Ultrafast VUV and soft X-ray pulses

(sources and properties)

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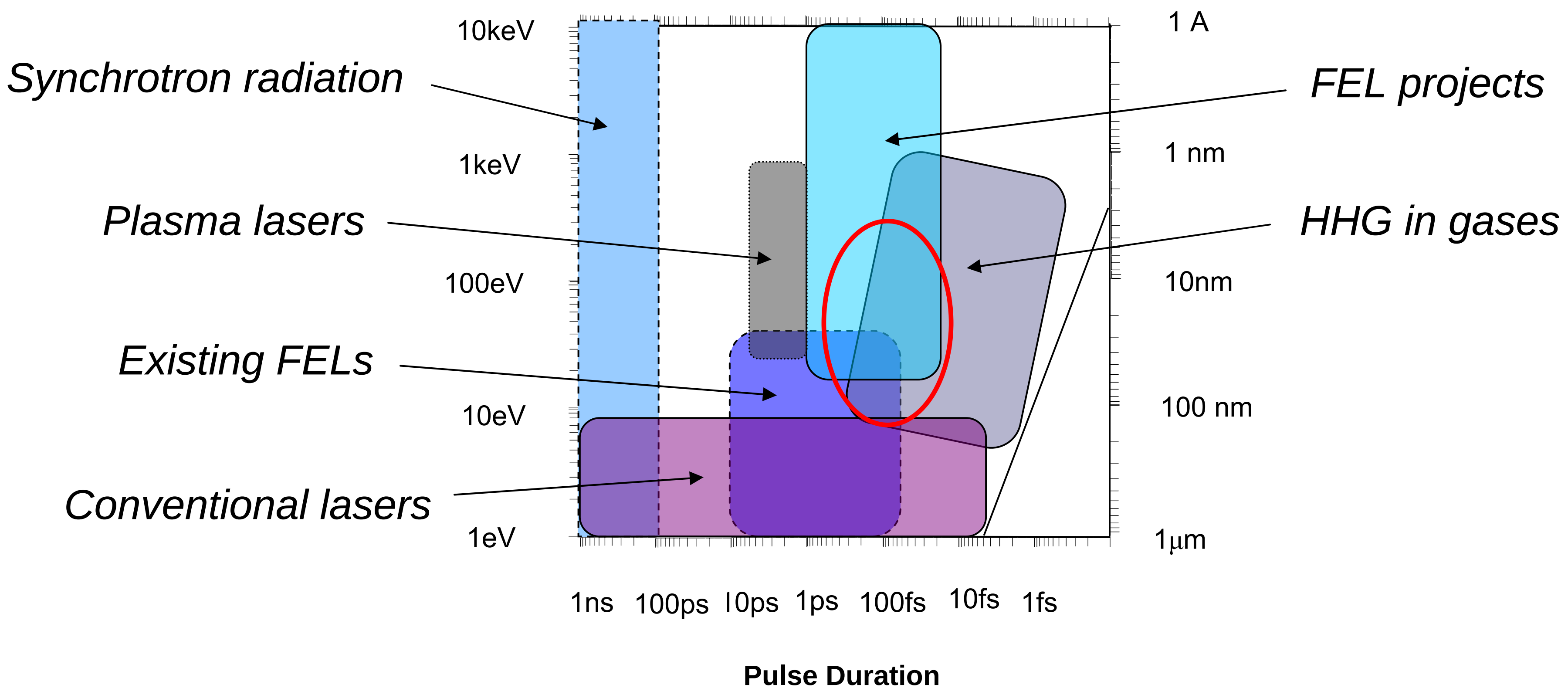
INTRODUCTION

Main sources of laser-like beams/pulses in the 180-3 nm range



M.B.Danailov, ICTP School
on Synchr.Rad. 2006

Harmonic generation

Regimes:

1. Peak power density from 10^3 to 10^{13} W/cm^2 - **weak perturbation limit**

Nonlinear polarisation :

$$\vec{P} = \varepsilon_0 (\chi^{(1)} \vec{E} + \chi^{(2)} \vec{E}^2 + \chi^{(3)} \vec{E}^3 + \ldots)$$

Phase matching:

$n\mathbf{k}_\omega = \mathbf{k}_{n\omega}$

In NL crystals :

- PM by birefringence
- $\chi^{(2)} \sim 10^{-12}$ m/V

efficienciy of SHG (2ω)~50% ,THG(3ω)~15%,… FHG(5ω)~1%

Limits:

- transparency region : 6.9 eV BBO, ~8eV KBBF , ~10eV SBBO
- No phase matching for SHG , mixing with longer wavelengths

Shortest wavelengths: 157 nm , FHG of Ti: sapphire in KBBF (1)
130 nm , SHG (not in PM!) in SBBO

HG in gases

Features:
-Odd harmonics only
-Transmission in the VUV-EUV
-Low nonlinear susceptibility

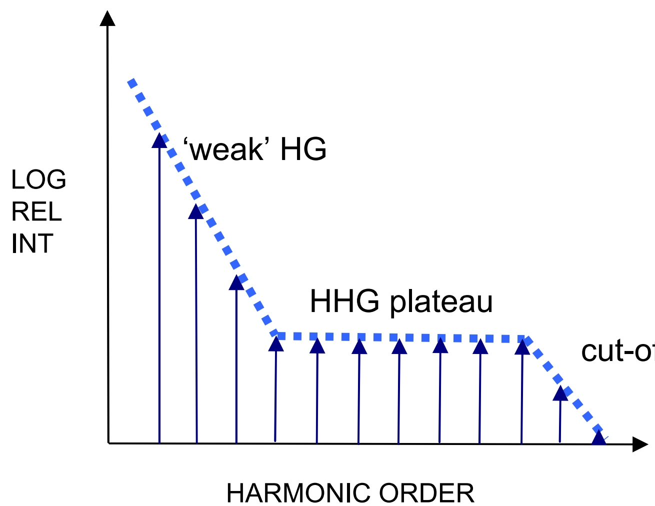
$$\eta = \frac{P_3}{P_1} = \frac{3\pi^2}{\varepsilon_0^2 c^2 \lambda_1^4} N^2 [\chi_{\lambda_3}^{(3)}]^2 P_1^2 |\Phi|^2$$

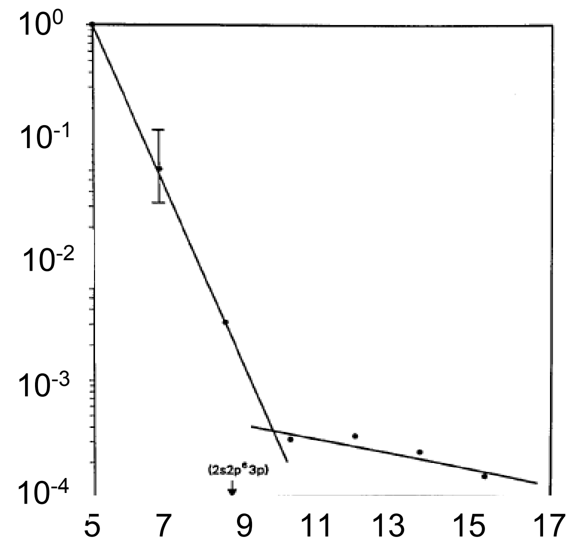
(in SI units)

- Regions where Δk~0 (or small enough) can be found by adjusting gas mixture and focusing conditions
- Feasible for THG in the EUV starting with laser wavelength in the deep UV
Excimer or Third harmonic YAG : 3% efficiency in generating 118. 2 nm (10.5 eV) in gas cell with mixture Xe:Ar;
Tuneable source (Nd:YAG harmonic+dye) for tuneable THG in gas jets -> 10^{-4} efficiency in generating 70- 100 nm (~18 – 10 eV)
Can be extended down to about 60 nm (~20 eV) by use of Ti:sapphire harmonics in BBO as a source to generate ~10μJ per pulse (2 to 5×10^{12} ph/pulse)

HHG in gases

- At very high intensities (>10^{14} W/cm^2) the weak perturbation limit breaks ->plateau in the harmonic conversion efficiency





From McFerson et al, JOSA B 4 (1987), 595

- Theory:

Semiclassical: Corkum Phys.Rev.Lett.**71** (1994); Kulander et al, Proc.SILAP III, ed. B.Piraux (Plenum), 95-110.

Fully quantum-mechanical treatment : Lewenstein et al, Phys.Rev.A 49 (1994), 2117

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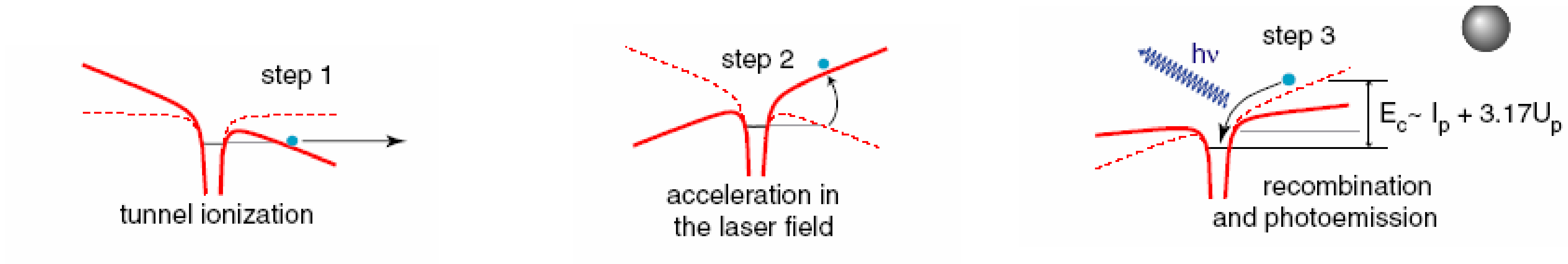
Three-step model of HHG



The classical picture correctly predicts most of the observed features

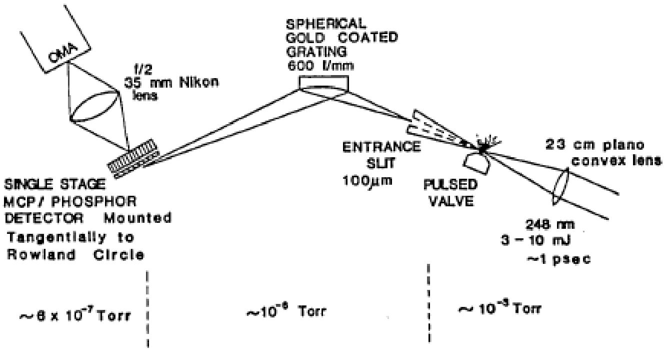
Cutoff: $h\nu_{max} = I_p + 3.2U_p$, where $U_p = e^2E^2/(4m\omega^2) \sim I_L\lambda^2$

Some effects related to the quantum phase may strongly influence the spectrum, pulse shape and spatil coherence of the generated harmonics

HHG in gases

Main directions of development

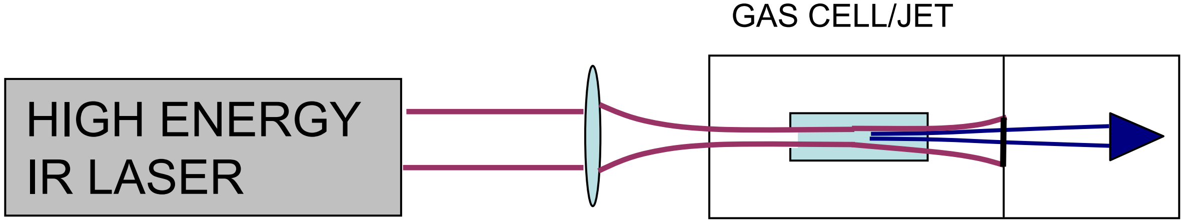
A. Phase-matching
1. HG in waveguide (hollow fibre)
2. Corrugated waveguide: quasi-phase matching
3. Non-adiabatic self-phase matching (HHG with very short pulses)



From McFerson et al, JOSA B 4 (1987), 595

B. Long wavelength excitation for increasing cutoff

C. HHG with temporally shaped pulses



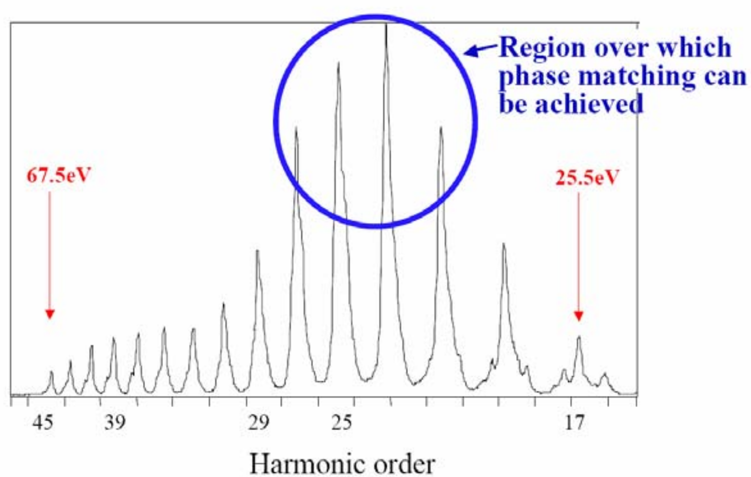
HHG in gases

A.1. Phase matching in guided wave HHG

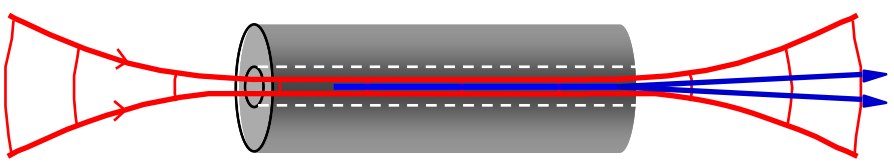
Fundamental Light wave vector

$$k = \frac{2\pi}{\lambda}\left(1 + Na\delta(\lambda) - \frac{1}{2}\left[\frac{Unm\lambda}{2\pi a}\right]^2 - \frac{1}{2}\frac{N_e r_e \lambda^2}{\pi}\right)$$

vacuum **gas** **waveguide** **ionization**



Hollow fibre



C. Durfee et al., Opt Lett 22, 1565 (1997)

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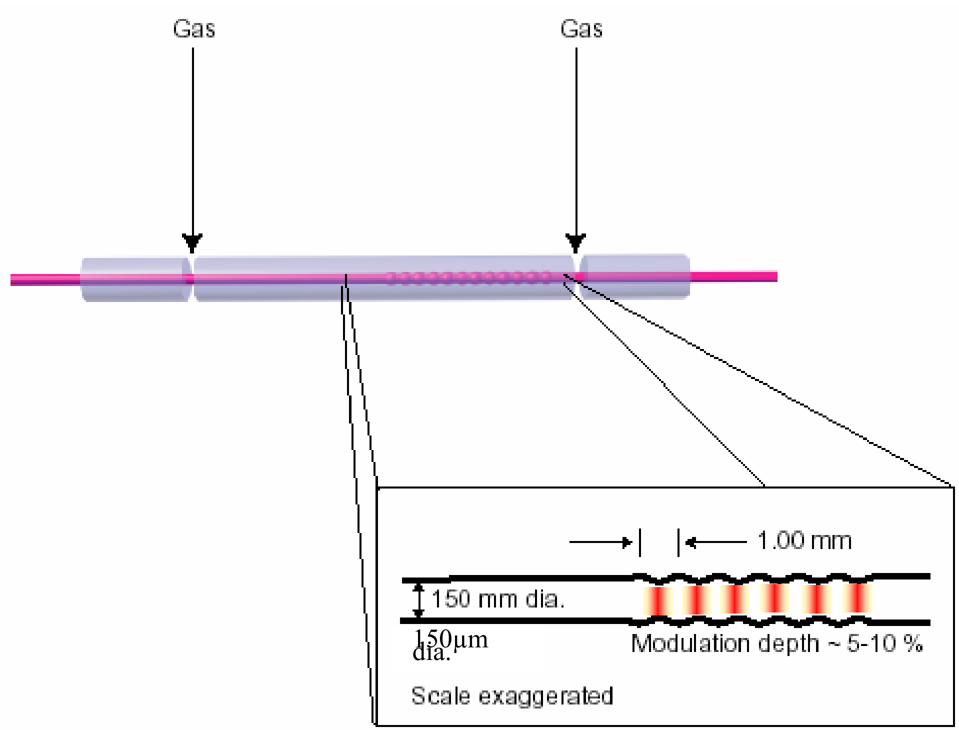
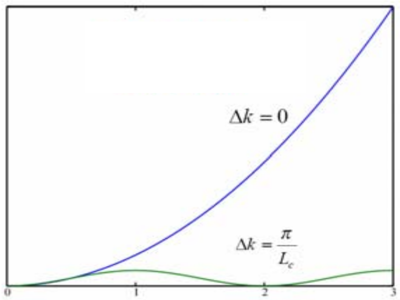
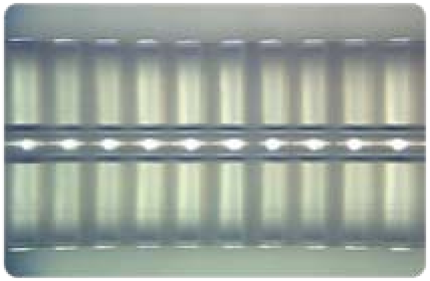
A.2. Quasi-Phase Matching (QPM) in waveguide HHG







Slide from H.Kapteyn

A. Paul et al, *Nature* **421** (2003), 51

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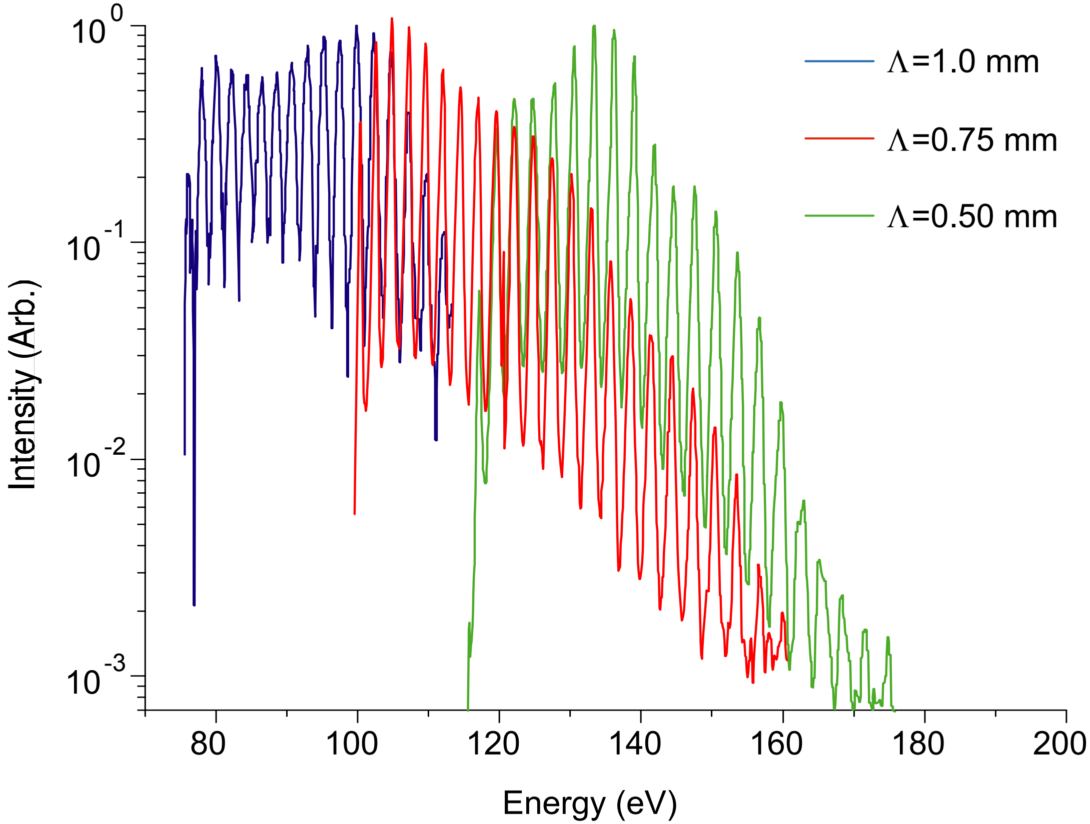


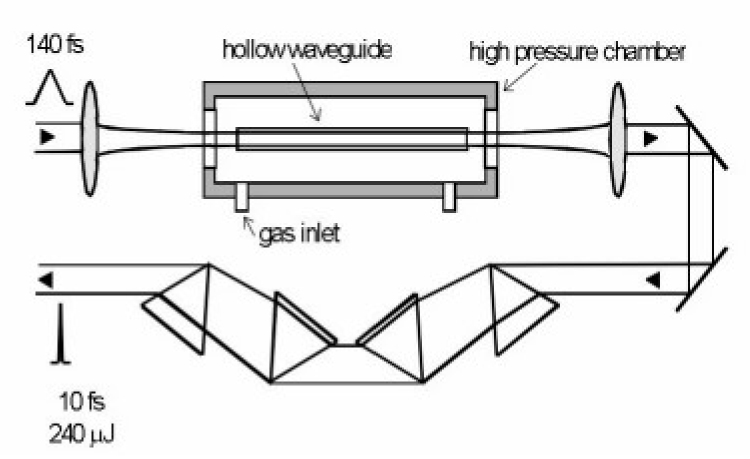
Cutoff shift to higher energy by QPM, A. Paul et al, *Nature* **421** (2003) 51

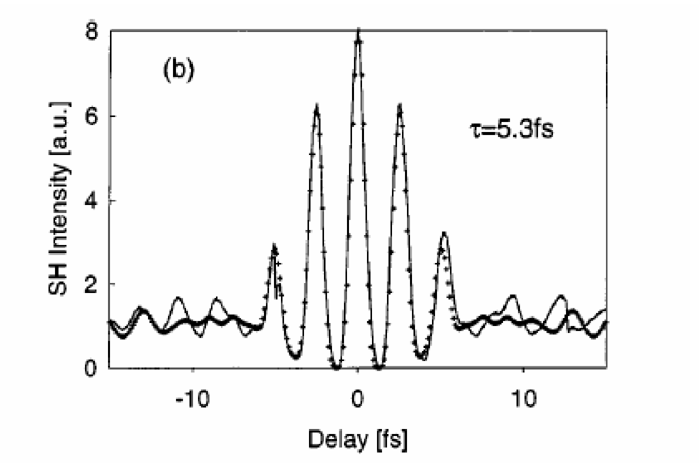
HHG in gases

A.3. Use of very short pulses: non-adiabatic regime

Few-cycle fundamental pulse (~5 fs at 800 nm)

(approach for generation proposed at Politecnico di Milano and Viena, demonstrated 5 fs , 70 µJ)





M. Nisoli et al, **Opt. Lett. 22**, 522 (1997)

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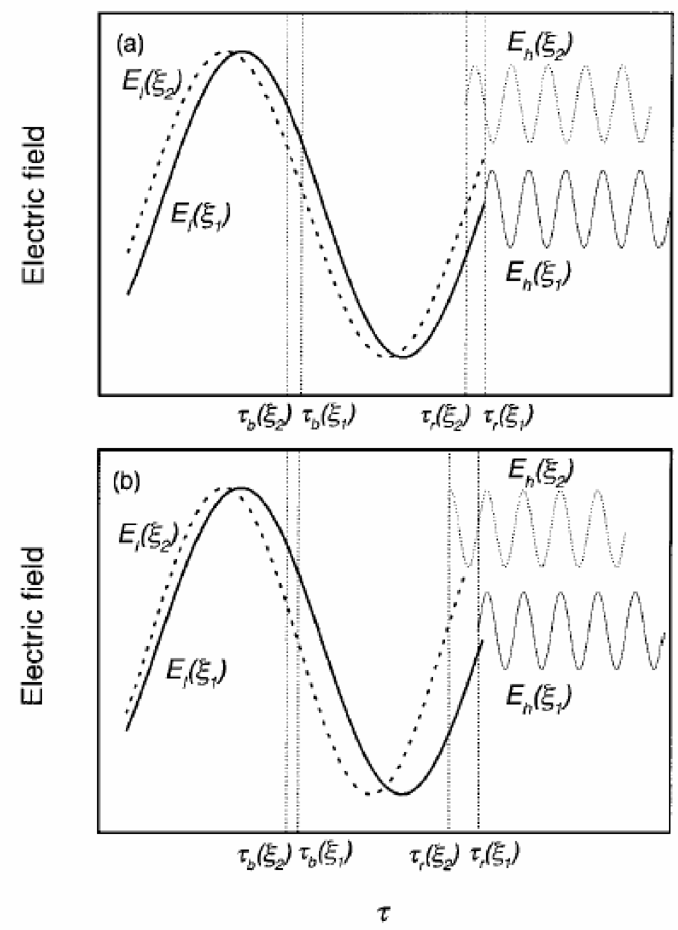
A.4. Non-adiabatic self-phase matching (NSPM)

10

Very short pulses focused to 0.2-1x10[16] W/cm[2]
Proposal and numerical simulations: Tempea et al, *Phys Rev Lett* **84** (2000)4329)
Experimental results : E.Seres et al, *Phys Rev Lett* **92 (2004), 163002**

Laser source: 5 fs, 300 μJ , focused to 30-40 μm
Medium: thin jet (0.5 mm), 0.5 bar



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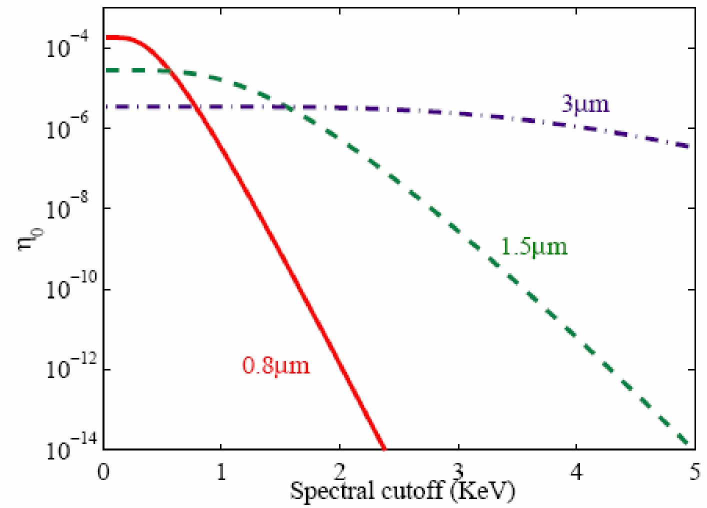
A.4. Increase wavelength of excitation – cutoff increase expected

$h\nu_{max} \sim I_p + I_L\lambda^2$

Needs development of high intensity systems in the 2-3 μm region

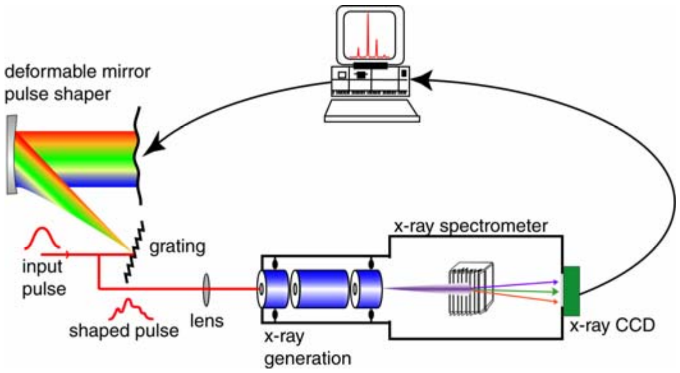


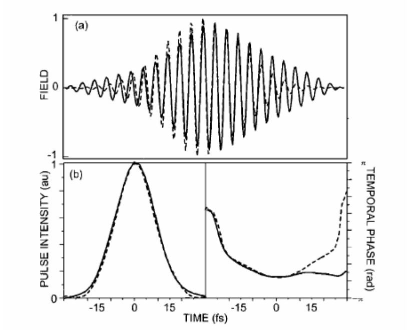
A. Gordon et al, Opt. Express **13**, 2941-2947 (2005)

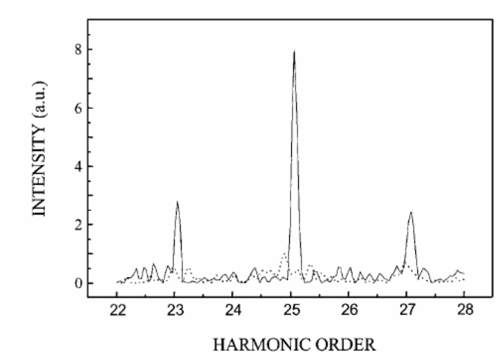
HHG in gases

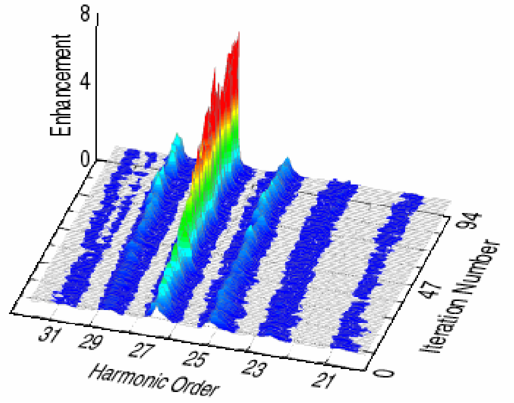
Temporal pulse shaping

Optimization of harmonic jield for
a given harmonic order : small changes
In the driving pulse temporal phase induce
substantial enhancement









Theory : Christov et al, PRL 86 (2001), 5458

Bartels et al, Nature **406** (2000) 164

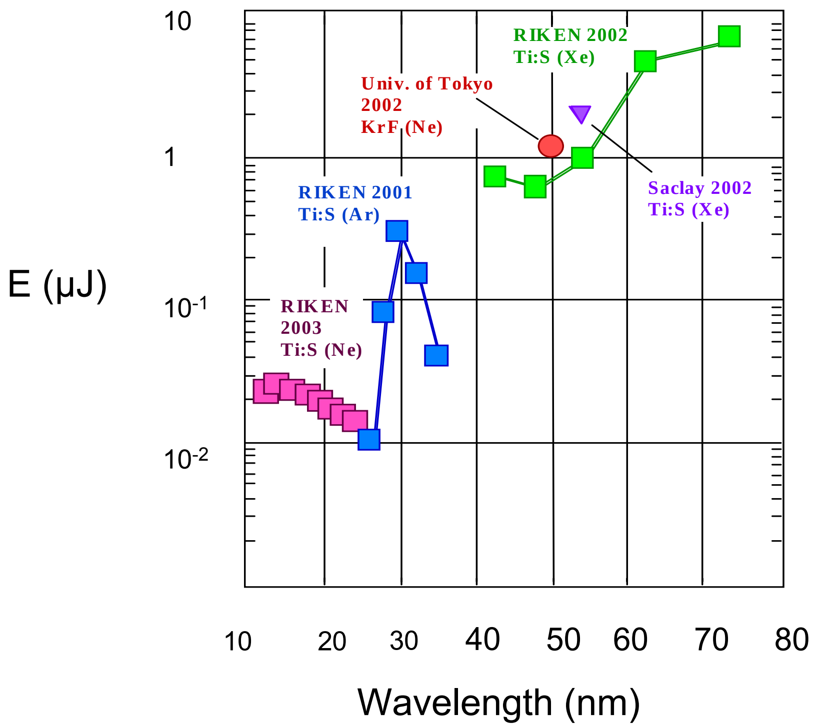
HHG in gases

PARAMETERS

Pulse energy

- Above 1µJ from 40 to 80 nm
-10-100 nJ in the 10-40 nm range

Laser source: Ti:saphire at 800 nm
For low rep rate high-energy regime: E_p~30-50 mJ, t_p ~30-50 fs , rep rate ~ 10 Hz
Geometry: loose focusing (f_l ~2-5 m)
For low-medium energy HHG:
E_p~2-3 mJ, t_p<30 fs , ~1KHz , sharper focusing f_l<1m



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PARAMETERS

Max photon energy

10^2-10^3 ph/s within 10% bw at **1.3 keV**

(J.Seres et al, Nature 433 (2005), 596);

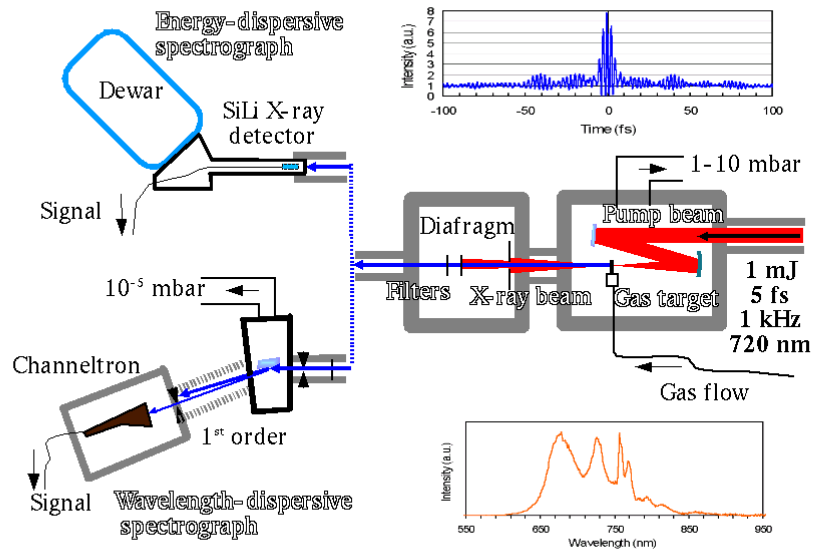
$2x10^5$ ph/s at **700 eV**

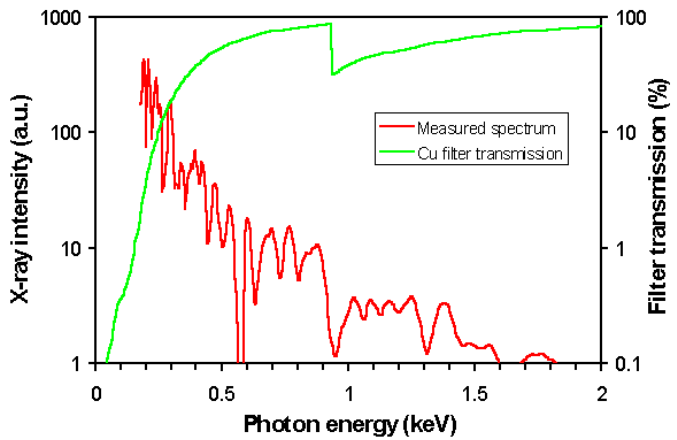
$2x10^7$ ph/s at **280 eV**

$1x10^8$ ph/s at **200 eV**

$5x10^8$ ph/s at **100 eV**

(E.Seres et al, *PRL* **92 (2004), 163002)**





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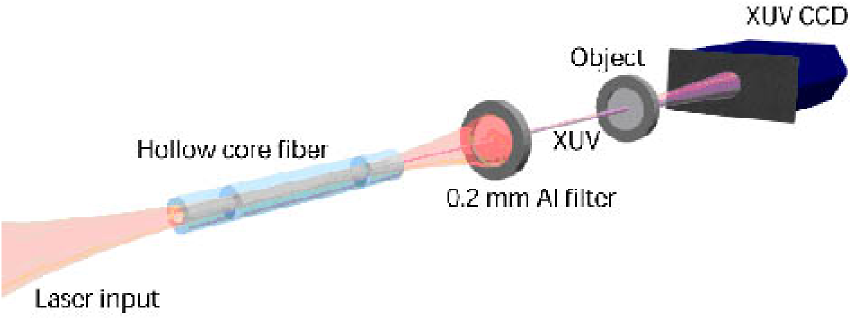
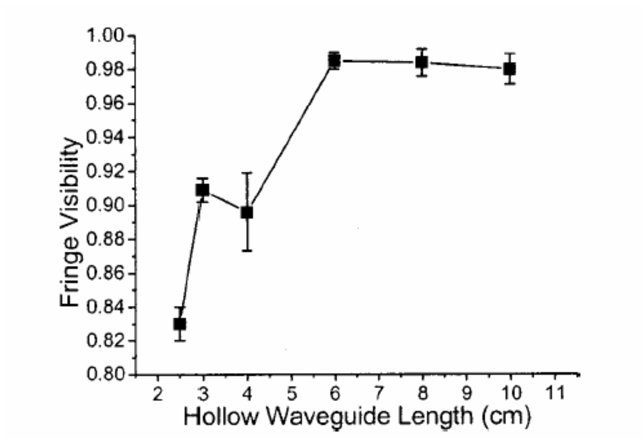
Parameters

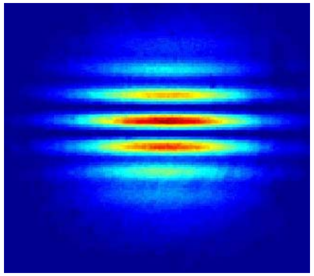
Spatial coherence – depends strongly on the generation scheme

Nearly 100% fringe visibility with 3 to 5 segment hollow-fibre filled with Ar, 40 Torr, harmonic order 23-39 (36-45 eV)

A.Libertun et al, Appl Phys Lett **84** (2004), 3903







Setup and Young fringes produced at 13 nm by the Kapteyn-Murnane group

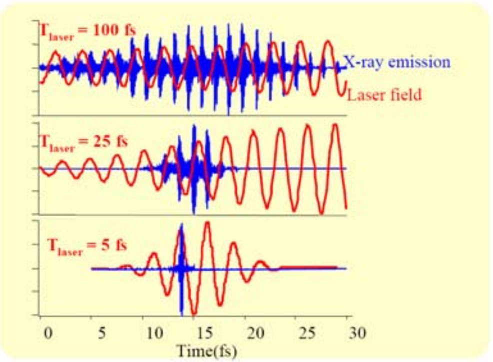
HHG in gases

Parameters

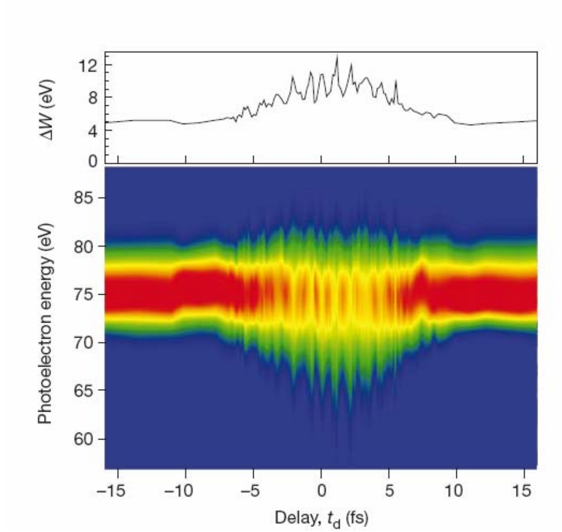
Temporal properties and attosecond pulse generation

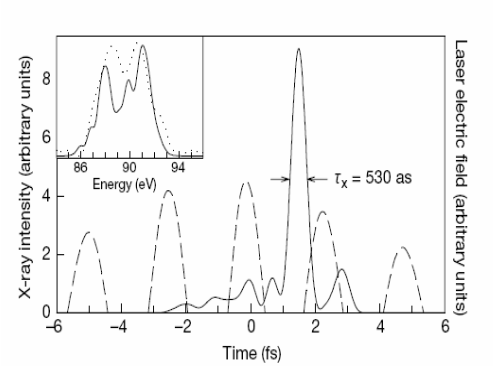
Two approaches:

1. Isolation of single as peak by using a few-cycle IR pulse and selecting the cutoff of HHG in a thin jet



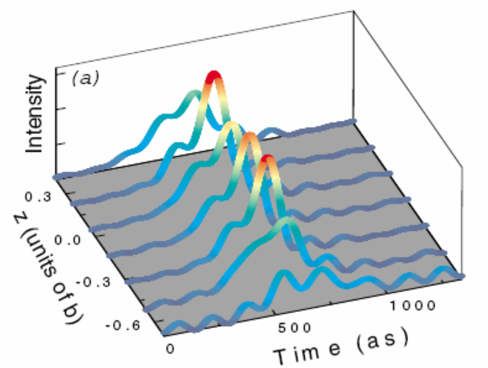
Christov et al, Phys.Rev.Lett **78** **(1997)1251**





Hentschel et al, Nature **414** **(2001) 504**

2. Generation of atosecond pulse train , if the harmonics in the plateau are phase locked . IR source: 45 fs, 40 mJ; gas jet: 1 mm Ne



Mariesse et al, Phys Rev Lett **93** (2004), 163901