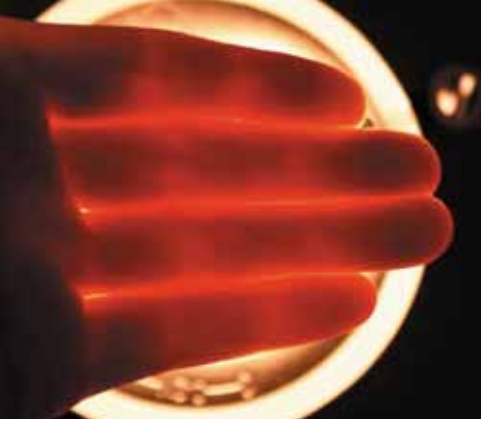

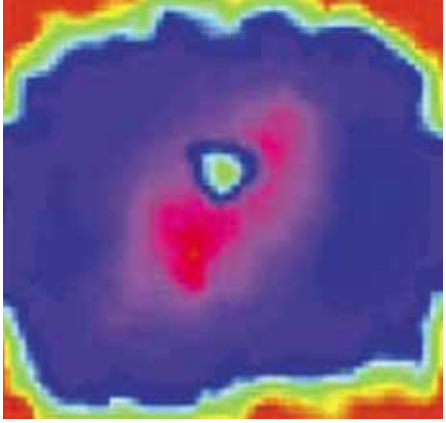

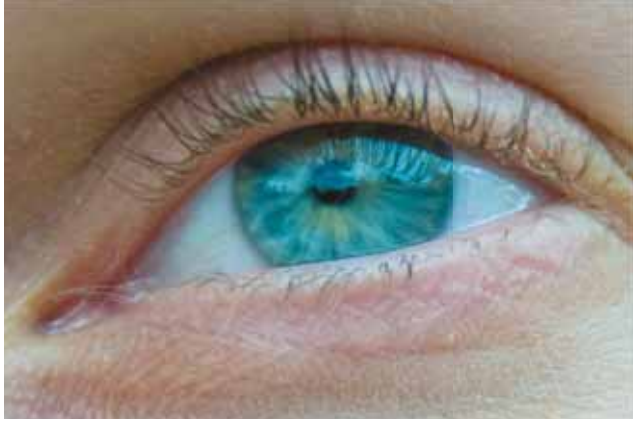

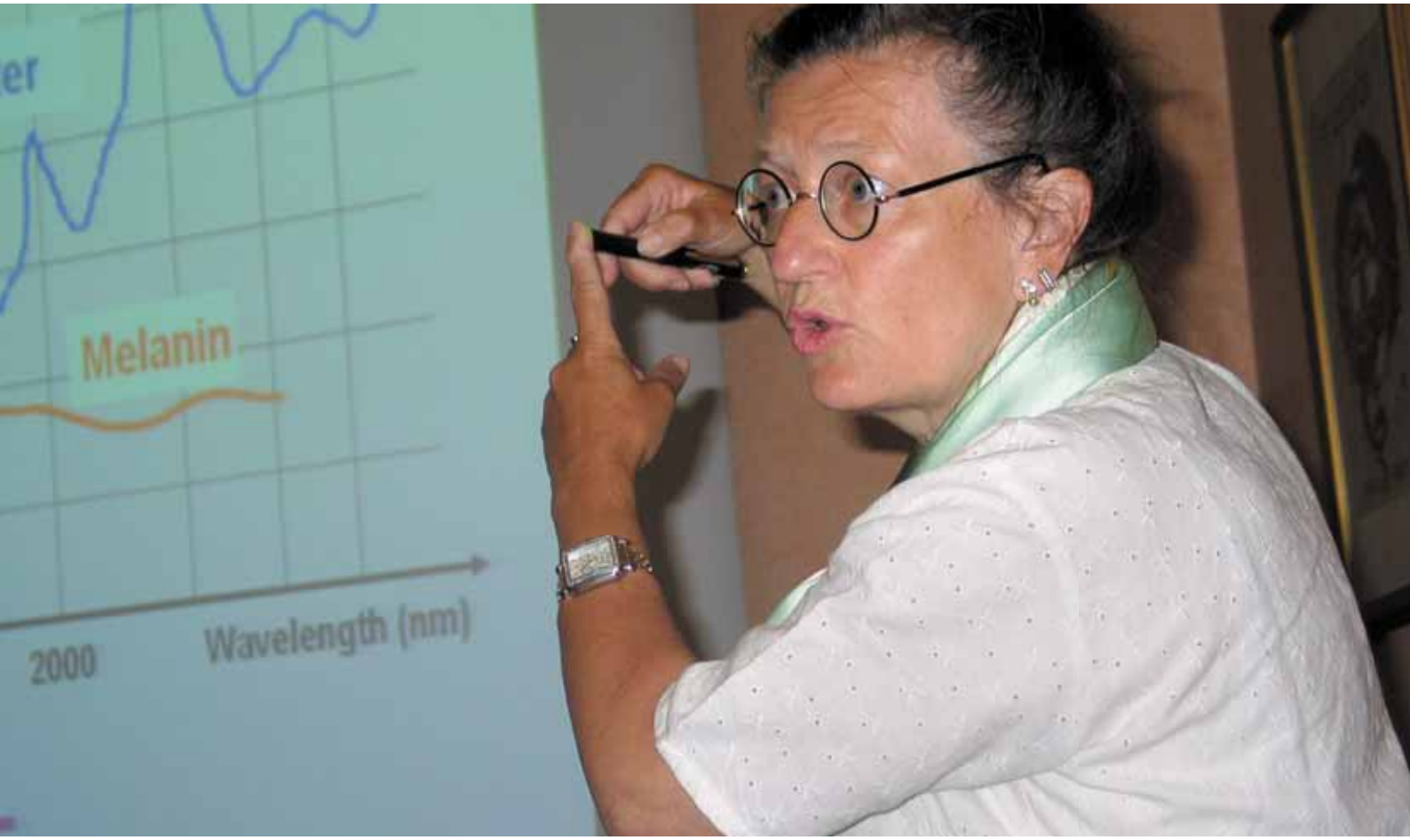
Melanin
2000
Wavelength (nm)

LUND UNIVERSITY

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www.llc.lu.se

Atomic Astrophysics
www.astro.lu.se

Atomic Physics
www.atomic.physics.lu.se

Chemical Physics
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Combustion Physics
www.forbrf.lth.se

Lund University Medical Laser Centre
www.mlc.lu.se

MAX-lab
www.maxlab.lu.se

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