Generation and properties of HHG radiation

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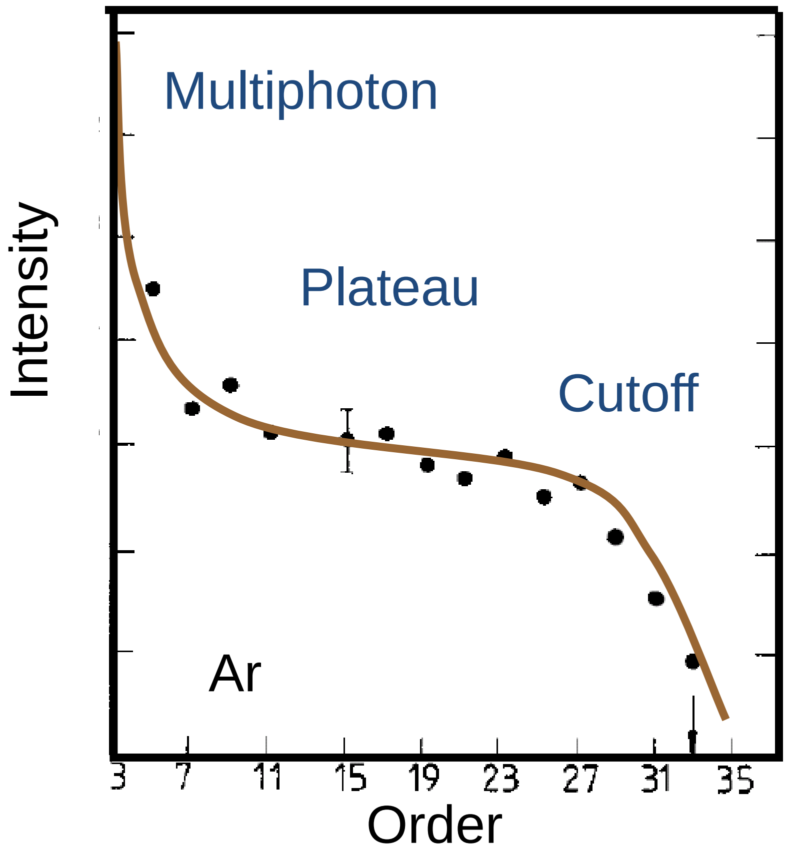
Lund University

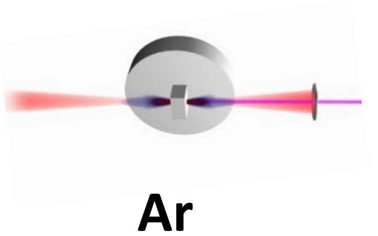
TUTORIAL

Generation of high harmonics



Nd-YAG 1 μm

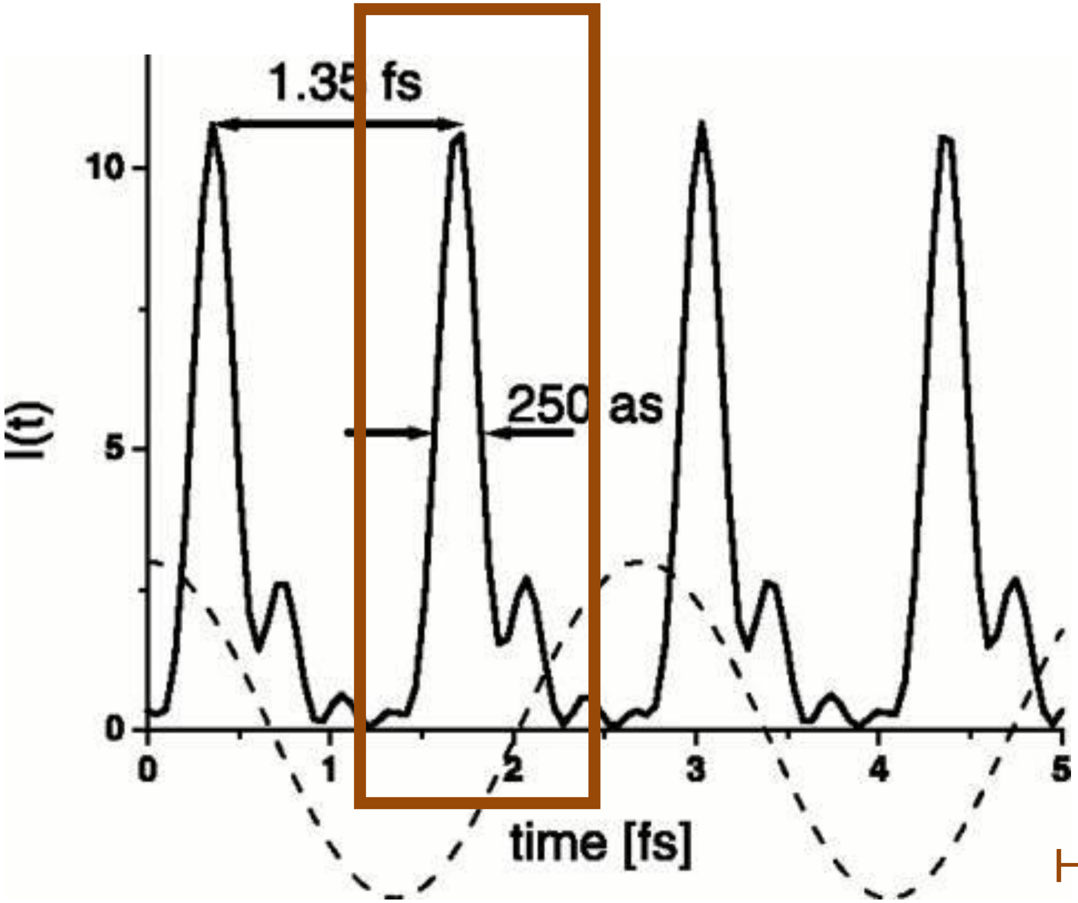
30 ps



Ferray, J. Phys B 1988

McPherson, JOSA B 1987

Generation of attosecond pulses



Paul et al., Science, 2001

Henstchel et al., Nature, 2001

Kienberger et al., Science, 2002

Single attosecond pulses

Outline

1. HHG/ Atto for the beginner

2. HHG/ Atto for the more advanced

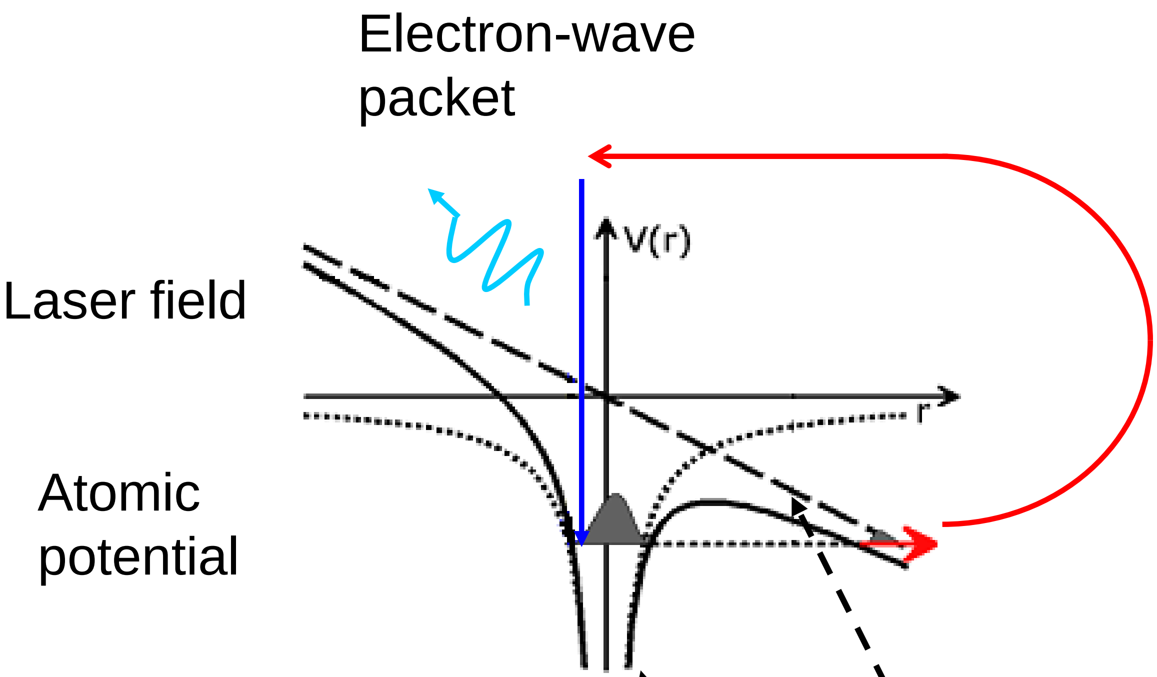
3. HHG : experiment

4. HHG : simulation

5. Properties of HH

6. HHG : application

Atoms in strong fields



$$i\hbar\frac{\partial\Psi}{\partial t}=-\frac{\hbar^2}{2m}\nabla^2\Psi+\left[-\frac{e^2}{4\pi\varepsilon_0 r}+eE_0\cos(\omega t)z\right]\Psi$$

Tunneling

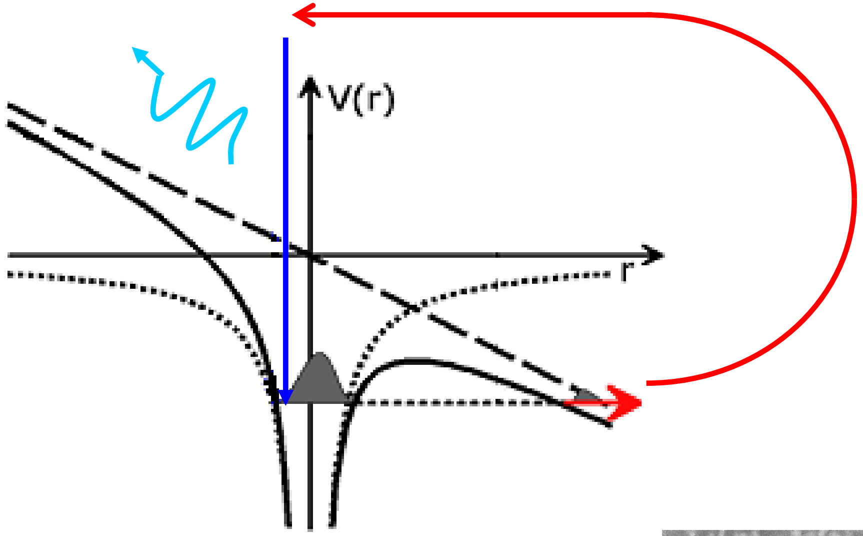
Acceleration

Return and
recombination

Atoms in strong fields

Electron-wave
packet

Laser field



Atomic
potential

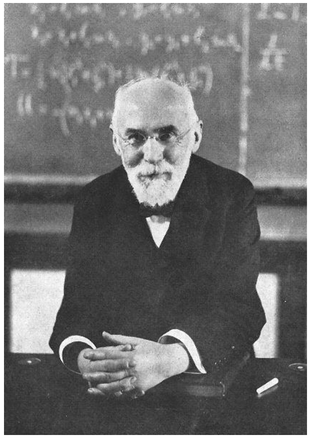
Tunneling

Acceleration

Return and
recombination

$$m\frac{d\vec{v}}{dt} = -e\vec{E}$$

$$E_{ph} = \tfrac{1}{2}mv^2 + I_p$$



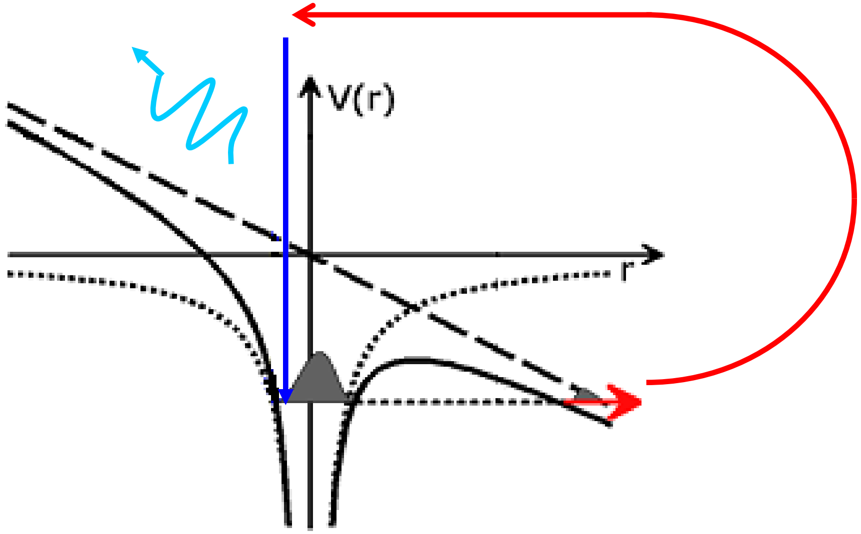
Corkum, PRL,1993

Schafer et al. PRL, 1993

Atoms in strong fields

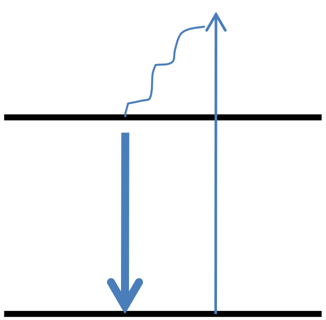
Electron-wave packet

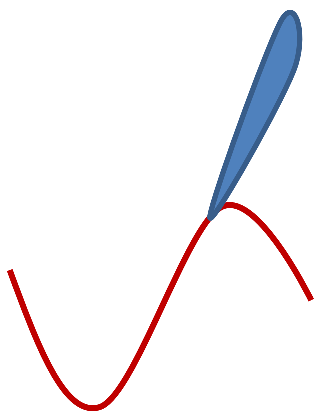
Laser field



Atomic potential

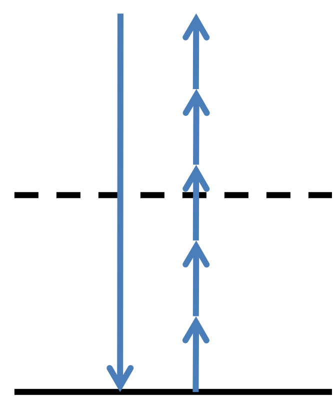
Not a laser



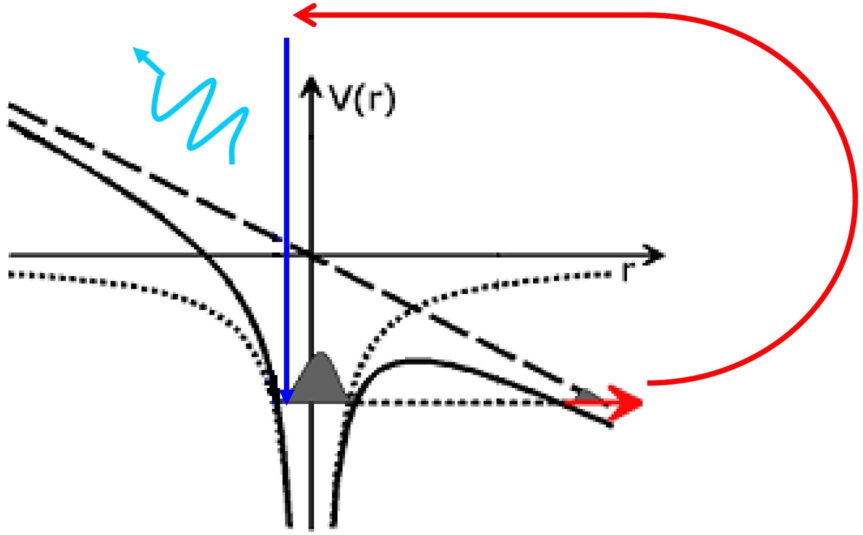


Not synchrotron radiation / FEL

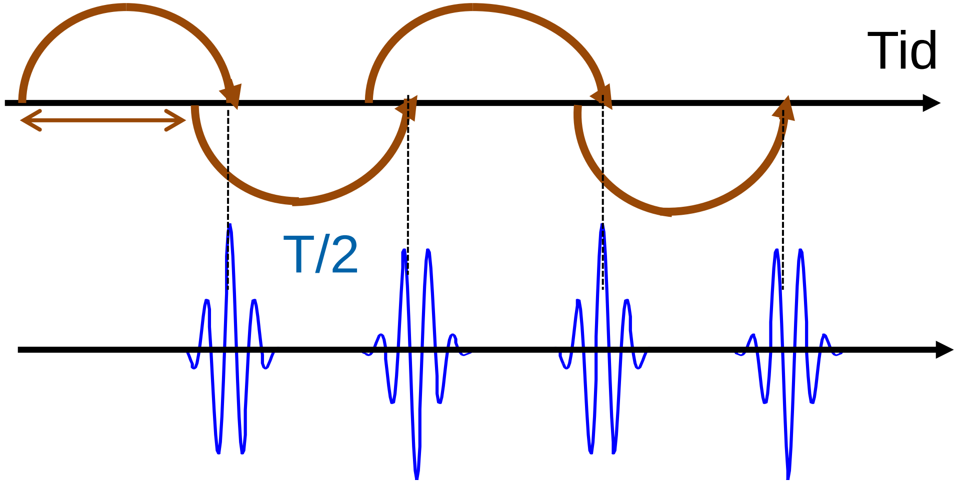
Parametric process – nonlinear optics



Atoms in strong fields

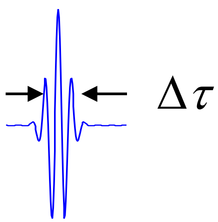


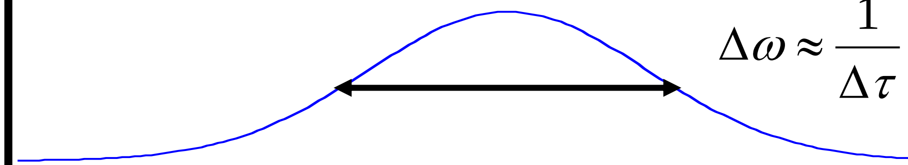
T= Laser period = 2.6 fs



From the time to the frequency domain

Time domain → Frequency domain





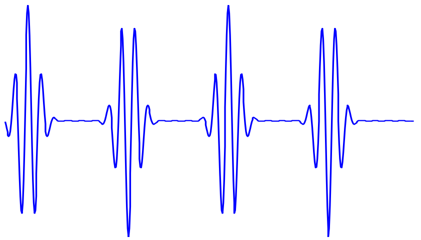
$$\Delta\omega \approx \frac{1}{\Delta\tau}$$

Electric field in time E(t)

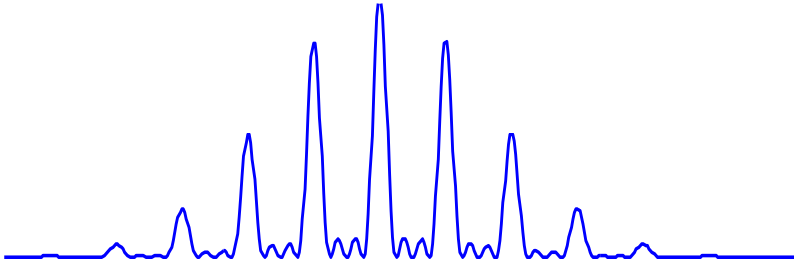
Power spectrum $|E(\omega)|^2$

Harmonics = Interferences of attosecond pulses

Time domain

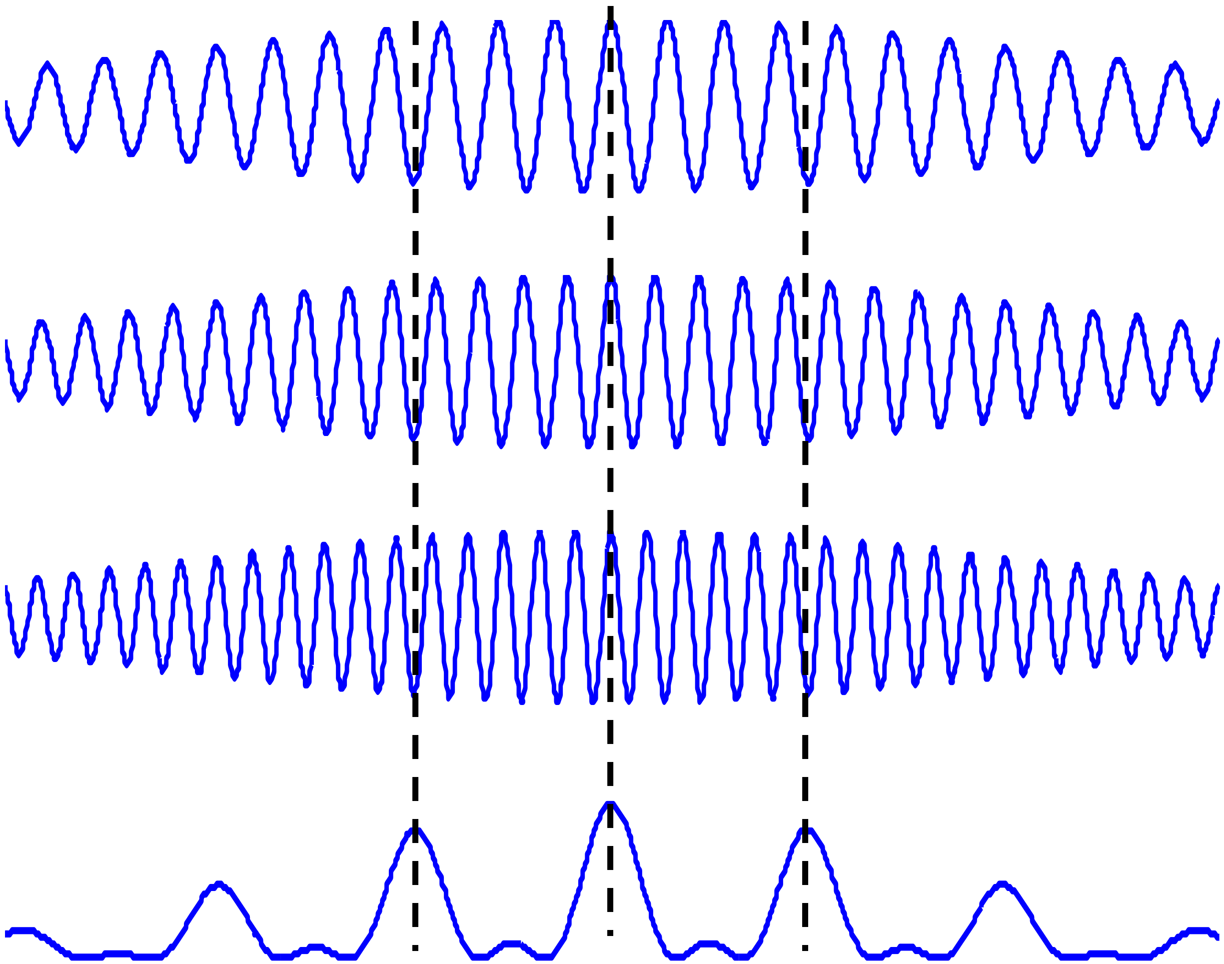


Electric field in time E(t)

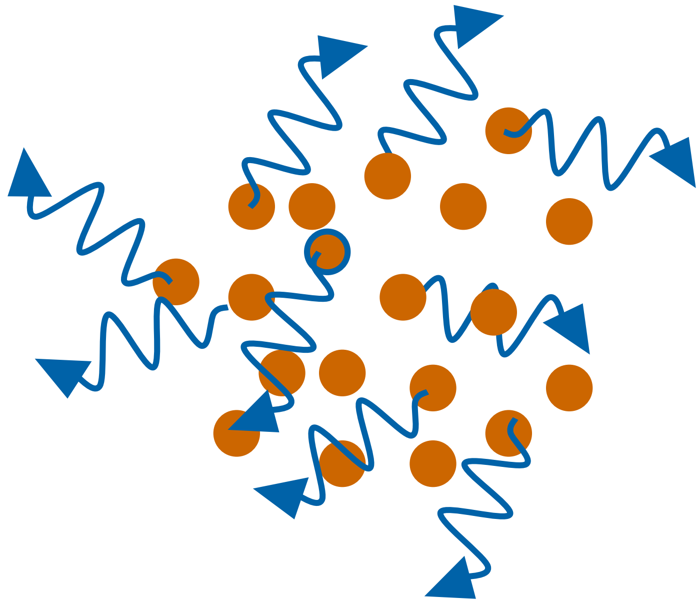


Power spectrum $|E(\omega)|^2$

Attosecond pulses = Sum of phase-locked harmonics

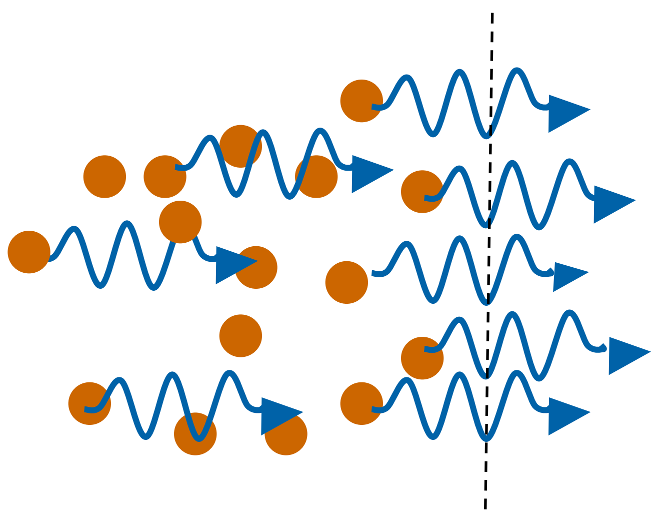


NOT: Incoherent radiation from a collection of atoms



- Laser-like radiation
- Spatially and temporally coherent
- Macroscopic emission

A nonlinear optical phenomenon



Phase matching condition

Outline

1. HHG/ Atto for the beginner

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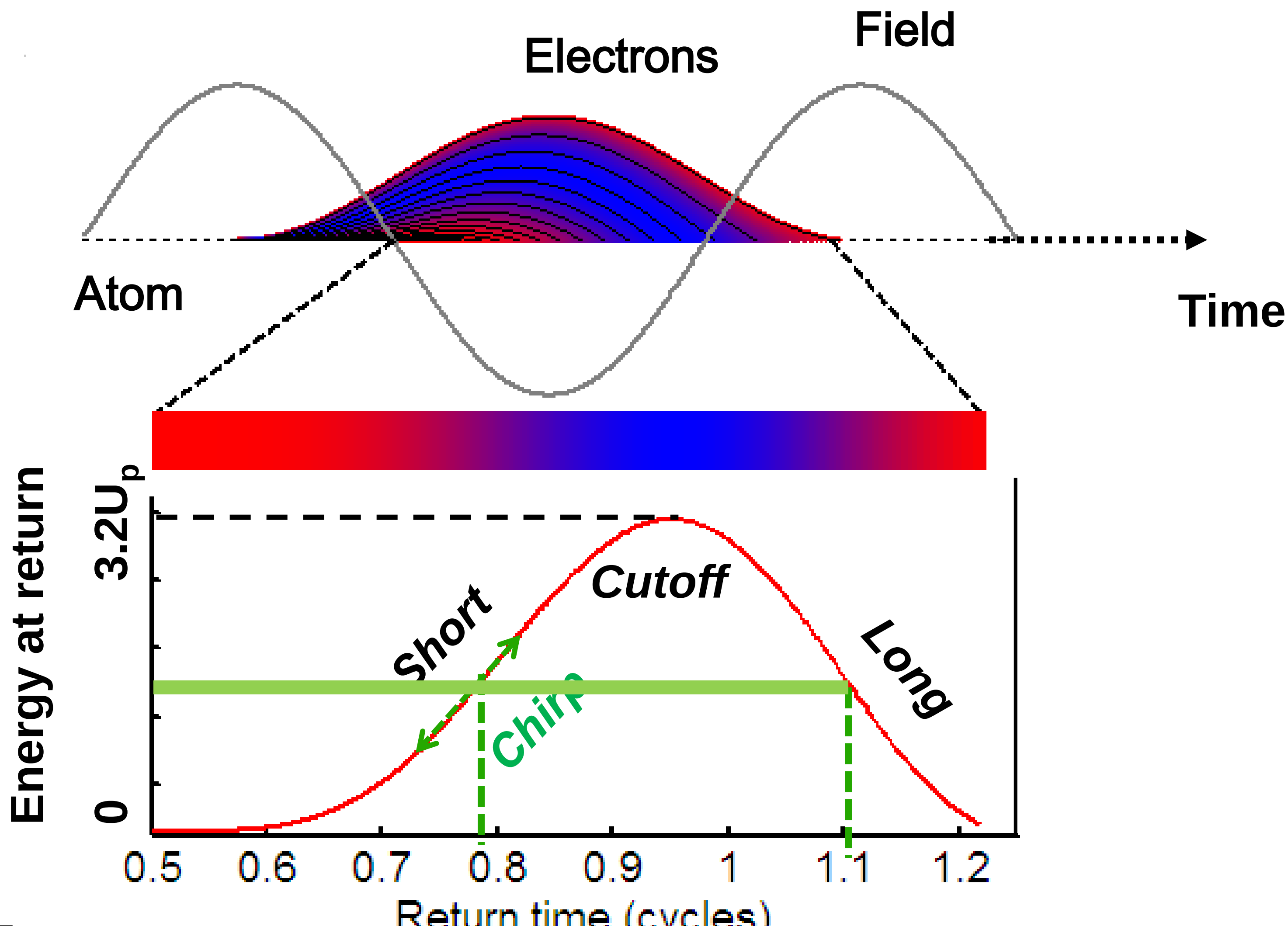
3. HHG : experiment

4. HHG : simulation

5. Properties of HH

6. HHG : application

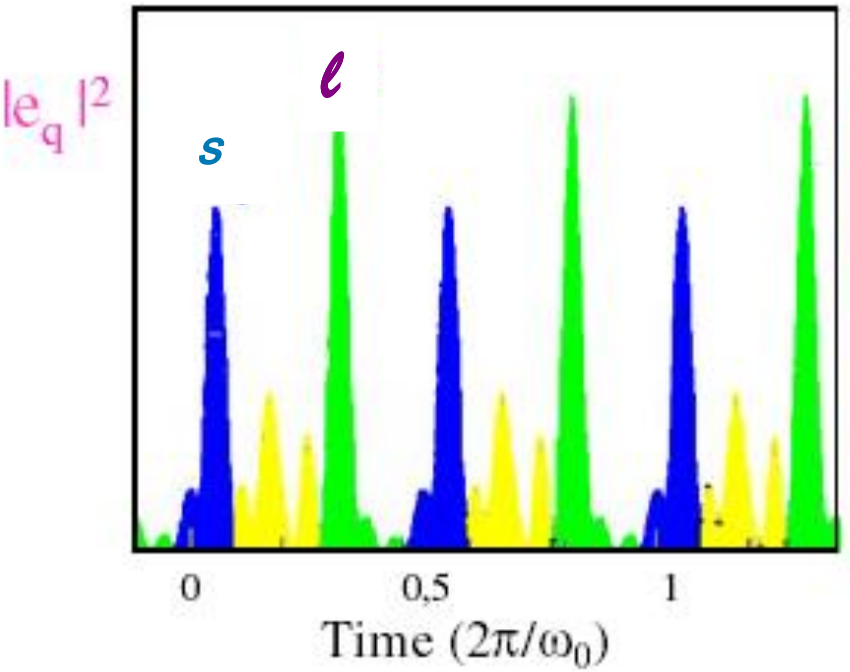
Single atom response



$E_{ph} = I_p + E_c$

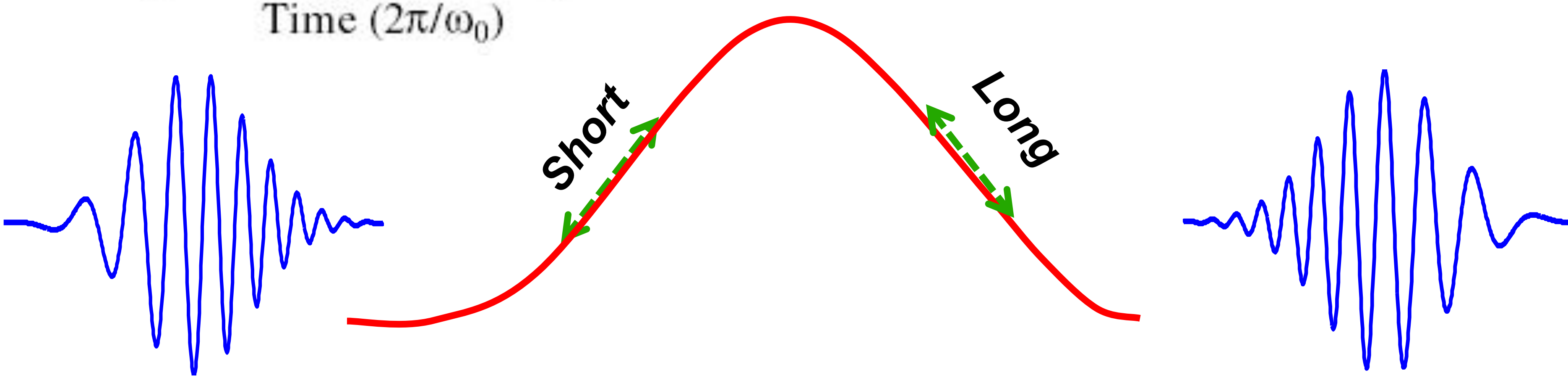
Multiple pulses per half cycle

Attosecond time domain



Multiple pulses /half cycle

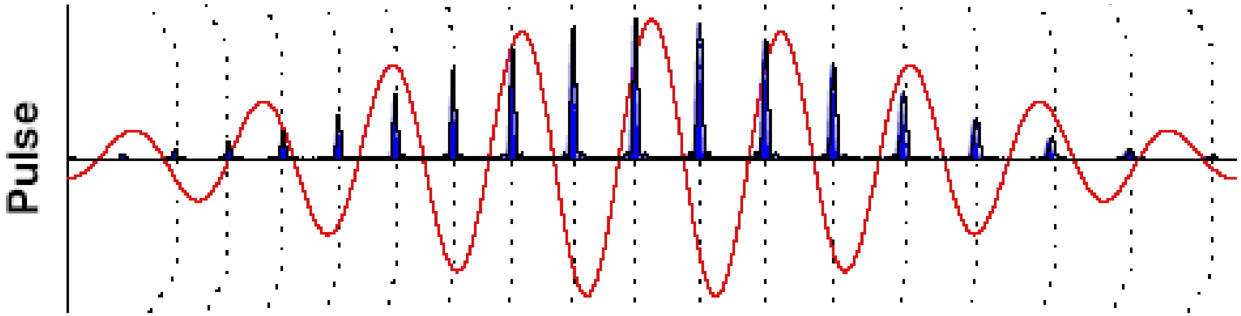
Chirp



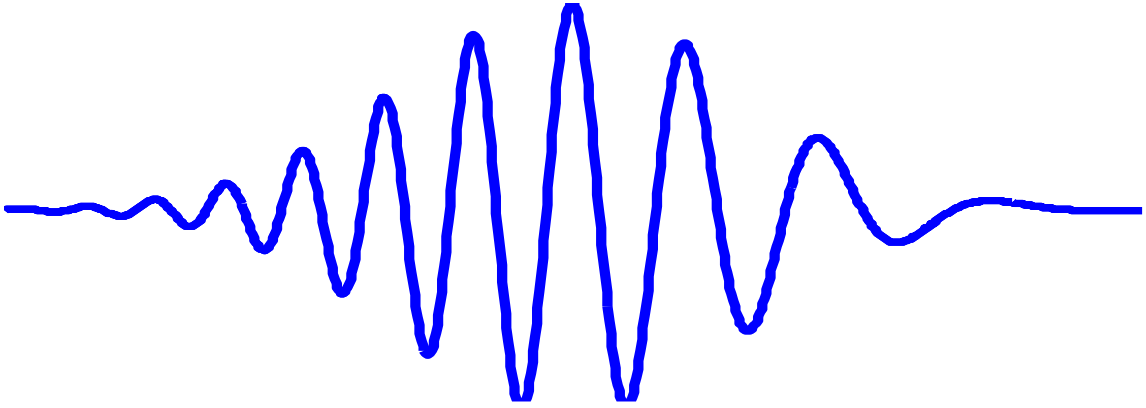
Positive chirp

Negative chirp

Femtosecond time domain
Individual harmonics



$$E_q(t) = A_q(t)\ \ e^{-iq\omega t - i\alpha_q I(t)}$$



Negative chirp

Macroscopic response

Phase matching

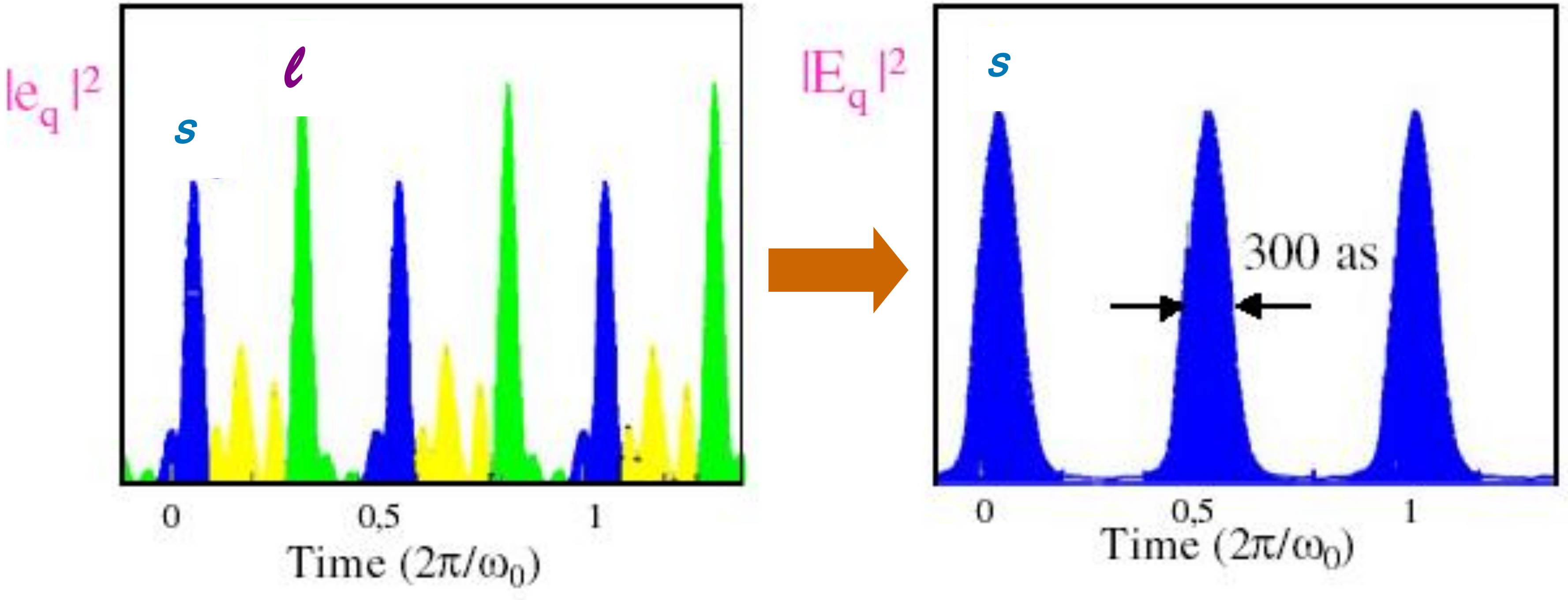
$$\delta\Phi_q = k_q z - q k_1 z + q \arctan(z/b) + \alpha_q I(z)$$

Dispersion

Gouy

Single atom response

Dispersion= Neutral atoms + free electrons



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Group

"Harmonic team"
Rafal Rakowski
Piotr Rudawski
Jörg Schwenke
Christoph Heyl

"Atto team"
Johan Mauritsson
Per Johnsson
Mathieu Gisselbrecht
Thomas Fordell
Kathrin Klünder
Marcus Dahlström
Miguel Miranda

"Seeding team"
Erik Mansten

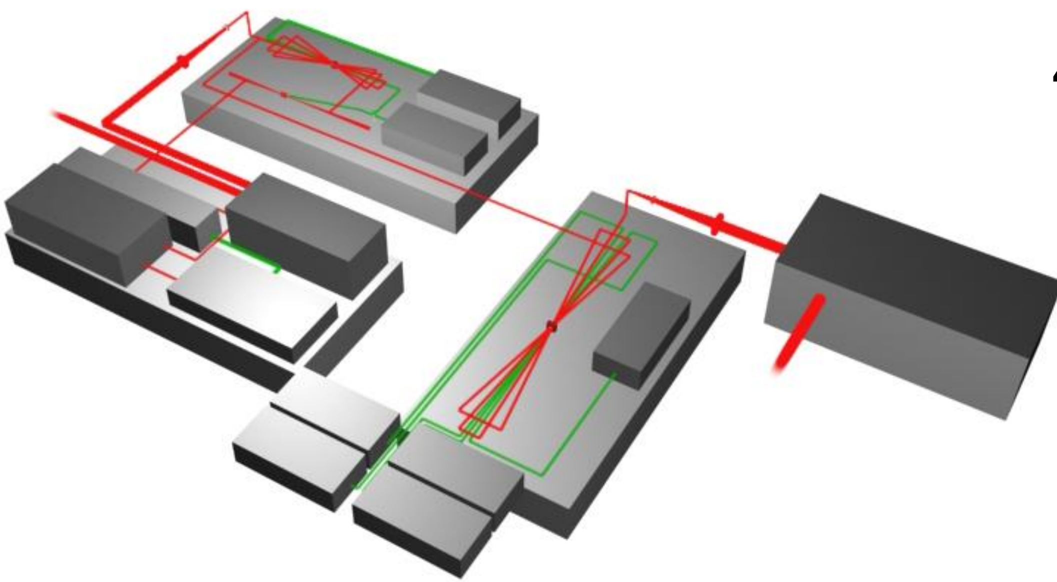
MAX-lab

Laser

From

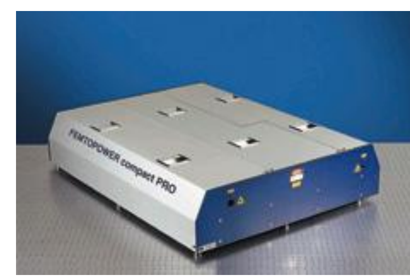
40 ps, 1064 nm, 50 mJ

Via



40 fs, 800 nm, 1J

To



5 fs, 800 nm, 1 mJ, CEP stabilized

High-Power Laser Facility

- Inaugurated 1992
- Lund Laser Centre 1995
- European large scale facility 1996

High-Intensity laboratory ←	Multi TW laser 10 Hz, 40 TW 40 fs	→ Intense XUV laboratory	Attosecond laboratory 1 kHz, 5 mJ, 35 fs phase-stabilized

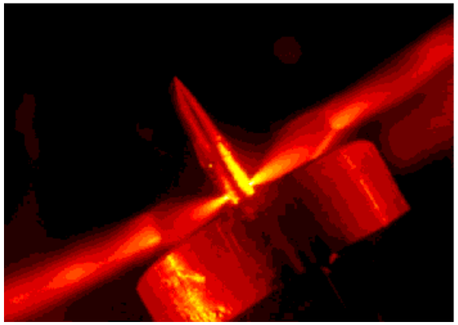
Sune Svanberg

Claes-Göran Wahlström

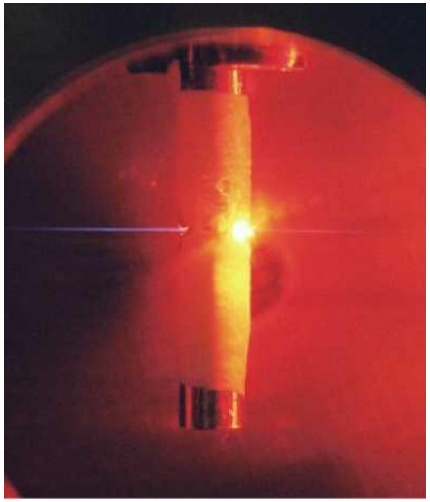
Anders Persson

500 m from MAX-lab

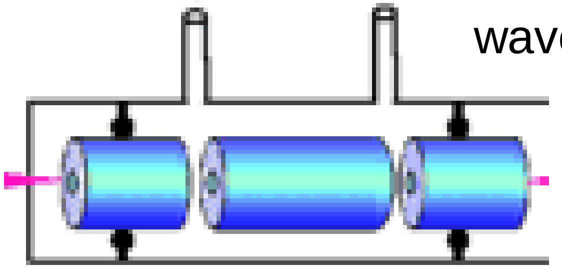
Gas medium



Gas jet

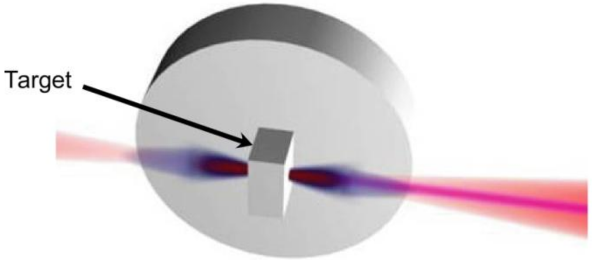


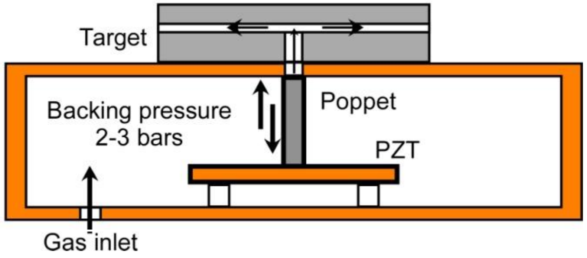
Effusive cell

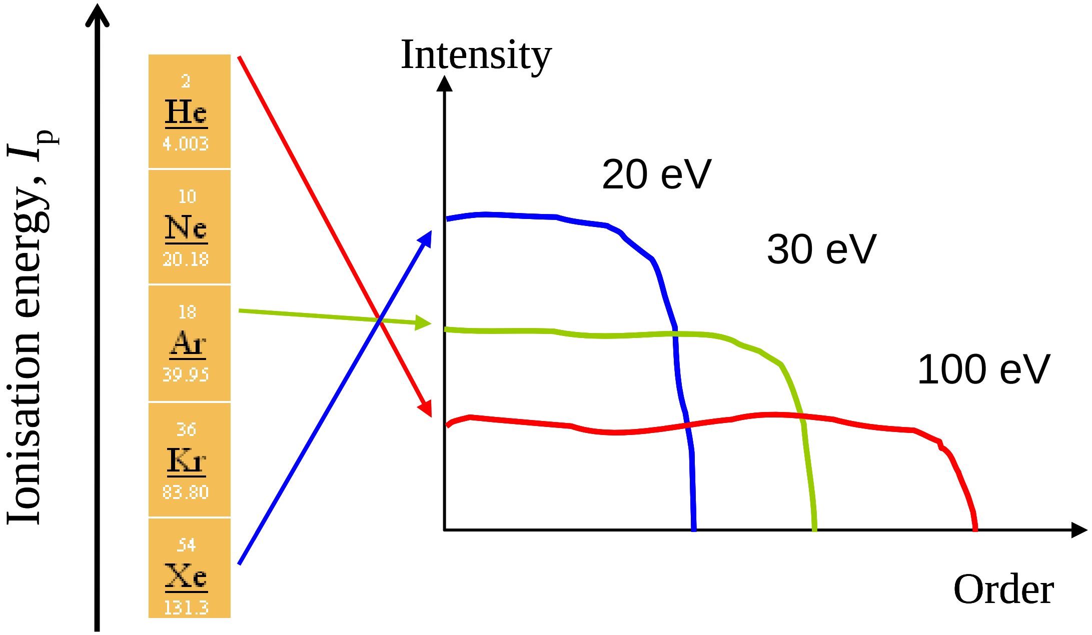


Hollow wave guide

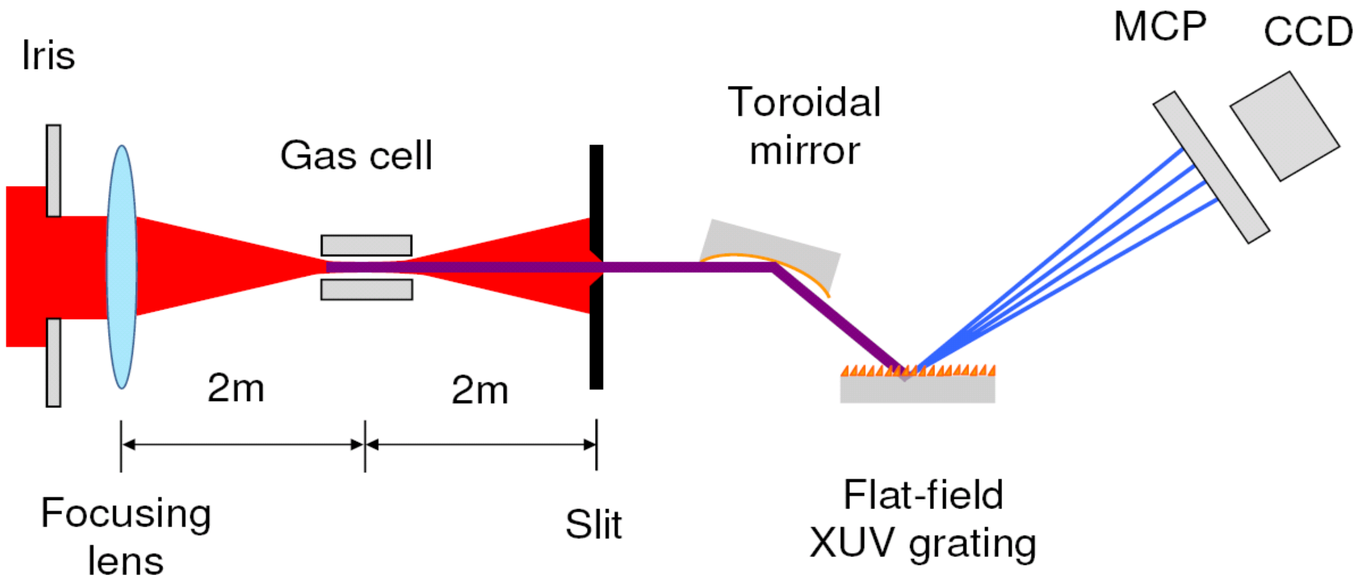
1 kHz-pulsed gas cell

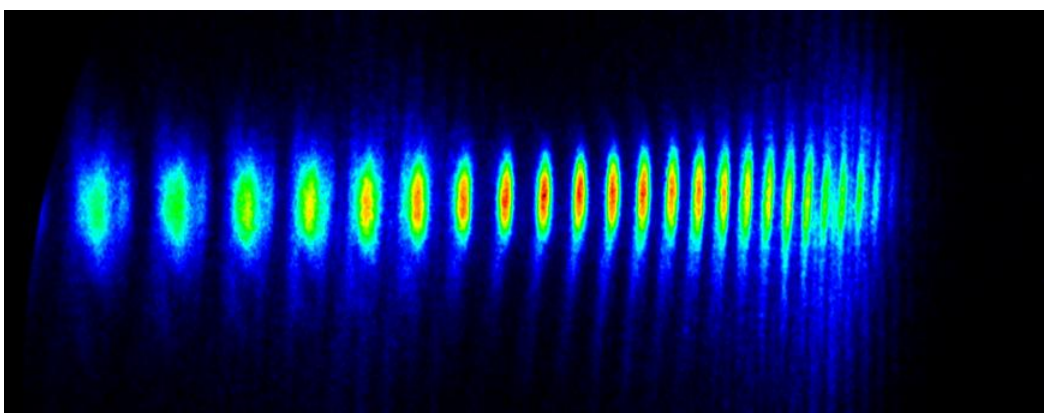


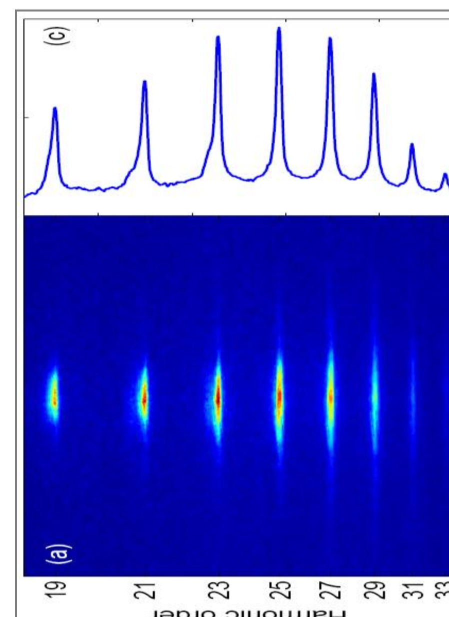




Detection of High Harmonics

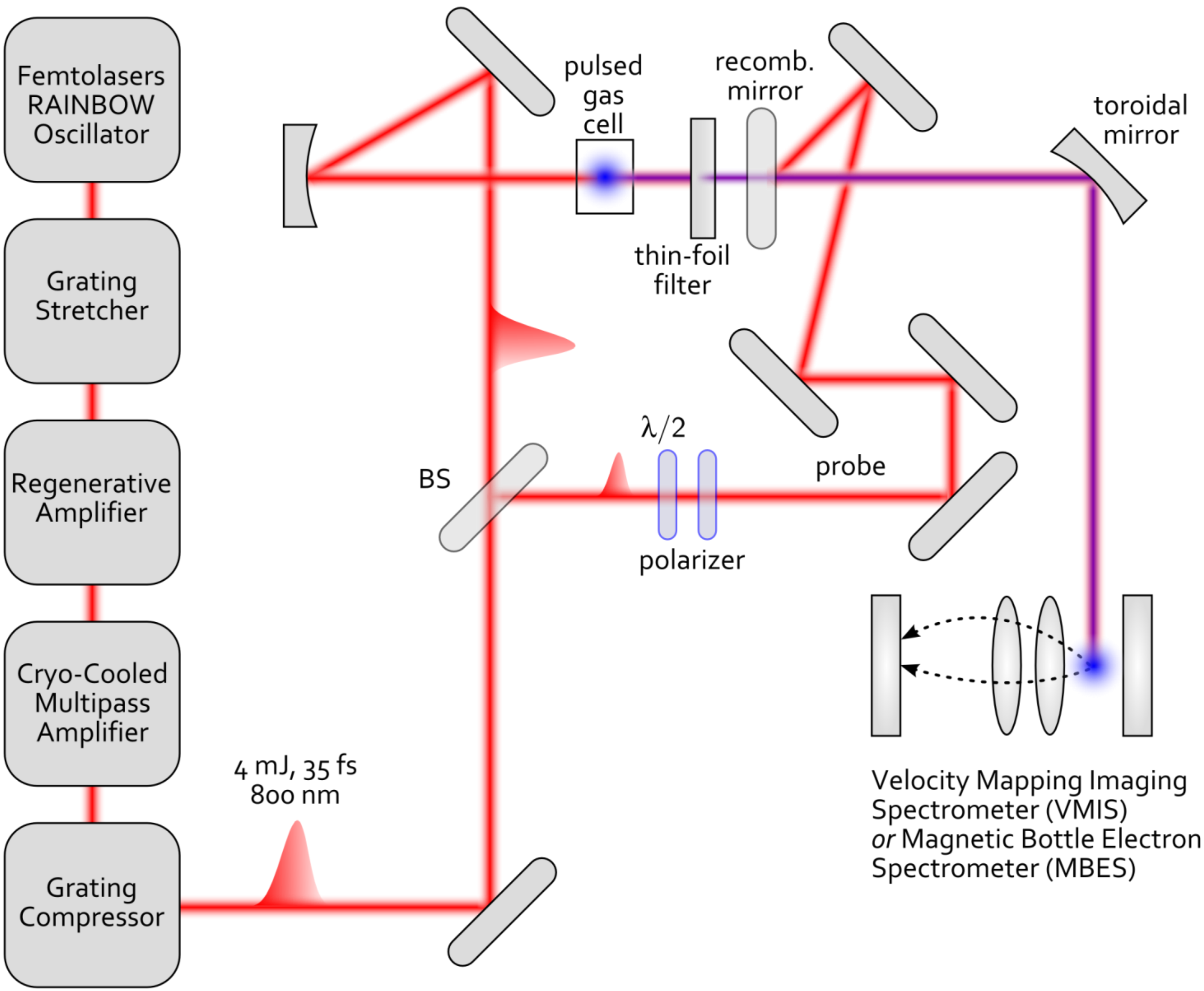






Nisoli et al., 2002

Attosecond experimental setup



Outline

1. HHG/ Atto for the beginner

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3. HHG : experiment

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5. Properties of HH

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The problem

$$i\hbar \frac{\partial \Psi(\vec{r},t)}{\partial t} = -\frac{\hbar^2}{2m}\nabla^2\Psi(\vec{r},t) + \left[-\frac{e^2}{4\pi\varepsilon_0 r} + e\vec{E}(\vec{r},t).\vec{r}\right]\Psi(\vec{r},t)$$

Time-dependent Schrödinger equation
Strong Field Approximation

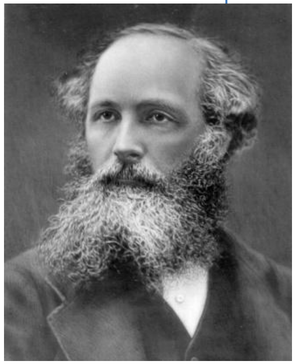
$$d(\vec{r},t) = <\Psi(\vec{r},t)\,|\,\vec{\varepsilon}.\vec{r}\,|\,\Psi(\vec{r},t)>$$

$$P(\vec{r},t) = N(\vec{r},t)d(\vec{r},t)$$

Coupled problem!

$$\nabla^2 E - \frac{1}{c^2}\frac{\partial^2 E}{\partial t^2} = \frac{1}{\varepsilon_0 c^2}\frac{\partial^2 P}{\partial t^2}$$

Coupled wave equations



Gaarde et al., 2006

Simplification of the problem

Paraxial approximation
Slowly-varying envelope approximation

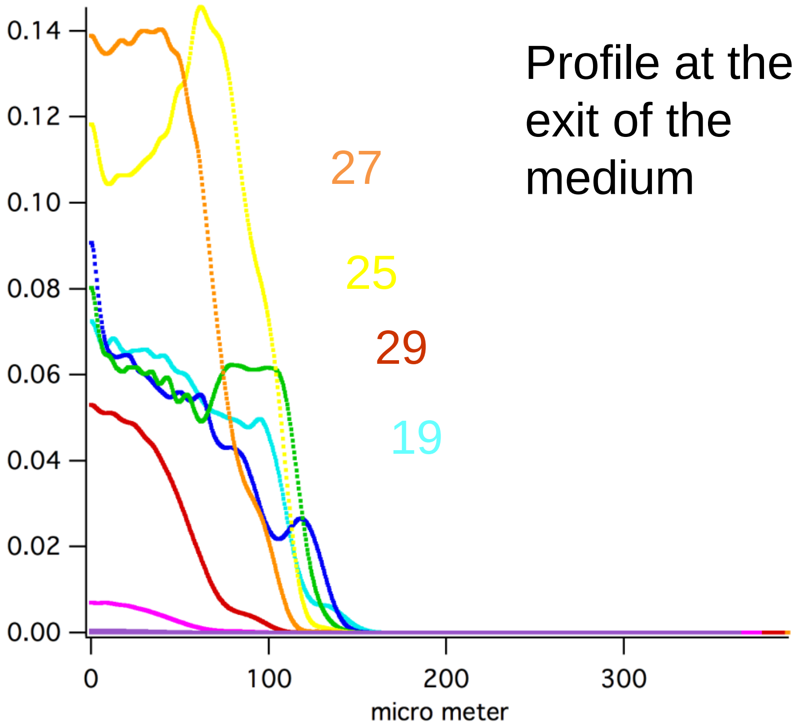
M. B. Gaarde, K. J. Schafer, M. Gisselbrecht, ALH

Time-dependent Schrödinger equation

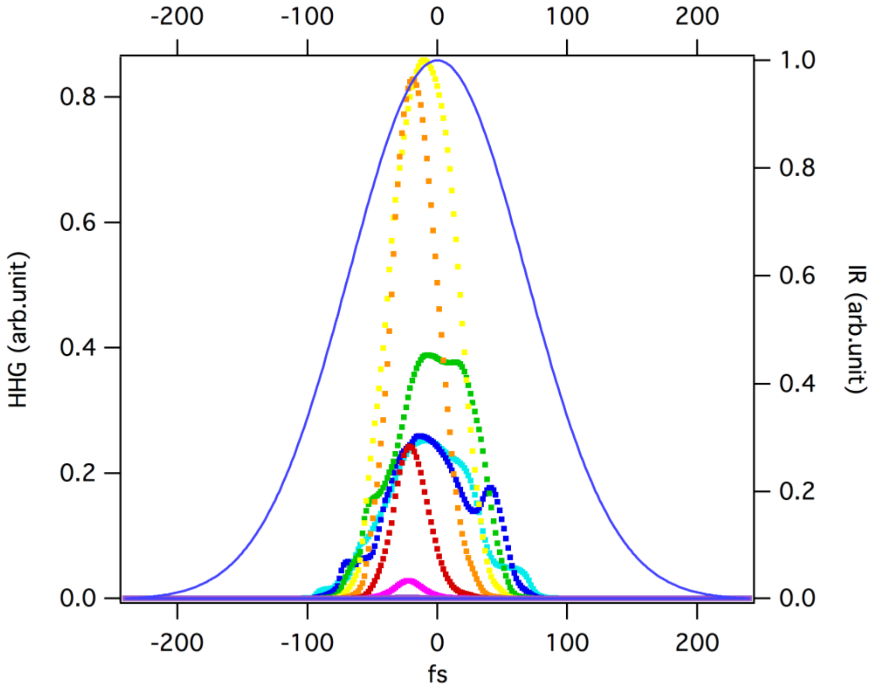
$$\nabla_{\perp}^{2} A_q + 2ik_q \frac{\partial A_q}{\partial z} = -\frac{q^2\omega^2}{\varepsilon_0 c^2} P_q^{NL} e^{-i\Delta k_q z}$$

Uncoupled!

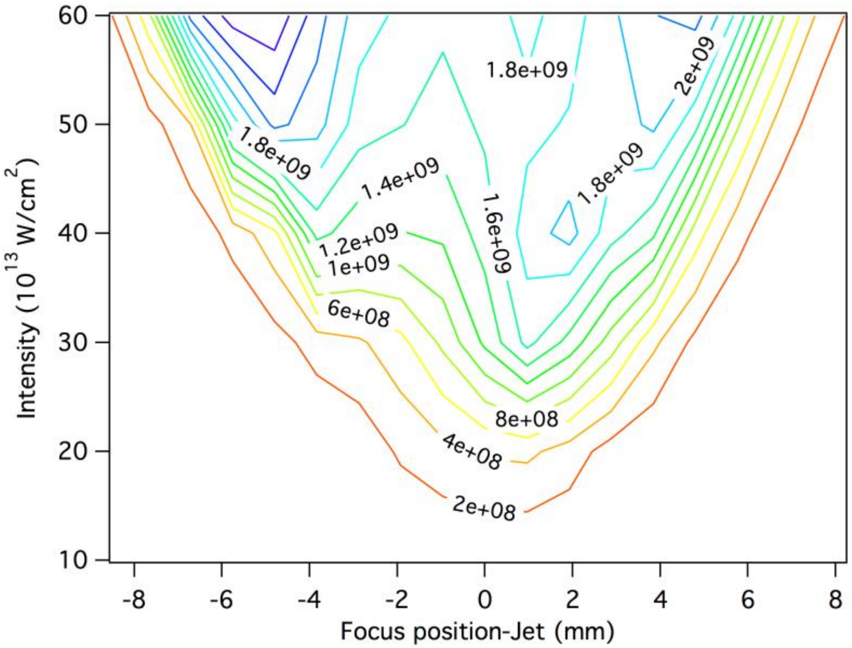
Profile at the exit of the medium



Temporal profile

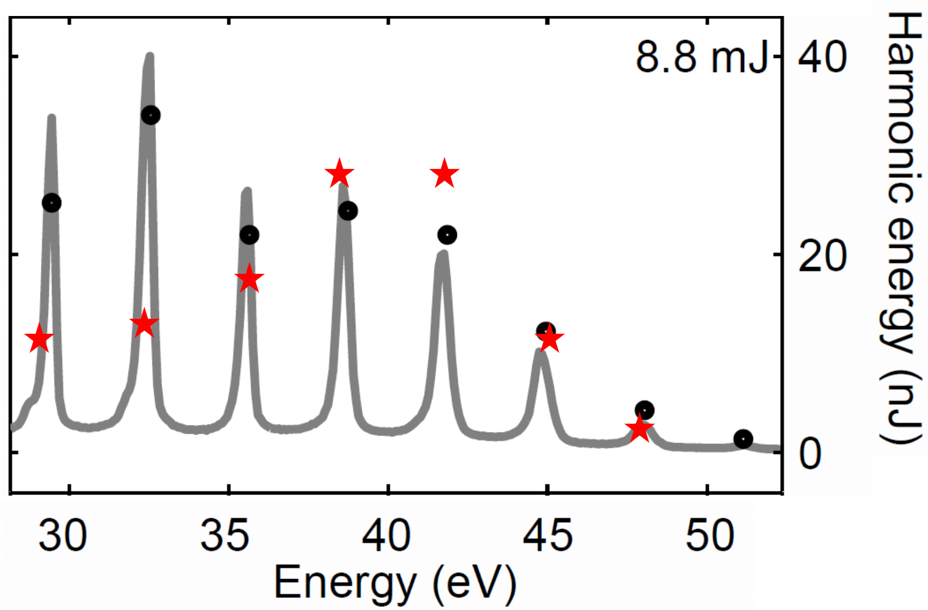


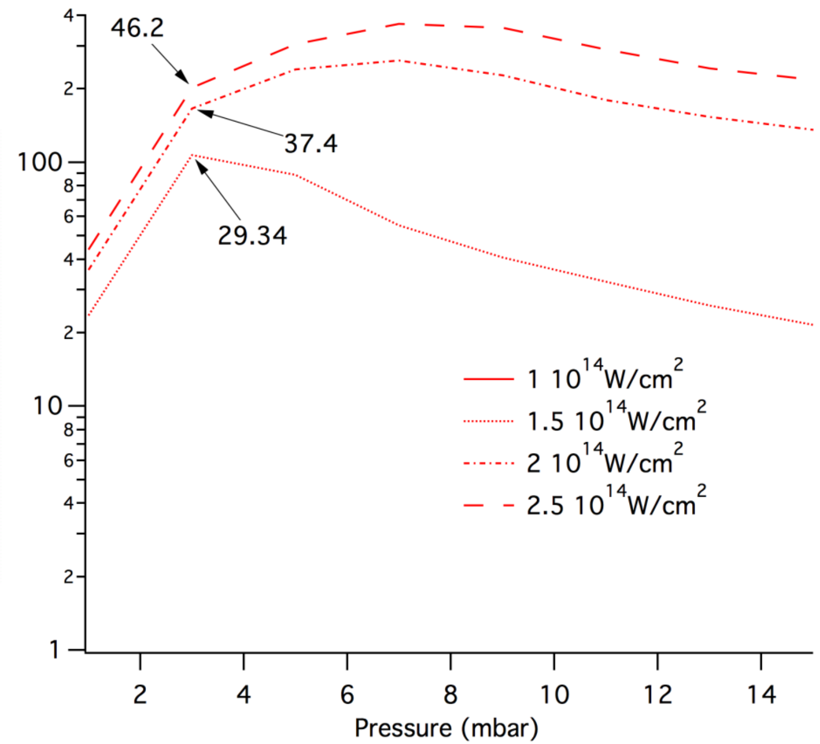
Optimisation of the problem



Complete numerical optimization of the number of photons vs:

- Confocal parameter,
- Focus position,
- IR intensity,
- Gas pressure





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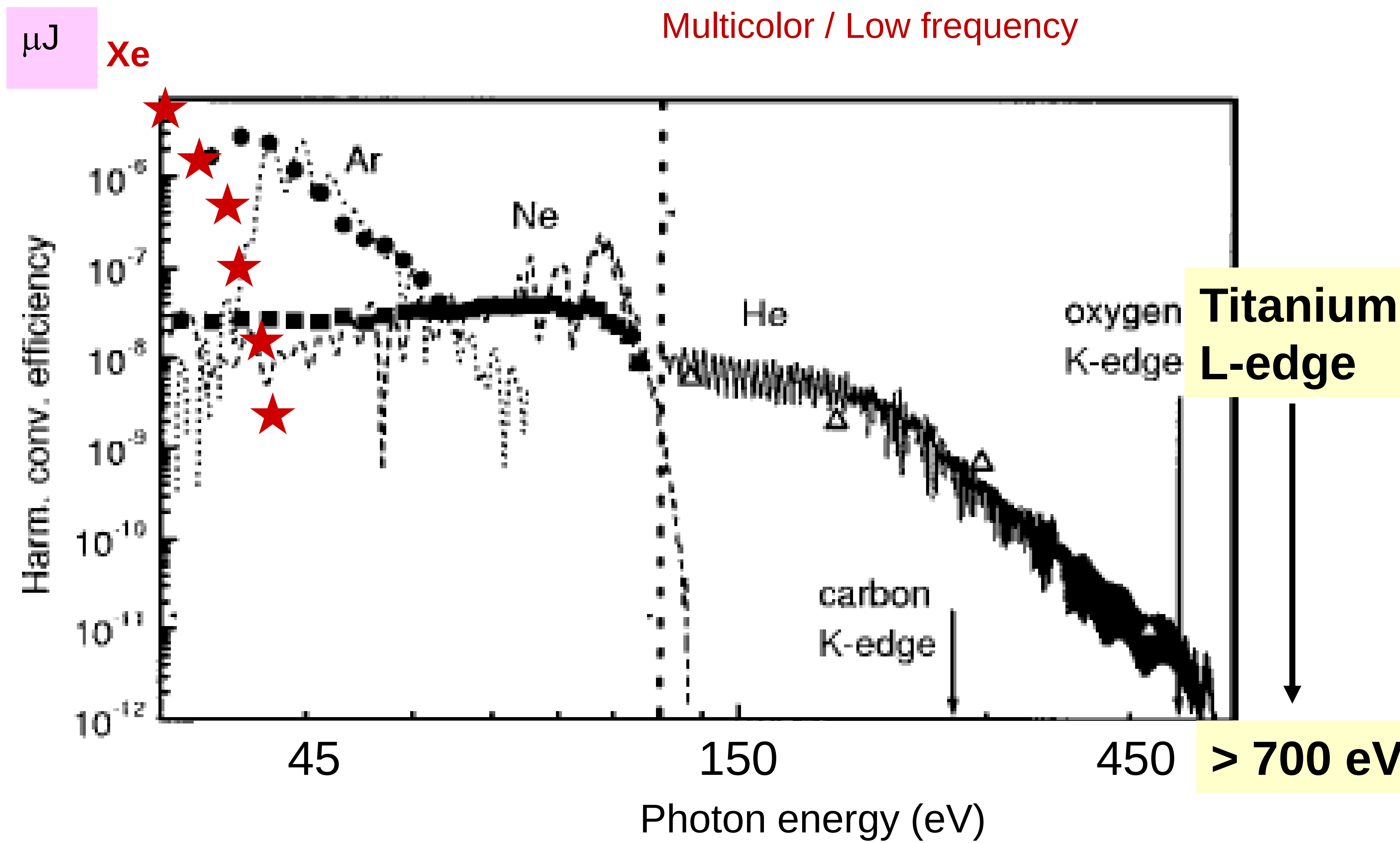
Spectral range and efficiency



Midorikawa, Salières

Murnane, Kapteyn

Brabec and Krausz, RMP, 2000

Seres et al., PRL 2004

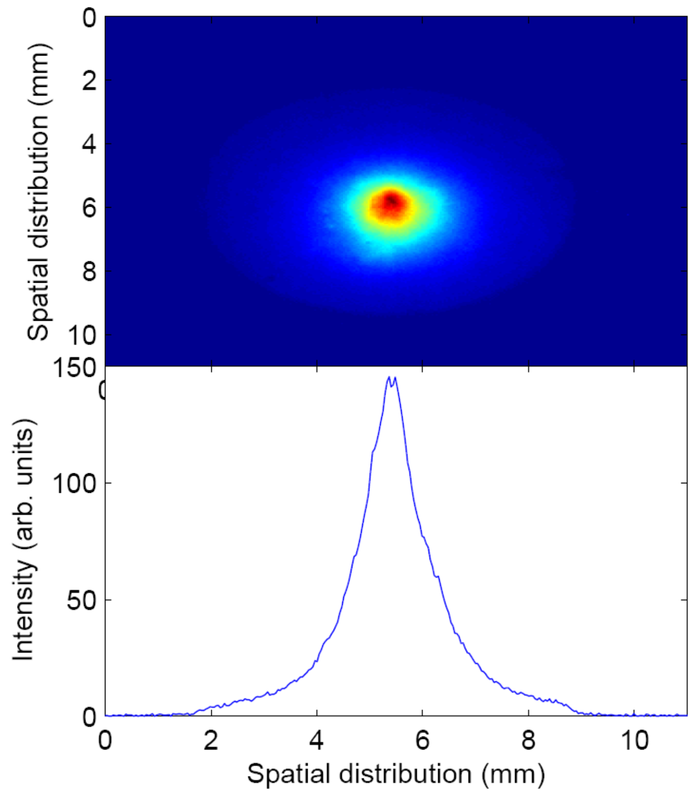
Energy per pulse and divergence

TABLE II. Optimized high-order harmonic energy and conversion efficiency.

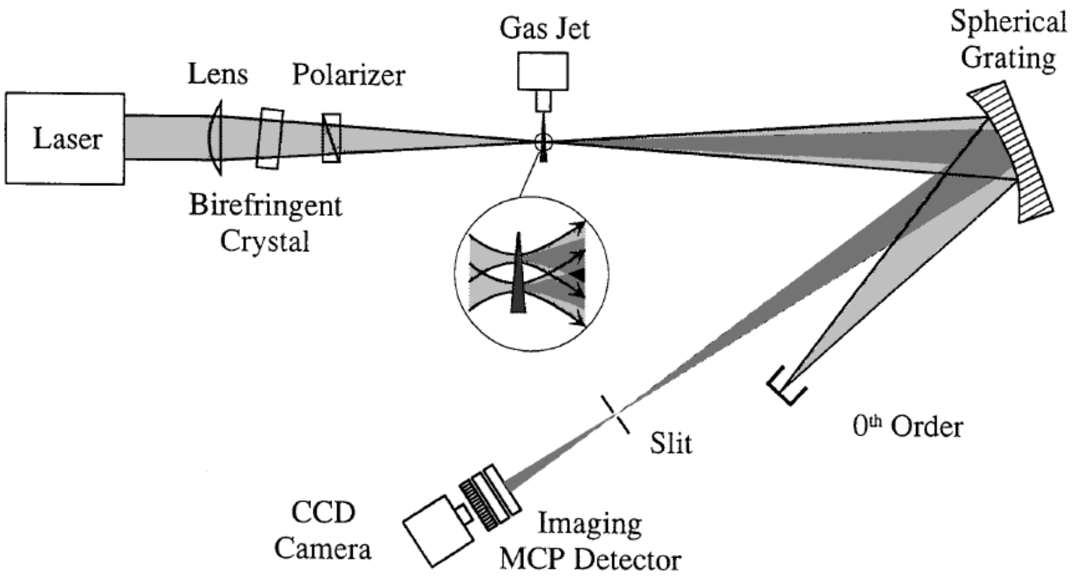
Harmonic order	17	19	21	23	25	27
Transmission	0.12	0.13	0.15	0.16	0.19	0.21
Photon number ($\times 10^{10}$)	3.03	2.98	3.10	2.63	1.60	1.41
Energy (μJ)	0.13	0.14	0.16	0.15	0.10	0.09
Efficiency ($\times 10^{-6}$)	6.8	7.5	8.6	8.0	5.3	5.0

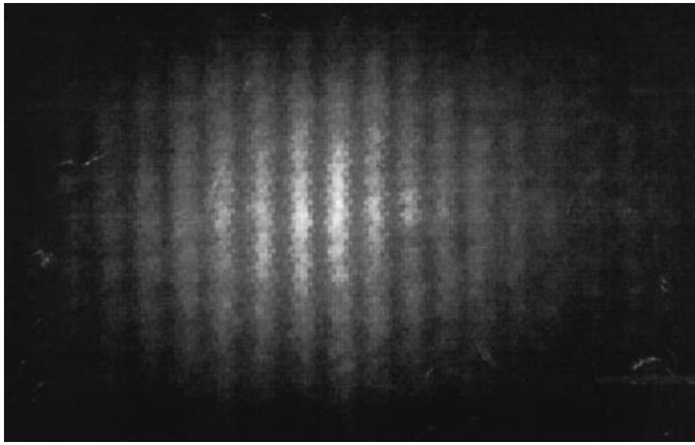
Loose focusing
Long medium
20 mJ

0.5 mrad



Coherence and Polarization of high harmonics





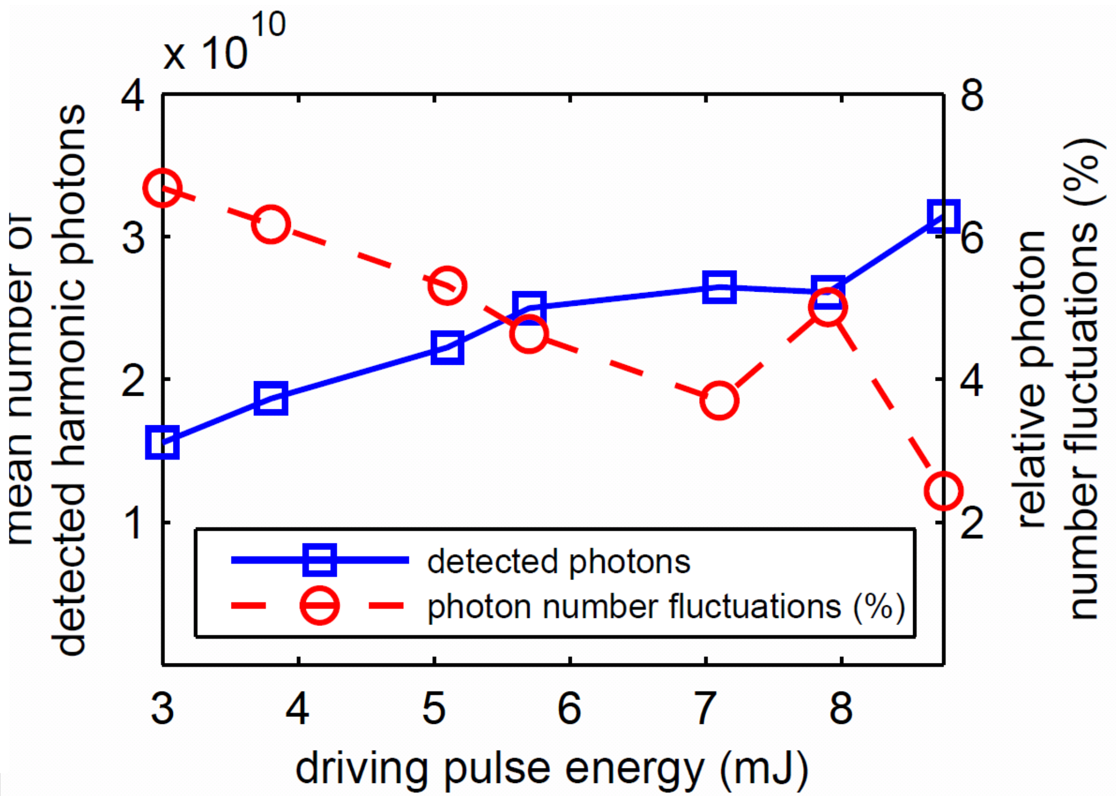
Spatial coherence: good!

Temporal coherence: limited by pulse duration and chirp

Polarization: normally linear – can be made circular by using two beams

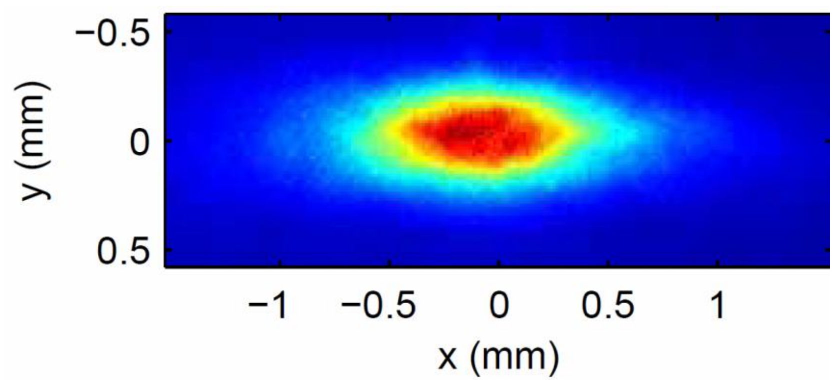
R. Zerne, PRL, 1997
M. Bellini, PRL, 1998

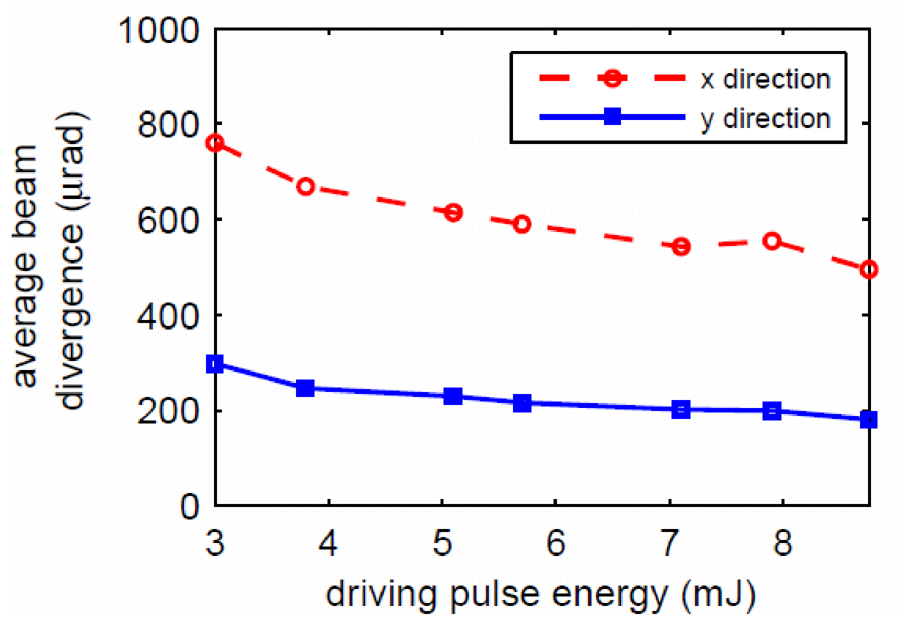
Number of Photons- Stability

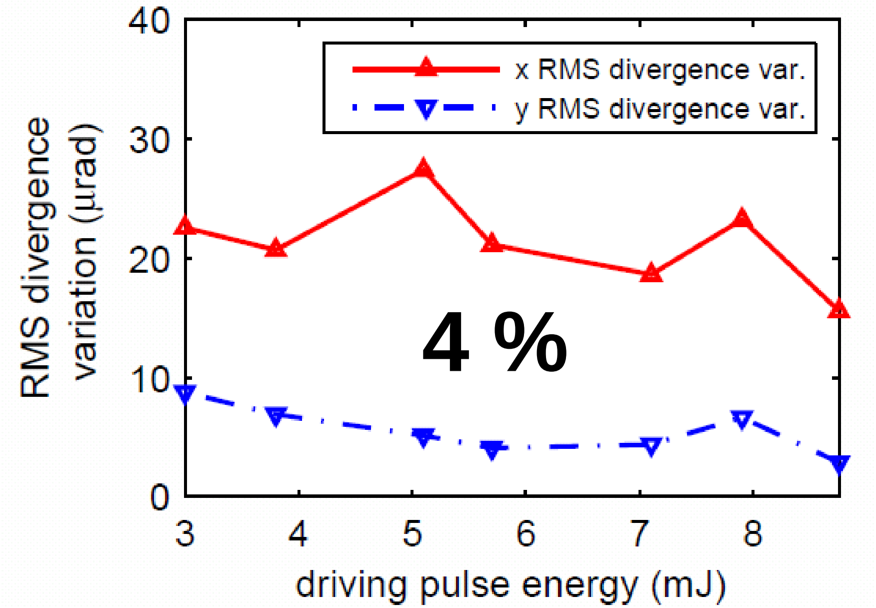


5%

Divergence and Pointing

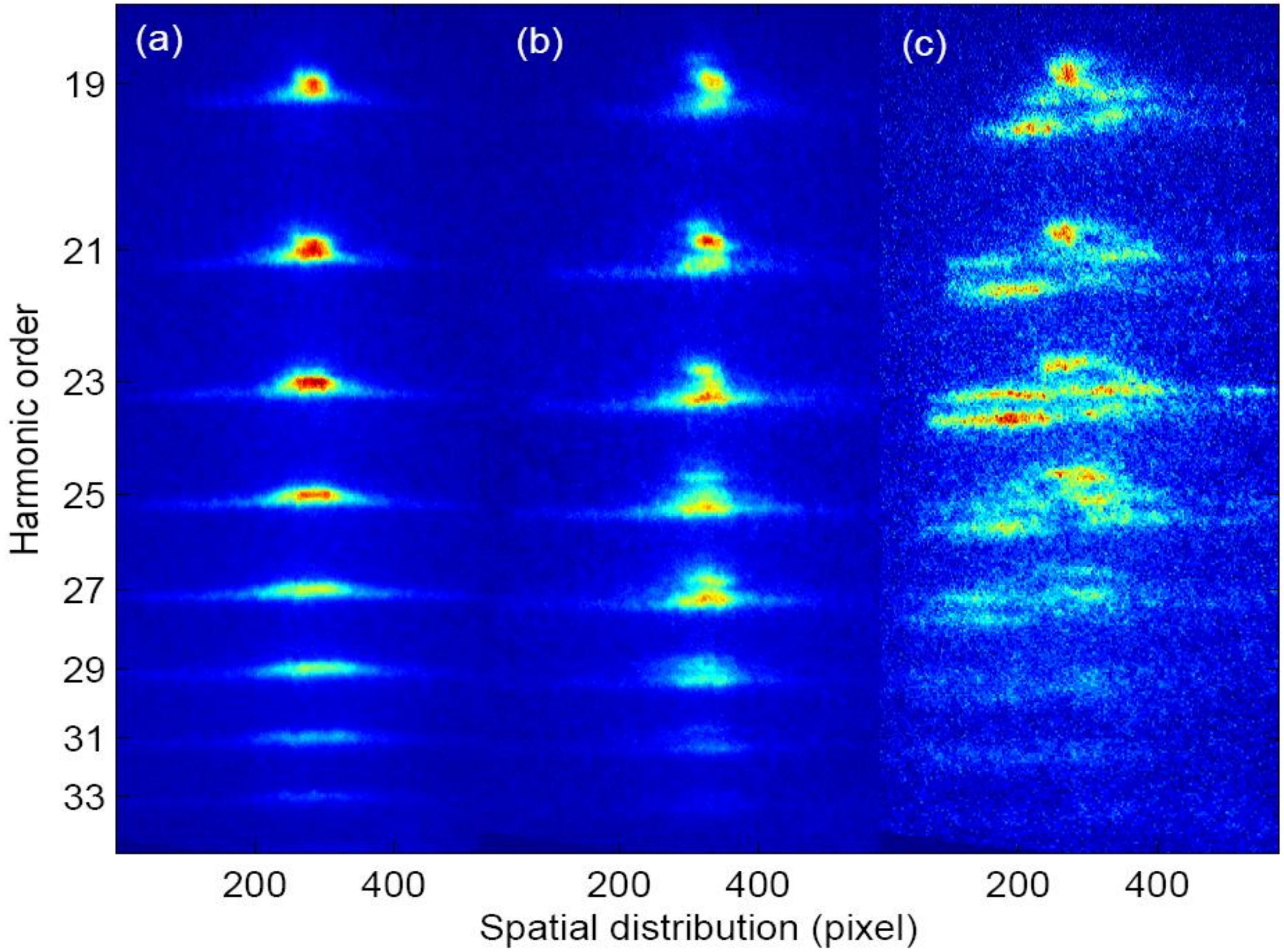






Pointing fluctuations : 3 %

Tunability of high harmonics



Increasing the intensity

Ch. Heyl

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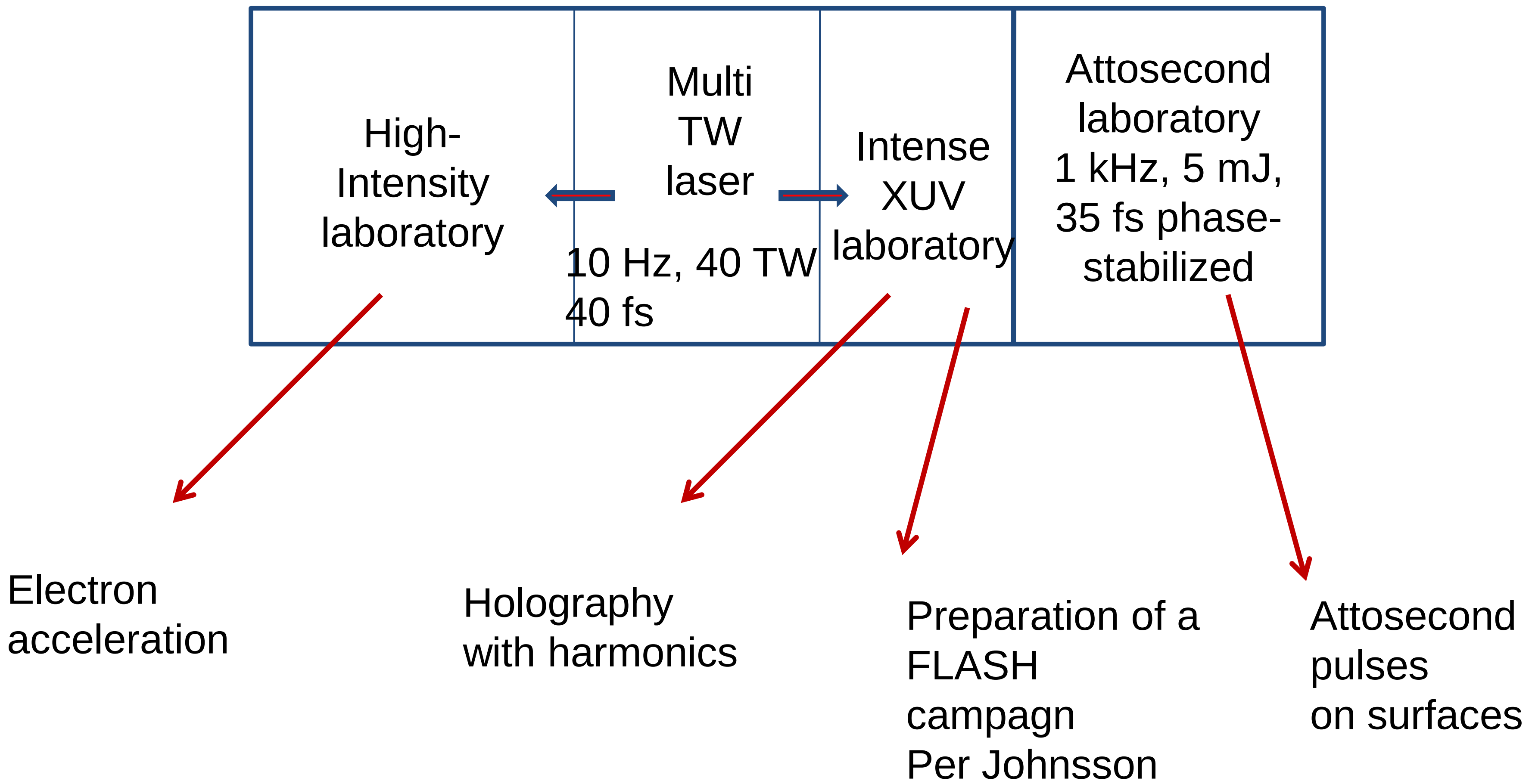
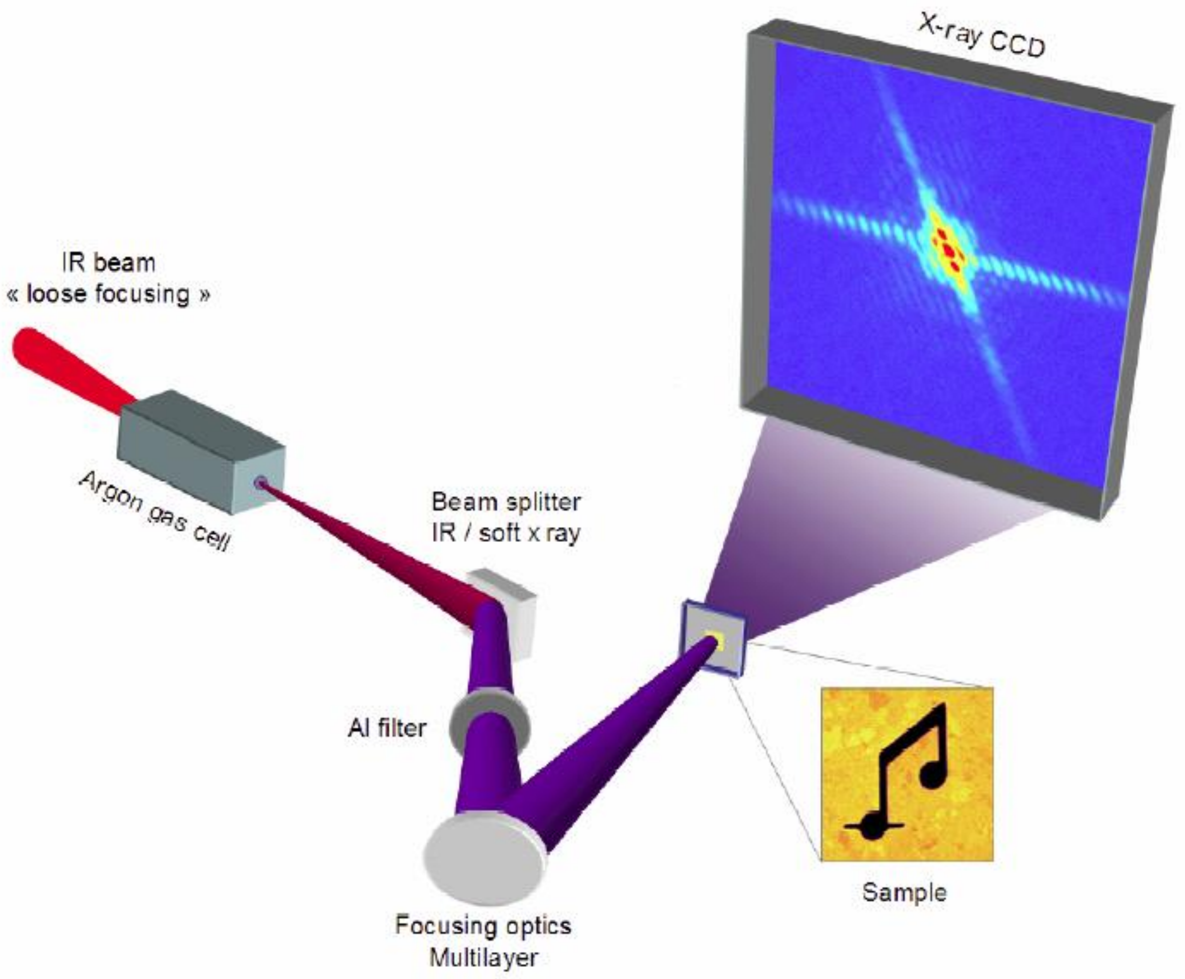
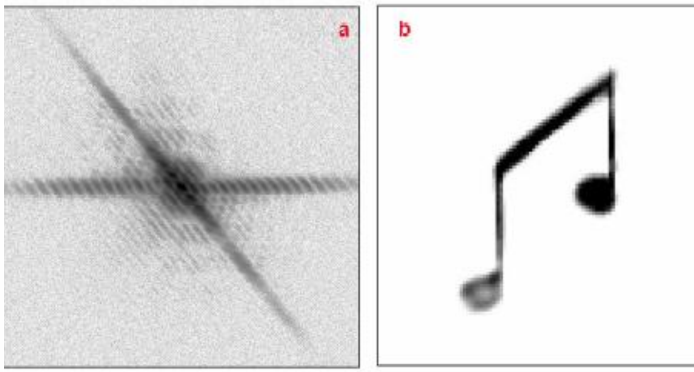
6. HHG : application   going on at the high-power laser facility

High-power laser facility



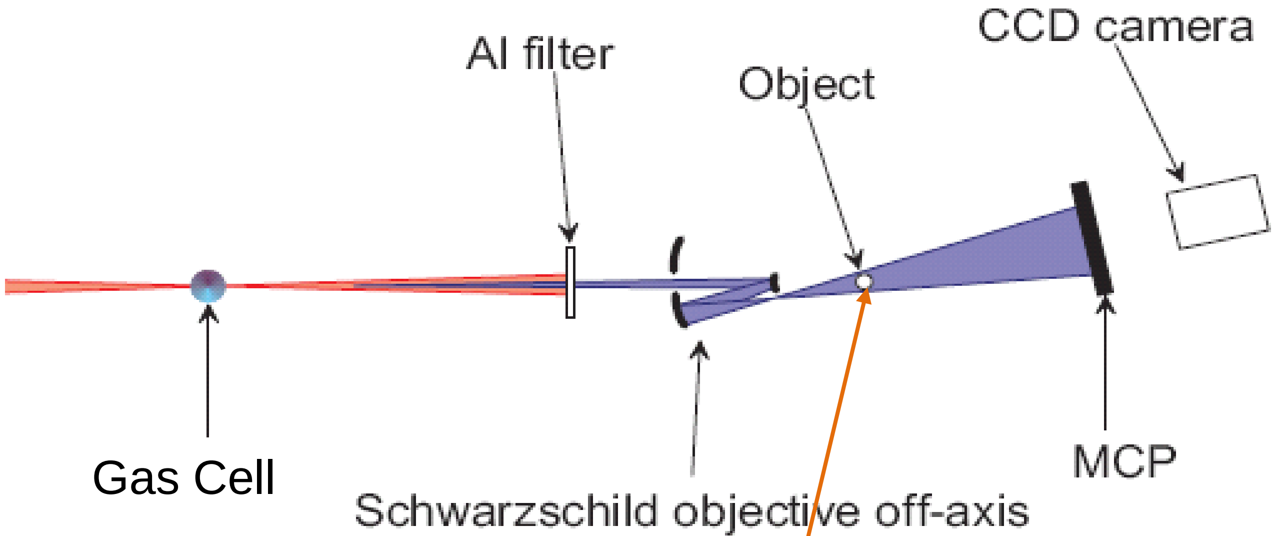
Coherent diffractive imaging with Harmonics



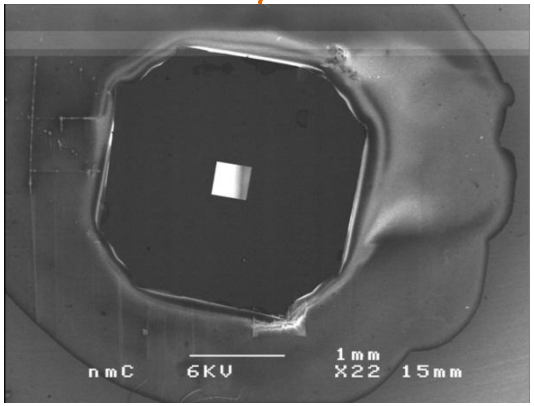


Kapteyn, Murnane
Ravasio et al., PRL, 2010

Digital In-Line Holography with Harmonics



Spot size ≈ 2 µm
Focal length 27mm



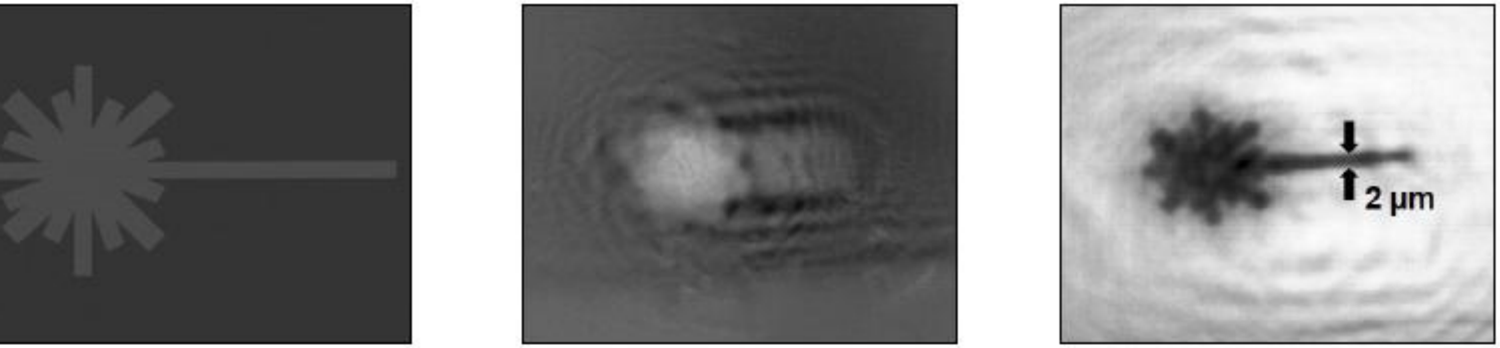
20 nm thin SiN membrane

Electron Beam Lithography

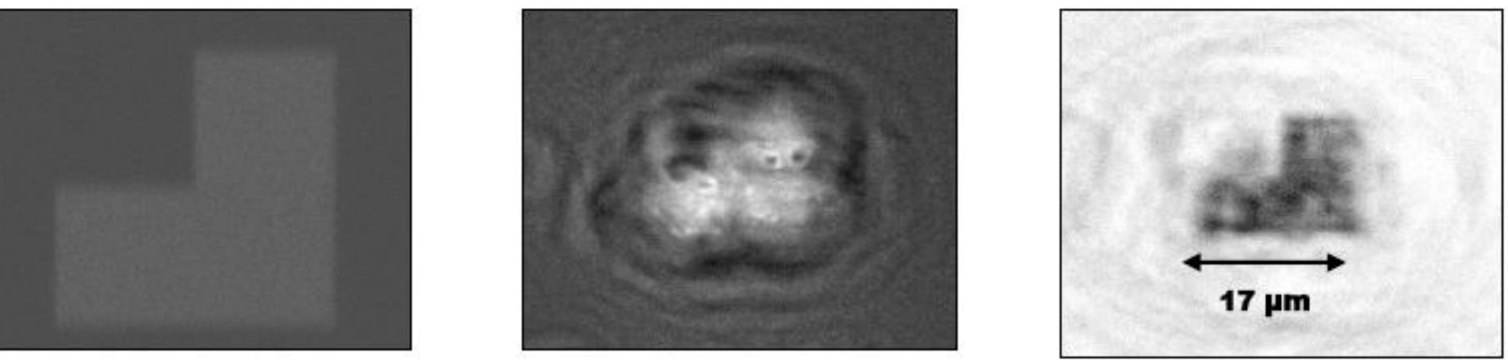
Experimental resolution: 1 µm

Single shot!

Digital In-Line Holography with Harmonics



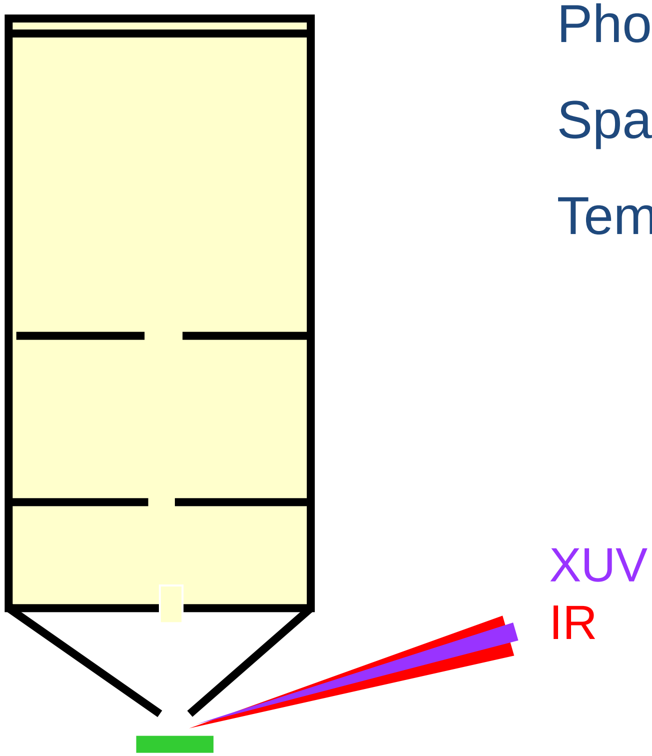
Amplitude object
Ni (5 nm) and Au (20 nm)



Phase object
Al (21.7 nm)

Time-resolved electron microscopy

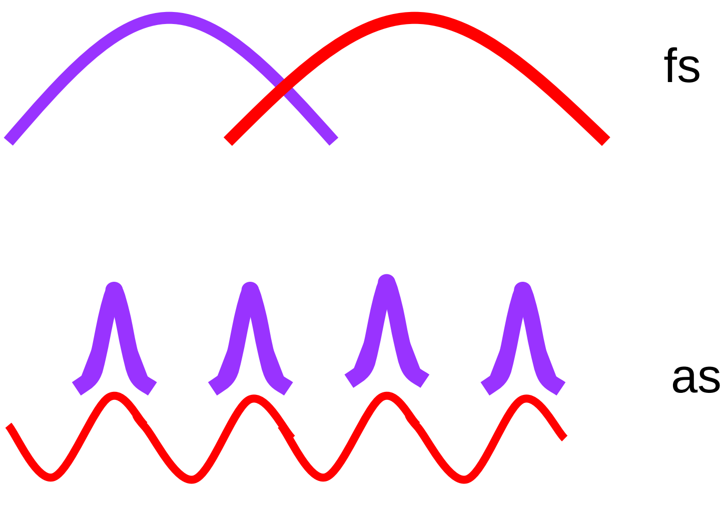
PEEM



Photoelectron emission microscopy

Spatial resolution: electron microscopy

Temporal resolution: pump/probe method



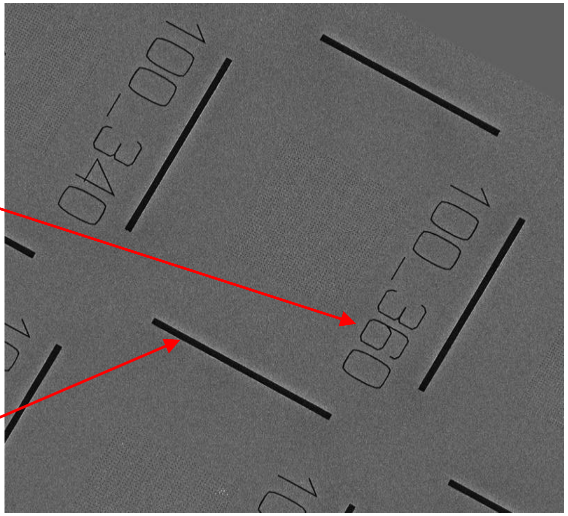
Imaging low energy electrons => very surface sensitive

Anders Mikkelsen

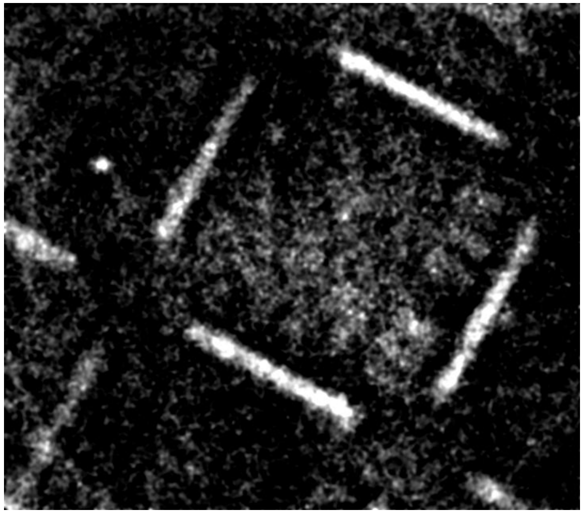
Images

200 nm linewidth

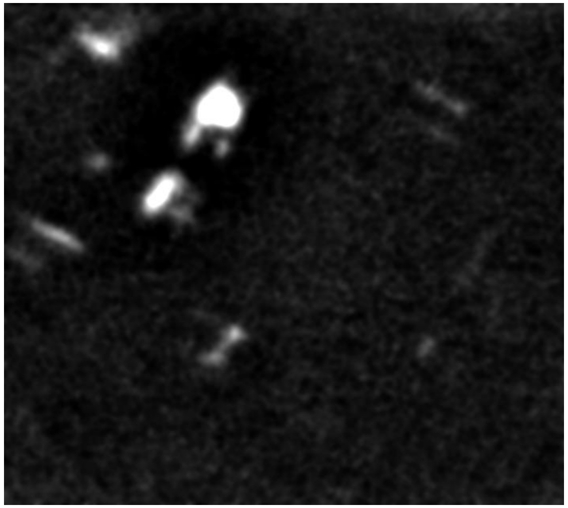
800 nm linewidth



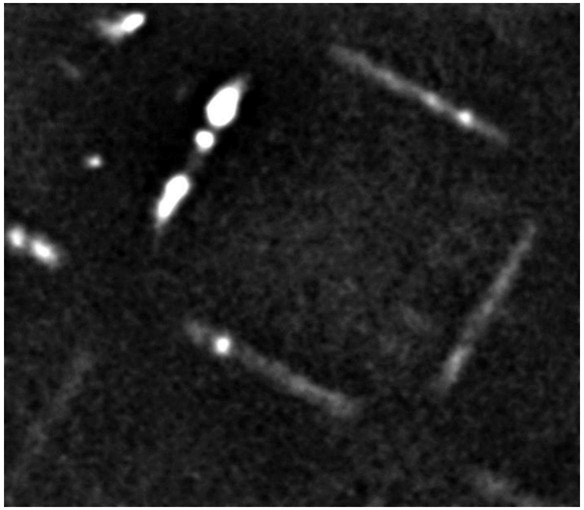
SEM image



PEEM + XUV laser



PEEM + IR laser



PEEM + IR + XUV

All images: 80x80μm^2


Thank you for
your attention
and welcome
to Lund !