Plasma dynamics and surface smoothing in the relativistic few cycle regime

S. G. Rykovanov[1,2], H. Ruhl[2], J. Meyer-ter-Vehn[1],
R. Hoerlein[1,2], B. Dromey[3], M. Zepf[3], and G.D. Tsakiris[1]

[1]Max-Planck-Institute fuer Quantenoptik, Garching, Germany
[2]Ludwig-Maximilians Universitaet Muenchen, Germany
[3]Queen's University Belfast, UK

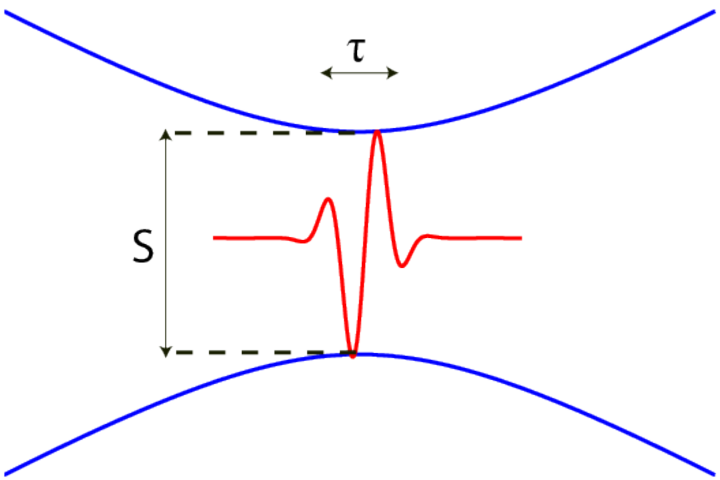
Outline

- Introduction
- Generation of surface harmonics
- Focusing of surface harmonics – a route towards the Schwinger limit
- Plasma surface dynamics – single particle model
- Influence of the surface corrugations on harmonics
- Surface smoothing and generation of collimated attosecond beams
- Conclusions

Introduction

$$I = \frac{E}{S\tau}$$

Solid-state laser systems have *reached* the **lambda-cubed** regime:



$$\lambda \sim 1\mu m \qquad \tau \sim \frac{\lambda}{c} = 3.3 fs$$

$$S \sim 1\mu m^2$$

The only way for further increase of intensity for solid state systems is **increasing the energy**

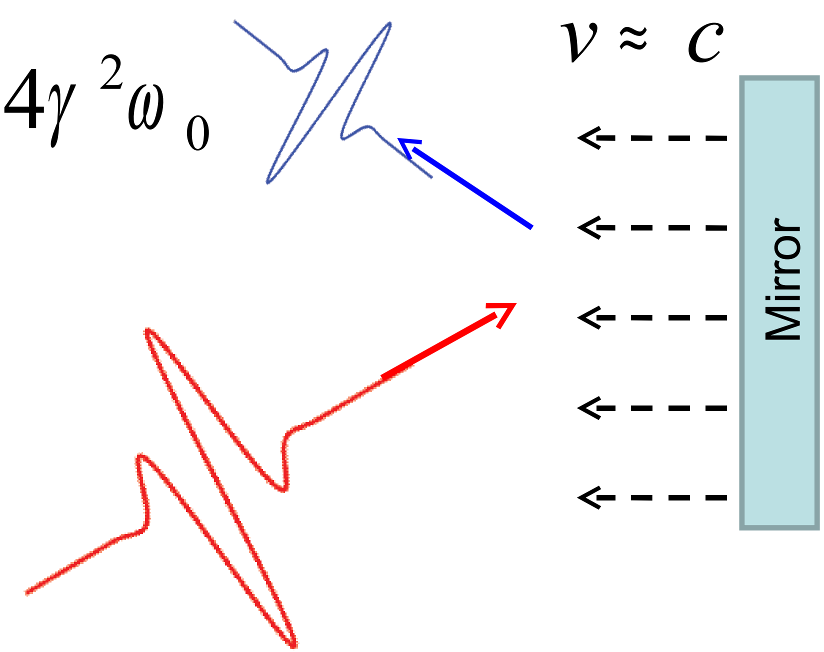
Introduction

$$I = \frac{E \cdot c}{\lambda^3}$$

Transformation of the laser wavelength:
Energy loss during the transformation vs the lambda-cubed

Doppler shift:

$$\omega = 4\gamma^2\omega_0$$

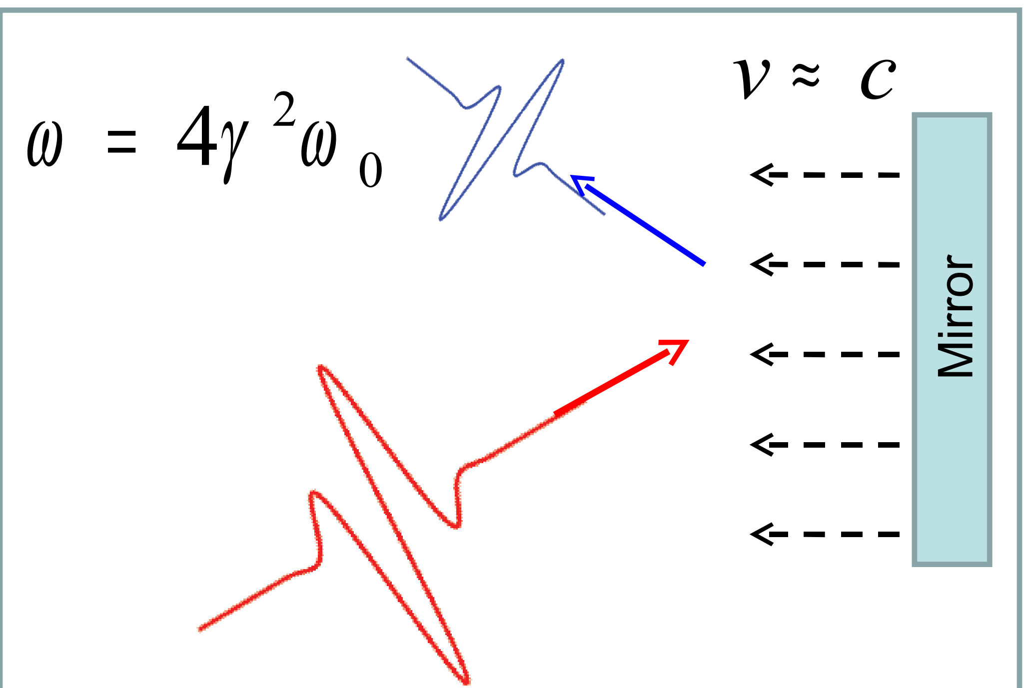


Introduction

$$I = \frac{E \cdot c}{\lambda^3}$$

Transformation of the laser wavelength:
Energy loss during the transformation vs the lambda-cubed

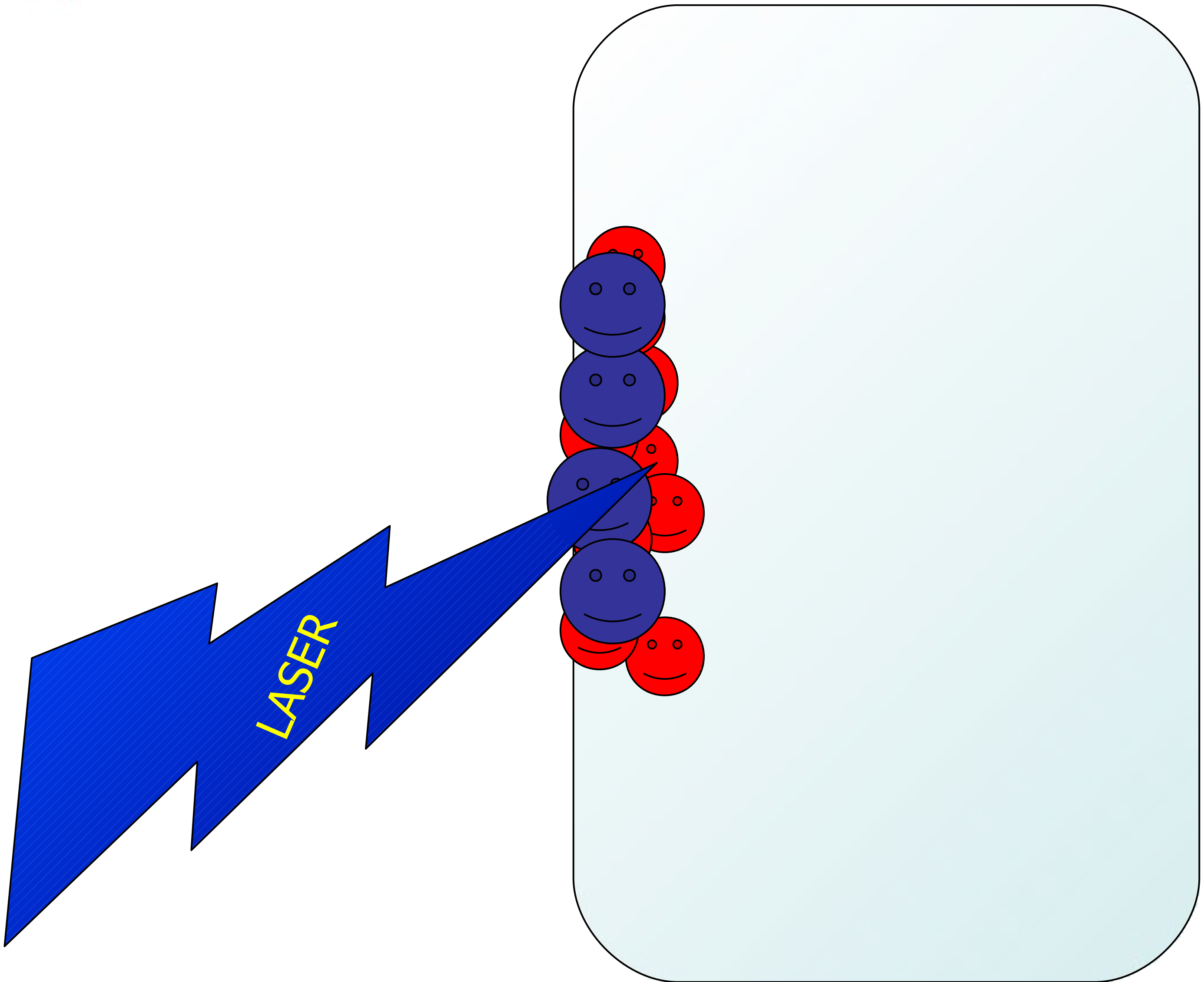
Doppler shift:



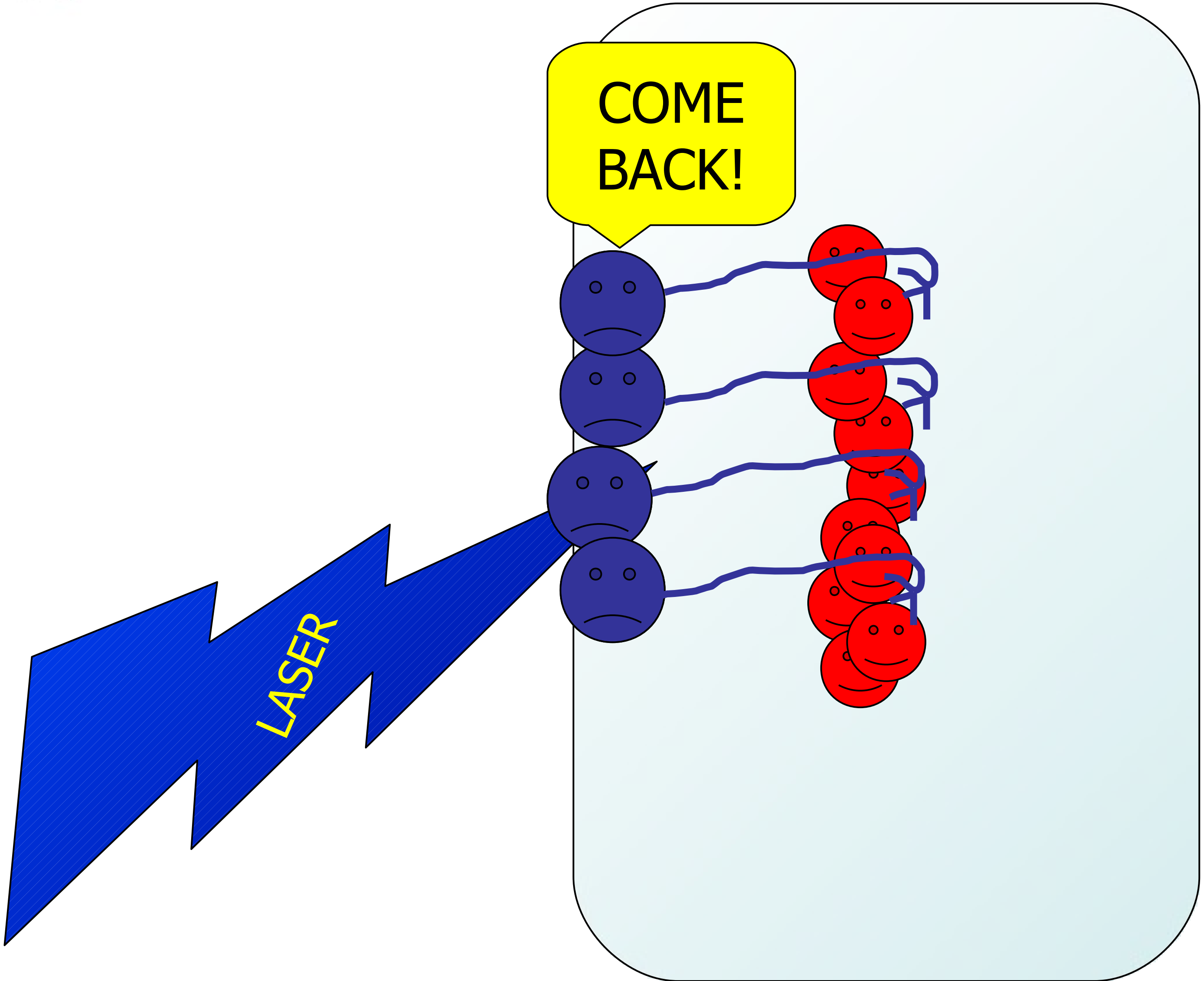
1. Electron bubbles (wakefields)
2. Thin foils (flying mirrors)
1. Bulk targets (surface harmonics)

Bulanov et al, PRL 91, 085001 (2003)
Meyer-ter-Vehn, Wu, EPJD, 55 (2009)
Esirkepov et al, PRL 103, 025002 (2009)
Gordienko et al, PRL 94, 103903 (2005)
Naumova et al, PRL 92, 063902 (2004)
Tsakiris et al, NJP 8, 1 (2006)
Mourou et al, RMP 78 (2006)

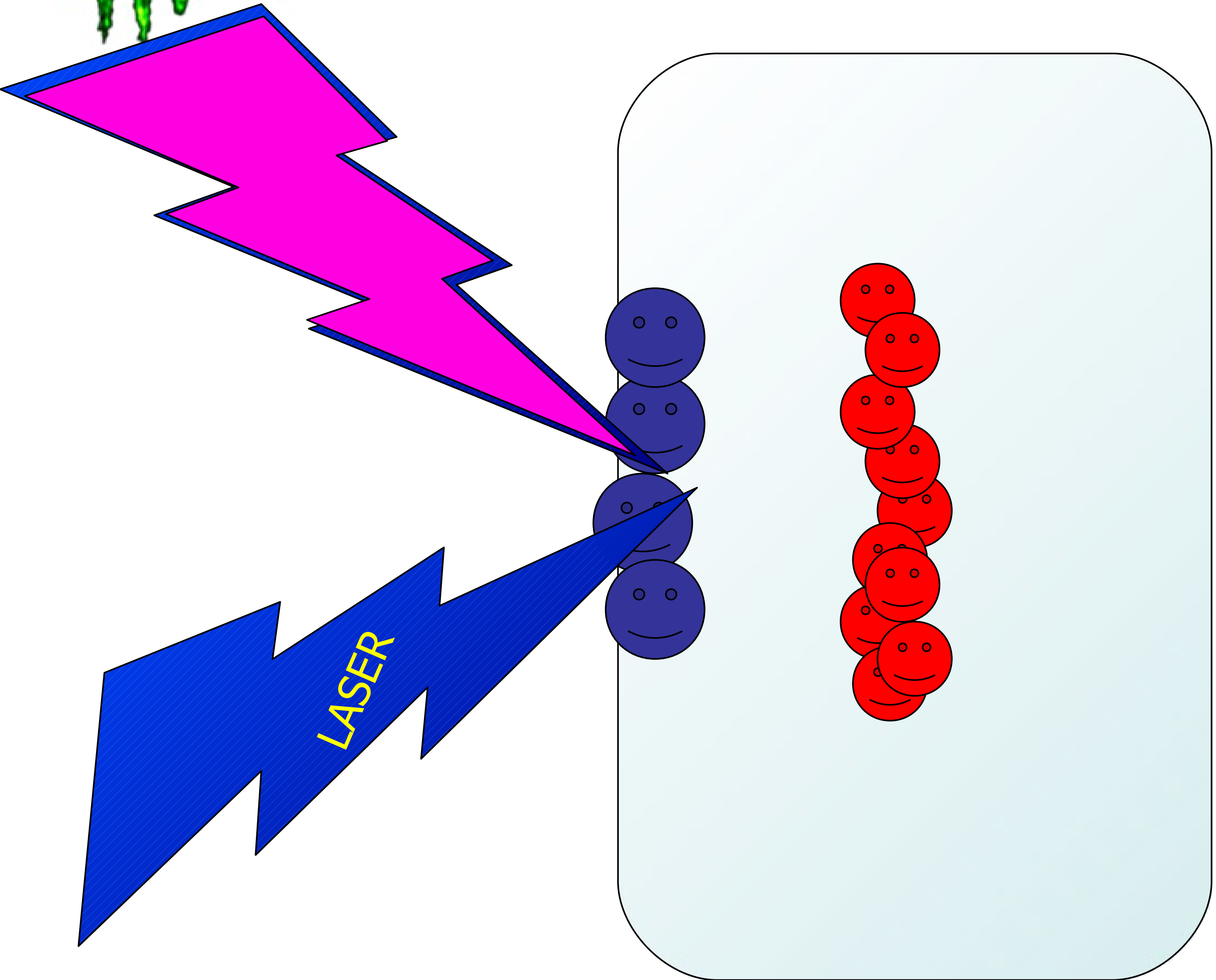
Surface harmonics. Mirror model



Surface harmonics. Mirror model

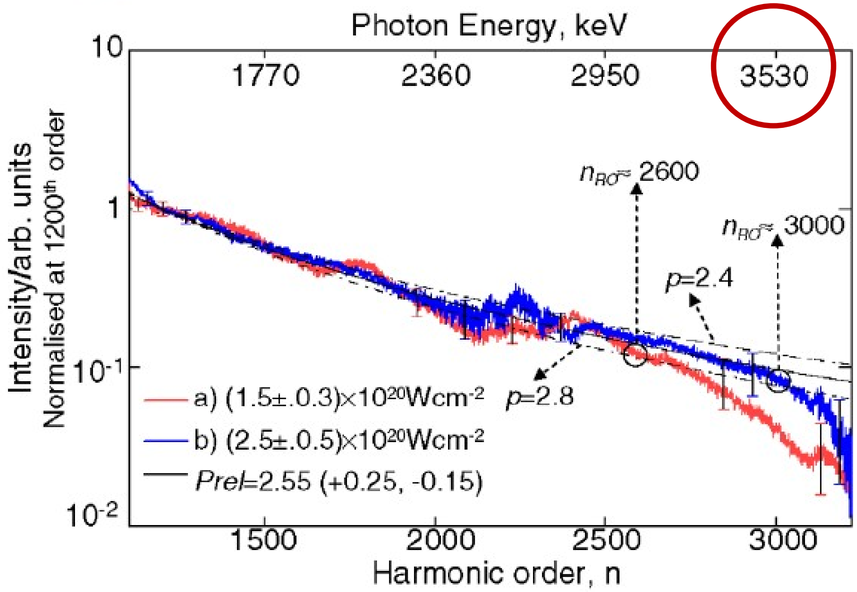


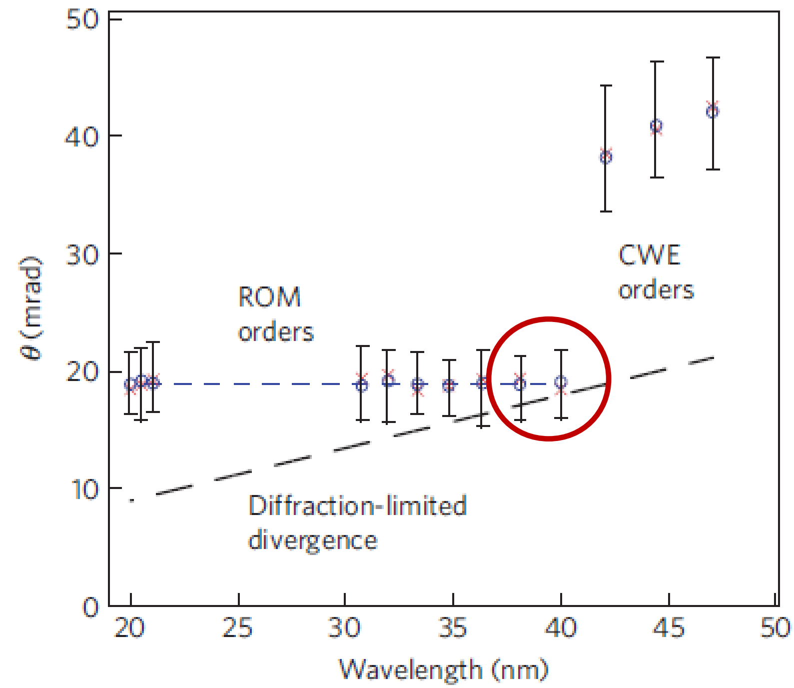
Surface harmonics. Mirror model

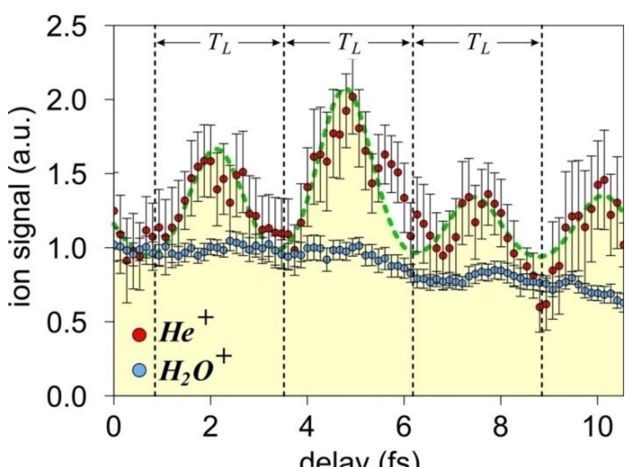


Surface harmonics

Surface harmonics are a coherent x-ray source





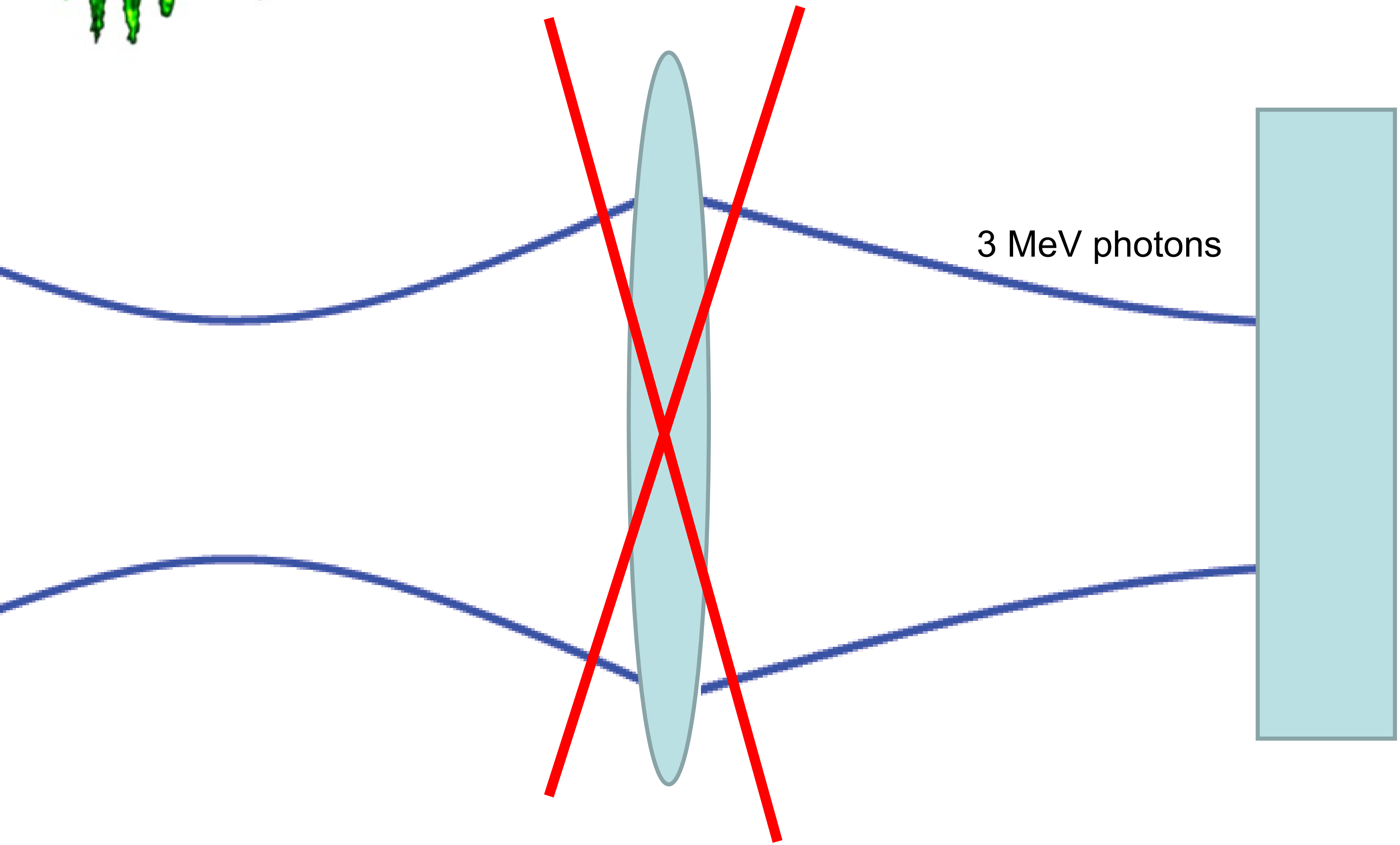


Energy up to 3.5 MeV
Diffraction limited performance
Attosecond structure

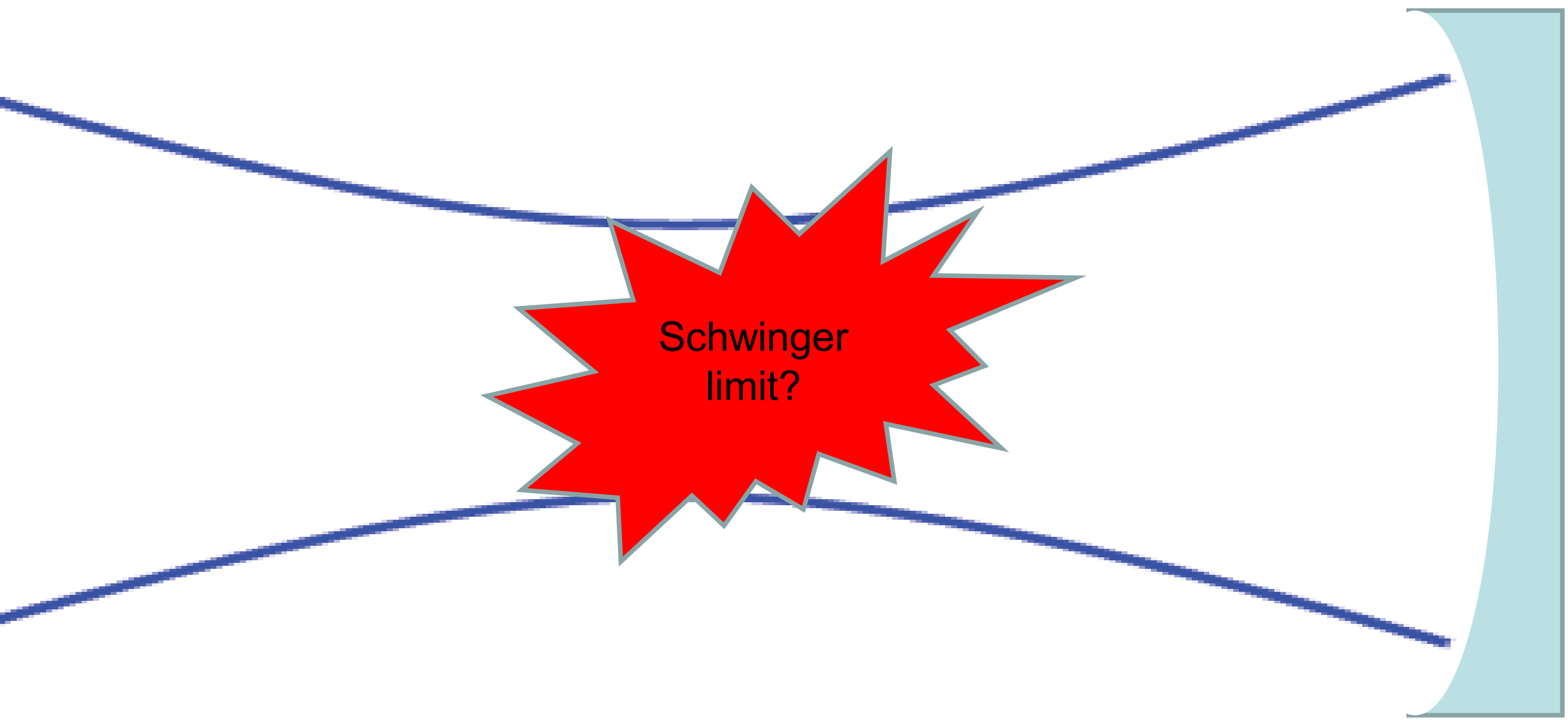
B. Dromey *et al, Nat Phys, 5, 146 (2009)*

Y. Nomura *et al.,* Nature Phys. 5, 124 (2009)

Harmonic focusing

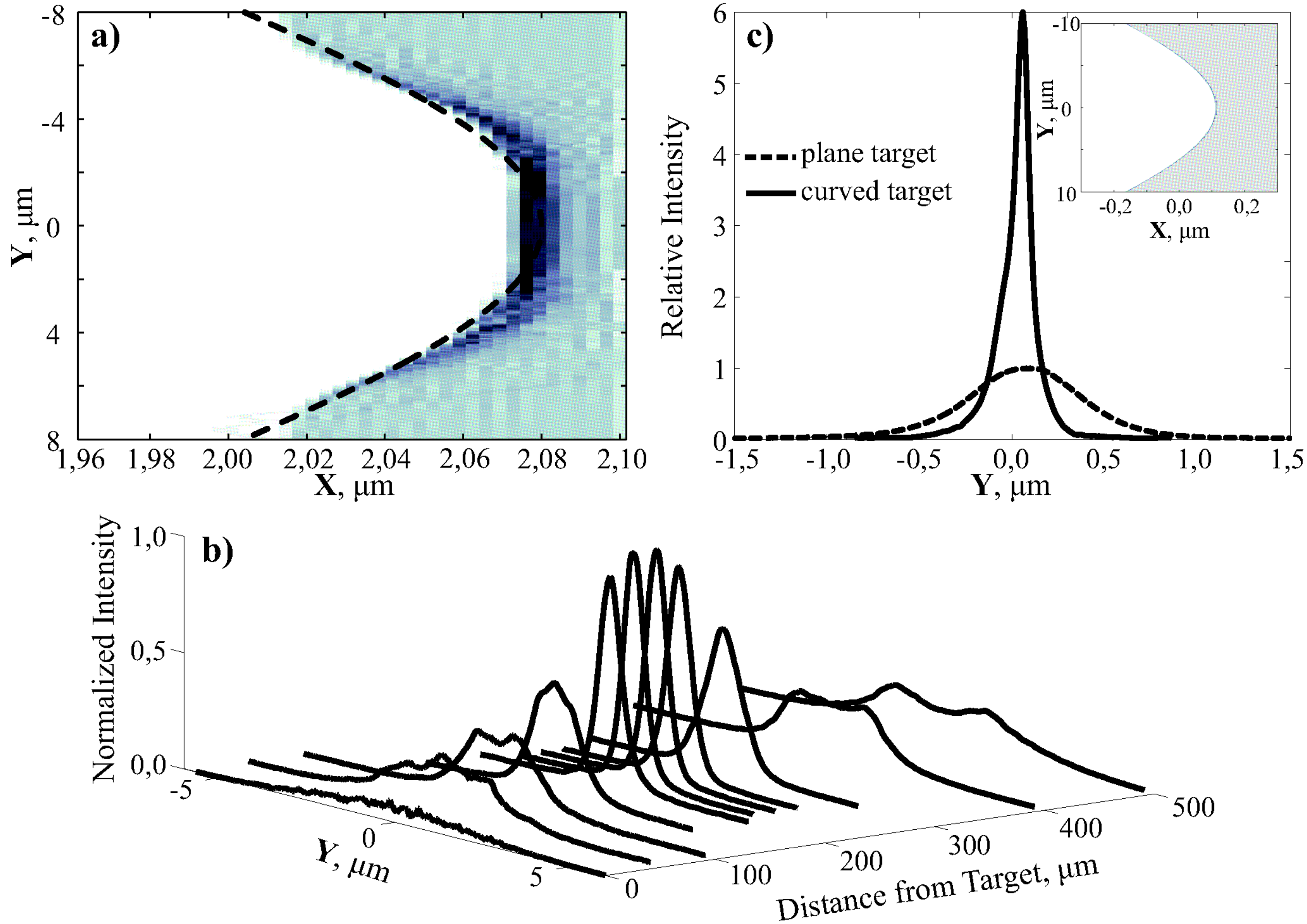


Harmonic focusing



Gordienko et al, PRL 94, 103903 (2005)
Hoerlein et al, EPJD, 55, 475 (2009)

Denting vs controlled focusing



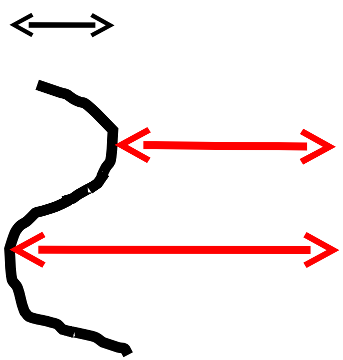
Hoerlein, Rykovanov et al, EPJD, 55, 475 (2009)

Surface roughness

Harmonic focusing idea heavily relies on the ***clean*** plasma surface.

Classical Rayleigh criterion:

h – characteristic roughness size



$$\Delta = 2h$$

$$\left.\begin{array}{l} \Delta > \dfrac{\pi}{2} \\ h > \dfrac{\lambda}{8} \end{array}\right\}$$ leads to diffuse scattering

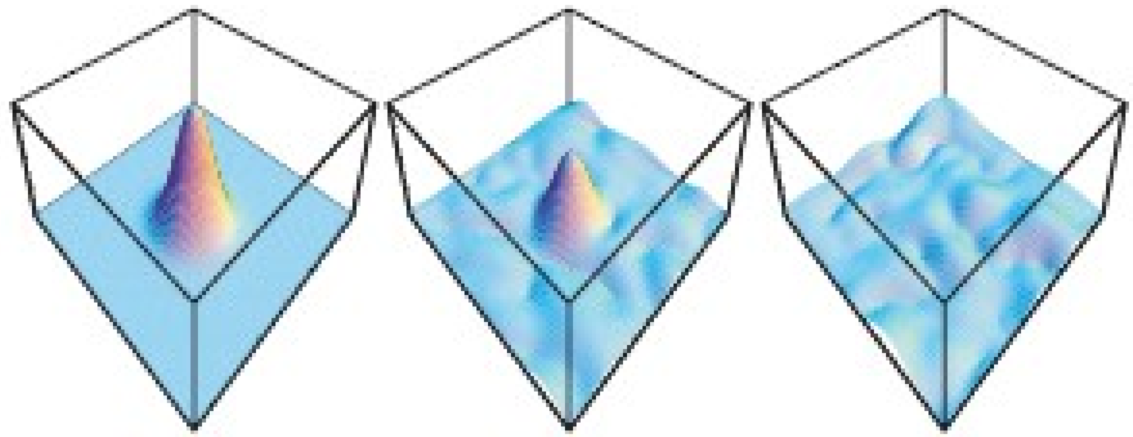
50 nm roughness would scatter the harmonics of any order

A. Ishimaru, *Wave Propagation and Scattering in Random Media. Volume II: Multiple scattering, turbulence, rough surfaces and remote sensing (Academic Press, New* York, 1978)

Surface roughness

Experimental results overview

Harmonic beam
From 20 to 40 harmonics
(20 nm to 40 nm)

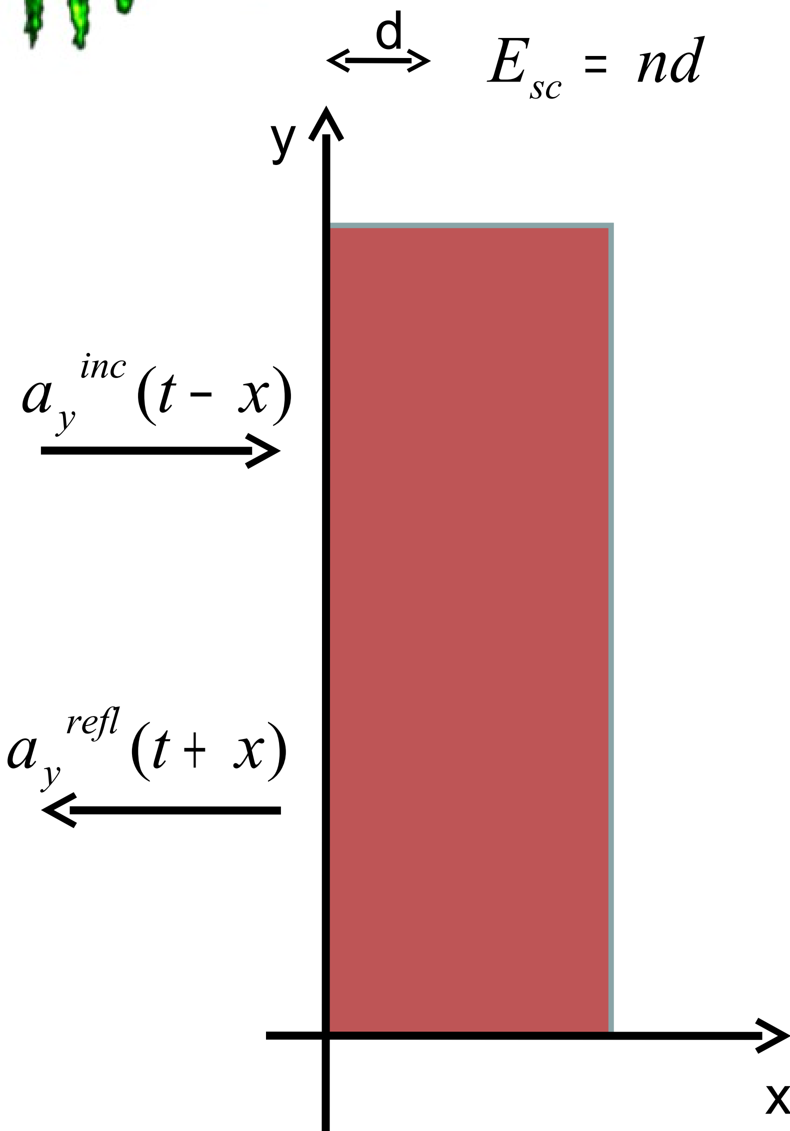


h<1 nm h~18 nm h~164 nm

Experimental results do not agree with the picture described on the previous slide.
We need to get insight into dynamics of the surface.

B. Dromey, et al, Nat Phys, 5, 146 (2009)

Simple model



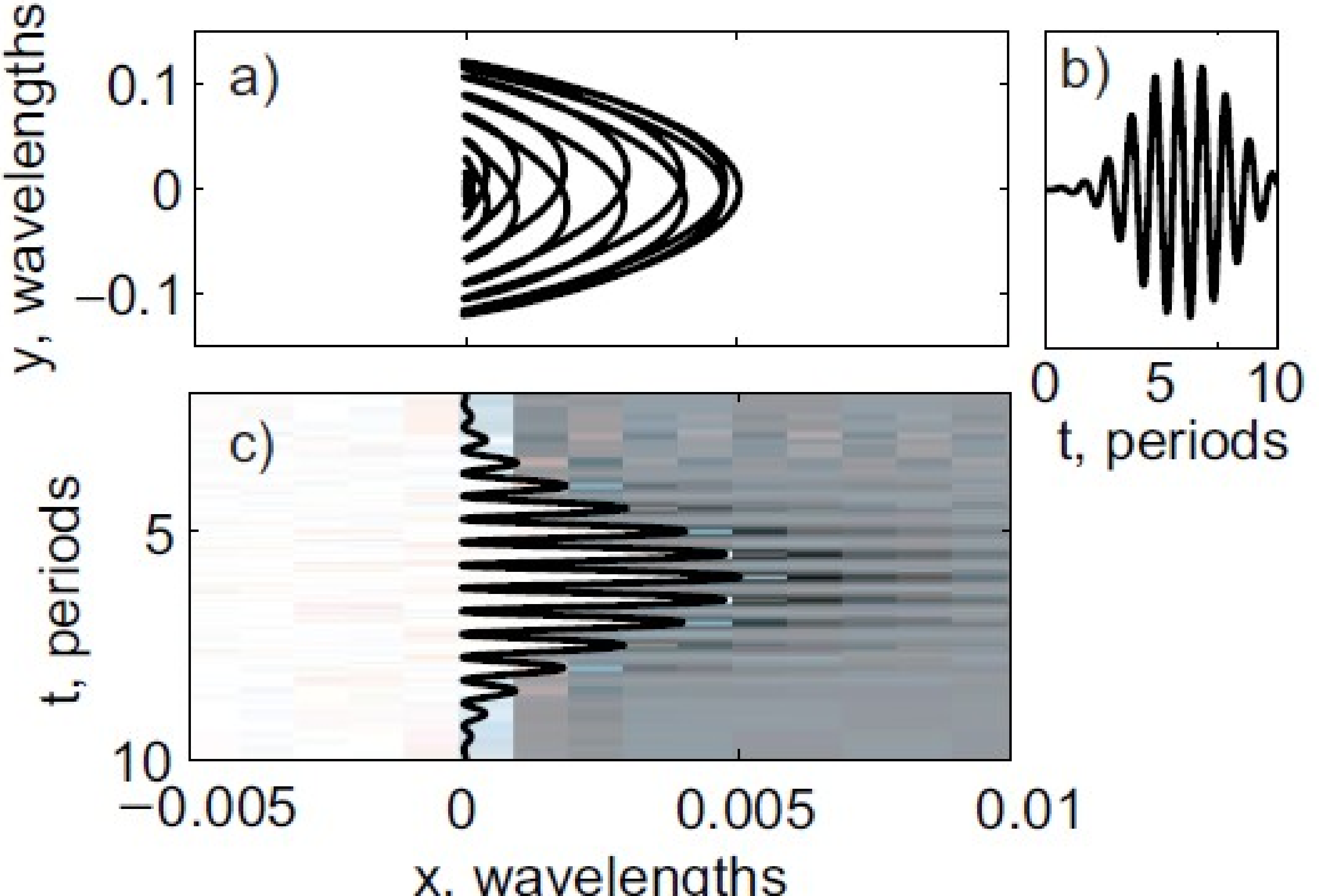
$$\begin{cases} \dfrac{dp_x}{dt} = -\beta_y \dfrac{\partial a_y(t,x)}{\partial x} + nx \\ p_y = a_y(t,x) \\ \dfrac{dx}{dt} = \dfrac{p_x}{\gamma} \\ \dfrac{dy}{dt} = \dfrac{p_y}{\gamma} \end{cases} \qquad \gamma = \sqrt{1+p^2}$$

$$a_y = -\frac{2E_i}{\sqrt{1+\omega_p^2}} \sin(t-x+\alpha) \cdot e^{-\omega_p(x'-x)}$$

$$\alpha = \arctan(\omega_p)$$

P. Mulser et al, PRL 101 (2008); Zaretsky et al, JPhysB (2004)

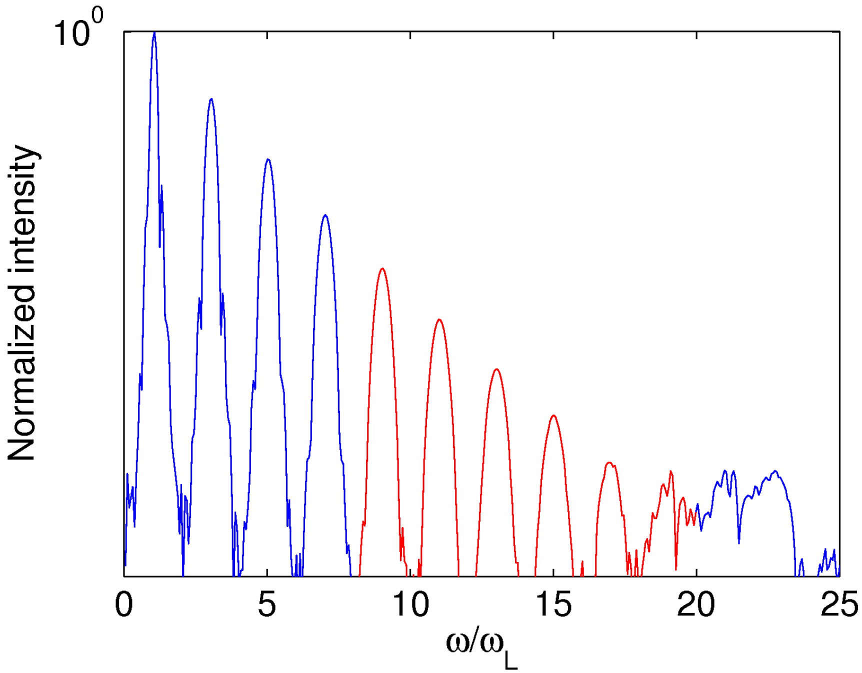
Simple model

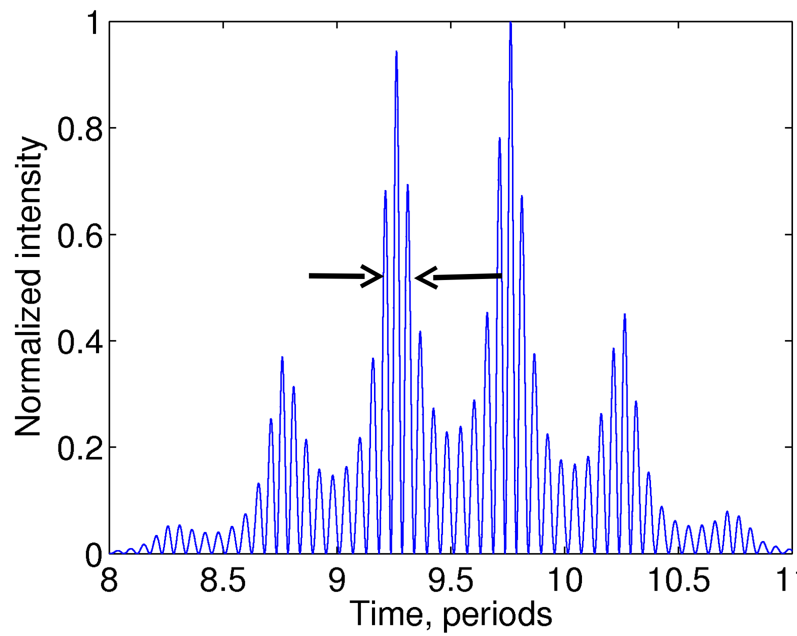


$a_0 = 10$ $\tau_{FWHM} = 4 cycles$ $n_e = 400 n_{cr}$

Emission of the harmonics

Knowing the trajectory of the particle one can get the emission from Lienard-Wiechert formulas



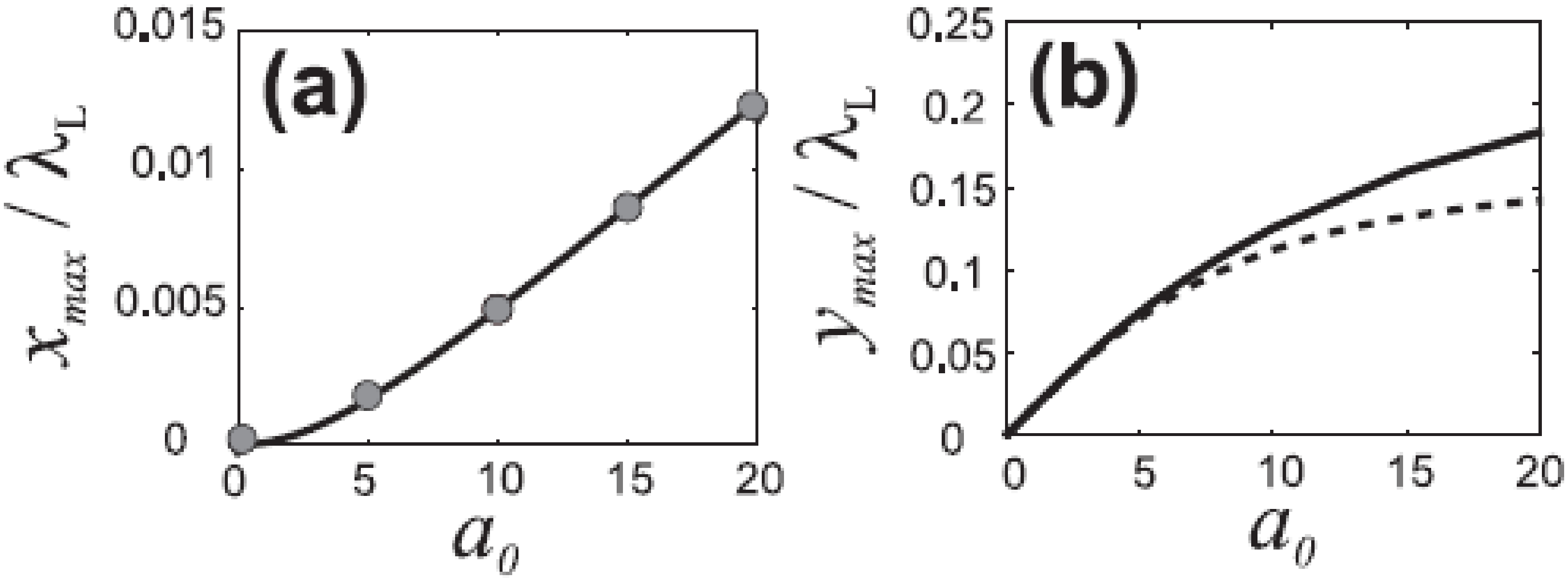


$$\tau < 1 fs$$

Train of attosecond pulses

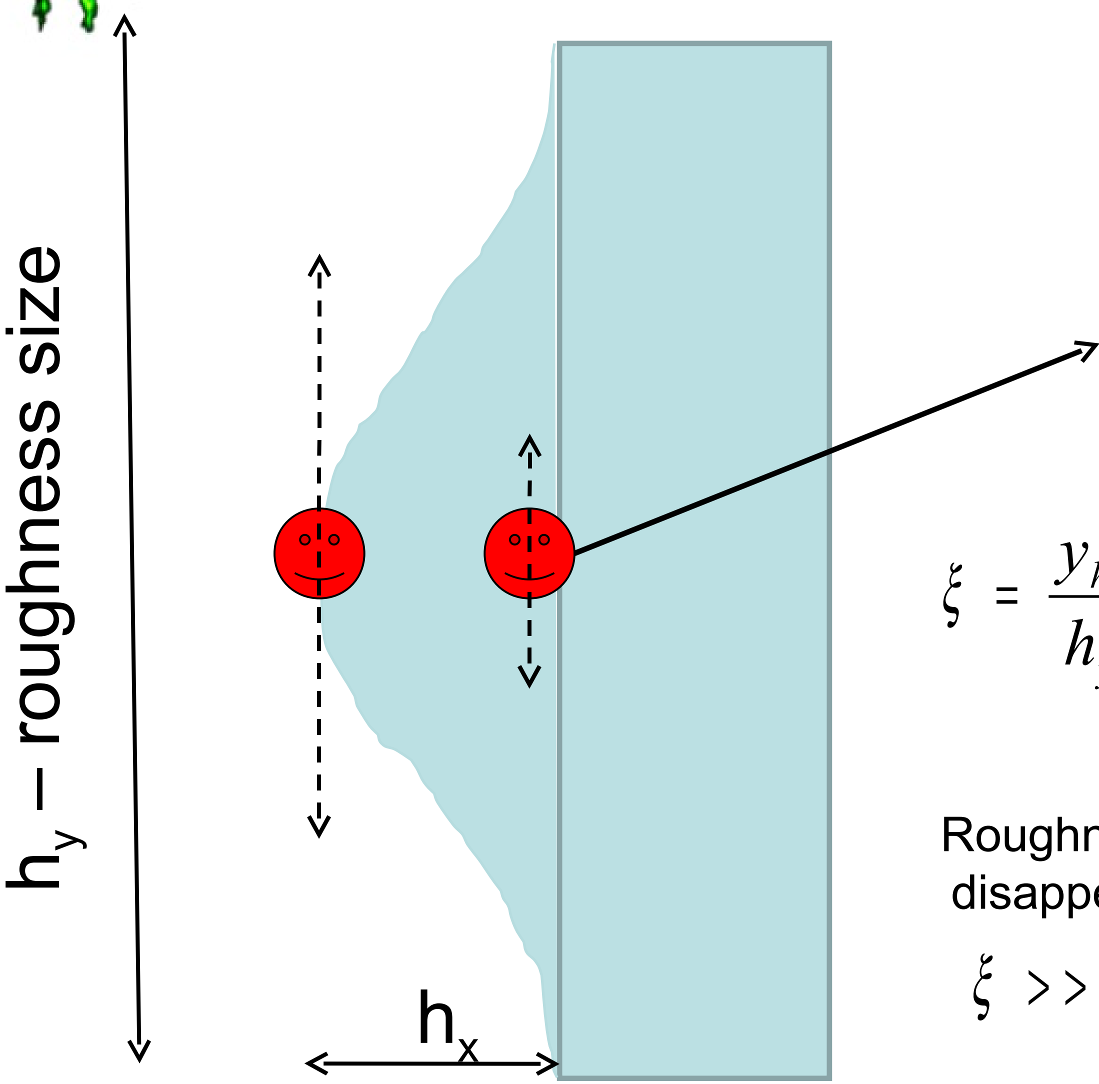
Particle amplitudes

$$y_{\max} \approx \frac{2a_0}{\sqrt{\omega_p^2 + 4a_0^2}}$$



Solid line – results of the model
Circles – results of the PIC simulations
Dashed line – estimate for the ymax

Smoothing criterion



$$y_{max} \approx \frac{2a_0}{\sqrt{\omega_p^2 + 4a_0^2}}$$

$$y_{hx} \approx \frac{2a_0}{\sqrt{\omega_p^2 + 4a_0^2}} \cdot e^{-\omega_p h_x}$$

$$\xi = \frac{y_{hx}}{h_y} = \frac{2a_0}{\sqrt{\omega_p^2 + 4a_0^2} \cdot h_y} \cdot e^{-\omega_p h_x}$$

Roughness disappears

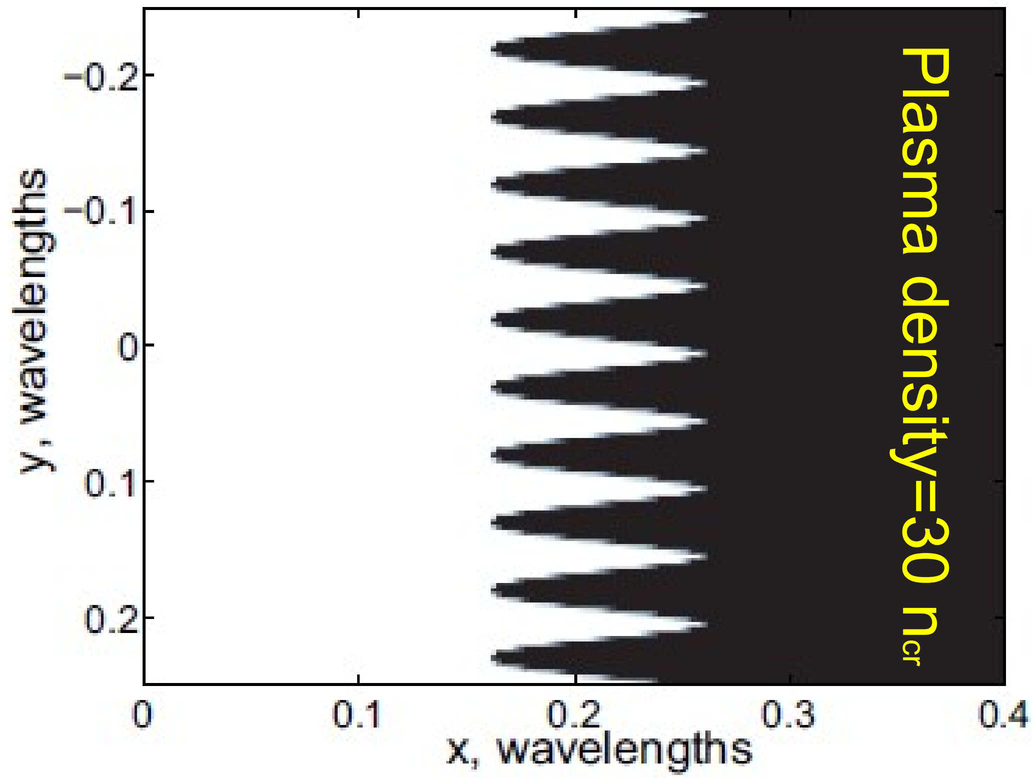
$$\xi >> 1$$

Roughness survives

$$\xi << 1$$

PIC simulations setup

a0=10, 2 cycle duration



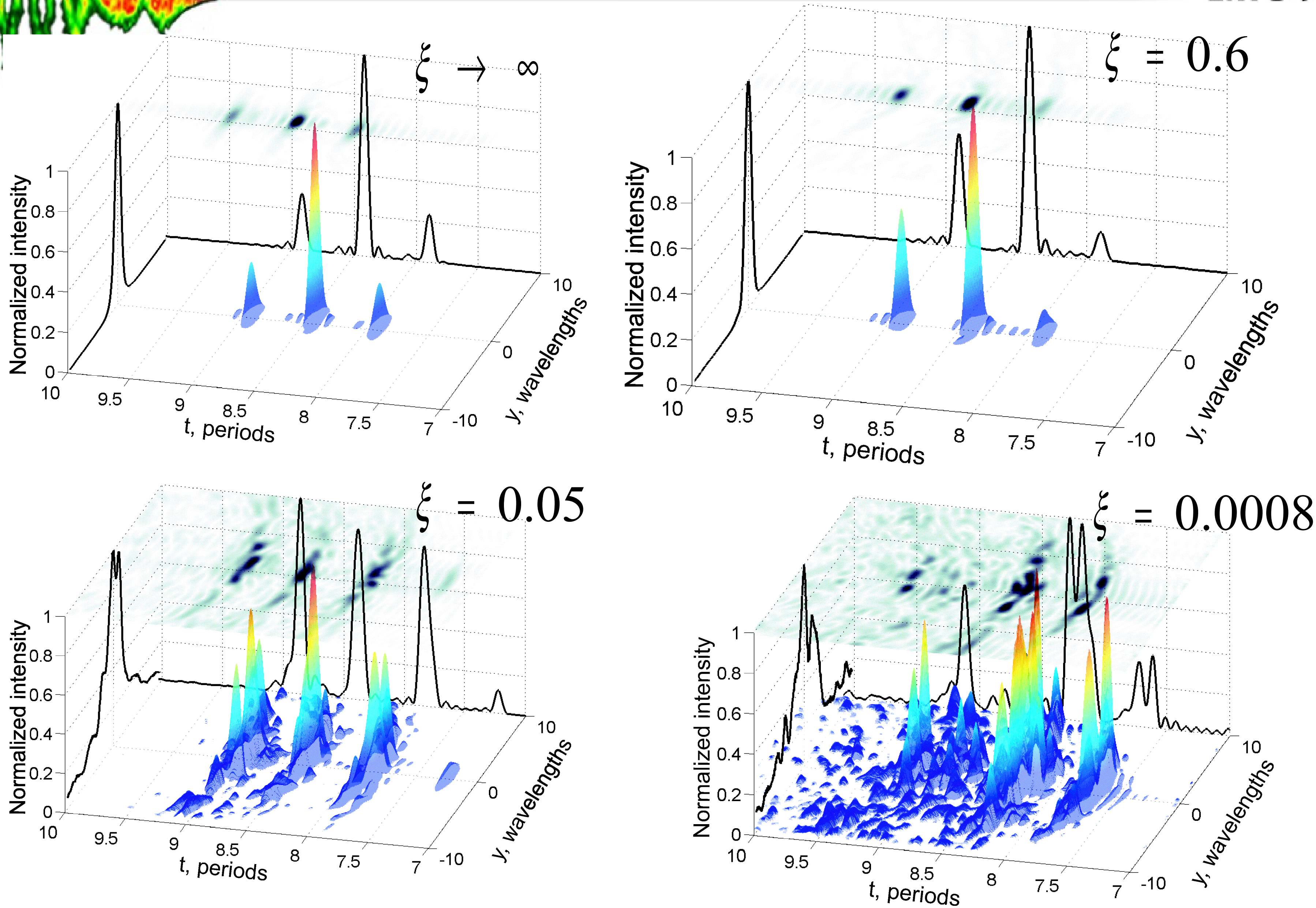
Roughness is assumed to be sinusoidal

Harmonic beam is taken from 15^{th} to 25^{th} (**40nm to 66 nm**)

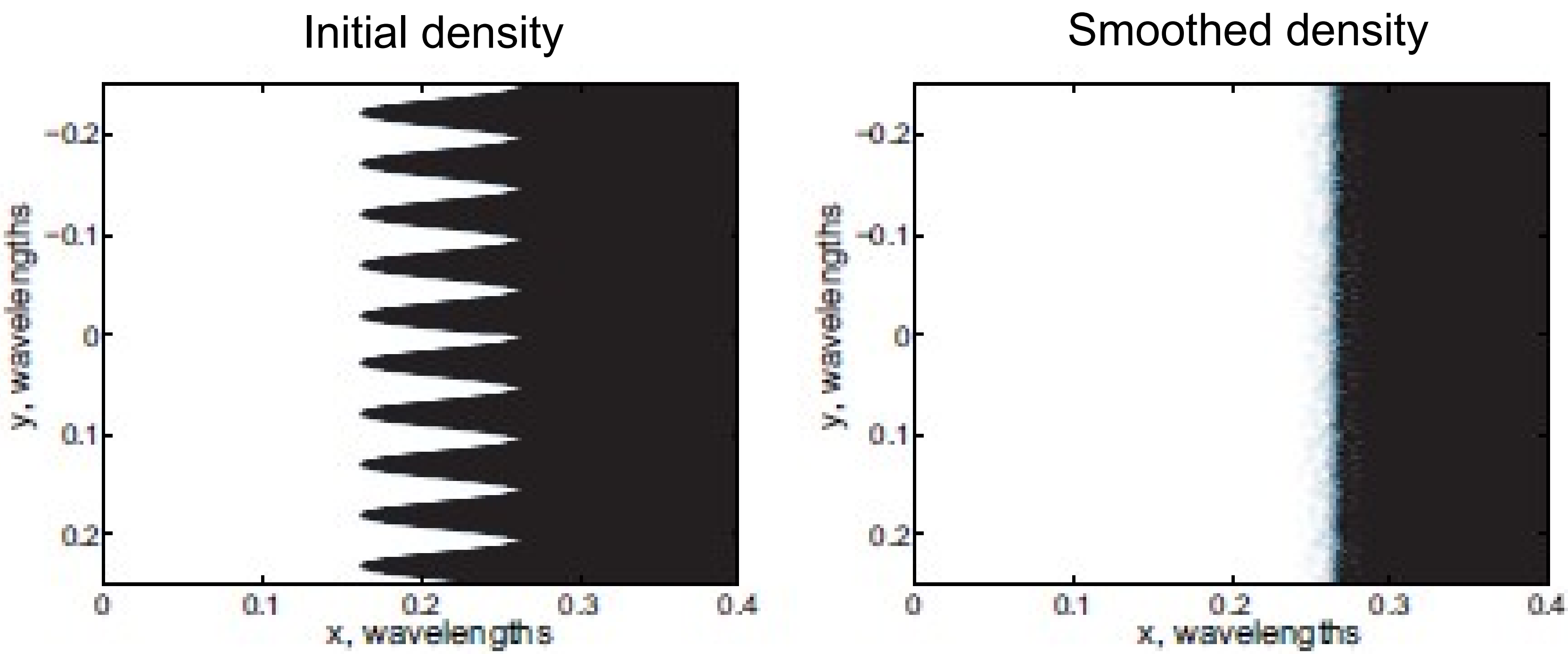
Roughness with **h=50 nm, 100 nm and 200 nm** is considered.

From the classical point of view the harmonic beam should be **scattered** for any of the simulated rough surfaces

PIC simulations results



Surface smoothing



S.G. Rykovanov et al, submitted, arXiv: 0908.3134v2

Summary

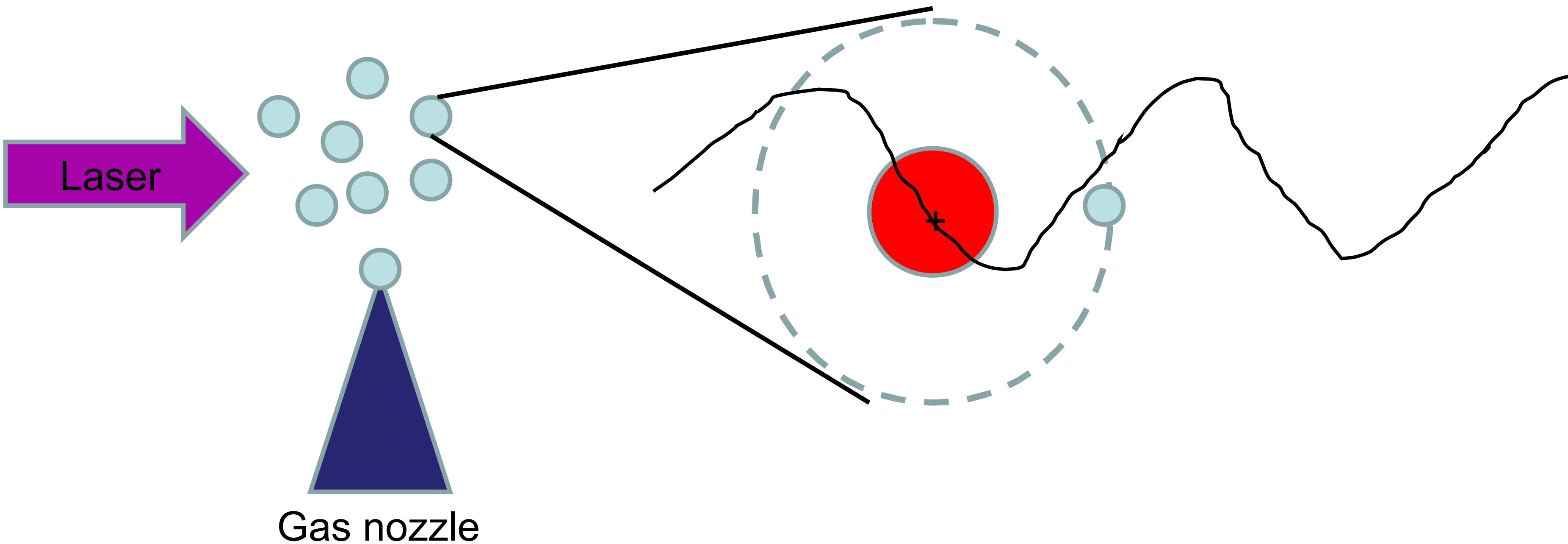
• Review of some ideas about frequency upshifting is presented

• All ideas about focusing and generation of upshifted radiation rely on the clean mirror surface

• But surface imperfections on a scale smaller than the laser wavelength can be neglected.

HHG in gases

$$\Delta\Omega\,\Delta t = 2\pi$$

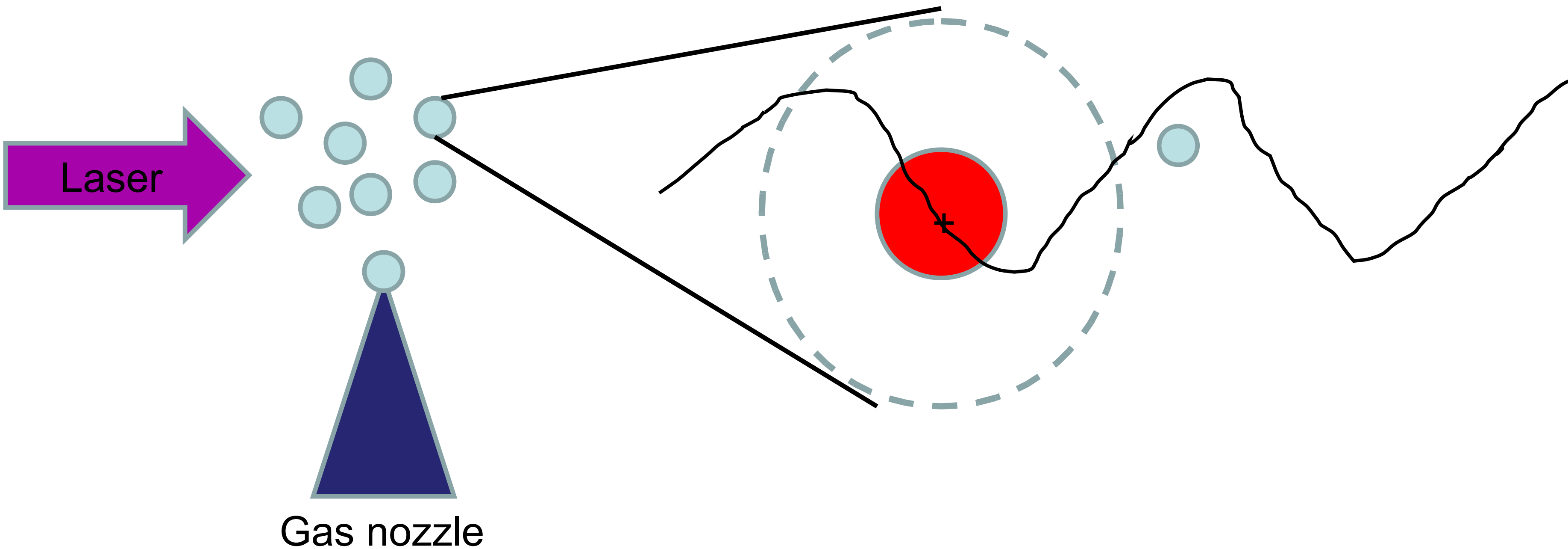


Paul Corkum 3-step model:

1. Multiphoton ionization. Electron leaves the parent ion

HHG in gases

$$\Delta\,\Omega\,\Delta\,t = 2\pi$$

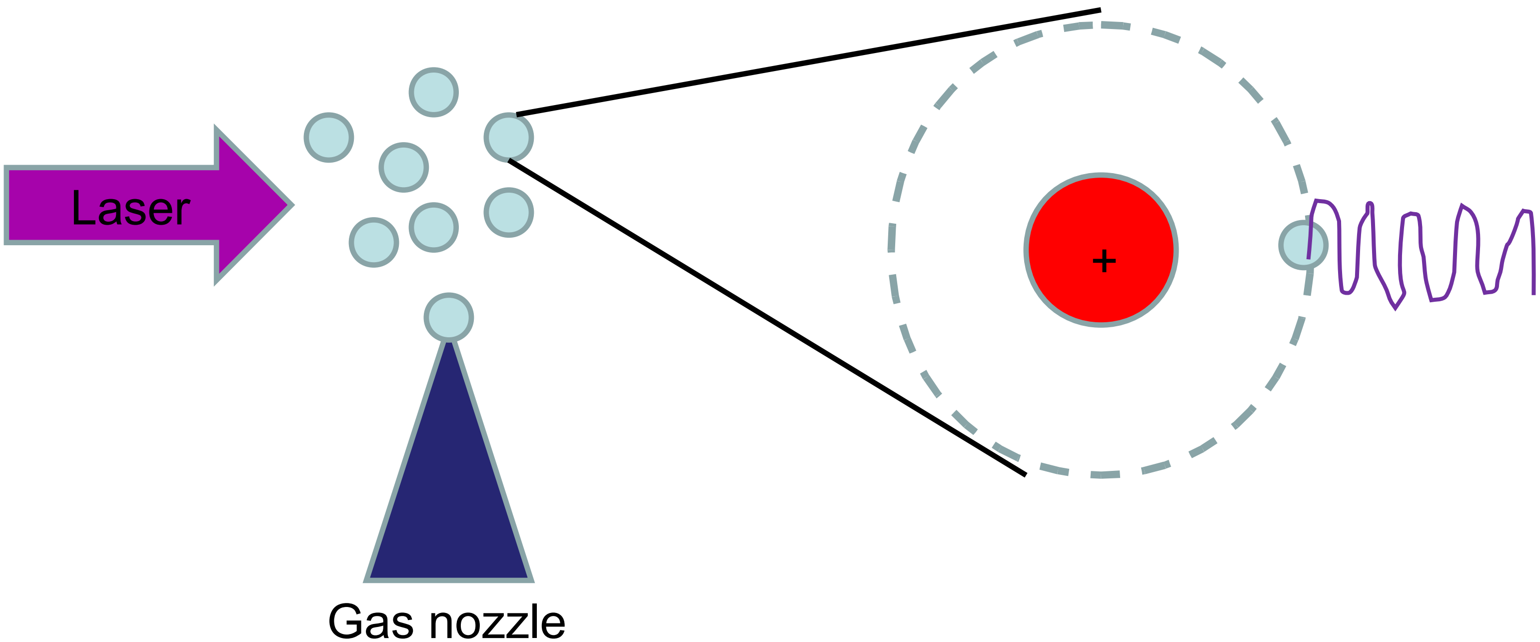


Paul Corkum 3-step model:

1. Multiphoton ionization. Electron leaves the parent ion
2. Electron accelerates in electromagnetic field (neglecting the bounding force, SFA)

HHG in gases

$$\Delta \Omega \, \Delta t = 2\pi$$

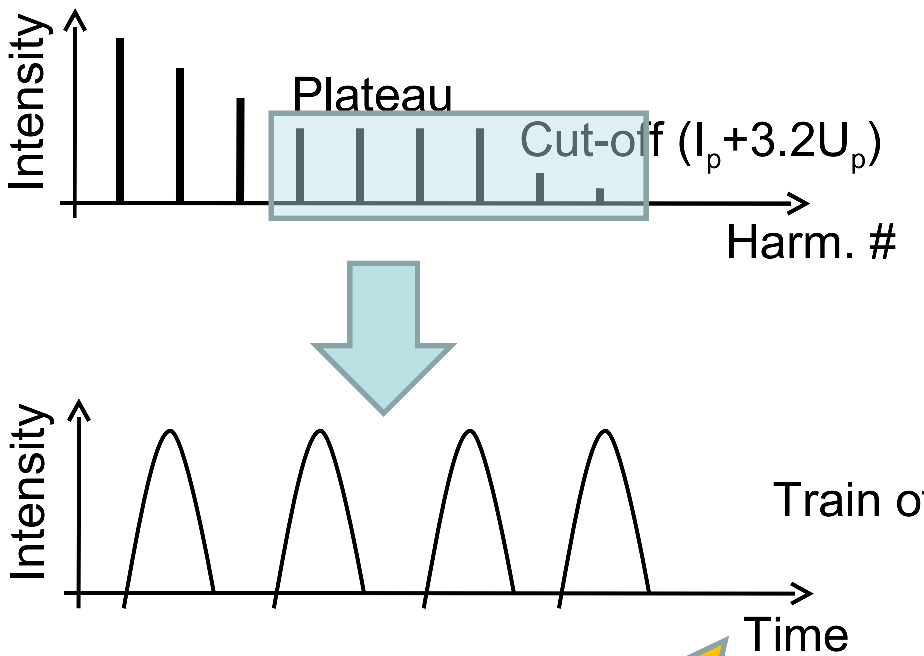


Paul Corkum 3-step model:

1. Multiphoton ionization. Electron leaves the parent ion
2. Electron accelerates in electromagnetic field (neglecting the bounding force, SFA)
3. Electron recollides with the parent ion emitting a photon

HHG in gases

Typical spectrum



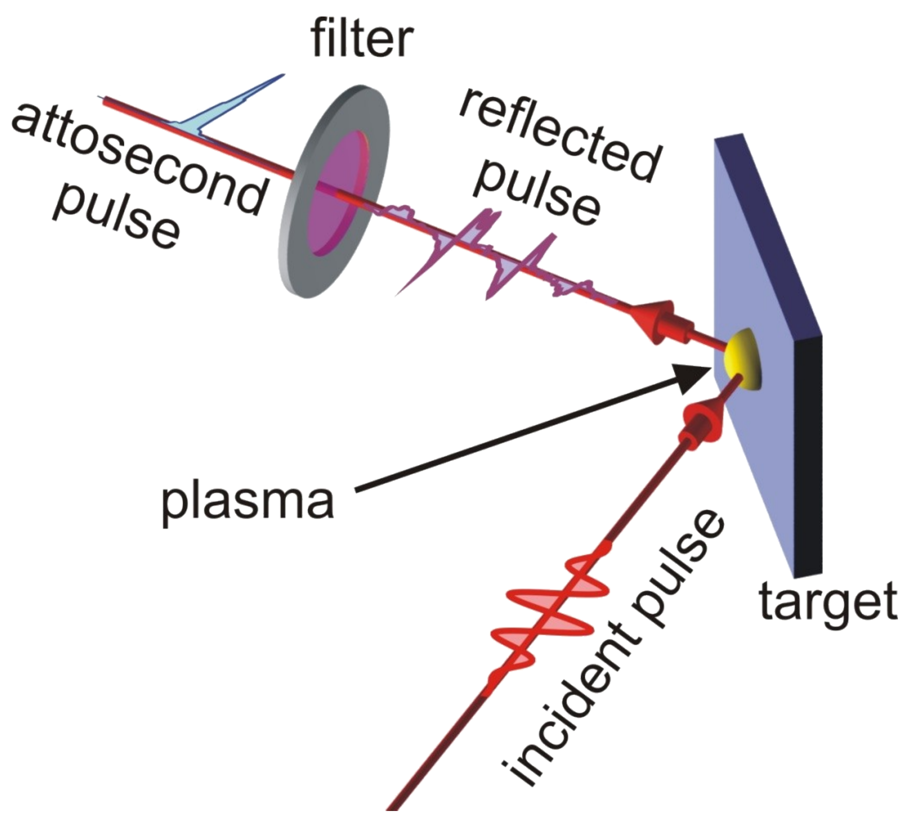
Train of attosecond pulses

Problems:
1.Low conve…
2.Limitations on ma… …pplied

Laser-plasma interaction offers a solution

Main part of the talk

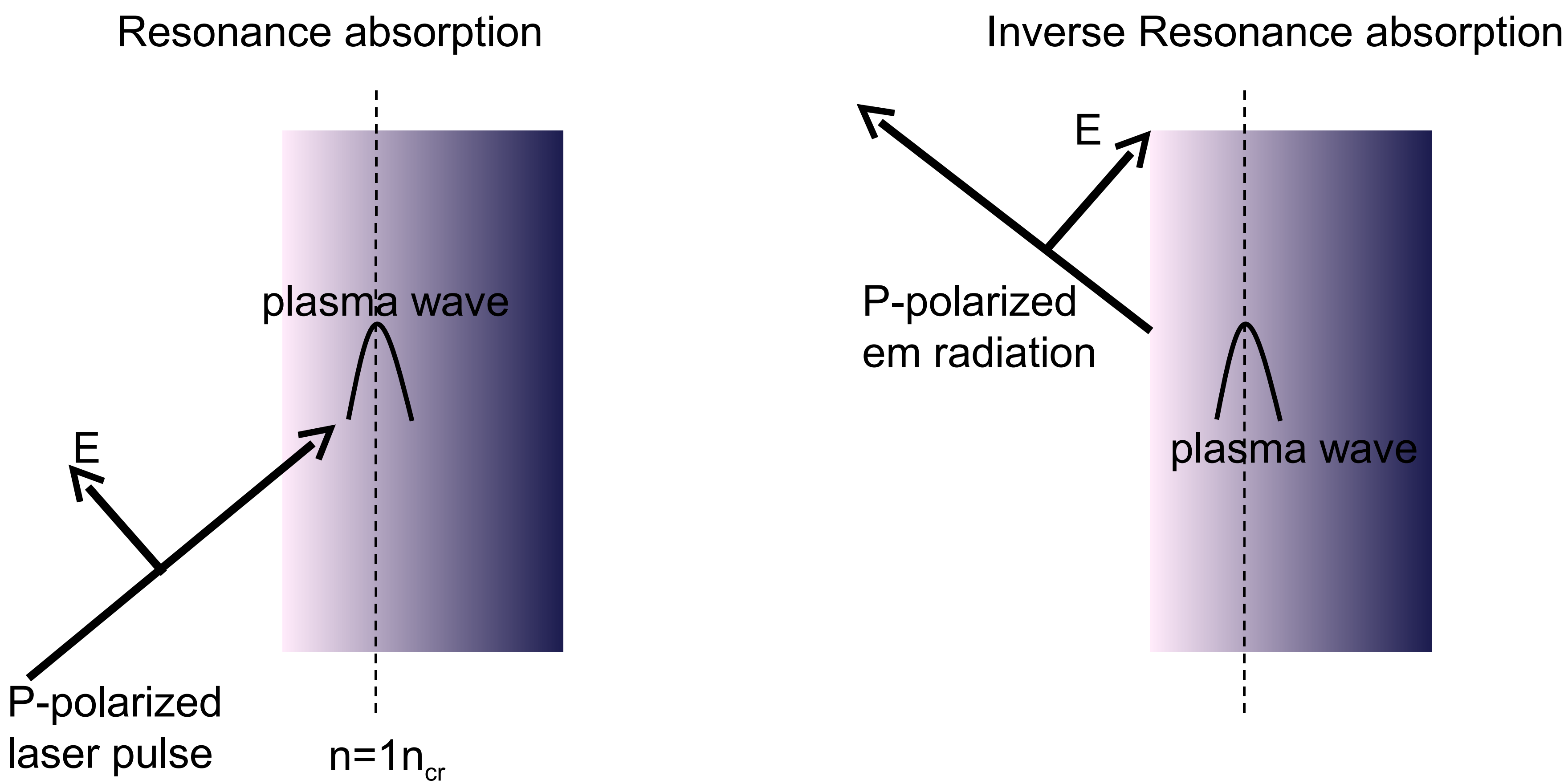
High-order harmonic generation in overdense plasmas



Picture from G. D. Tsakiris *et al*, New J. Phys. 8, 19 (2006)

Coherent Wake Emission

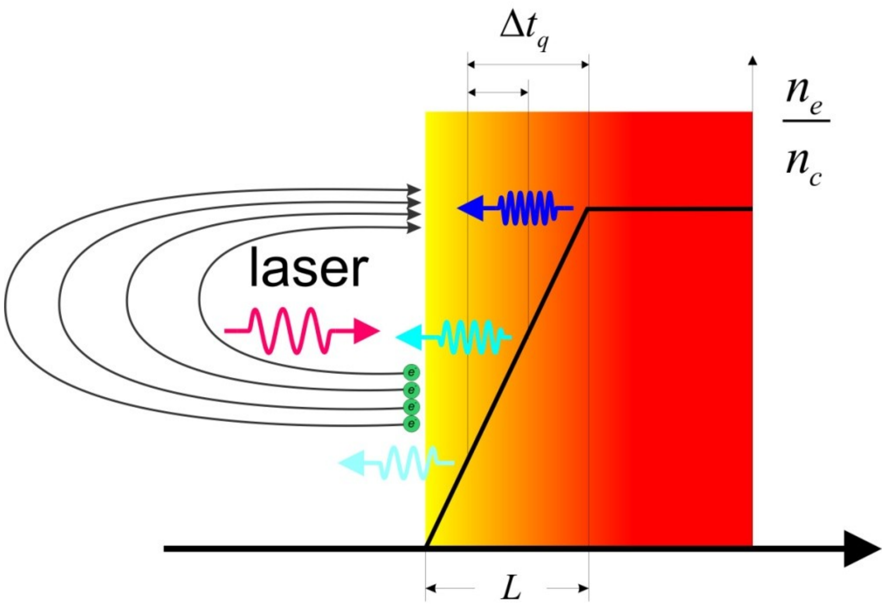
non-relativistic $a_L^2 = I_L \lambda^2 / (1.38 \times 10^{18}\ \mathrm{W}\,\mu\mathrm{m}^2/\mathrm{cm}^2) < 1$



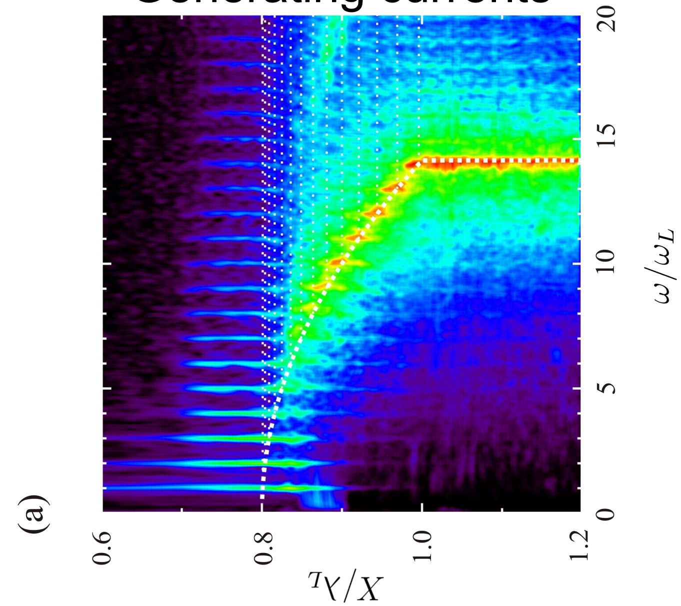
V.L. Ginzburg, Propagation of electromagnetic waves in plasmas

Coherent Wake Emission

non-relativistic $a_L^2 = I_L\lambda^2/(1.38\times 10^{18}\ \mathrm{W}\,\mu\mathrm{m}^2/\ \mathrm{cm}^2) < 1$



Generating currents



3-step model:

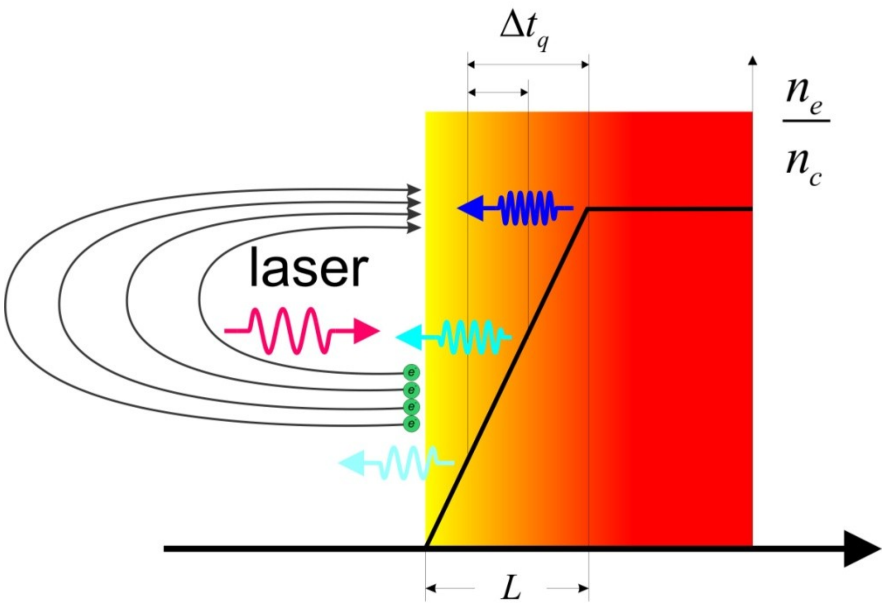
1.Electrons are launched into vacuum by electric field perpendicular to the target (Brunel electrons)

2.Electrons travel in the laser field and are eventually hurled back during the second half-cycle in the form of the bunches

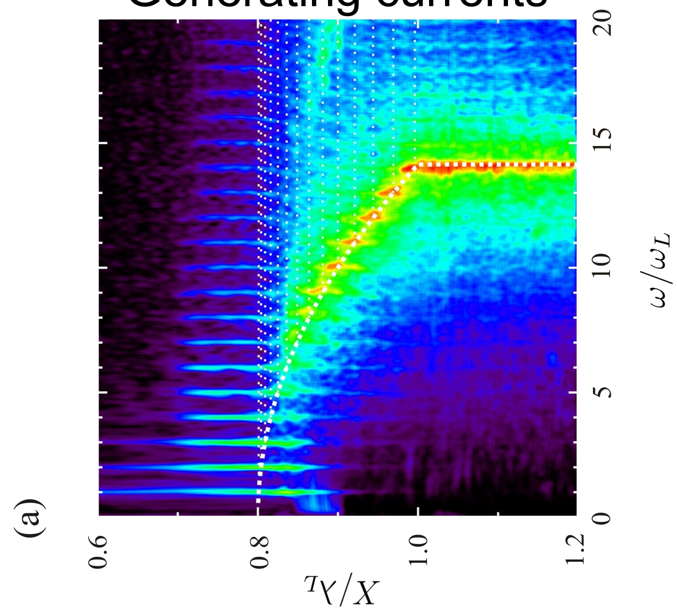
1.They excite resonantly driven plasma waves at the positions where $\omega_p = q\omega_L$ The plasma waves undergo linear mode conversion into EM-waves via inverse resonance absorption.

Coherent Wake Emission

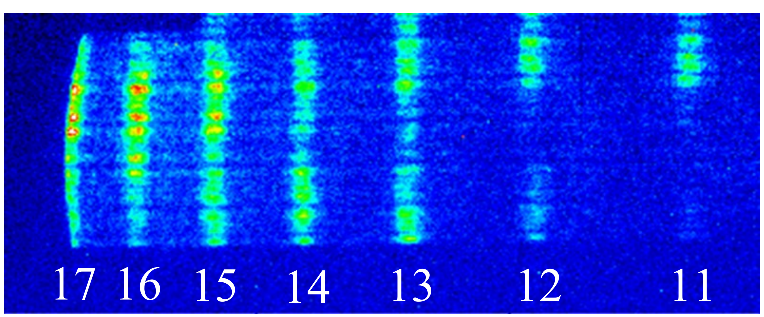
non-relativistic $a_L^2 = I_L \lambda^2 / (1.38 \times 10^{18}\ \mathrm{W}\,\mu\mathrm{m}^2/\mathrm{cm}^2) < 1$



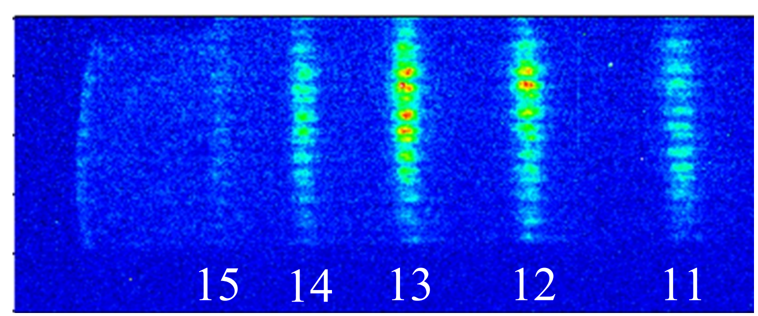
Generating currents



Glass Target (Density 2.6 g/cm^3):

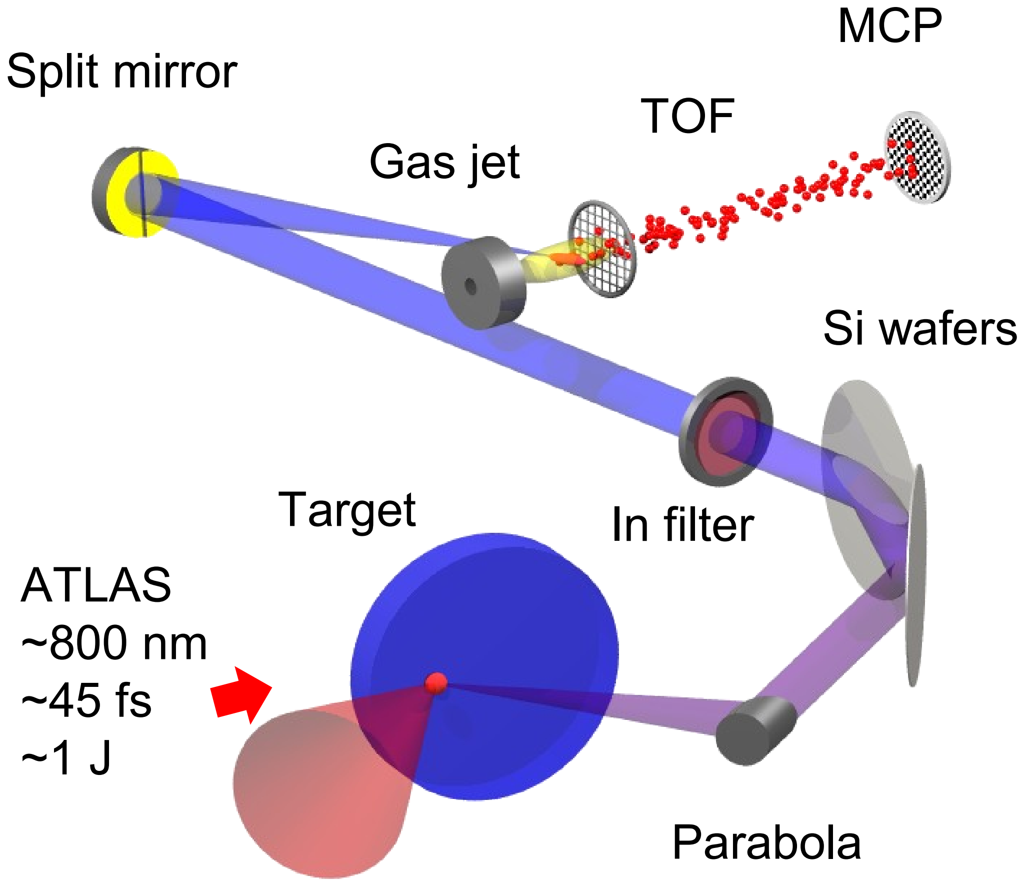


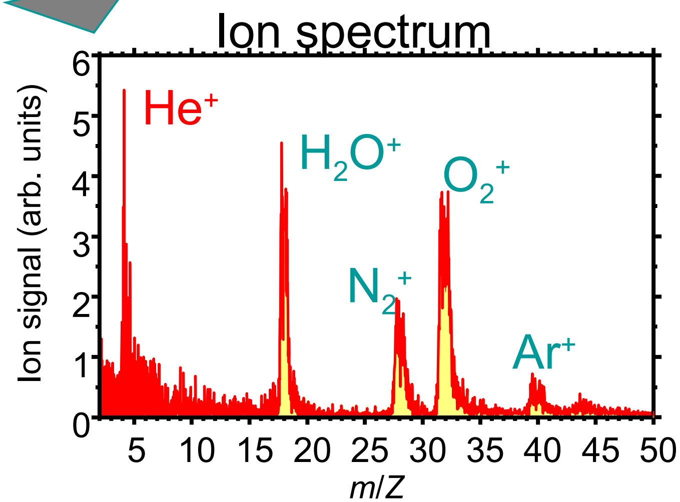
Plexiglass Target (Density 1.3 g/cm^3):



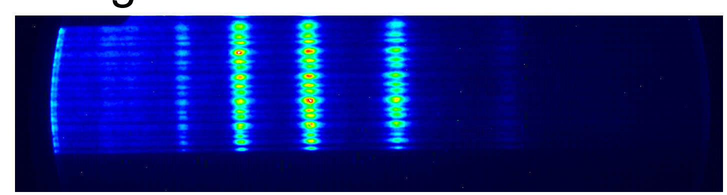
Temporal characterisation exp.

non-relativistic $a_L^2 = I_L \lambda^2 / (1.38 \times 10^{18}\ \mathrm{W}\,\mu\mathrm{m}^2/\mathrm{cm}^2) < 1$





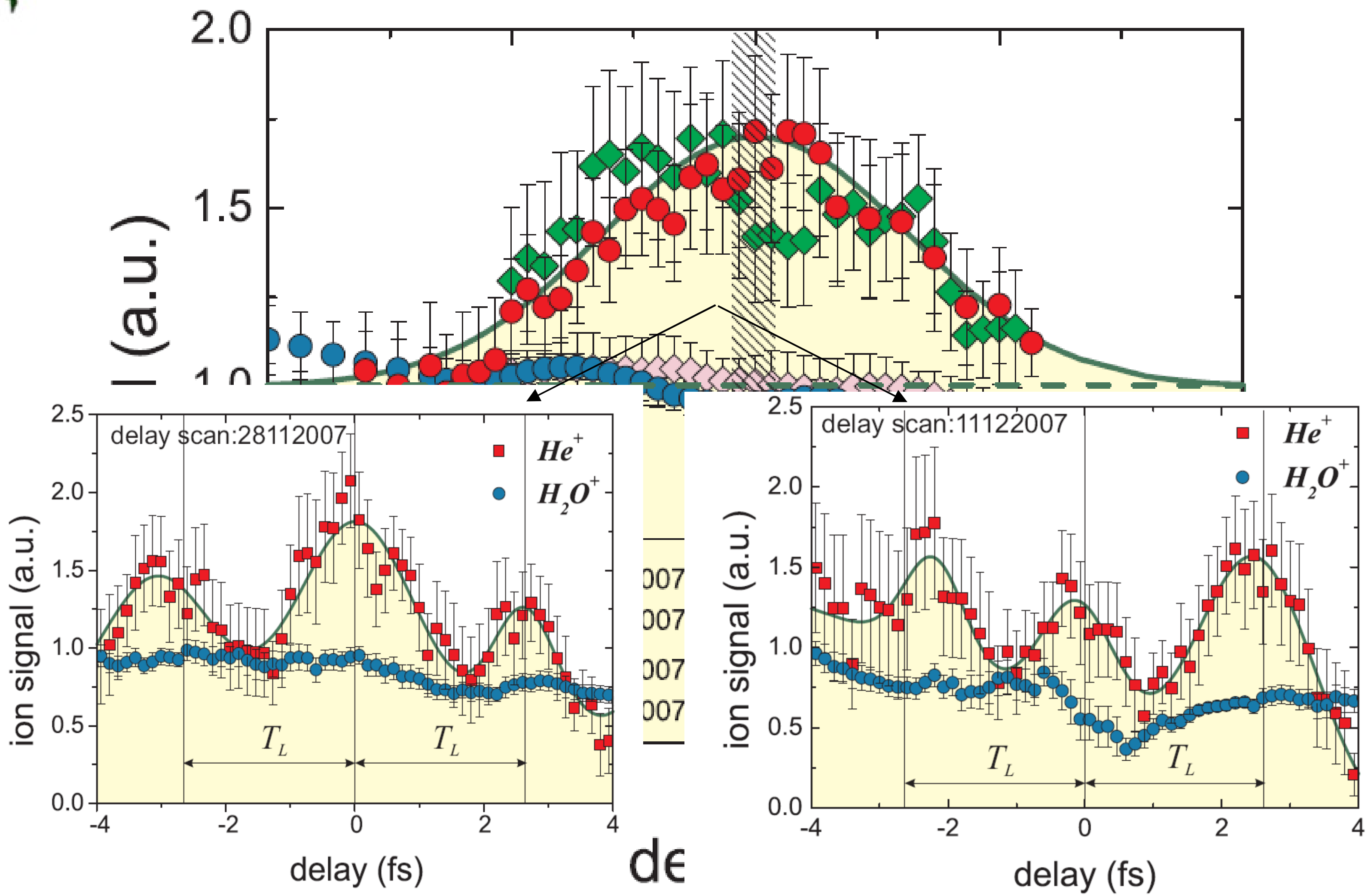
Plexiglas: No harmonic above 15th



Y. Nomura *et al.*, Nature Phys. 5, 124 (2009)

Coarse and fine volume AC scans

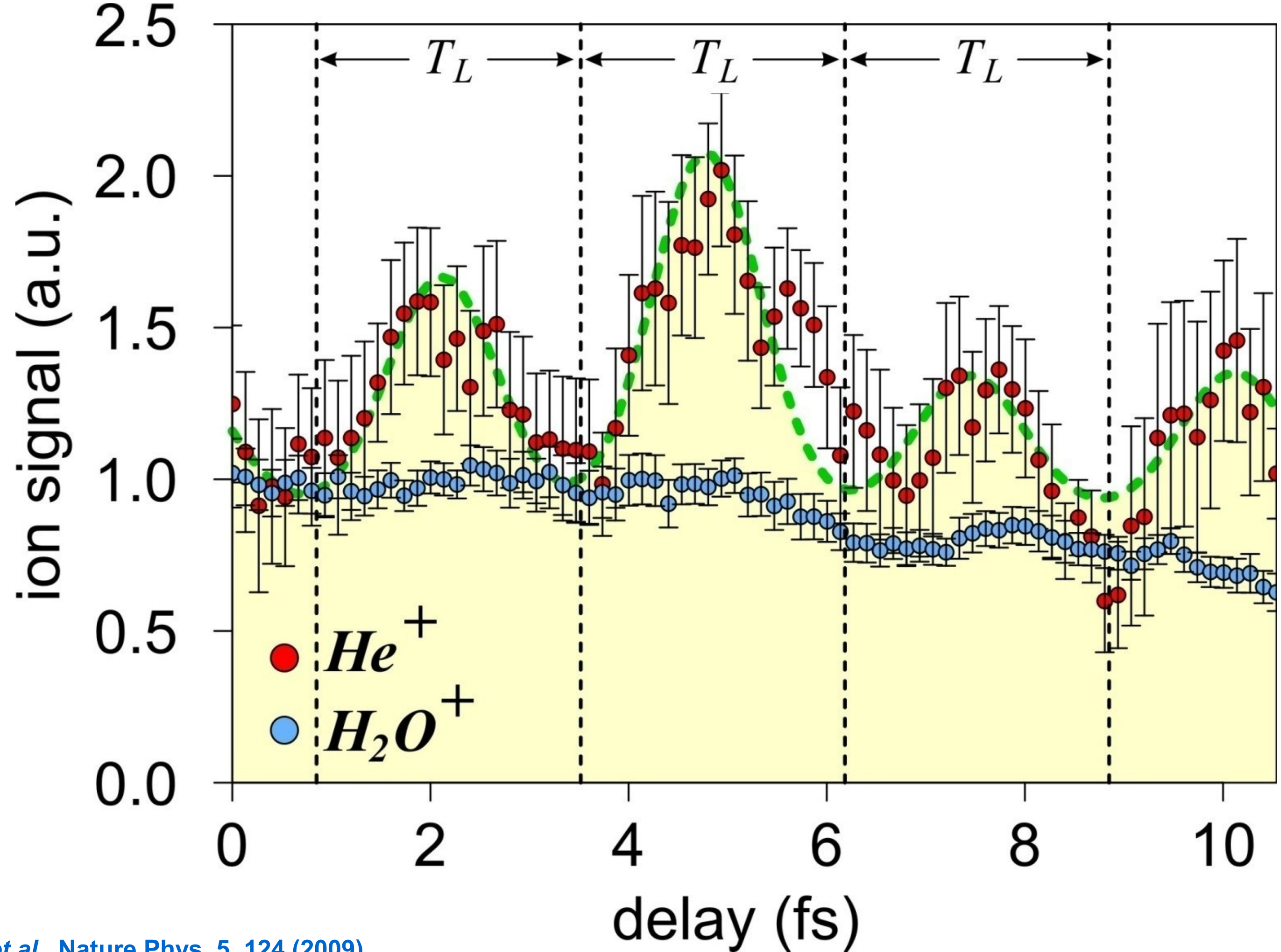
XUV emission duration ~45 fs



Y. Nomura *et al.*, Nature Phys. 5, 124 (2009)

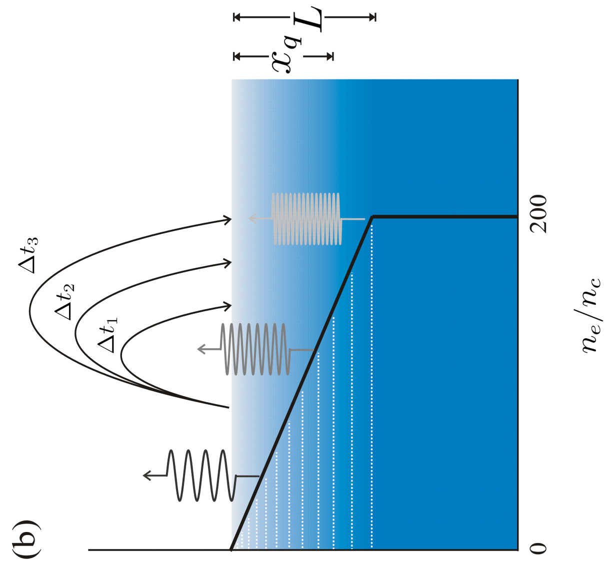
Autocorrelation measurements

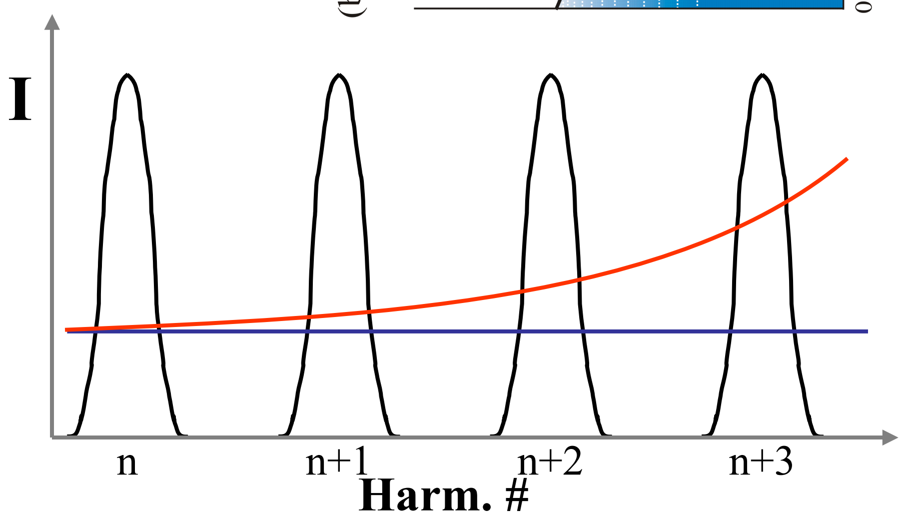
Fine scan: XUV pulse train with ~0.9 fs duration



Y. Nomura *et al.,* Nature Phys. 5, 124 (2009)

3 Temporal structure





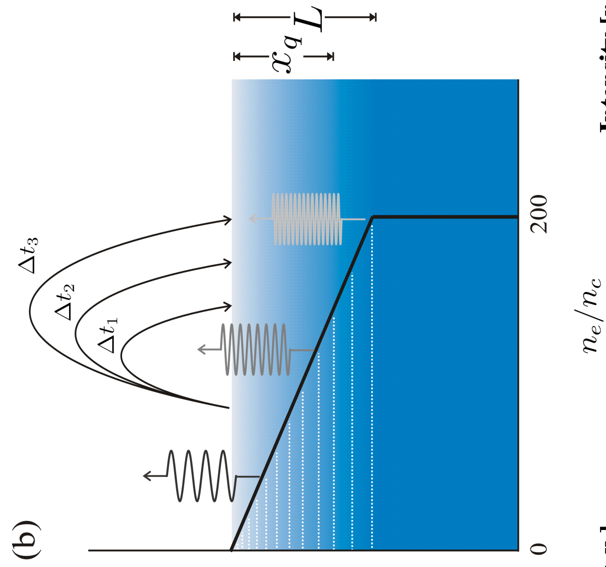
$$q_{\mathrm{co}} \approx \sqrt{\frac{n_{\mathrm{max}}}{n_{\mathrm{c}}}}.$$

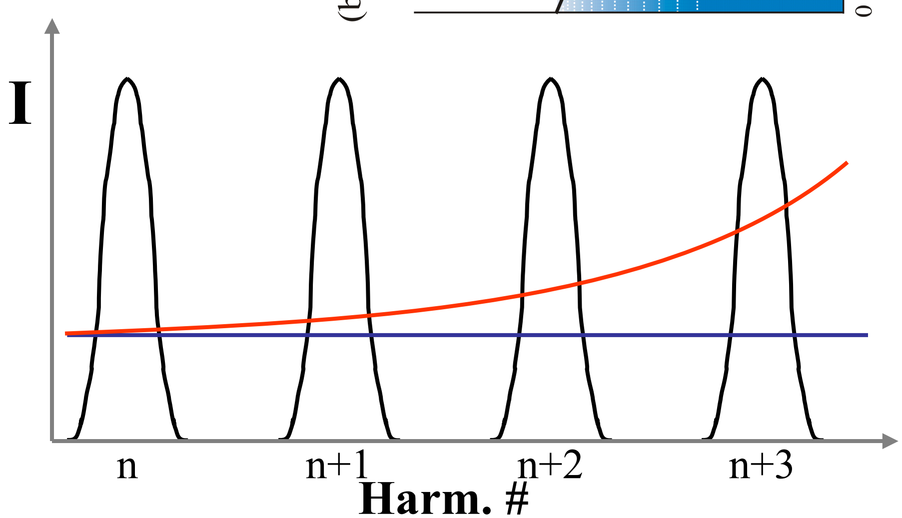
$$n_{\mathrm{e}}(x) = \frac{x}{L} n_{\mathrm{max}}.$$

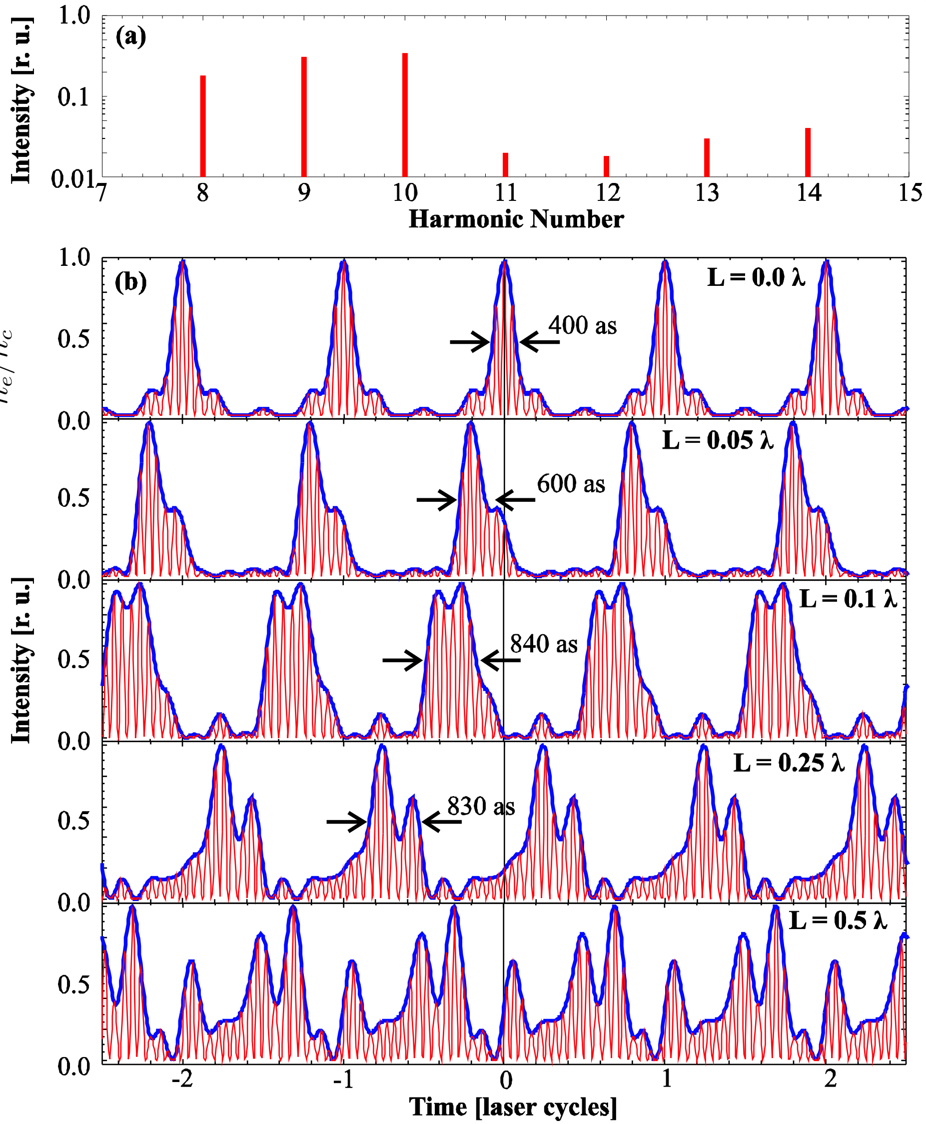
$$x(q) = L \frac{n_{\mathrm{c}}}{n_{\mathrm{max}}} q^2$$

$$\phi(q) = 2\pi \frac{L}{\lambda_{\mathrm{L}}} \frac{n_{\mathrm{c}}}{n_{\mathrm{max}}} q^3 (\sqrt{2} + \frac{2}{3}\sqrt{2})$$

Temporal structure

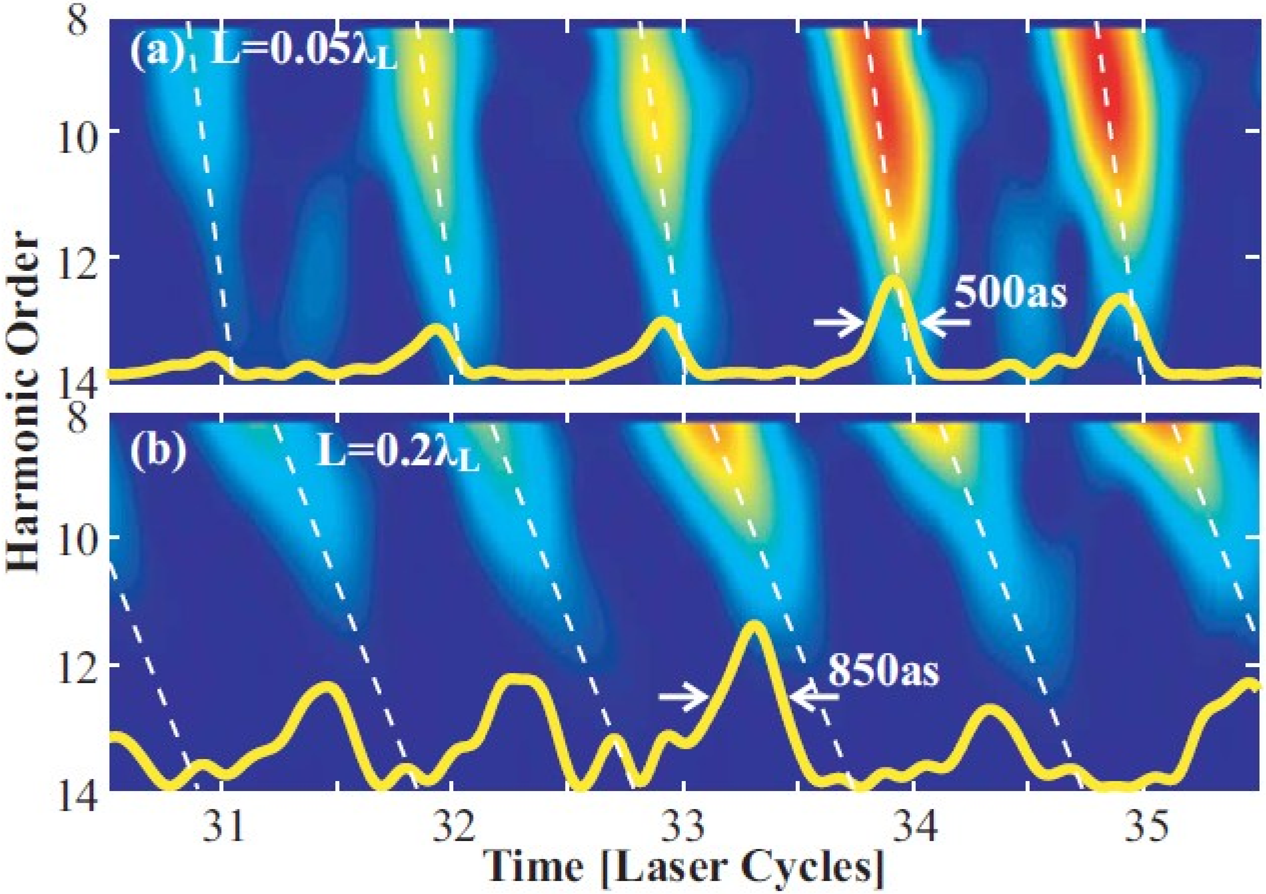




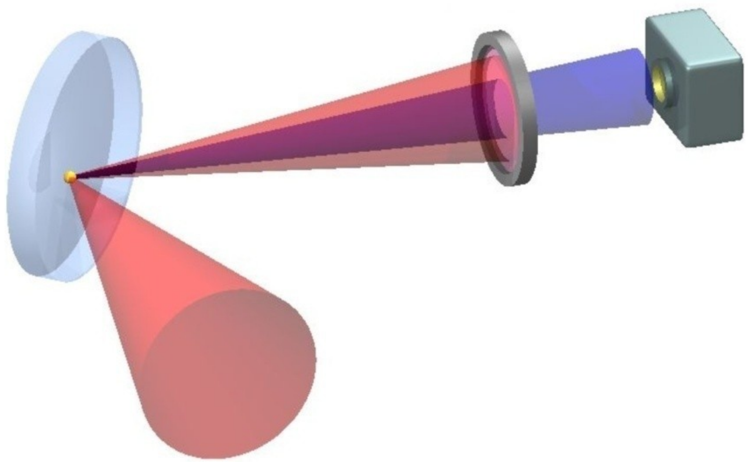


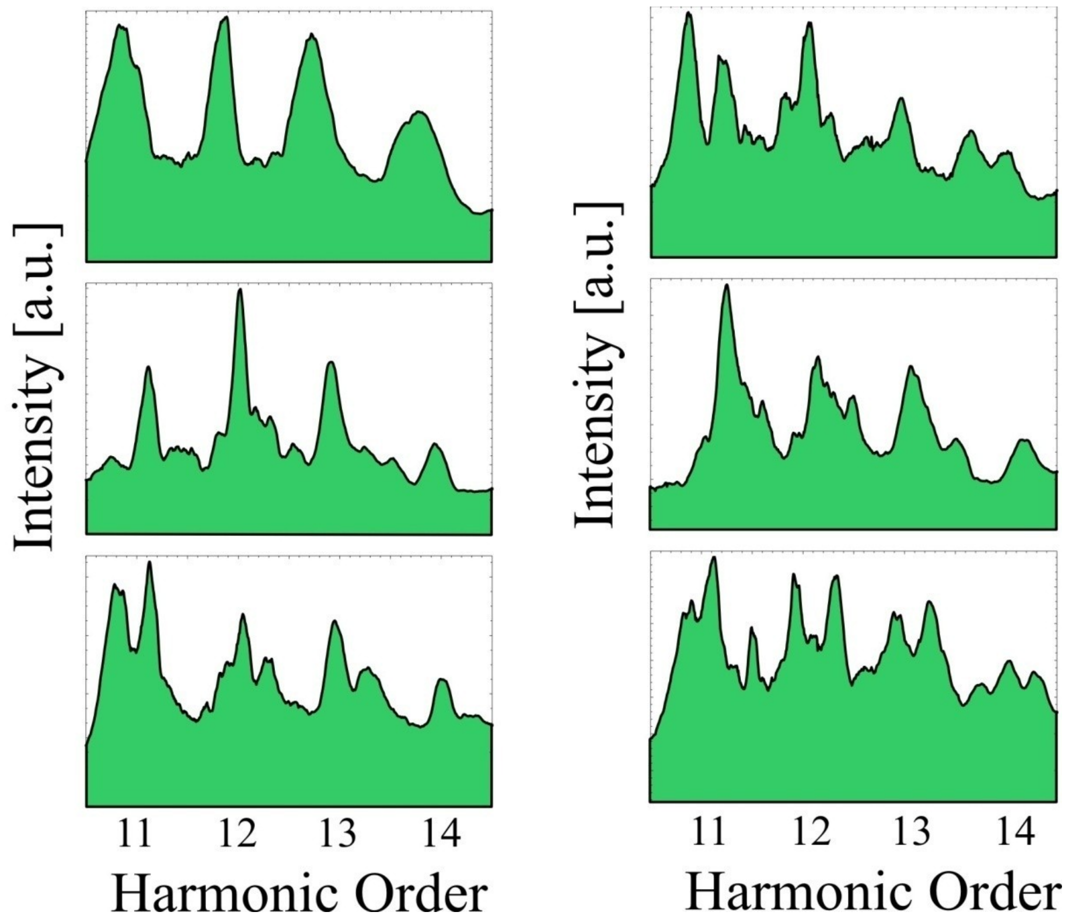
Temporal structure

Results of 1D PIC simulations. Wavelet analysis



Few-cycle harmonic emission



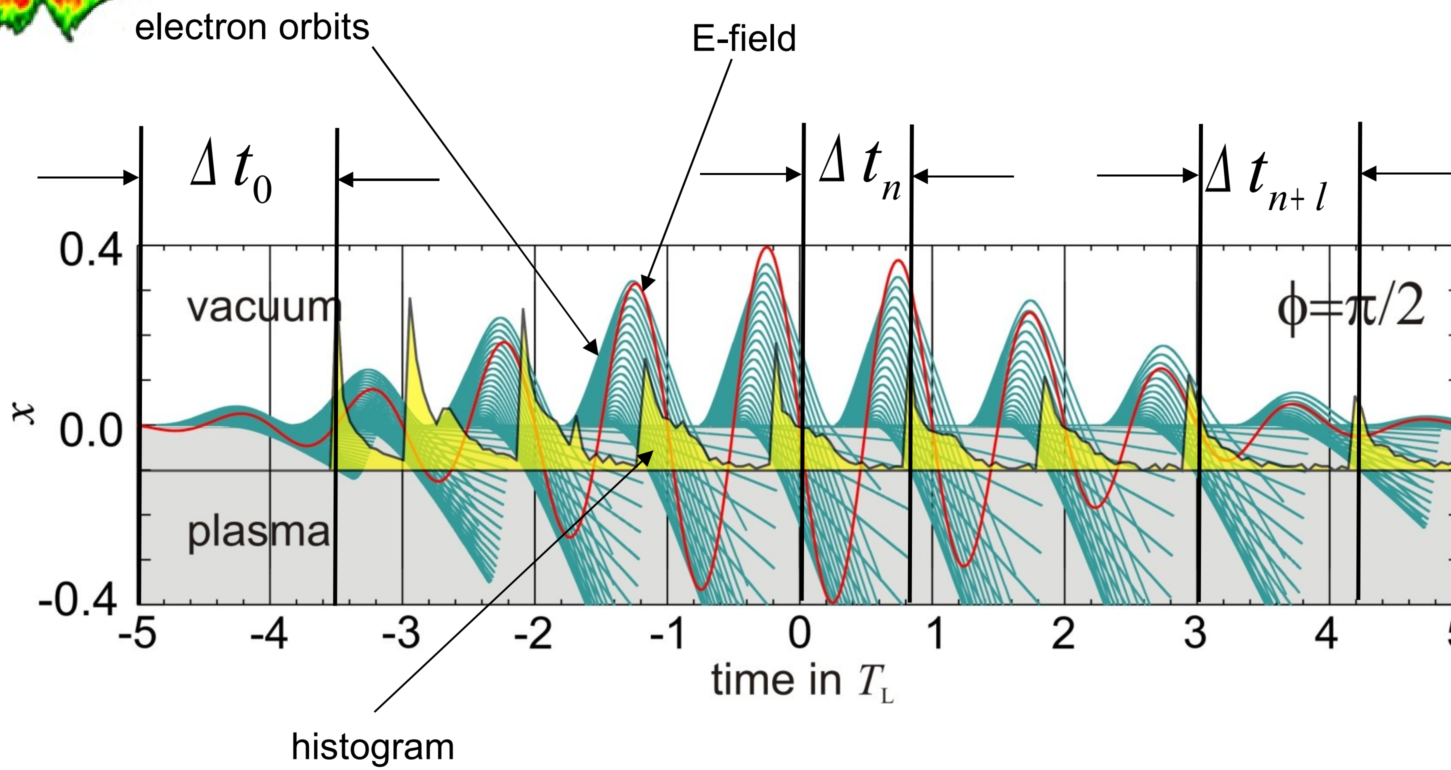


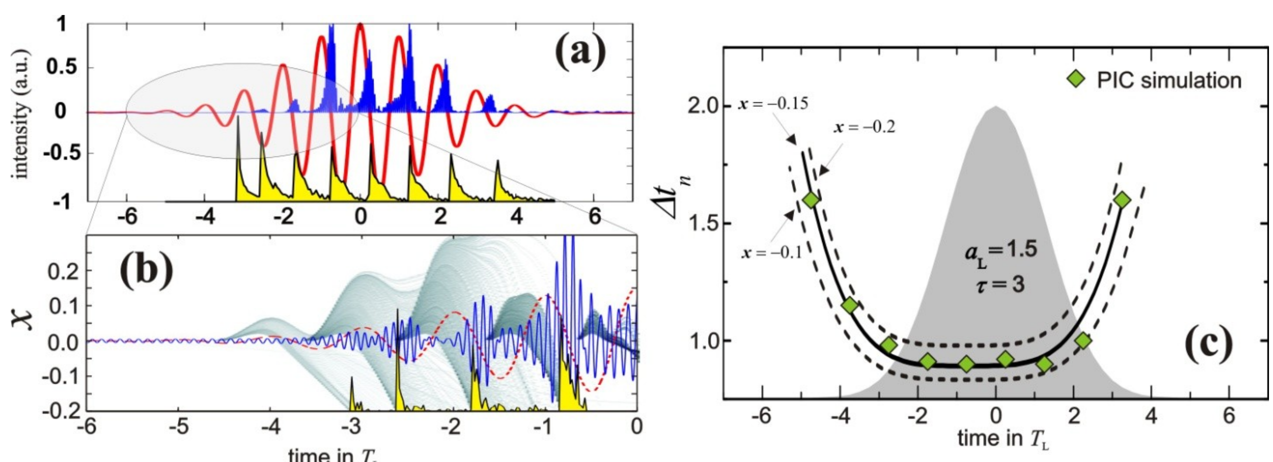
LWS-20 laser system
8fs, 160 mJ, 700 nm

- single shot spectra
- random CEP phase

R. Hoerlein, et al, submitted

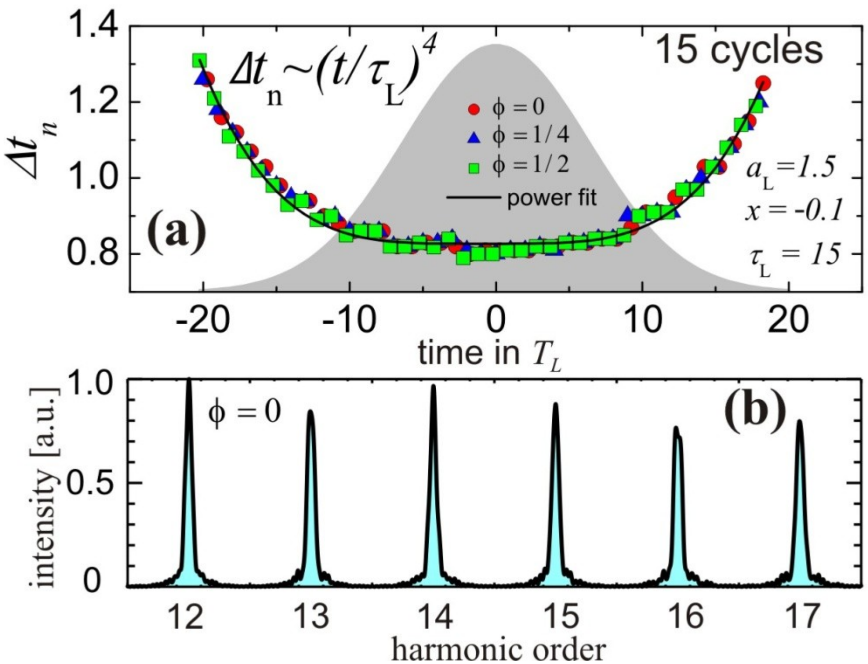
Electron dynamics at the interface



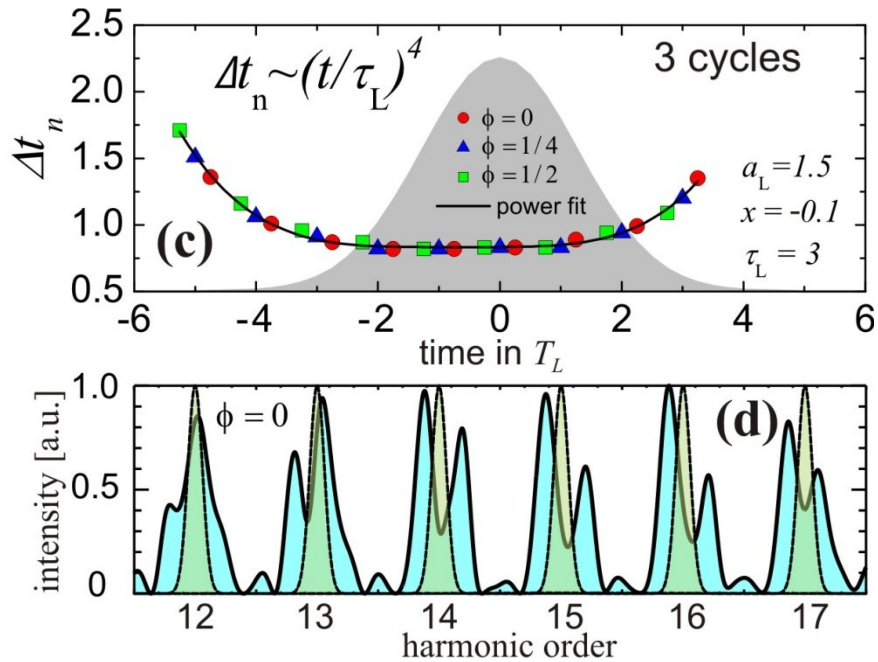


Effect on the HH spectrum

long pulse

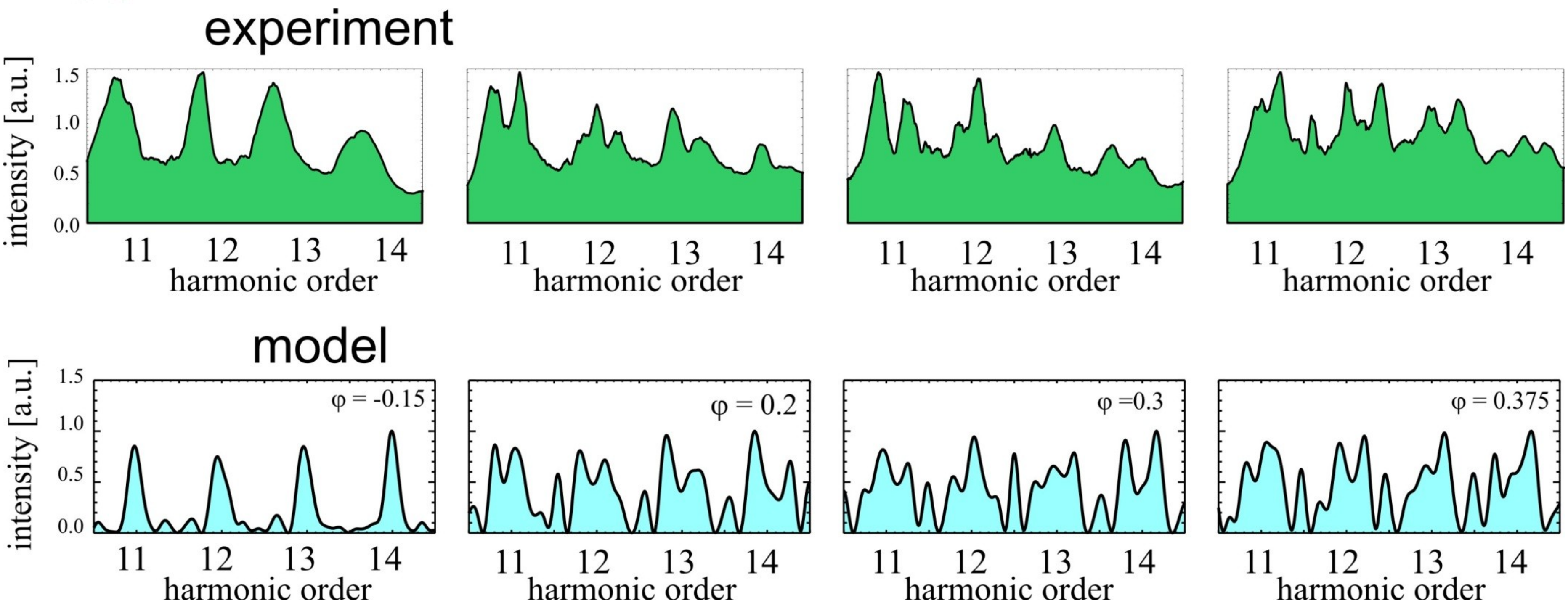


short pulse



R. Hoerlein, et al, submitted

Few-cycle harmonic emission



- single shot spectra
- random CEP phase

R. Hoerlein, et al, submitted

Coherent Wake Emission

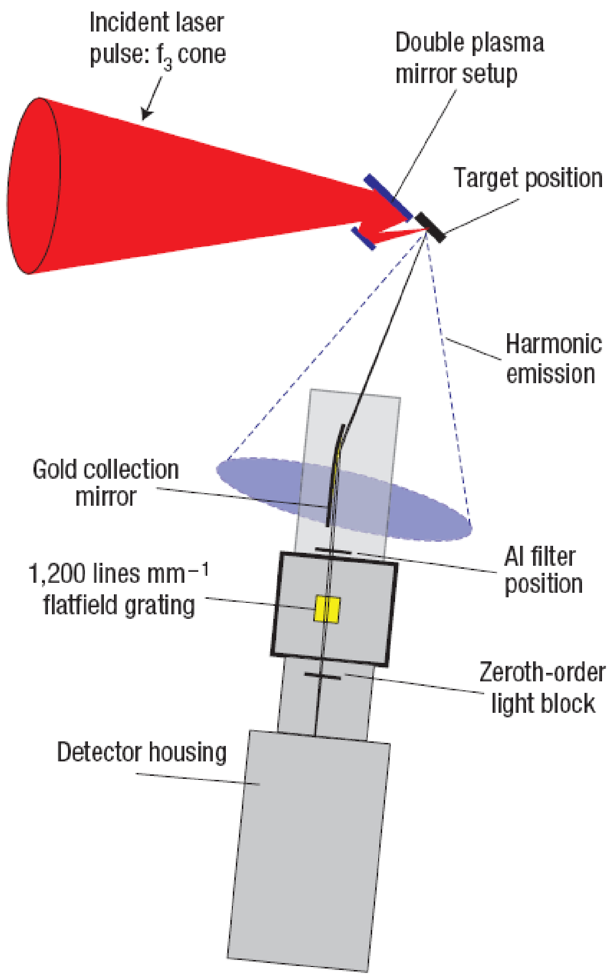
1. CWE harmonics are phase-locked and exhibit attosecond temporal structure
2. Experimentally proven spatial coherence (Thaury et al, Nat Phys, 4, 631 2008)
3. Estimated efficiency on the order of 10^{-4}
4. Might serve as a diagnostic tool

But

Limitations on the intensity of the laser pulse

Density dependent cut-off (not extendable to higher photon energies)

Power law decay



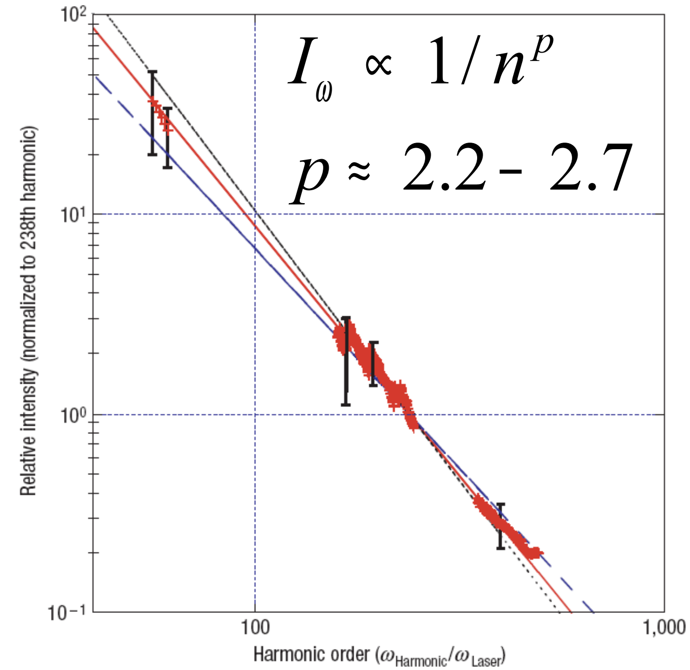


Figure 4 Relative intensity of harmonics normalized to the 238th harmonic (at the carbon K-edge). The lines are fits to the data with the exponent p as a fitting parameter such that $I(n)/I(238) = n^{-p}/238^{-p}$. The best fit (red line) corresponds to a value of $p = 2.5$ confirming harmonic production in the relativistic limit. The error bars indicate the uncertainty in the relative signal strength arising from the filter transmission and carbon contamination. The total uncertainty was calculated using standard error propagation analysis taking into account the individual uncertainty in each of the relevant quantities. The blue line corresponds to $p = 2.2$ and the black line corresponds to $p = 2.7$. The gaps in the spectrum correspond to spectral regions where the filters strongly absorb the harmonic radiation thus preventing a meaningful deconvolution.

S. Gordienko *et al*, Phys. Rev. Lett. 93, 115002 (2004).
B. Dromey *et al*, Nat. Phys. 2, 456 (2006).

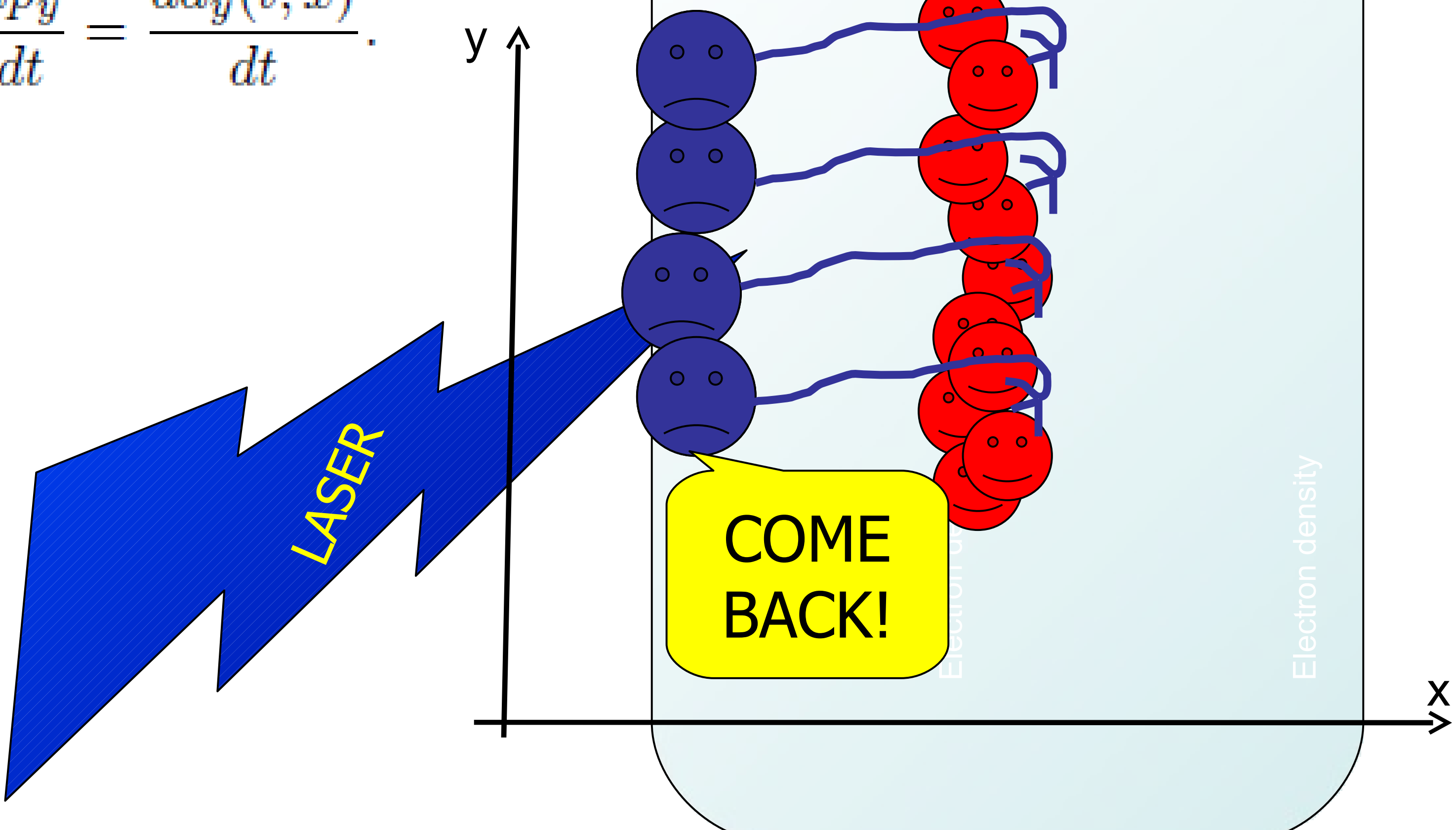
Simple model

Lorentz Force

RestoringForce

$$\frac{dp_x}{dt} = \beta_y \frac{\partial a_y(t,x)}{\partial x} + n_e x$$

$$\frac{dp_y}{dt} = \frac{da_y(t,x)}{dt}.$$

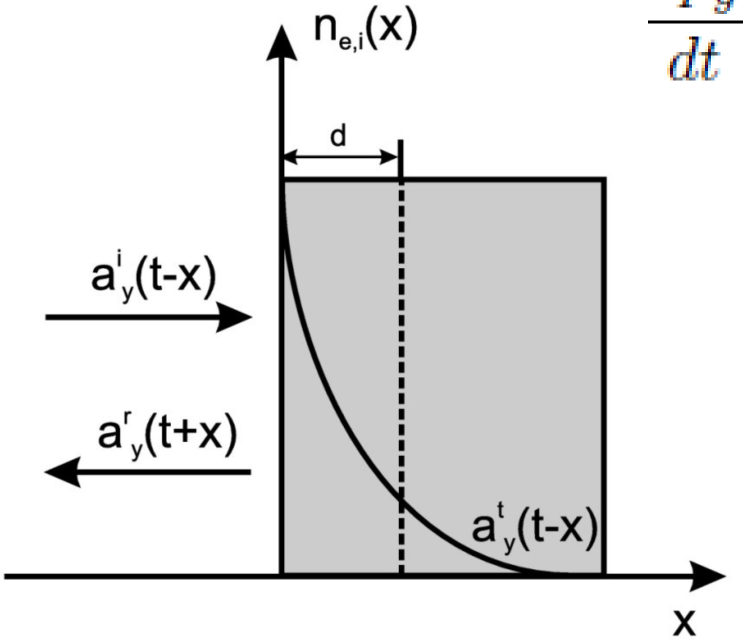


Simple model

$$\frac{dp_x}{dt} = \beta_y \frac{\partial a_y(t,x)}{\partial x} + n_e x$$

$$\frac{dp_y}{dt} = \frac{da_y(t,x)}{dt}.$$

$$a_y = ?$$



Boundary conditions:

$$E_{y,inc} + E_{y,refl} = E_{y,transmitted}$$

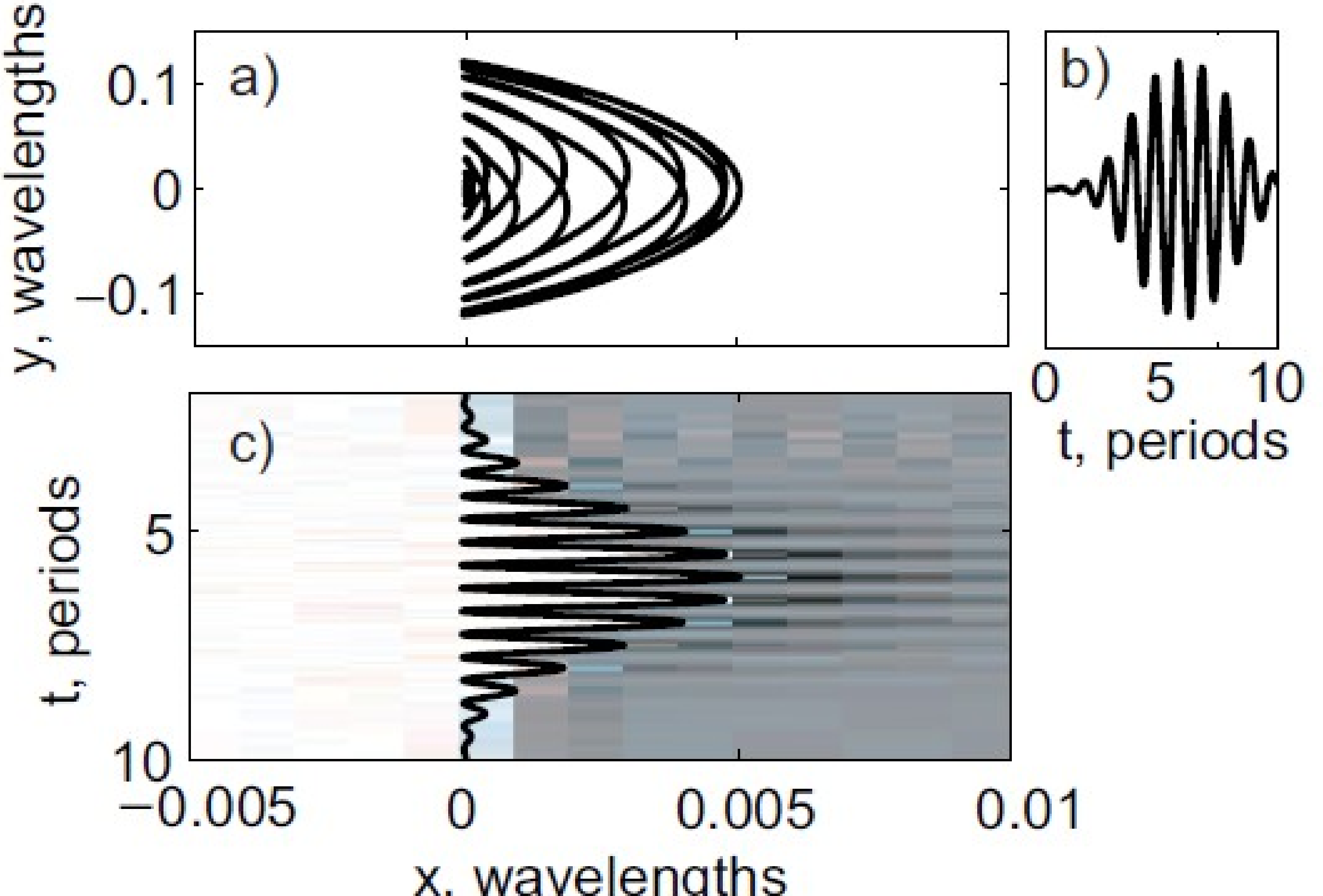
$$B_{z,inc} + B_{z,refl} = B_{z,transmitted}$$

$$E_{dr} = \frac{2E_i}{\sqrt{1+\omega_p^2}} \cos(t - x_p + \alpha)$$

$$\alpha = \arctan(\omega_p)$$

$$a_{dr,0} = \frac{2a_0}{\omega_p}$$

Simple model



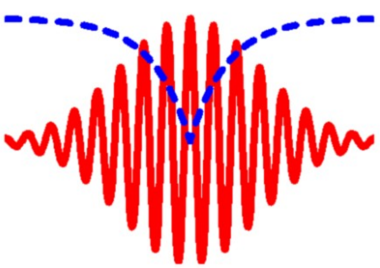
$a_0 = 10$ $\tau_{FWHM} = 4cycles$ $n_e = 400n_{cr}$

Controlling the temporal structure

Intense single attosecond pulses using temporal gating

Using very short pulses

Temporal gating of polarization

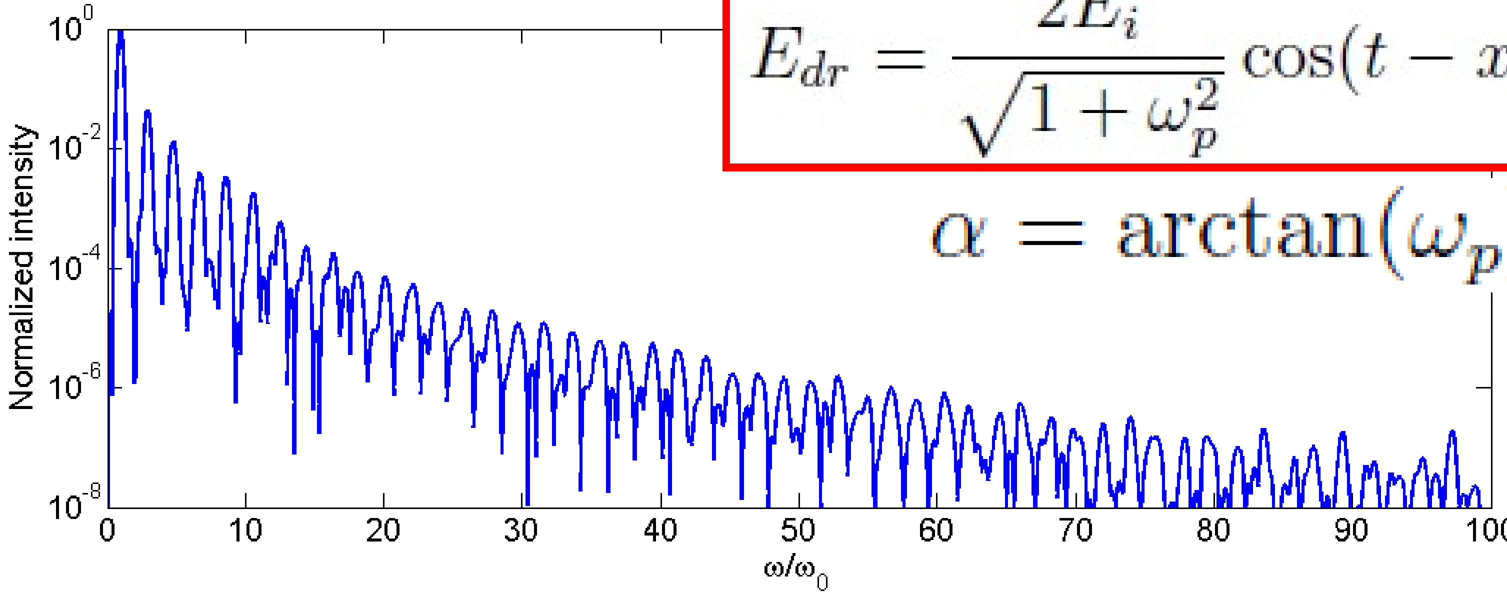


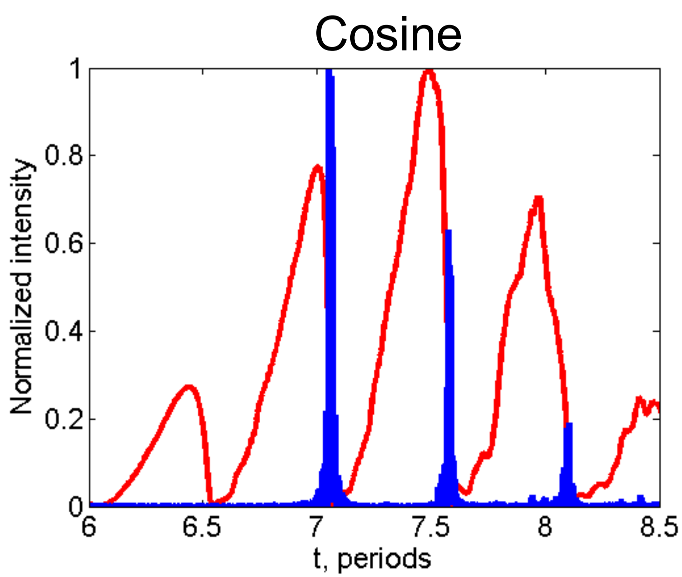
*G.D. Tsakiris et al, NJP **1**, 019 (2006)*

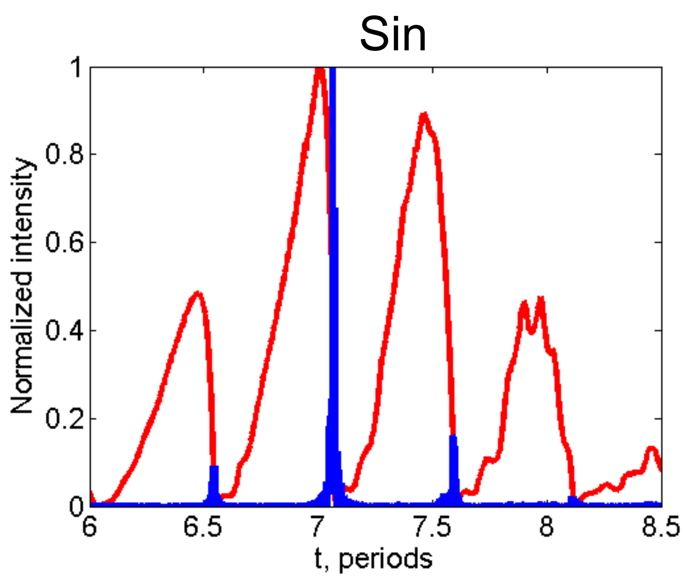
Intensity gating

$$E_{dr} = \frac{2E_i}{\sqrt{1+\omega_p^2}} \cos(t - x_p + \alpha)$$

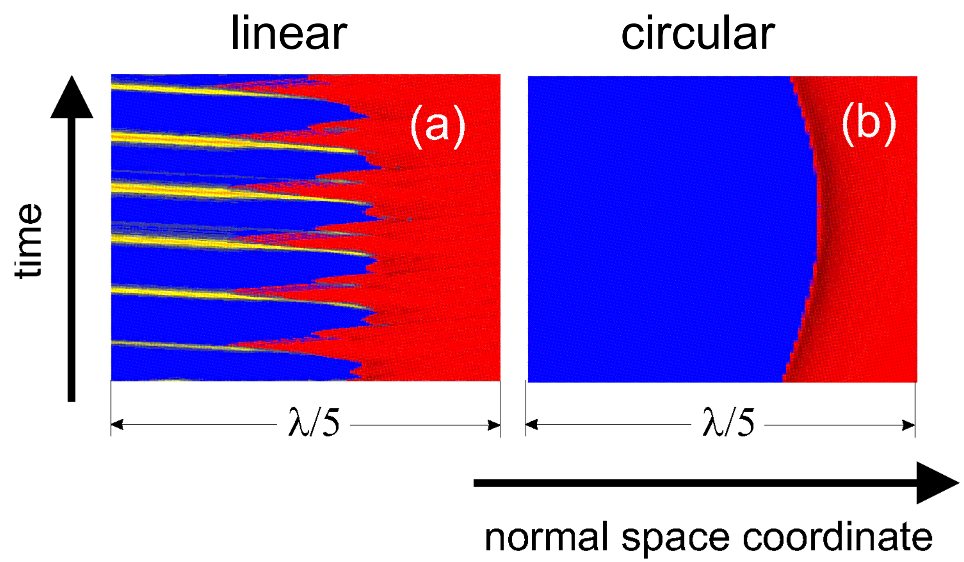
$$\alpha = \arctan(\omega_p)$$

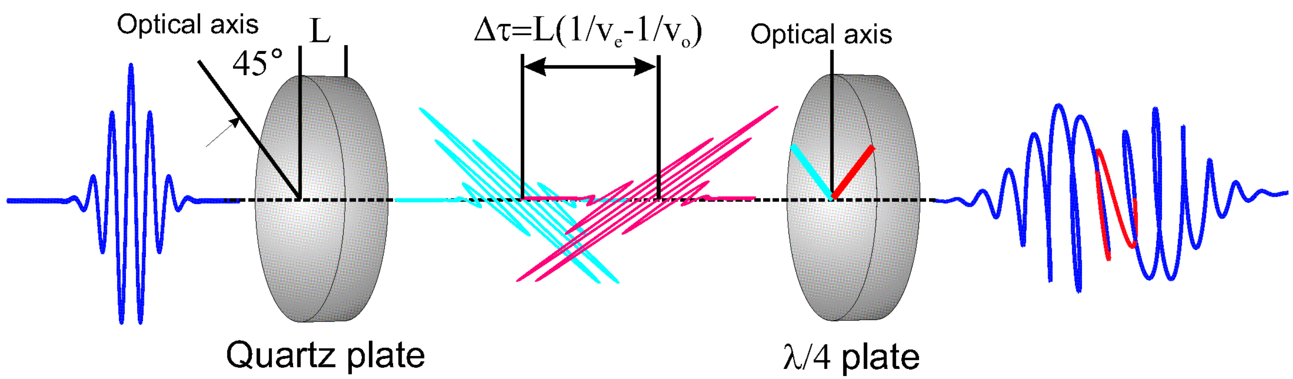






Polarization gating



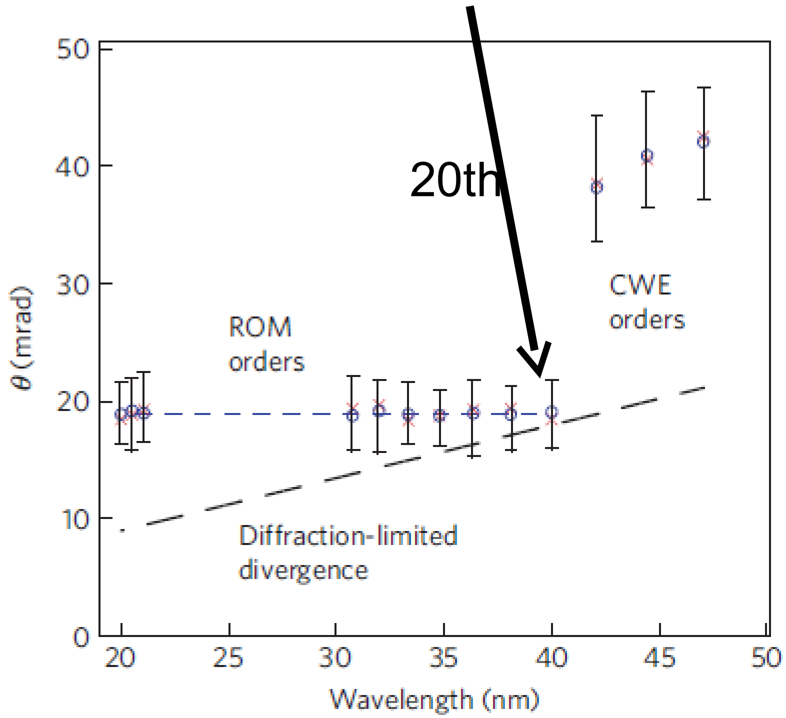


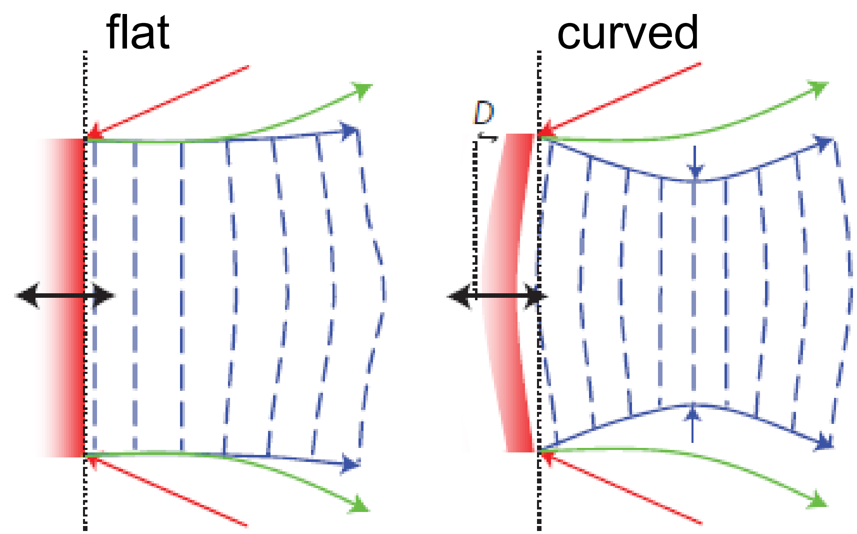
*S.G. Rykovanov et al, NJP **8**, 025025 (2008)*

Controlling the spatial structure

Experiments by B. Dromey et al

Diffraction limited performance of harmonics



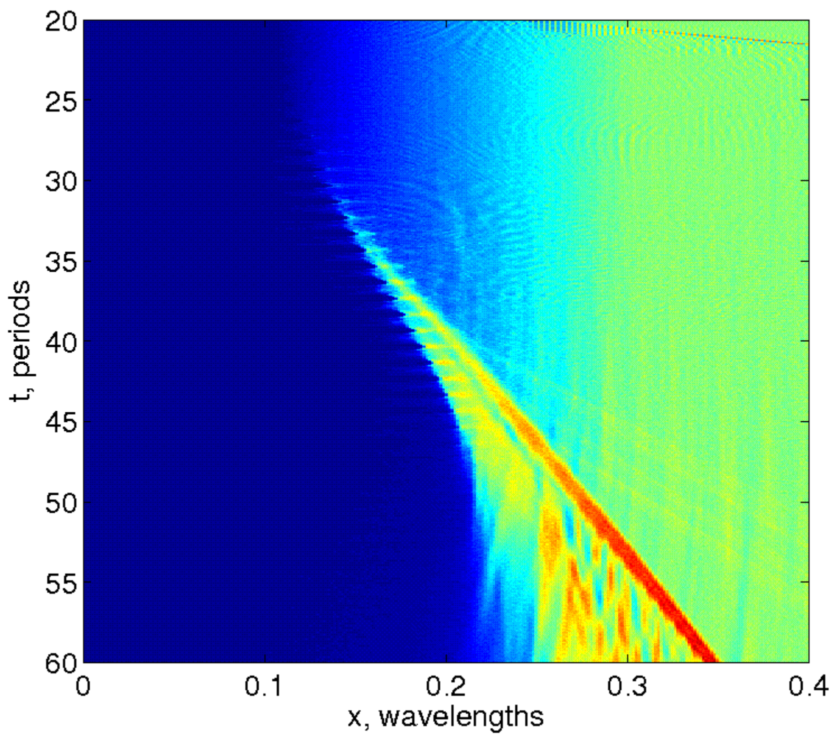


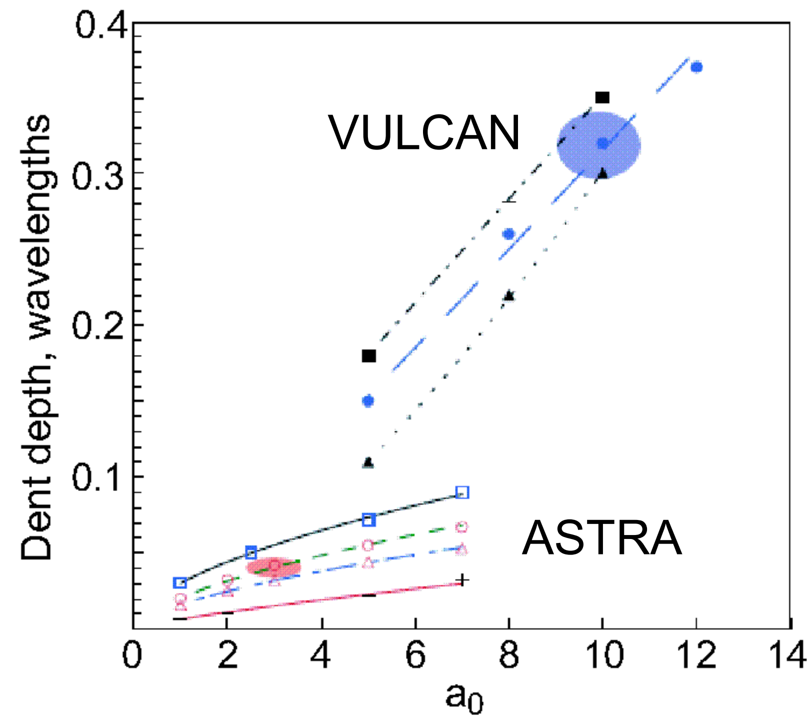
$$\Theta_q \propto \frac{\lambda_q}{D_q}$$

Dromey et al, Nat Phys, 5, 146 (2009)

Target denting

1. Adiabatic denting due to slow ion motion

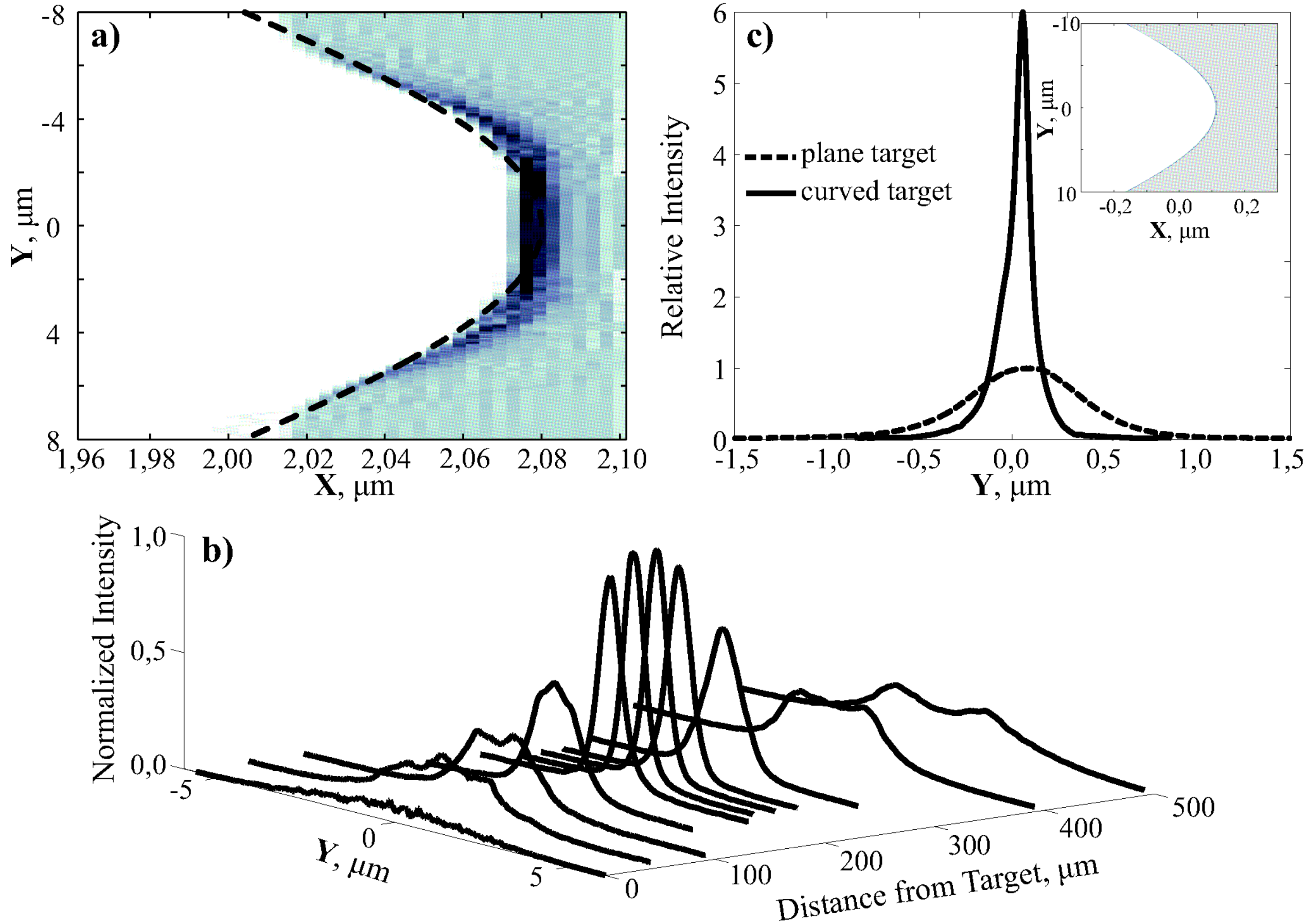




Dromey et al, Nat Phys, 5, 146 (2009)

Target denting

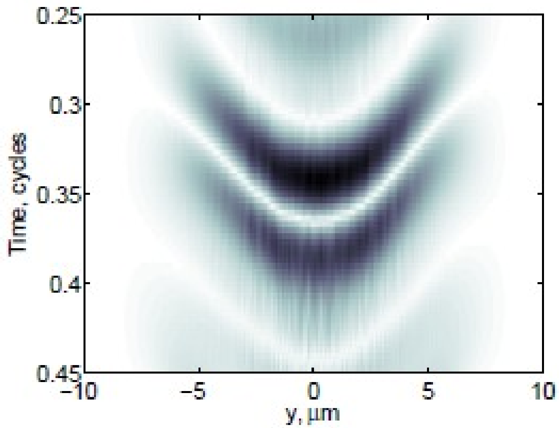
2. Non-adiabatic denting due to fast electron motion



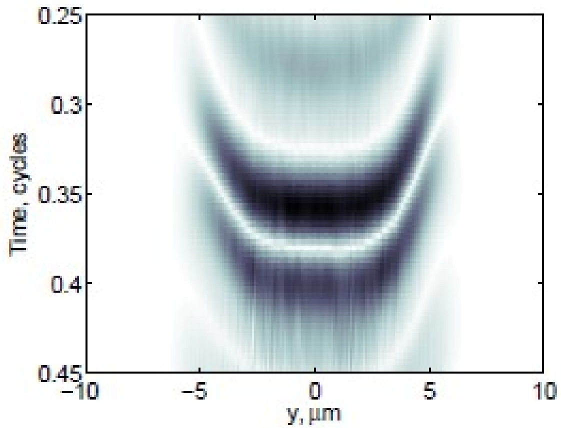
R. Hoerlein, S.G. Rykovanov, et al, accepted to EPJD

Controlling the divergence

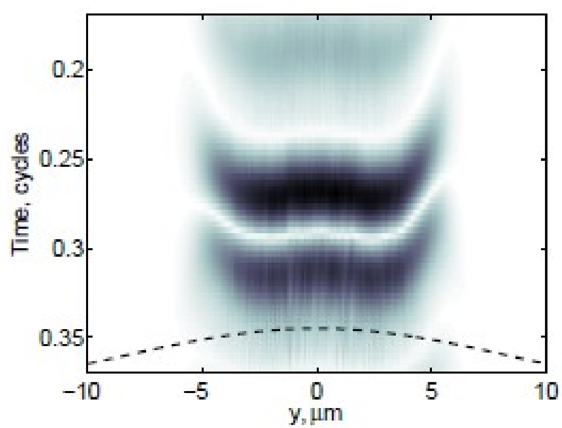
Gaussian pulse



Supergaussian pulse



Gaussian + convex target



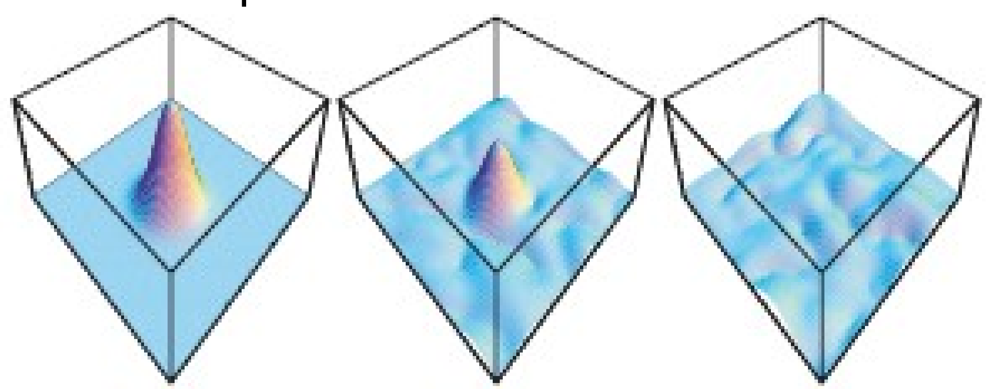
R. Hoerlein, S.G. Rykovanov, et al, accepted to EPJD

Surface roughness

1. The high-order harmonics structure (both temporal and spatial) may be affected by the surface corrugations
2. In classical problems the roughness on the order of the wavelength leads to diffuse scattering
3. Experiments do not totally agree with classical picture

Harmonic beam
From 20 to 40 harmonics
(20 nm to 40 nm)

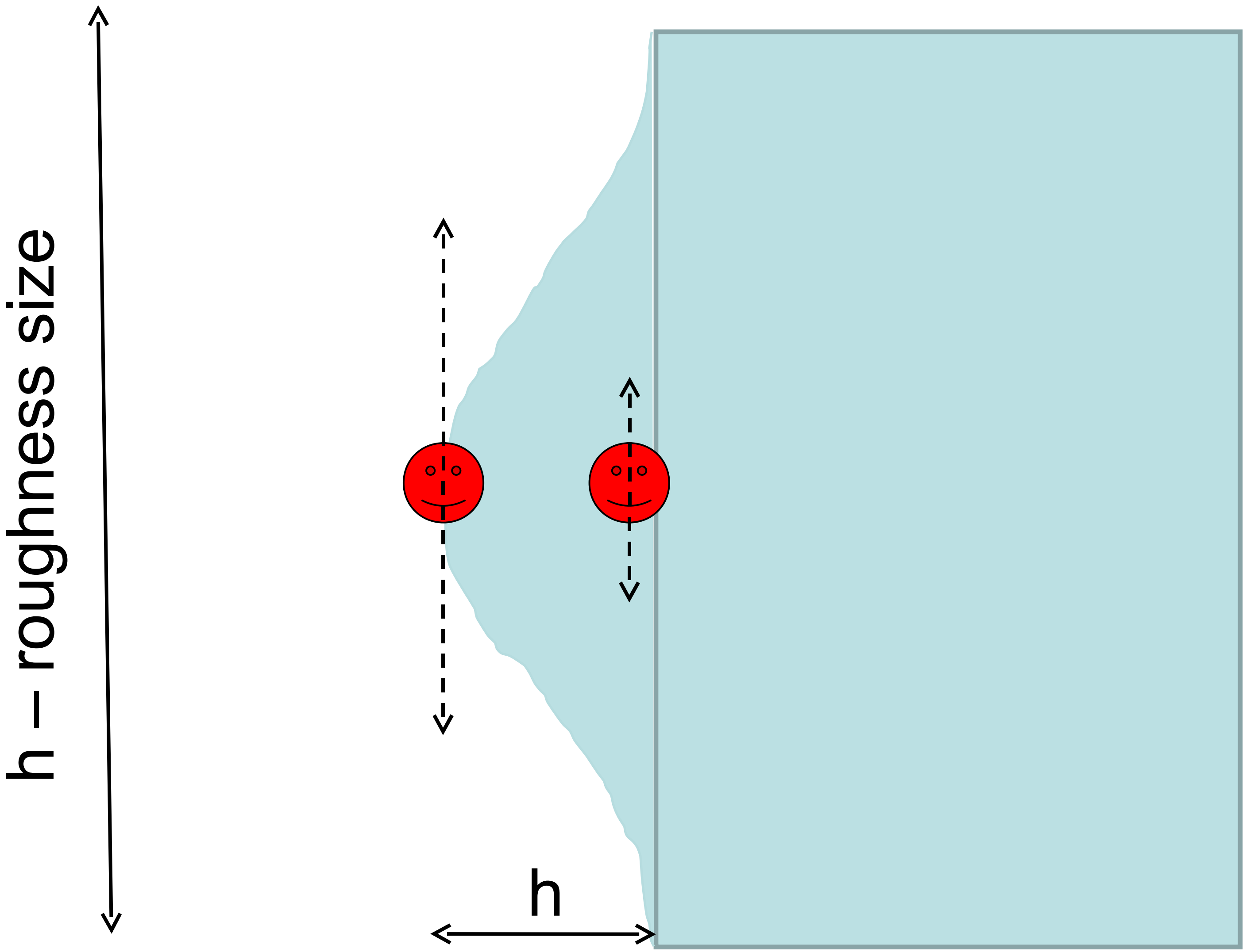
Experimental results overview



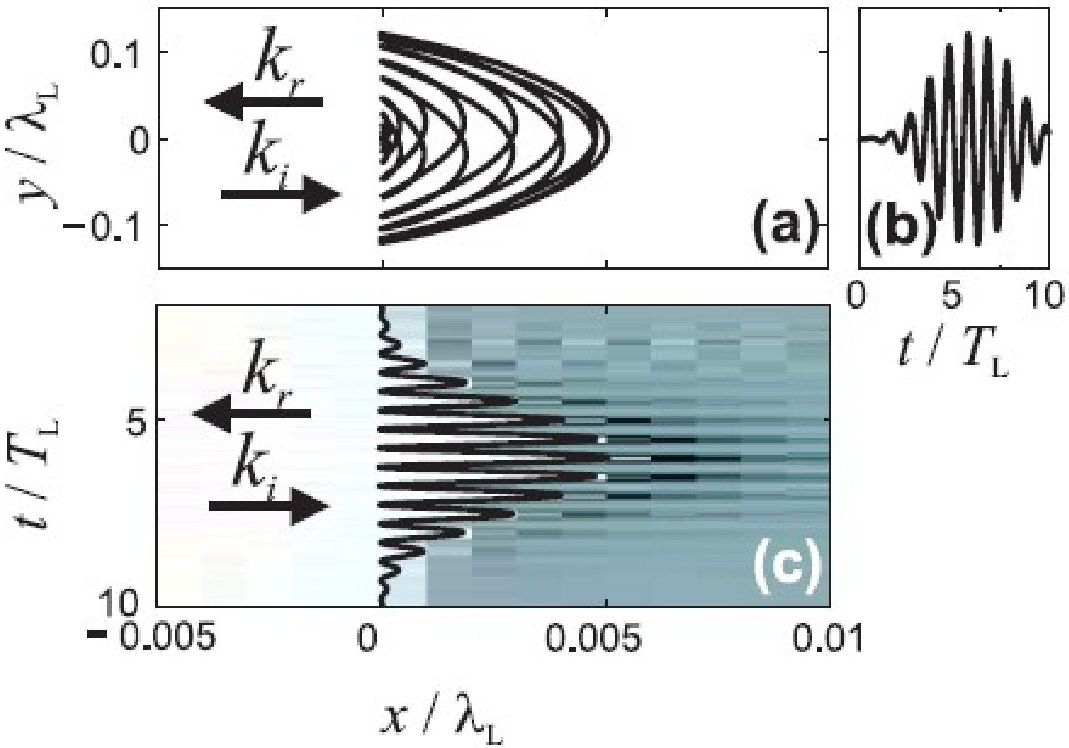
h<1 nm   h~18 nm   h~164 nm

B. Dromey, et al, Nat Phys, 5, 146 (2009)

Smoothing criterion



Smoothing criterion



Transverse amplitude:

$$y_{max} \approx \frac{2a_0}{\omega_p}$$

$$y_{max}(x) \approx \frac{2a_0}{\omega_p} \cdot e^{-\omega_p x}$$

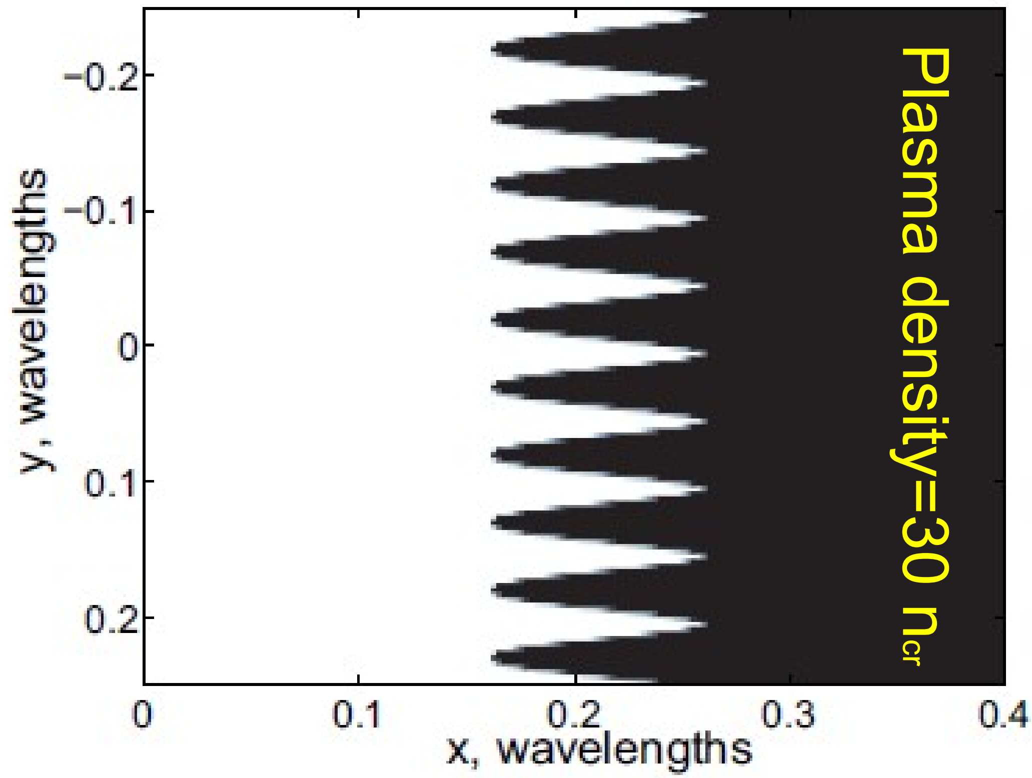
Smoothing criterion

$$\xi = \frac{2a_0}{\omega_p h} \cdot e^{-\omega_p h}$$

1. $\xi>1$ the roughness disappears
2. $\xi<1$ the roughness survives

PIC simulations setup

a0=10, 2 cycle duration



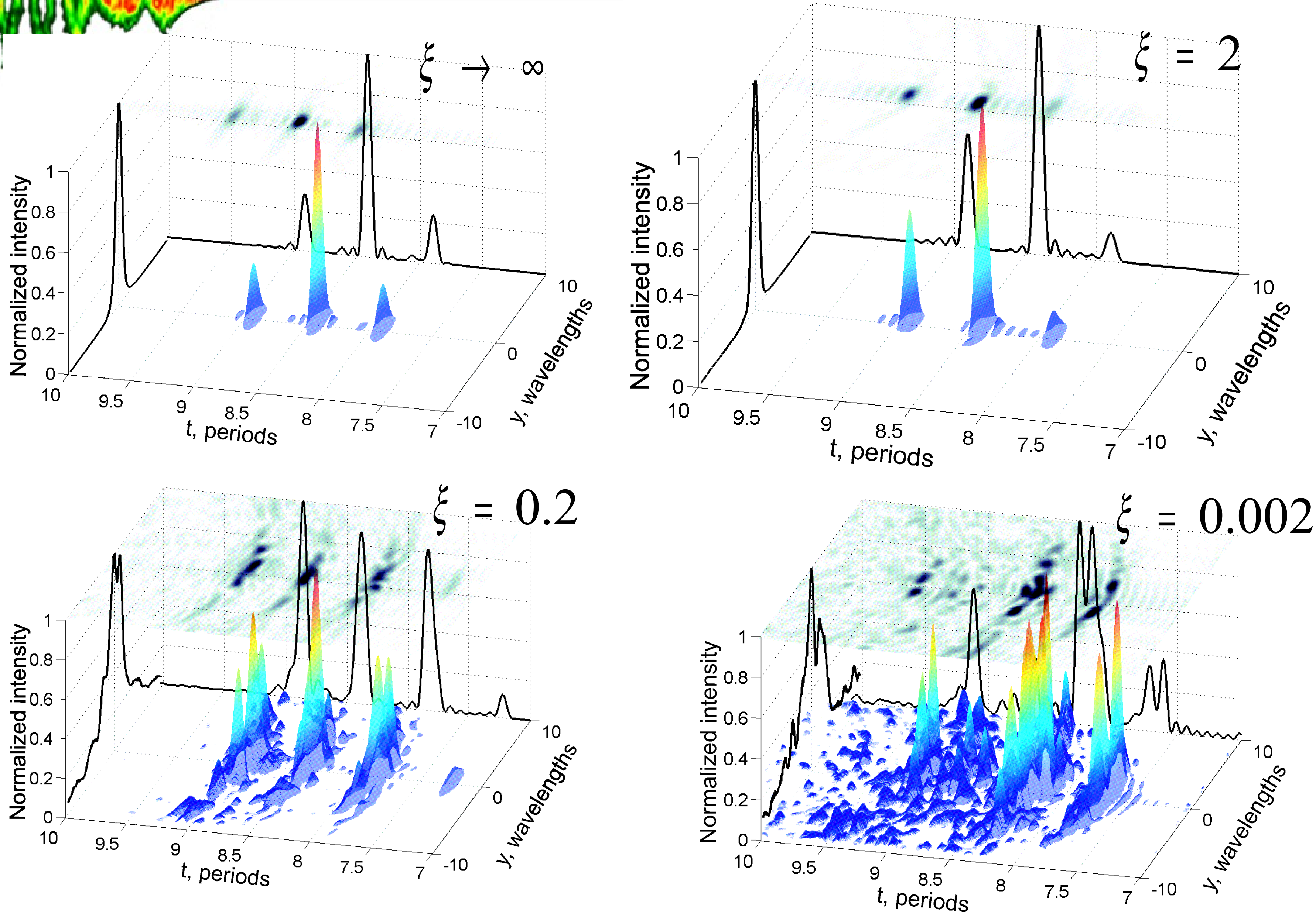
Roughness is assumed to be sinusoidal

Harmonic beam is taken from 15th to 25th (**40nm to 66 nm**)

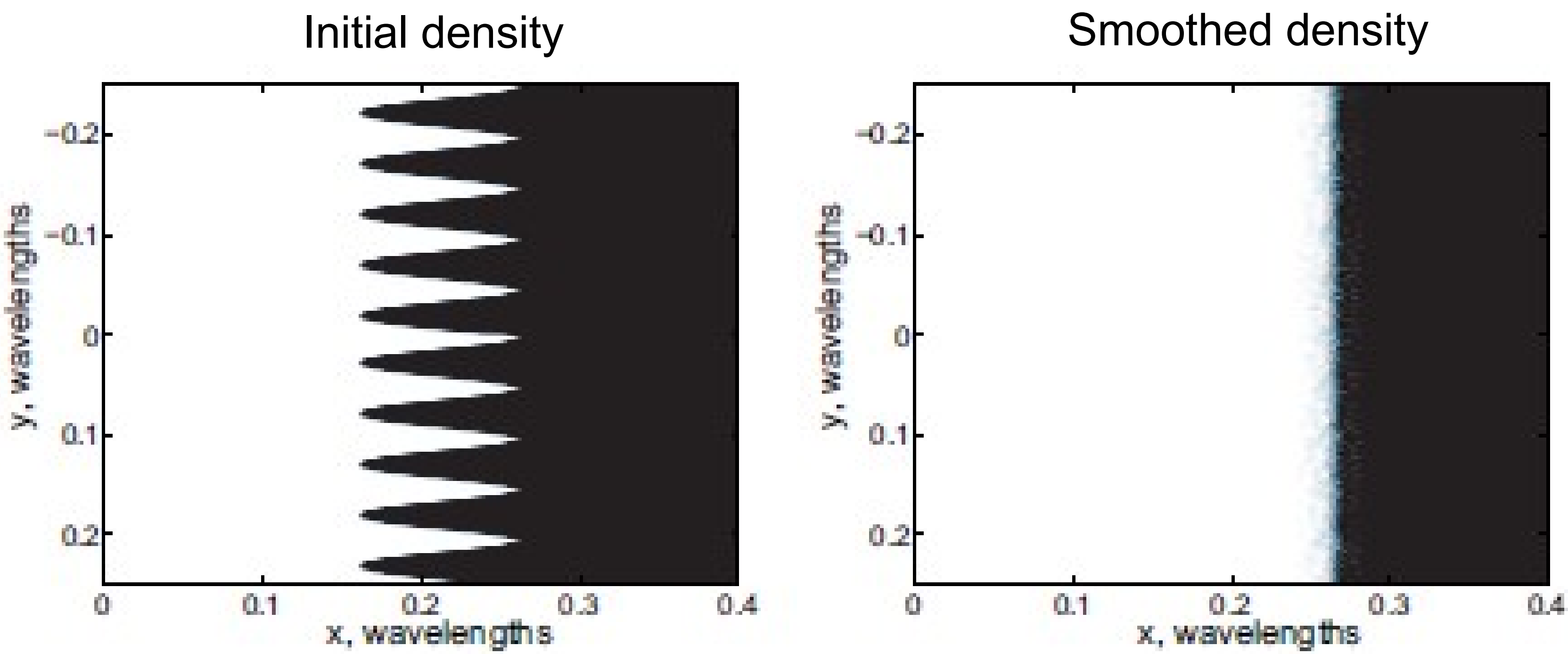
Roughness with **h=50 nm, 100 nm and 200 nm** is considered.

From the classical point of view the harmonic beam should be **scattered** for any of the simulated rough surfaces

PIC simulations results



Non-adiabatic smoothing



S.G. Rykovanov et al, submitted, arXiv: 0908.3134v2

Summary

1. The idea behind generation of single attosecond pulses is reducing the number of surface oscillations. This can be done through the intensity gating or the polarization gating techniques.

2. Target denting leads to the *parasitic* harmonic focusing.

3. The *parasitic* harmonic focusing can be overcome by straightening the wavefronts of emitted harmonics. This can be done by appropriate laser and target shaping.

4. The *controlled* harmonic focusing is possible using the concave targets and may lead to the new physics regimes (QED).

5. Non-adiabatic surface smoothing can be sufficient to allow the diffraction limited harmonic beaming.

Conclusions

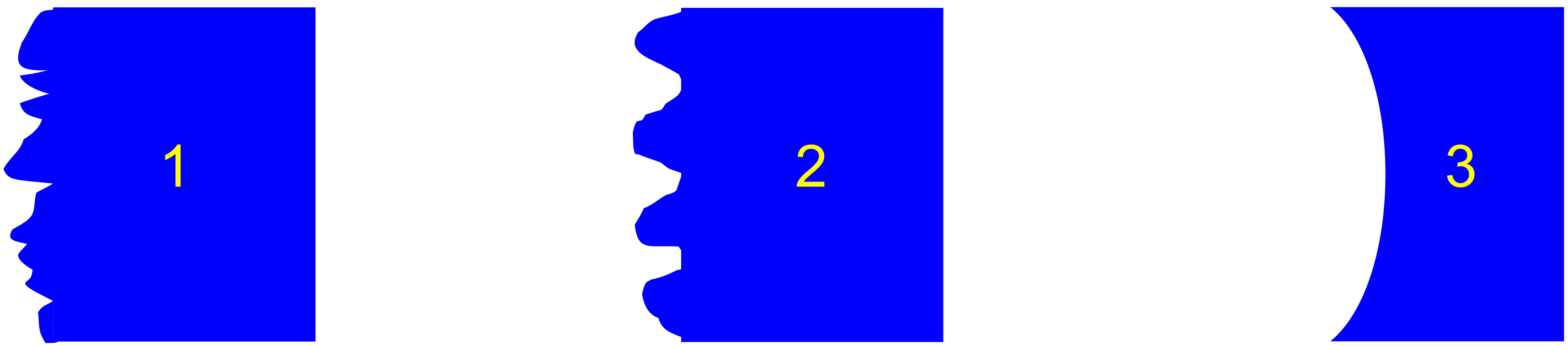
1. Two mechanisms of harmonic generation – CWE and OM
2. Both mechanisms produce coherent harmonic beams
3. A possible route towards the intense single attosecond pulses

Surface structure

Δr<<λ
Surface roughness

Δr~λ
Scattering, gratings

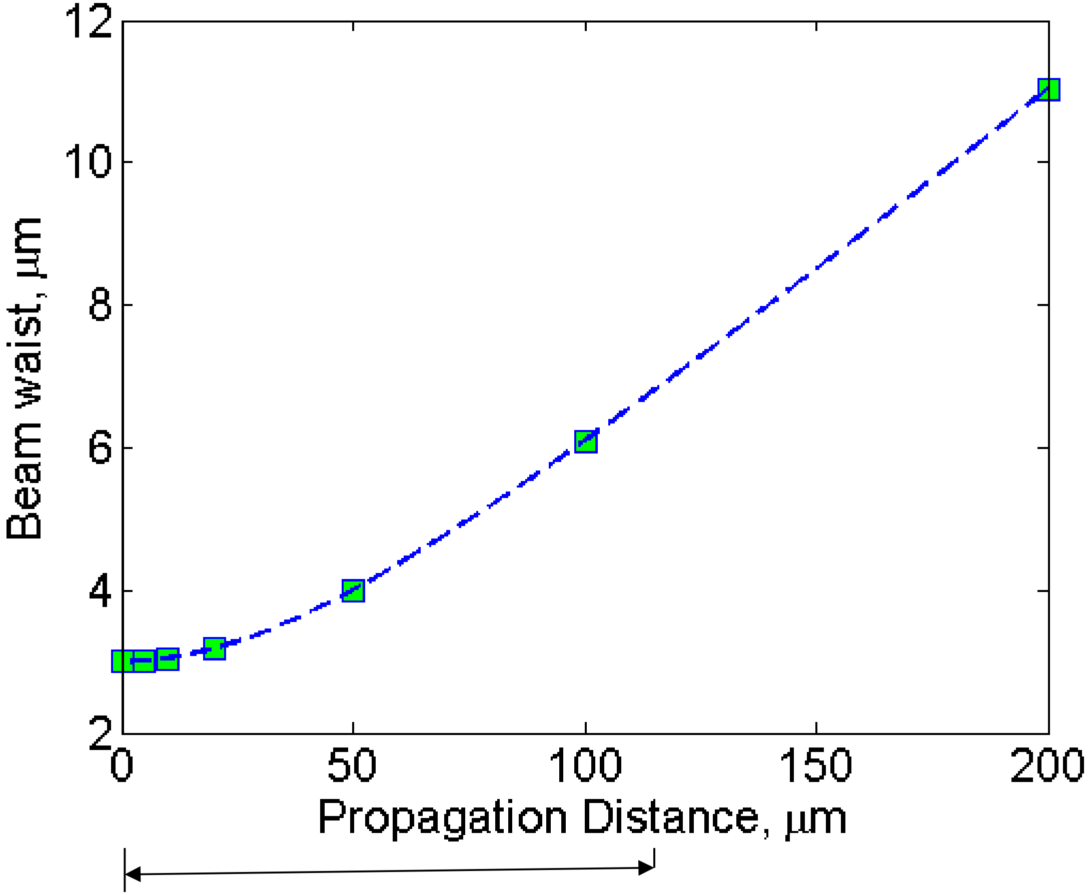
Δr>>λ
Focusing optics,
Ponderomotive denting

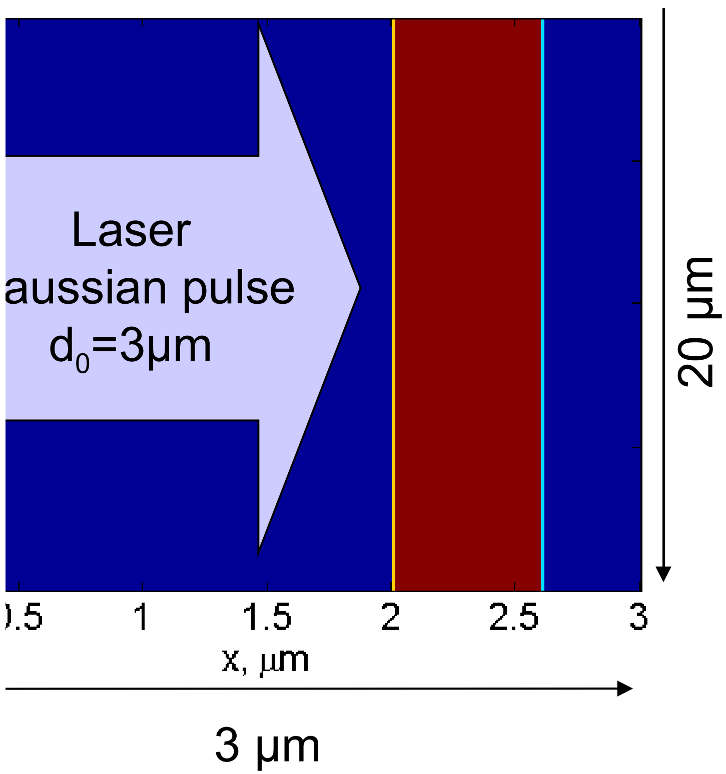


Numerical tool. Farfield test

Farfield via Kirchhoff-Integral

2D PIC code
Plasma density = 10 n_{cr}
Laser Intensity = $1.37 \cdot 10^{14}$ W/cm^2
=3 nm



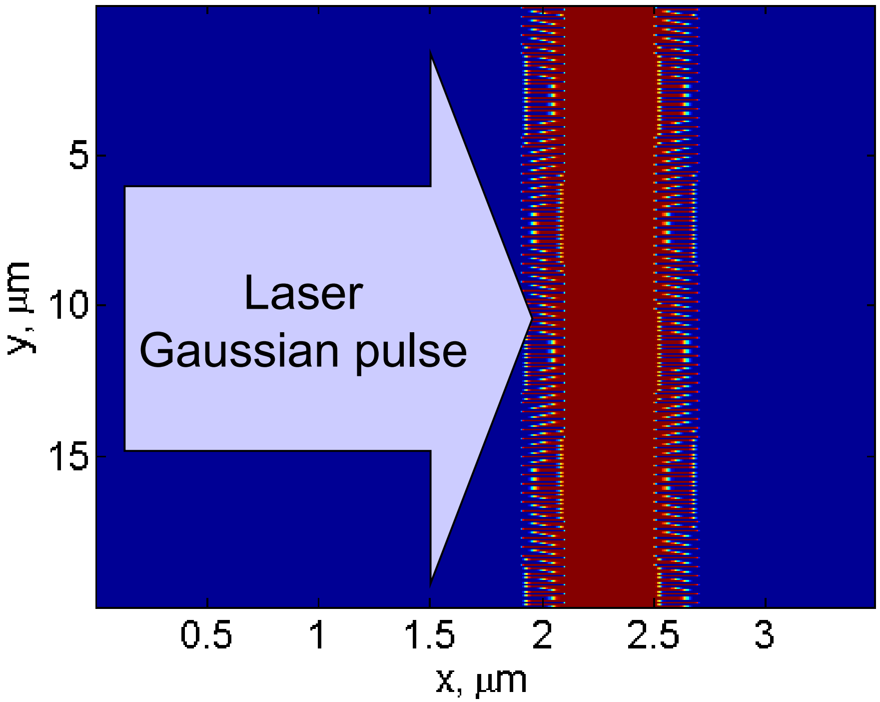


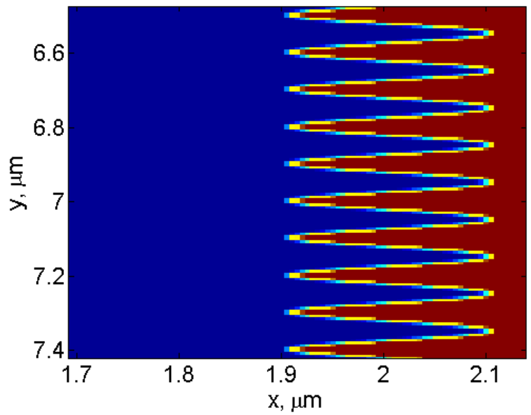
Surface roughness

2D PIC simulations + Farfield propagation

Plasma density = 10 n_{cr}

Laser Intensity = $1.37 \cdot 10^{20}$ W/cm^2

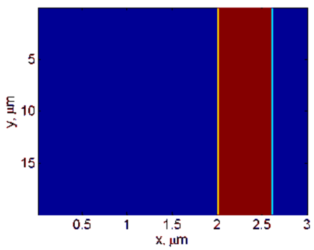




$$n(x,y) = \Theta\left(x - a \cdot \cos\left(\frac{1}{a}y\right)\right)$$

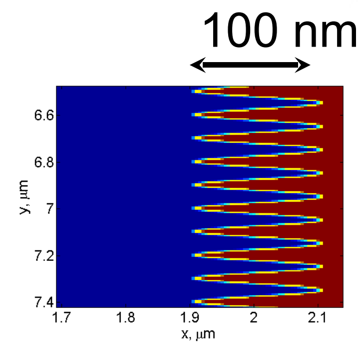
a<<λ

Surface roughness 100nm

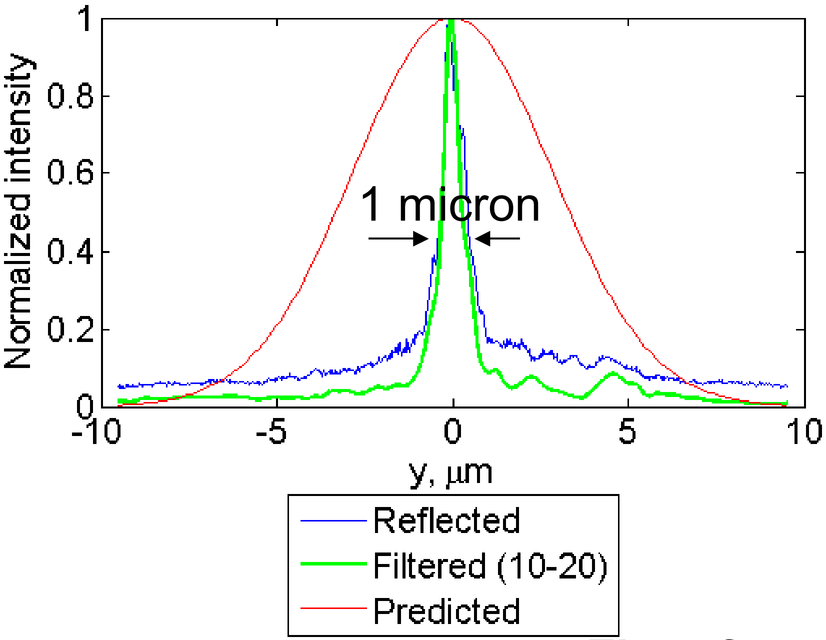


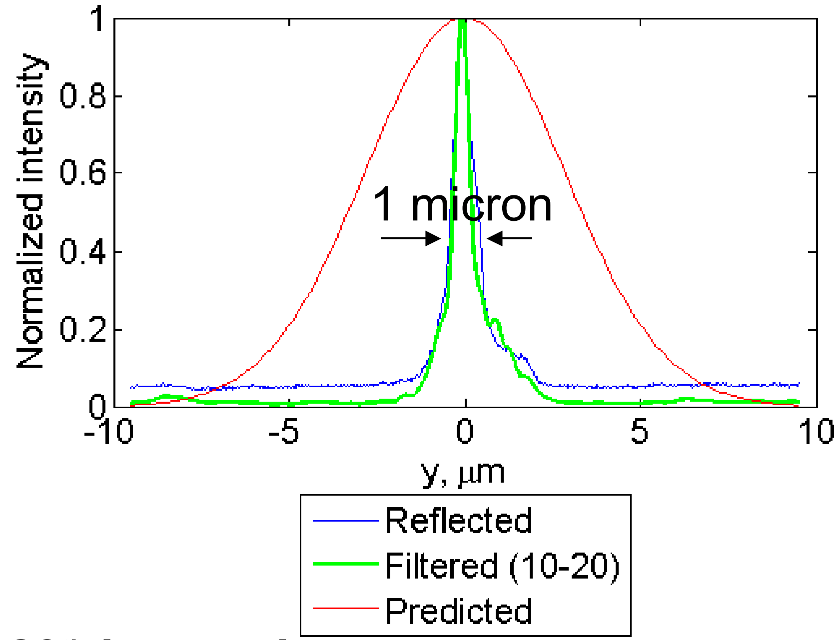
Clean surface

Rough surface 1



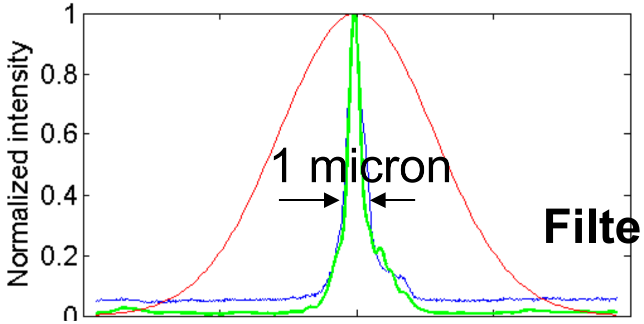
Beam waist 50 microns away
from the target

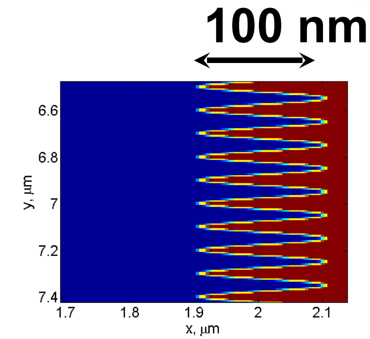




Filter from 10th to 20th harmonic

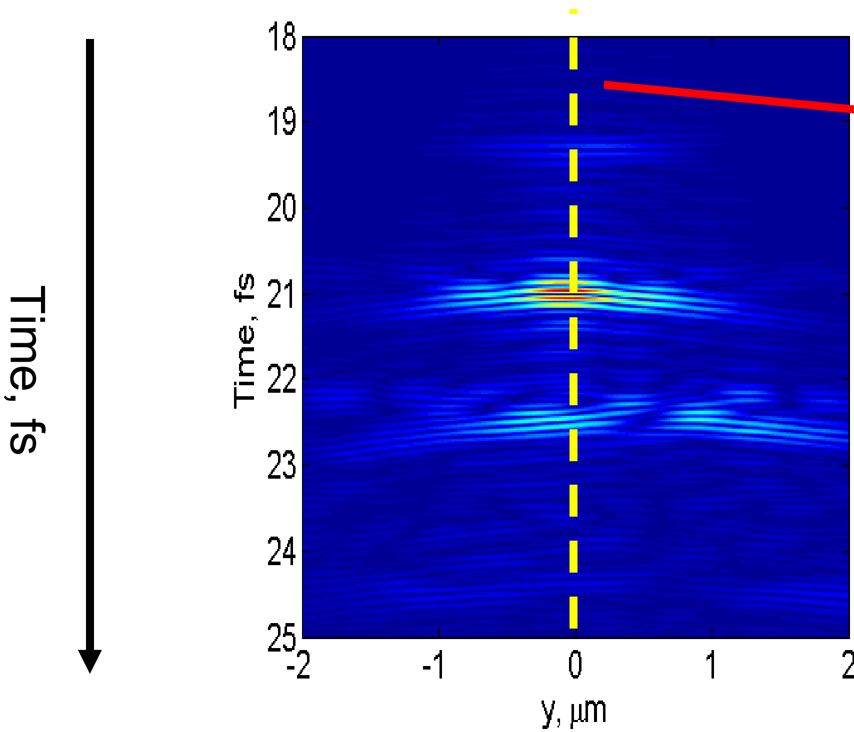
Surface roughness 100 nm

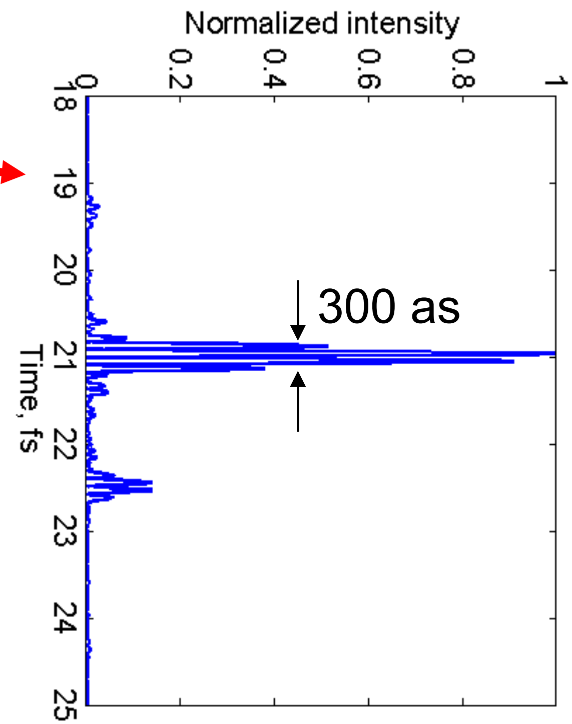




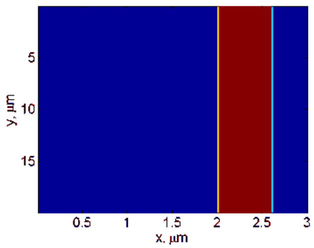
Rough surface 1

Filter from 10th to 20th harmonic



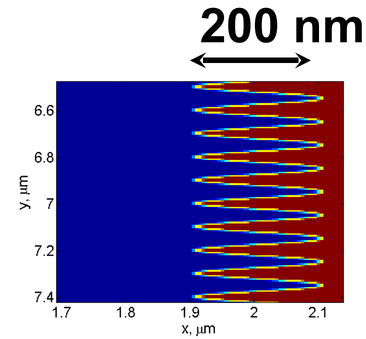


Surface roughness 200 nm

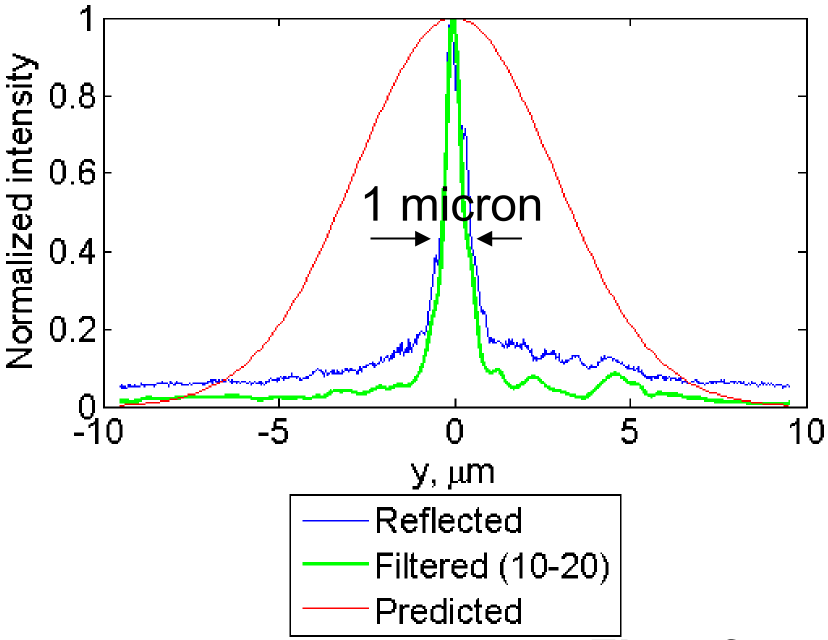


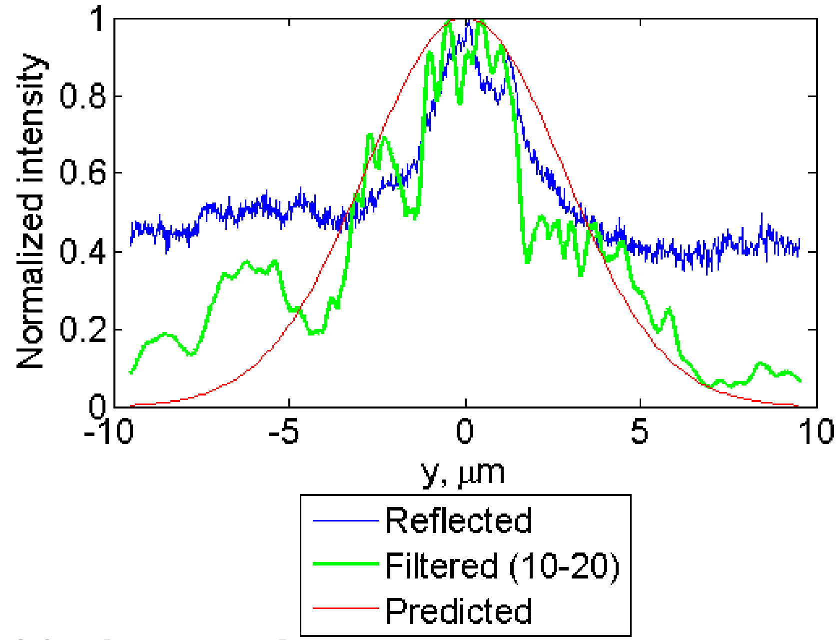
Clean surface

Rough surface 2



Beam waist 50 microns away
from the target

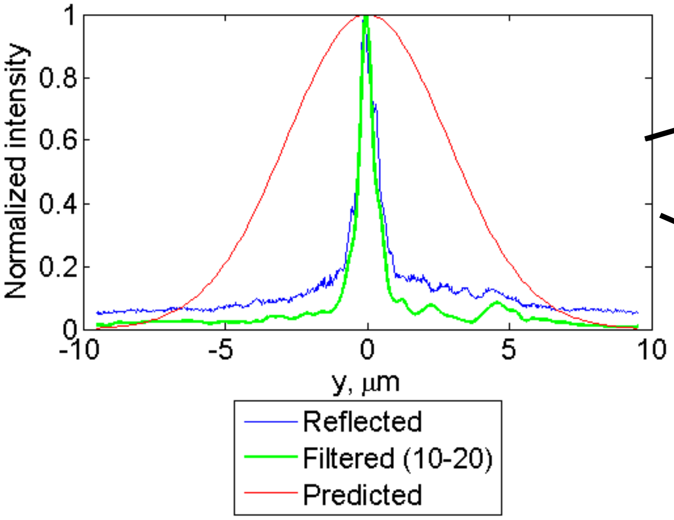




Filter from 10th to 20th harmonic

LAP Meeting, 28 July 2008

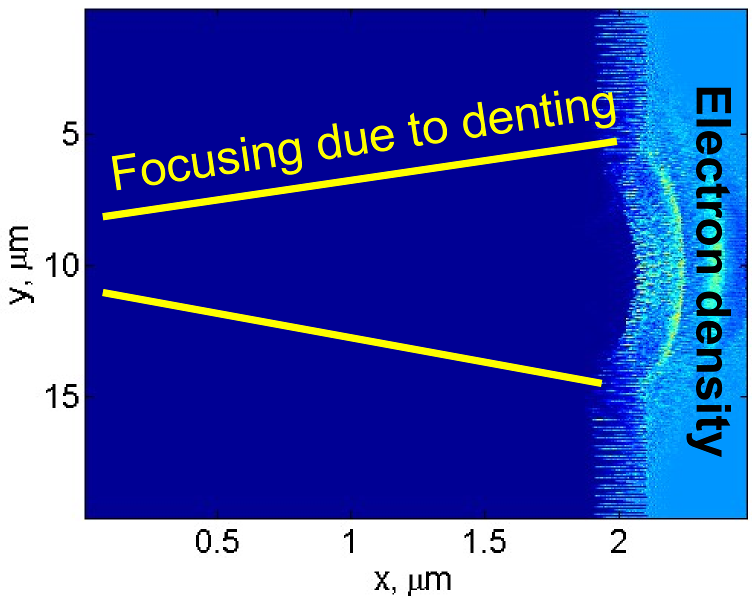
Two interesting facts



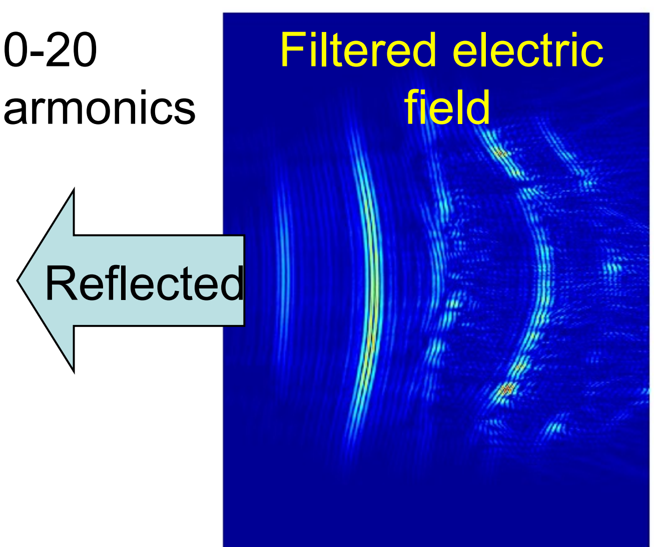
1) The beam waist of the reflected beam is much less than predicted by the gaussian optics

2) Surface roughness on the order of the filtered harmonics wavelength doesn't change the divergence and time structure !!!

Two interesting facts



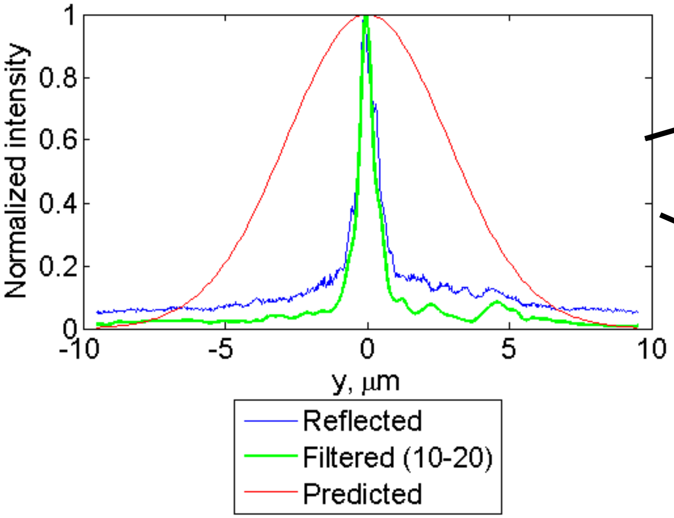
10-20 harmonics



1) The beam waist of the reflected beam is much less than predicted by the gaussian optics

1) Surface roughness on the order of the filtered harmonics wavelength doesn’t change the divergence and time structure !!!

Two interesting facts



1) The beam waist of the reflected beam is much less than predicted by the gaussian optics

1) Surface roughness on the order of the filtered harmonics wavelength doesn't change the divergence and time structure !!!

Relativistic surface smoothing

Relativistic surface smoothing

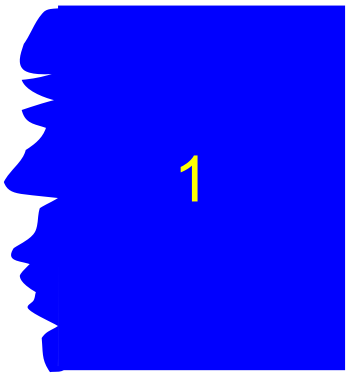
Electron excursions are on the order of 200 nm in both directions

Relativistic surface smoothing

Surface structure

Δr<<λ

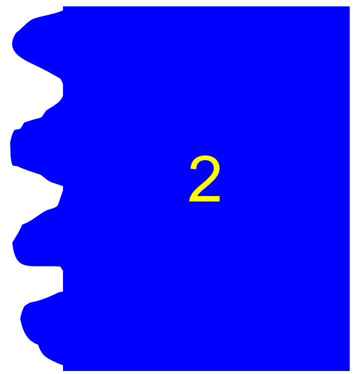
Surface roughness



Relativistic surface smoothing predicts the same divergence in the case when the roughness amplitude is less then surface oscillatory motion

Δr~λ

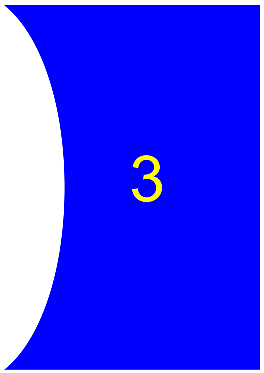
Scattering, gratings



Surface roughness > electron amplitudes, efficient scattering of harmonics

Δr>>λ

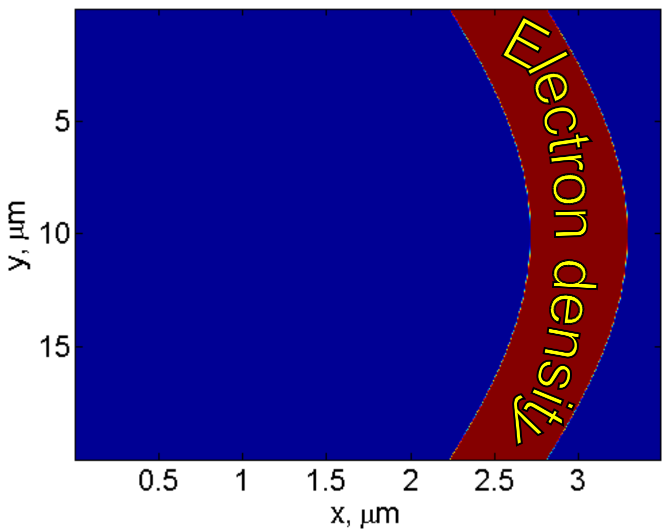
Focusing optics,
Ponderomotive denting

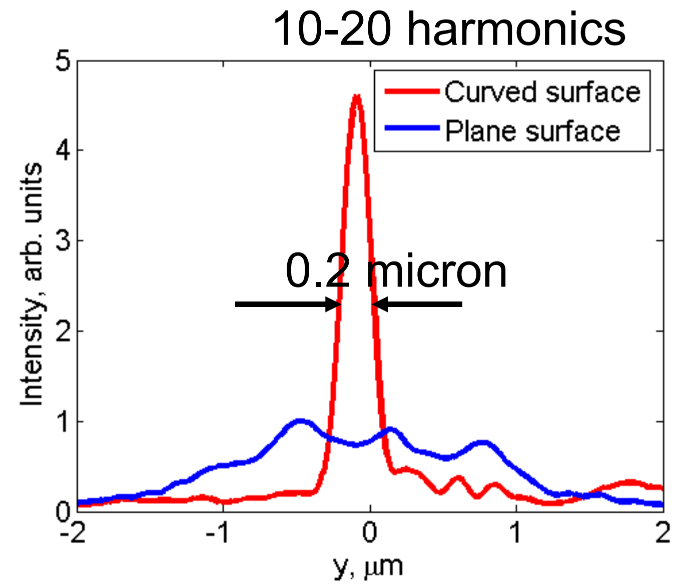


Denting produces uncontrolled focusing.

Controlled focusing?

Harmonics focusing





Initial energy = 50 mJ

Energy percent in 10-20 harmonics range = 0.5%

Spot size = 200 nm

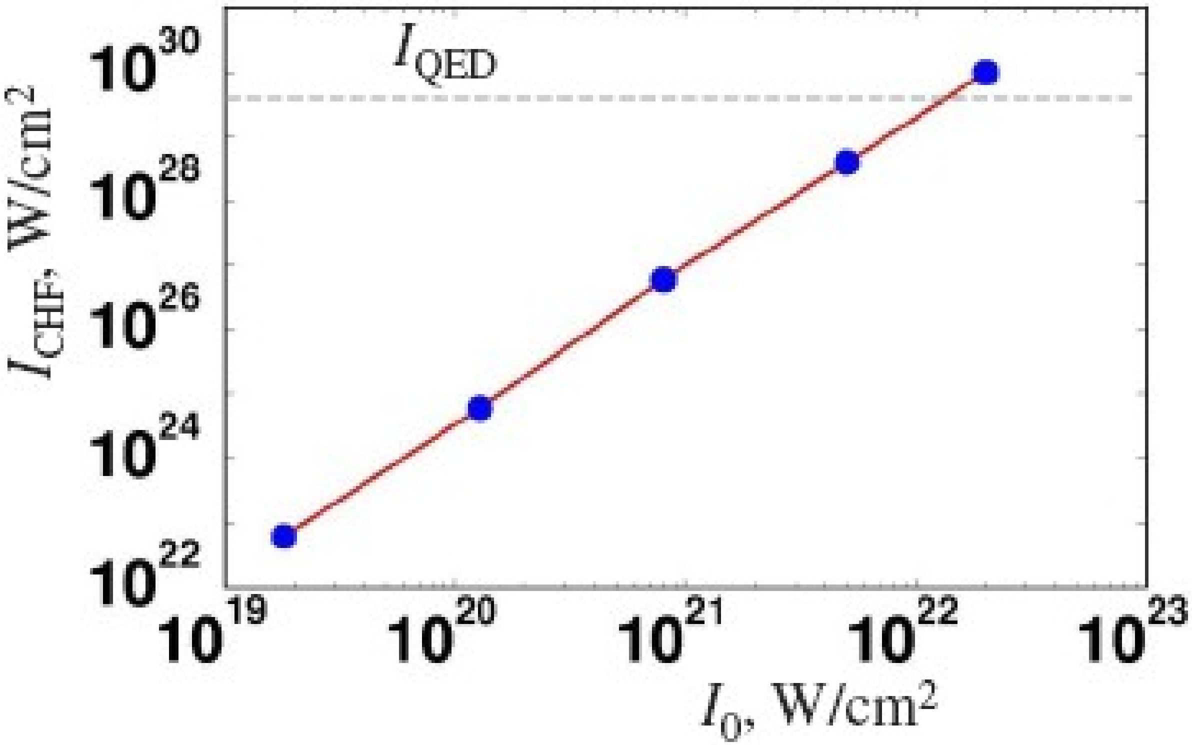
Duration = 300 as

E=0.25 mJ
$I=2 \cdot 10^{21} W/cm^2$

<u>Ideal performance</u>:
Spot size = 0.075 micron
Duration = 100 as
E=0.25 mJ
$I \sim 5 \cdot 10^{22} W/cm^2$

Harmonics focusing

S. Gordienko, et al, PRL, 94, 103903 (2005)
"Coherent Focusing of High Harmonics"



Theoretically it is possible to reach Schwinger limit with laser pulses with intensity ~ 10^{23} W/cm^2

Factors limiting the performance

Problem:

- Surface roughness
- Denting
- Nonlinearity of the process
- Plasma scaling length

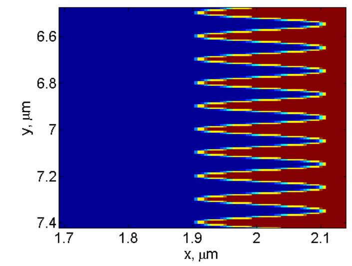
Notes and solution:

Factors limiting the performance

Problem:

- Surface roughness
- Denting
- Nonlinearity of the process
- Plasma scaling length

Notes and solution:



Scattering if Δr>100 nm

In experiments Δr=164 nm exhibits no harmonics signal

Relativistic smoothing for Δr<<100nm

Solution:

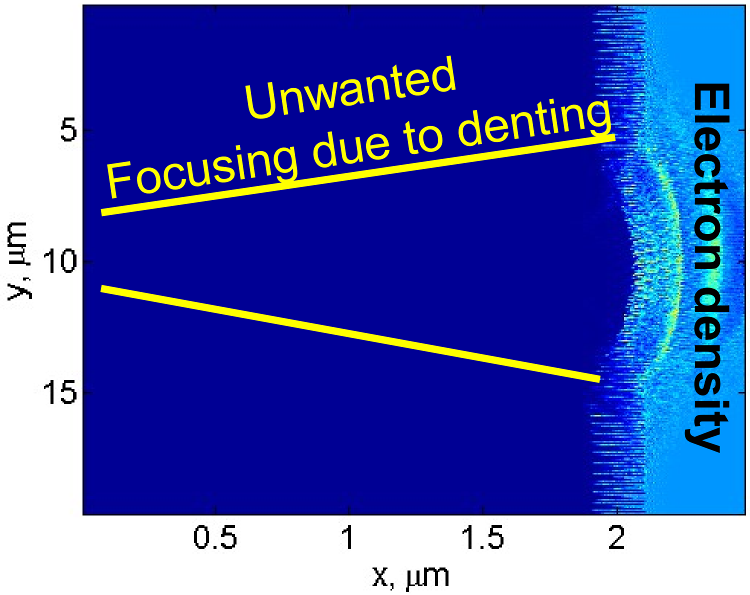
Use “clean” surfaces

Factors limiting the performance

Problem:

- Surface roughness
- Denting
- Nonlinearity of the process
- Plasma scaling length

Notes and solution:



Solution:

Use bigger laser spot sizes

Use supergaussian pulses

Factors limiting the performance

Problem:

- Surface roughness
- Denting
- Nonlinearity of the process
- Plasma scaling length

Notes and solution:

Theory predicts $\omega_{cutoff} \sim \gamma_{max}^3$

γ_{max} – maximum gamma-factor of the surface (*Baeva et al, PRE, 2007*)

Thus the spectrum in the wings of the pulse differs from the spectrum in the peak of the pulse

Solution:

Use bigger laser spot sizes

Use supergaussian pulses

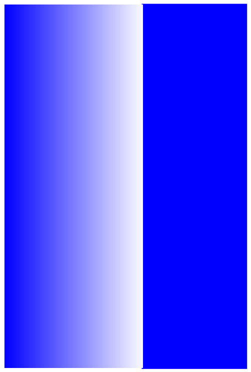
An der Bruegge, Pukhov, Phys. Plasmas, 2007

Factors limiting the performance

Problem:

- Surface roughness
- Denting
- Nonlinearity of the process
- Plasma scaling length

Notes and solution:



Divergence highly depends on the plasma scaling length due to strong surface distortion in the "soft" region

*M. Geissler, et al, **NJP,** 9 218 (2007)*

Solution:

Use plasma mirrors

Use clean pulses

Conclusion

Problem:

- Surface roughness
- Denting
- Nonlinearity of the process
- Plasma scaling length

Solutions:

- Clean target surface
- Curved surface to control harmonics focusing
- Clean laser pulse (plasma mirror)
- Big laser spot or supergaussian intensity distribution
- Short laser pulses to ensure single attosecond pulses and to be on the time scale where surface instabilities are not present

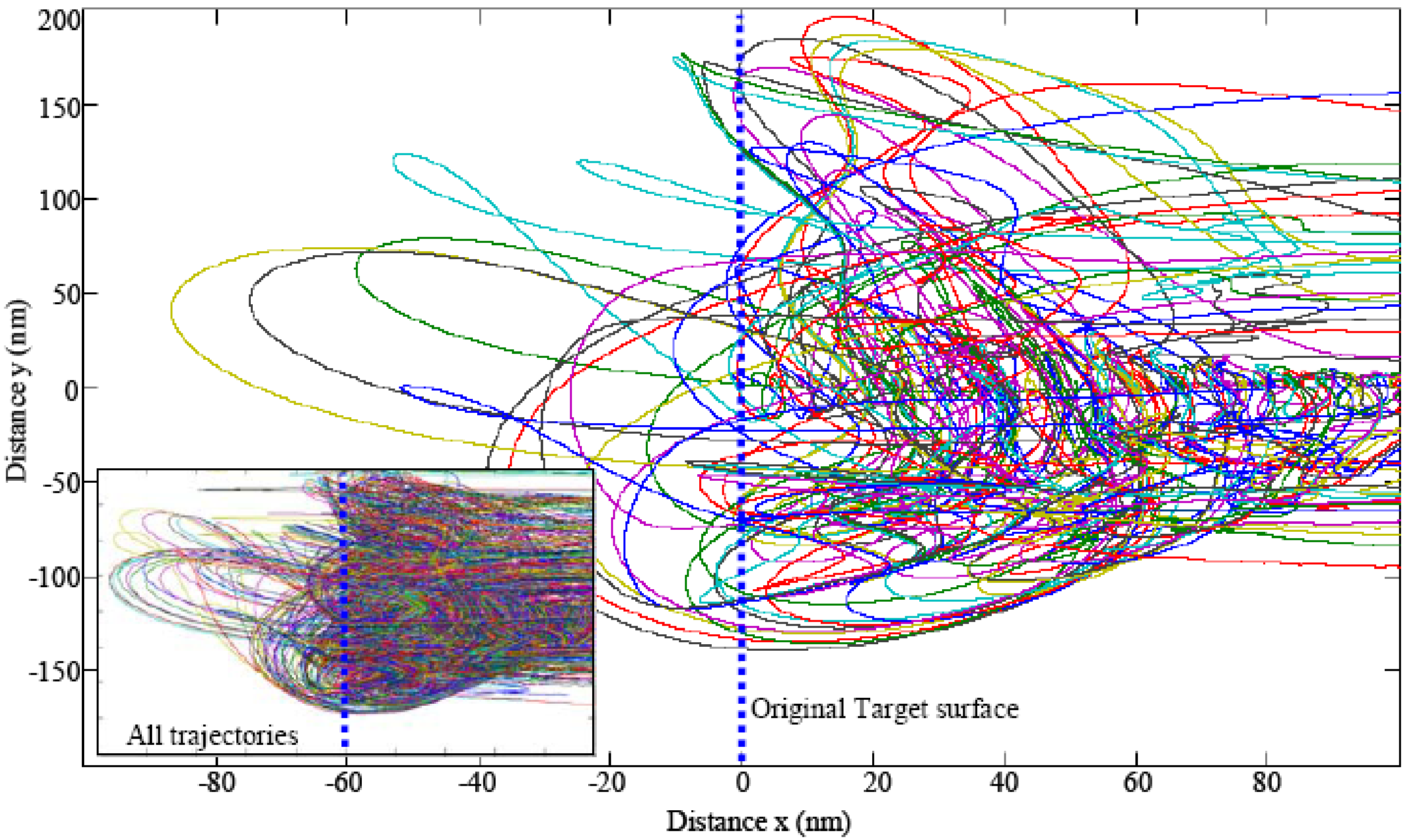
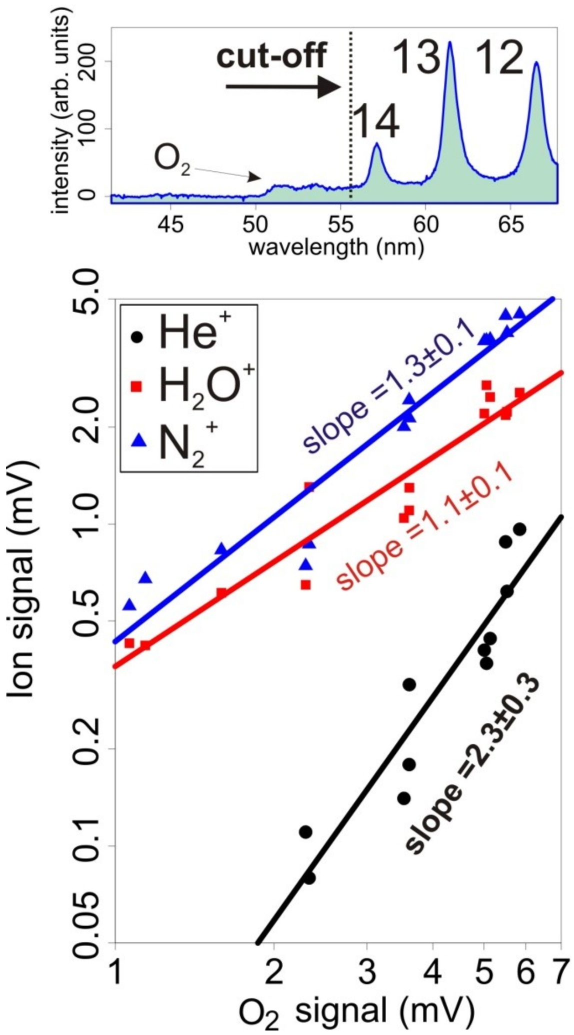


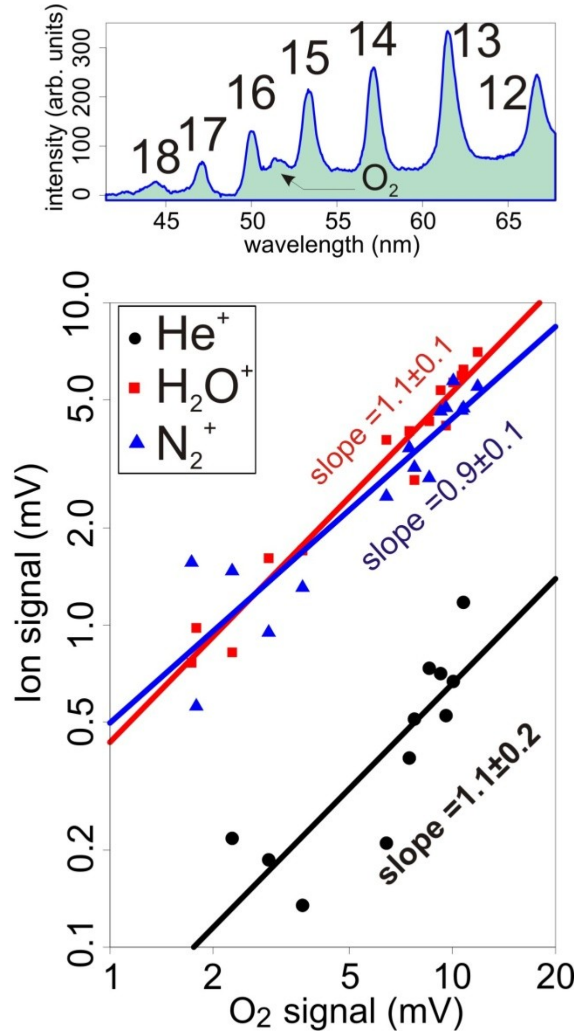
Figure 4. The typical spatial extent of electron trajectories with respect to the original target surface, as obtained from PIC simulation, for Astra laser parameters - oblique incidence(30°) and a0=3. Other simulation parameters were chosen to reduce complexity, such as a two cycle pulse, but the principle remains the same. The inset shows all of the trajectories included in the simulation while the main figure shows every 20th trajectory plotted for clarity. It is clear that electrons traverse paths in both the transverse (y) and longitudinal (x) direction with respect to the driving laser that are far greater than the surface roughness that could affect harmonics generated in the Astra experiment.

Two-photon ionization of Helium

Low density target



High density target



Y. Nomura *et al.*, Nature Phys. 5, 124 (2009)