atom physics seminar

ultra short laser pulses

creation and application
ultra short laser pulses

overview

- what? - why? - how?
- creation and optimisation
- typical experimental setup
- properties of existing pulsed lasers
- applications
ultra short laser pulses

What are ultra short laser pulses?

Pulses are called ultra short if they only consist of a few wave cycles.

One wavelength of 790nm corresponds to 2.6 fs => few cycle pulses mean short pulses.

Simple Gaussian „gedanken“ pulses

\[ E(t) = E_0 \cdot e^{-\frac{t^2}{T}} \cdot \cos(\omega_0 t) \]
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Why do you want to create ultra short laser pulses?

• high time resolution
  to resolve eg. vibration modes in H$_2$ molecules

• high energy densities
  for plasma physics, electron motion controlling, material procession
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How do you create them?

\[ E(t) = E_0 e^{-\Gamma t^2} \cos(\omega_0 t) \]

\[ E(\omega) \propto e^{-\frac{(\omega - \omega_0)^2}{4\Gamma}} \]

We need a spectrum with a certain bandwidth to have a fine time resolution. And we need a method to superpose the modes in a way, that a short pulse comes out.
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creation of laser pulses

• short pulse needs a high bandwidth
  → estimation via uncertainty relation

\[ \hbar \Delta \omega \Delta t \geq \frac{\hbar}{2} \]

\[ \rightarrow \Delta \omega \geq \frac{0.5}{\Delta t} \]

\[ \Delta t = 10 \text{ fs} \]

\[ \rightarrow \Delta \omega \geq 5 \times 10^{13} \text{ Hz} \]

exact value for gaussian pulses:
\[ \Delta \omega \Delta t \geq 0.441 \]
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creation of laser pulses

In wavelength this means:

$$\Delta \lambda = c \frac{\Delta \omega}{\omega_c^2 - \Delta \omega^2} \neq \frac{c}{\Delta \omega}$$

$$\omega_c = \frac{c}{\lambda_c} = \frac{c}{790\text{nm}} \approx 3.79 \times 10^{14} \text{Hz}$$

$$\Rightarrow \Delta \lambda \approx 106 \text{nm}$$

we need a laser medium which amplifies wavelengths from about 740nm to 840 nm

**Titan:Saphir laser:** 670 to 1070 nm with maximum at 790 nm.
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creation of laser pulses

but in the cavity of a laser there are only some wavelengths allowed
→ standing waves → Fabry-Pérot interferometer

condition for standing waves

\[ \frac{\lambda}{2} n = L \Rightarrow \lambda_n = \frac{2L}{n} \]

difference between two adjacent modes

\[ \Delta \omega = \frac{\pi c}{L} \]
Question: What happens if the spectrum gets discrete?
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creation of laser pulses

• independent phase of the modes
  => continuous wave lasers

• locked phase of the different modes
  => train of pulses
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mode locking

active mode locking:
• acousto-optic modulator with frequency f
• amplitude modulation through diffraction
modulated function $\sim \cos(\omega t)\cos(ft)$
exites frequencies $\omega - f$ and $\omega + f$

addition theorem:

$$\cos(x) \cdot \cos(\delta x) =$$

$$\frac{1}{2} \cos(x + \delta x) + \frac{1}{2} \cos(x - \delta x)$$

$$\Delta \omega = \frac{\pi c}{L} \quad \text{if } f = \Delta \omega \Rightarrow \text{mode locking}$$
mode locking

active mode locking:

considered in time domain its shutting and opening a weak gate

the time between two pulses is given by the resonator length $\tau = 2L/c$
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mode locking

**passive mode locking:**
- refraction depends on intensity - Kerr effect
- gaussian power distribution
  ⇒ the refractive index experienced by the beam is greater in the centre than at the edge.
  ⇒ the Kerr medium works like a lens for high intensity light.
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pulse behaviour an optimisation

- dispersion of the pulses in a medium
- compensation of the dispersive effects
- pulse amplifying and optimal compression
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dispersion

The non-linear dispersion has the following effects

\[ F(z, t) = \sqrt{\frac{1}{c\varepsilon_0 n^2 A_{eff}}} \text{Re} \left\{ A(z, t) e^{i(\omega_0 t - k(\omega_0)z)} \right\} \]

\[ k(\omega) = k_0(\omega) + k_1|\omega_0| \Delta \omega + \frac{k_2|\omega_0|}{2} \Delta \omega^2. \]

k1: inverse group velocity
k2: group dispersion: different wavelengths have different speed => spreading of the envelope

this is called upchirp

but no change in the \( \omega \) spectrum
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fourier limit

fourier transformation

this theoretical limit is called fourier limit
and the aim is to reach this limit through compressing methods
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compensation: prism compression

Through the distance $l$ you can adjust the compensation: If $l$ becomes larger, the red beam travels a longer and longer distance through the prism where its velocity is smaller.
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compensation: grating compression

diffraction of light depends on wavelength
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chirped pulse amplification

avoiding high peak powers in the amplifier through stretching

or dispersive medium (glass)

pumped Ti:S crystal
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a real pulse laser

Nd:YAG pump laser

400μJ@25fs

prism compressor

amplifier with pockels cell

oscillator

Nd:YAG pump laser

4nJ@12fs

oscillator

Nd:YAG pump laser

Nd:YAG pump laser

Nd:YAG pump laser
ultra short laser pulses

a real pulse laser

neodym doted yttrium aluminium granat solid state laser
ultra short laser pulses

a real pulse laser

Nd:YAG pump laser

amplifier with pockels cell

oscillator

Nd:YAG pump laser
ultra short laser pulses
a real pulse laser

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4nJ@12fs
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fourier limit

this theoretical limit is called **fourier limit**
and the aim is to reach this limit through compressing methods
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laser pulses in a non-linear medium – Kerr effect

\[ F(z, t) = A(z, t) e^{i(\omega_0 t - k_0(\omega_0)z)} \]

\[ k(I(t)) = \frac{\omega_0}{c} (n_0 + n_2 I(t)) \]

\[ F(z, t) = A(z, t) e^{i(\omega_0 t - k_0(\omega_0)z - \frac{\omega_0}{c} n_2 I(t) z)} \]

\[ \phi(t) = \frac{\omega_0}{c} n_2 I(t) \quad \Delta \omega = -\dot{\phi} \]
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laser pulses in a non-linear medium – kerr effect

\[ \phi(t) = \frac{\omega_0}{c} n_2 I(t) \]

\[ \Delta \omega = -\dot{\phi} \]

⇒ frequency widening
⇒ possibility to compress the pulse even more (smaller fourier limit)
increasing the bandwith

- $n_2$ is small so you need long non-linear dispersive media
- high intensity => use of inert gas. Solid medium would be destroyed
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properties of todays pulsed lasers

<table>
<thead>
<tr>
<th>laser type</th>
<th>pulse energy</th>
<th>duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ti:S λ\text{central}: 795nm</td>
<td>400 µJ/pulse</td>
<td>25 fs</td>
</tr>
<tr>
<td>compressed</td>
<td>100 µJ/pulse</td>
<td>5-10fs</td>
</tr>
<tr>
<td>X–ray or XUV</td>
<td>~1 µJ/pulse</td>
<td>~650 as</td>
</tr>
</tbody>
</table>

with fs-laser pulses there are intensities of about $10^{15}$ W/cm$^2$ possible.

solar constant: 0.1366 W/cm$^2$

⇒ intensity of sunlight shining on the area of Austria bundled to one cm$^2$

These are values of 5 years old dissertations so the current state of the art in energies/intensities are orders of magnitudes higher.
How are ultra fast processes measured with ultra short pulses?

example:

oscillations of deuterium molecules
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vibration of D$_2$

deuterium molecule in the ground state

D$_2$ potential a.u.

nucleus distance a.u.
Vibration of $D_2$

multi photon ionisation

$P \sim |n|^n$
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Vibration of D$_2$

potential a.u.

nucleus distance a.u.

no longer an eigenstate

„Lochfraß“
Vibration of $D_2$ in ultra short laser pulses

Potential in a.u. vs nucleus distance in a.u.

- Superposition of almost only the first and second state oscillation with $\Delta \omega$. 
Vibration of D$_2$

 ultra short laser pulses

Vibration of D$_2$

high probability of ionisation

⇒ ionisation rate depends on time between ionisation of the first and the second pulse

low probability of ionisation

potential a.u.

nucleus distance a.u.
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Vibration of D$_2$

We get this graph to assign the frequency.

D$_2^+$ events x $10^4$

11.1 fs oscillations

delay time / fs

atom physics seminar – Moritz Zaiß – 26.06.07
Vibration of D$_2$

Fourier transformation of the measured data

11.1 fs oscillation agrees excellent with the theoretical value 11.14 fs

This time dependency was first time measured with 7 fs ultra short laser pulses in time domain
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applications of modern puls lasers

reaction microscope

laser pulse

E, B

D₂ gas

ion detector

electron detector

helmholtz inductors
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further applications of modern pulsed lasers

- meteorologic applications
- laser spectroscopy
- coherent control of electrons in atoms
- fine metal processing
- dental treatments
- fusion
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applications of modern puls lasers

three dimensional images in the air
visualization of "real 3D images" using laser pulses

gas discharge through high intensity

http://www.aist.go.jp/aist_e/latest_research/2006/20060210/20060210.html
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applications of modern puls lasers
http://www.aist.go.jp/aist_e/latest_research/2006/20060210/20060210.html
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summary

creation

• medium with band spectrum
• mode locking
• stretching
• amplifying
• increase the bandwidth
• compressing

⇒ ultra short laser pulses

application

• high time resolution for measurements of fast systems e.g. atomic systems
• high intensity and high precision e.g. material processing

⇒ excellent tool for future physics

Thank You for Your attention!
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sources

1. K. Zrost, “Wechselwirkung von Atomen und kleinen Molekülen mit intensiven, ultrakurzen

CPA: http://www.icuil.org/article.php?articlesID=10
applications: http://www.weltderphysik.de/de/1511.php
Fusion: http://www.llnl.gov/str/Petawatt.html
Plots: MuPad, gnuplot
Vibration of D\textsubscript{2}

Now the R-wavepacket of the D\textsubscript{2} oscillates with a certain frequency. We can measure this frequency if we shoot another pulse which ionizes the D\textsubscript{2}. If we vary the time between the pulses and measure the rate of D\textsubscript{2} we will find, that the events oscillate, too.

Ionisation is more probable

Ionisation is less probable
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applications of modern puls lasers

Figure 6. Contrast of conventional inertial confinement fusion (ICF) and the fast-ignitor ICF, which is used on the Petawatt laser.