THz makes X-Ray

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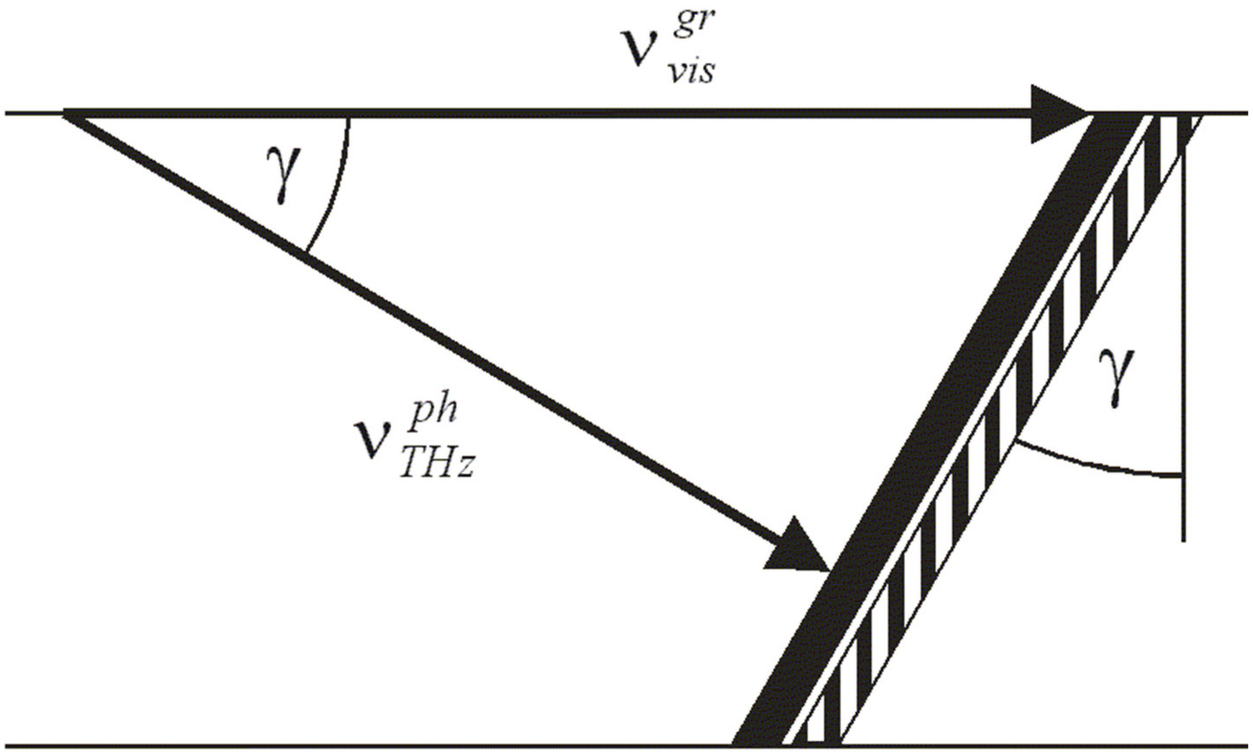
Motivation
Velocity matching by tilting of the pump-pulse-front

J. Hebling et al: Optics Exp. **10**, 1161 (2002)

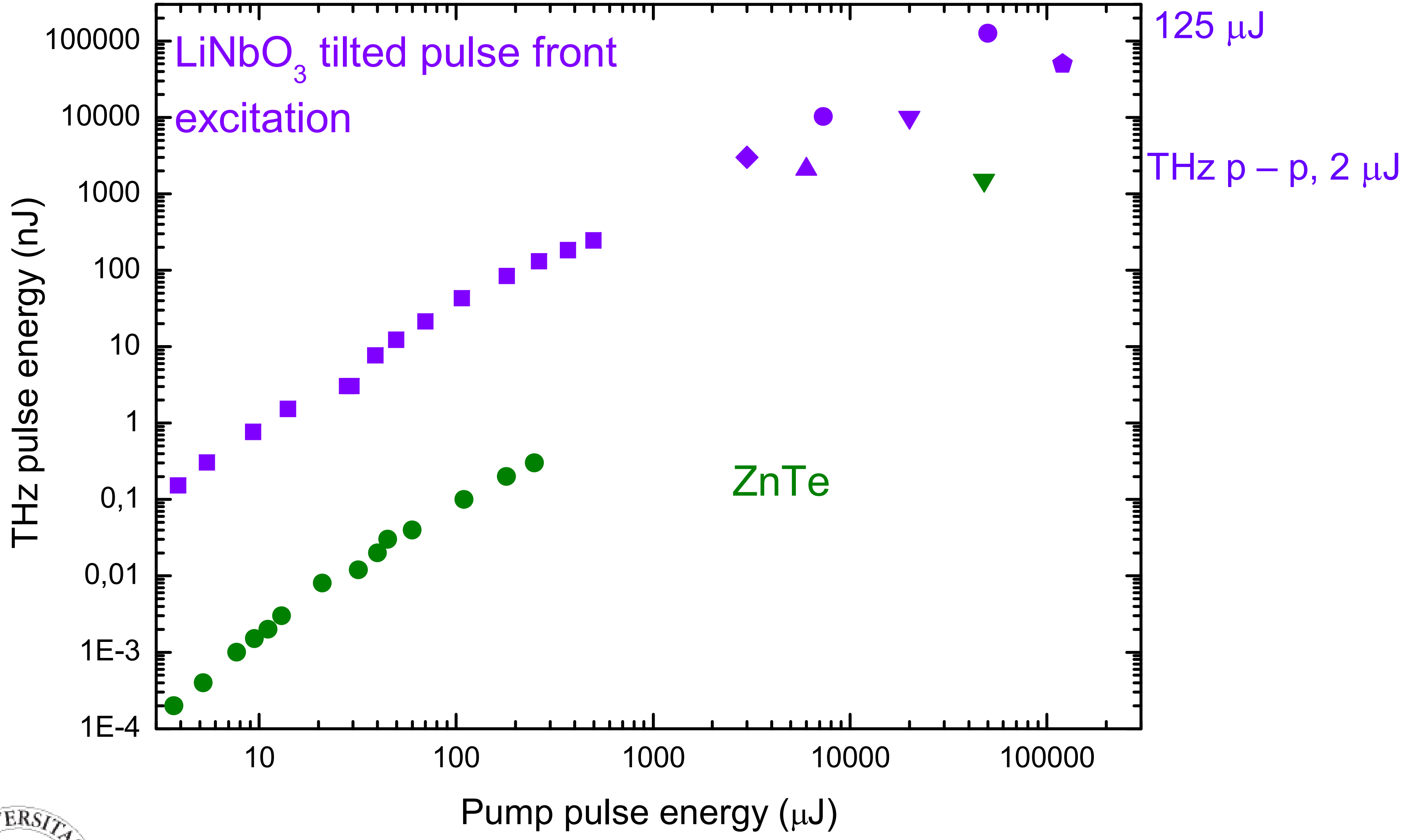


THz radiation excited along the tilted pulse front propagates perpendicularly to this front → velocity matching condition:

$$v_{vis}^{gr} \cdot \cos\gamma = v_{THz}^{ph}$$

Motivation

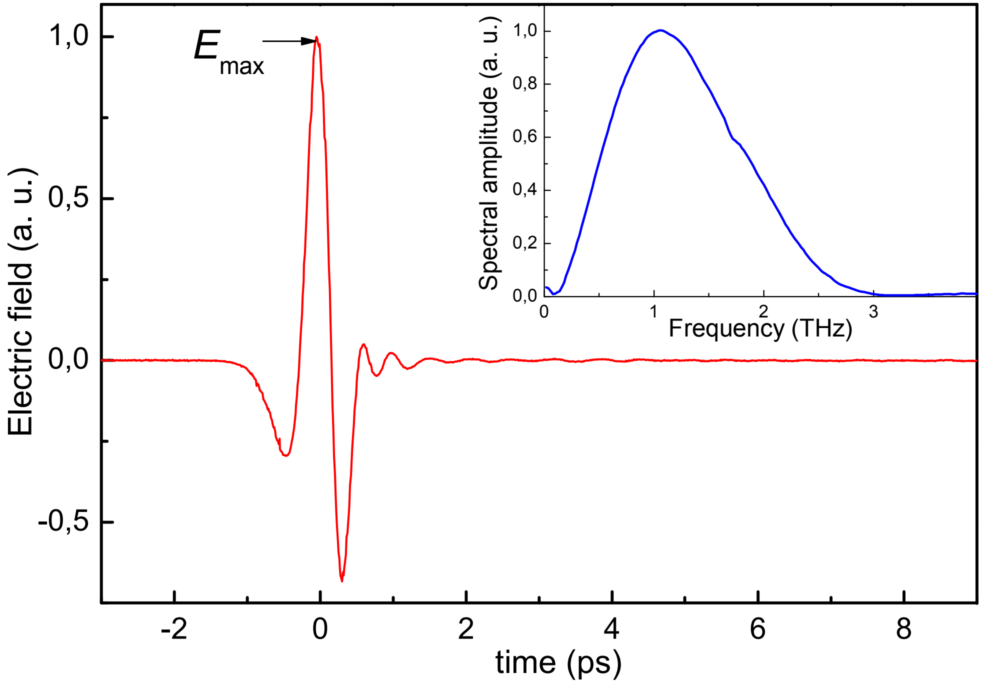
Comparison of THz pulse generation by ZnTe and by LN



Field strength of focused pulses: 0.2 – 1.2 MV/cm

Motivation

Classification of THz pulses by peak electric field (energy)



- Linear (TDTS) THz spectroscopy (E_{max} ≈ 100 V/cm → 10 fJ energia)
- High field THz pulses (E_{max} ≈ 100 kV/cm → μJ energia)

Applications of high energy THz pulses

- Nonlinear THz optics (self-phase-modulation, Kerr-effect)

- Nonlinear THz spectroscopy (THz pump - probe)

- Electron wave packet sampling (streaking)

Frühling: Nature Photonics **3**, 523 (2009)

Schütte et al.: Opt. Express **19**, 18833 (2011)

- Alignment/orientation of molecules

Stapelfeldt, Seideman: Rev. Mod. Phys. **75**, 543 (2003)

Fleischer et al.: Phys. Rev. Lett. **107**, 163603 (2011)

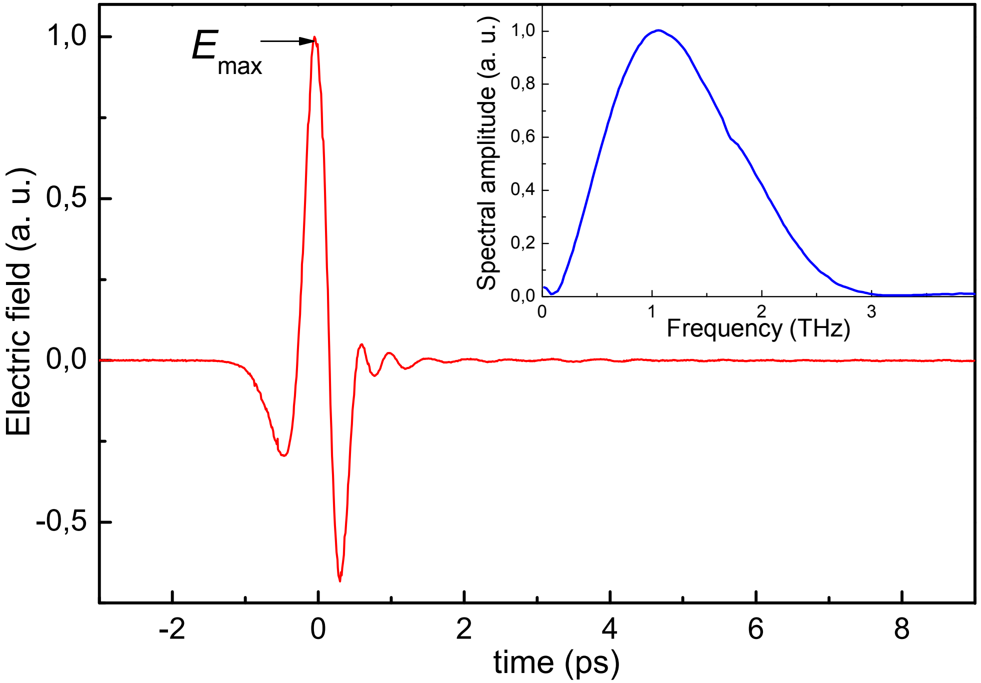
Kitano et al.: PRA **84**, 053408 (2011)

- „Single-shot” THz imaging

- „Single-shot” THz multi spectral imaging

Motivation

Classification of THz pulses by peak electric field (energy)



- Linear (TDTS) THz spectroscopy (E_{max} ≈ 100 V/cm → 10 fJ energia)
- High field THz pulses (E_{max} ≈ 100 kV/cm → μJ energia)
- Extreme high field THz pulses
  (E_{max} ≈ 100 MV/cm → 10 mJ pulse energy)

Tomorrow: Alan Fischer: 500 μJ, József Fülöp: 125 μJ

Application possibilities of THz pulses having extreme high electric field strength

- Increasing the cut-off frequency of HHG (E_{THz} = 20 ÷ 80 MV/cm)
- Quasi-phase-matched attosecond pulse generation (E_{THz} = 2 ÷ 6 MV/cm)
- Temporal compression of electron bunches by THz pulses
- Single-cycle (or shaped) pulse generation on the 50 nm – 400 nm wavelength range by coherent Thomson-scattering
- Ultrashort X-ray pulse generation by incoherent Thomson-scattering
- THz driven undulator for UV – X-ray generation

Increasing the cut-off frequency of HHG

HHG in the presence of THz electric field

- **Combined THz + IR** fields

$$E(t) = E_0 \cos(\omega_{IR} t) + E_1 \cos(\omega_{THz} t)$$

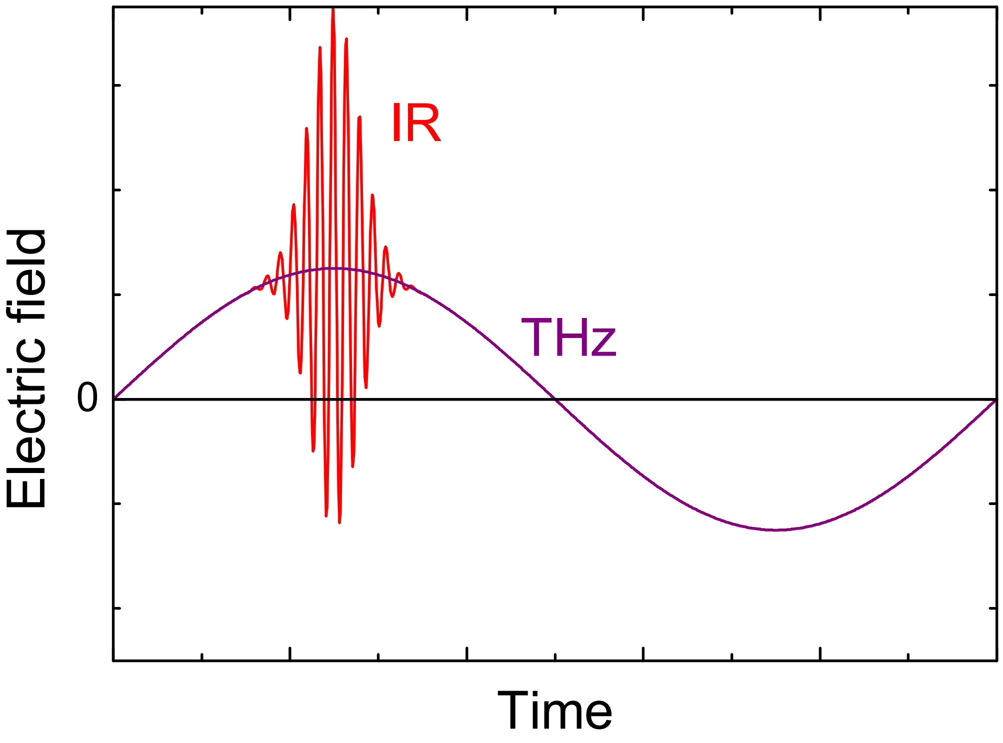
- **THz broken the symmetry of IR field**

  Hong et al., Opt. Expr. 2009

- **One as pulse per IR cycle**

- **Spectrum consists both odd and even harmonics**

  Lewenstein, PRA 1994



E. Balogh et al.: Phys. Rev. A (2011), University of Szeged

Increasing the cut-off frequency of HHG

1560 nm

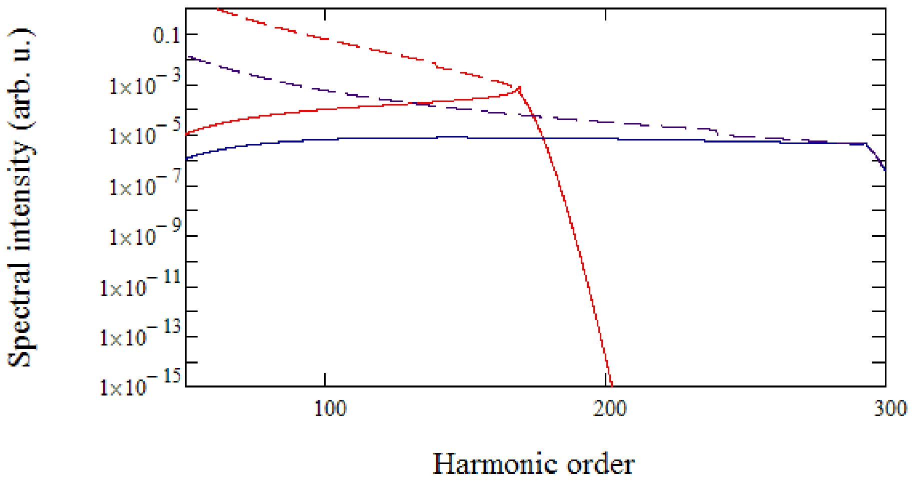
800 nm

Both odd and even harmonics →→ only one as pulse per IR period

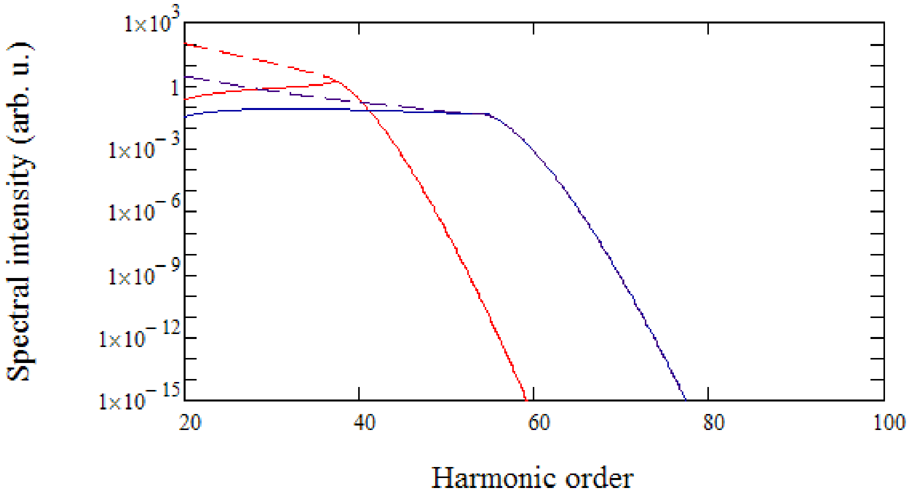
I_{IR} = 2 × 10^{14} W cm^{-2}

m(coffindex$_1$) = 37.92 E_{IR} = 388 MV/cm

E1 = 4 × 10^9 V/m



E0 = 3.881 × 10^{10} V/m E1 = 4 × 10^9 V/m

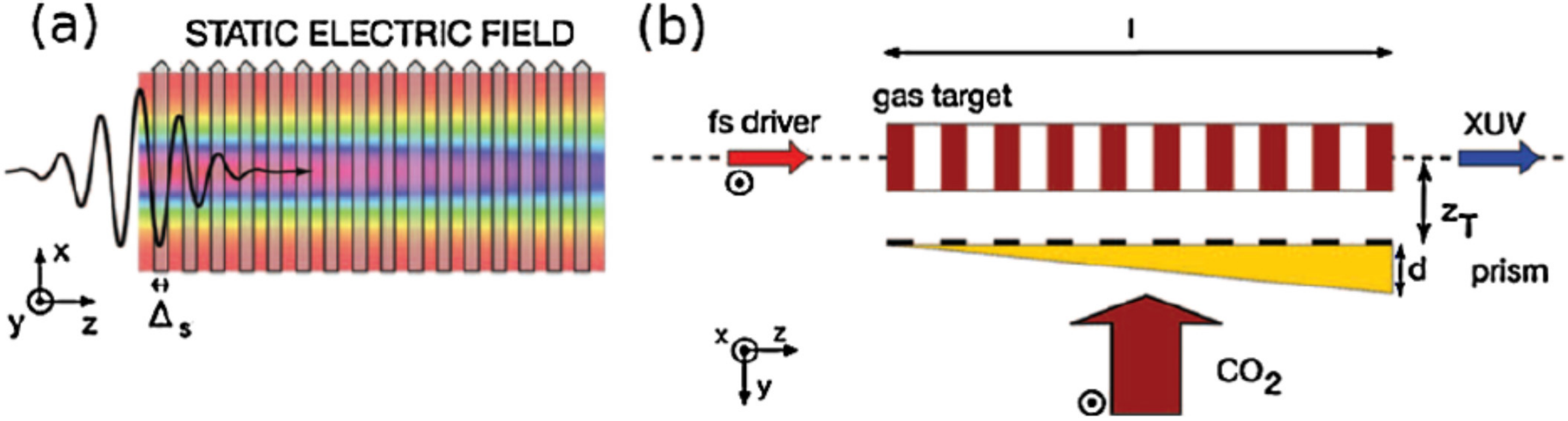


E_{THz} = 0 … 40 MV/cm

E. Balogh et al.: Phys. Rev. A (2011), University of Szeged

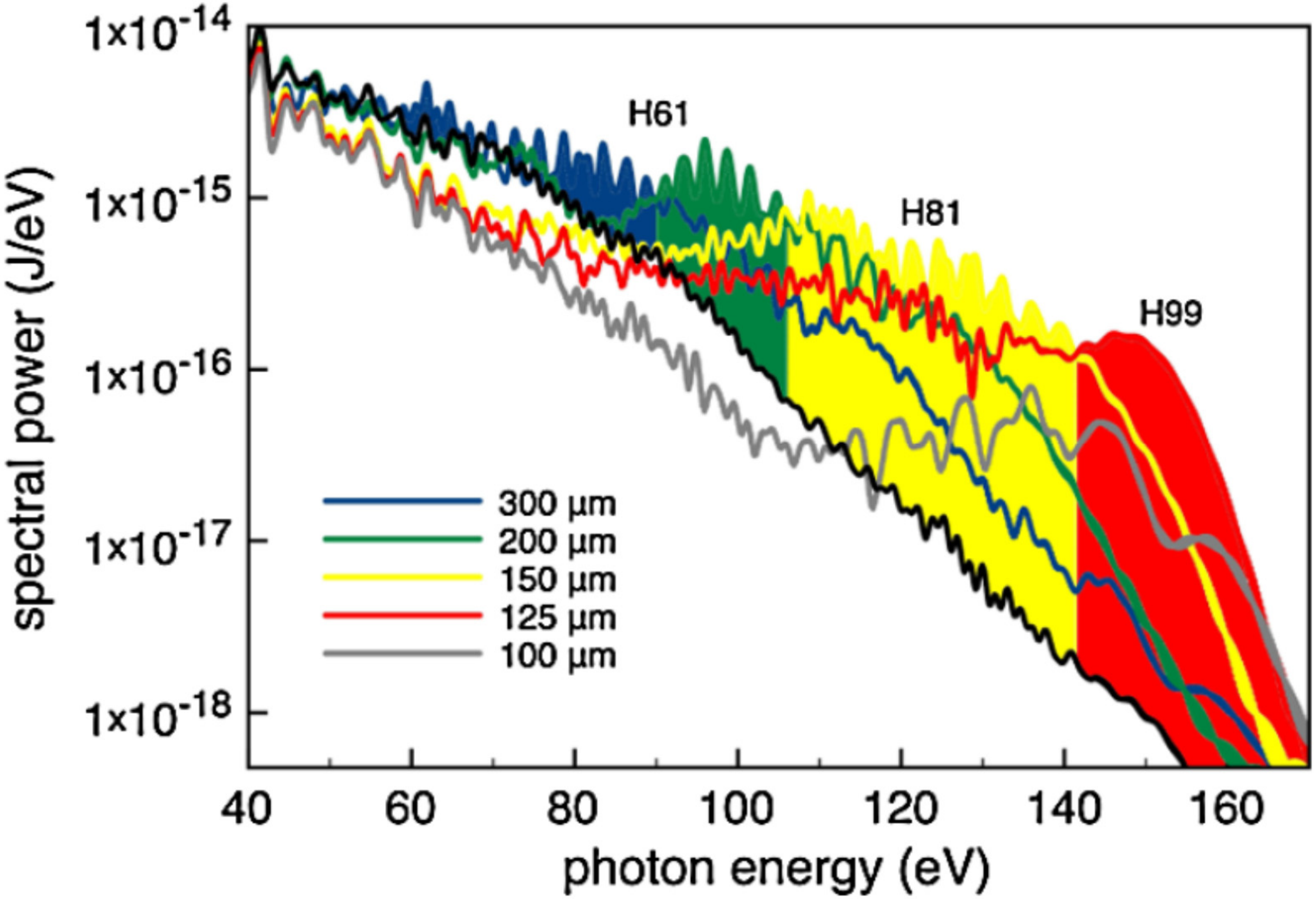
Quasi-phase-matched attosecond pulse generation

Spatially periodically modulated mid-IR (CO_2 laser)



C. Serrat, J. Biegert: Phys. Rev. Lett. **104**, 073901 (2010)

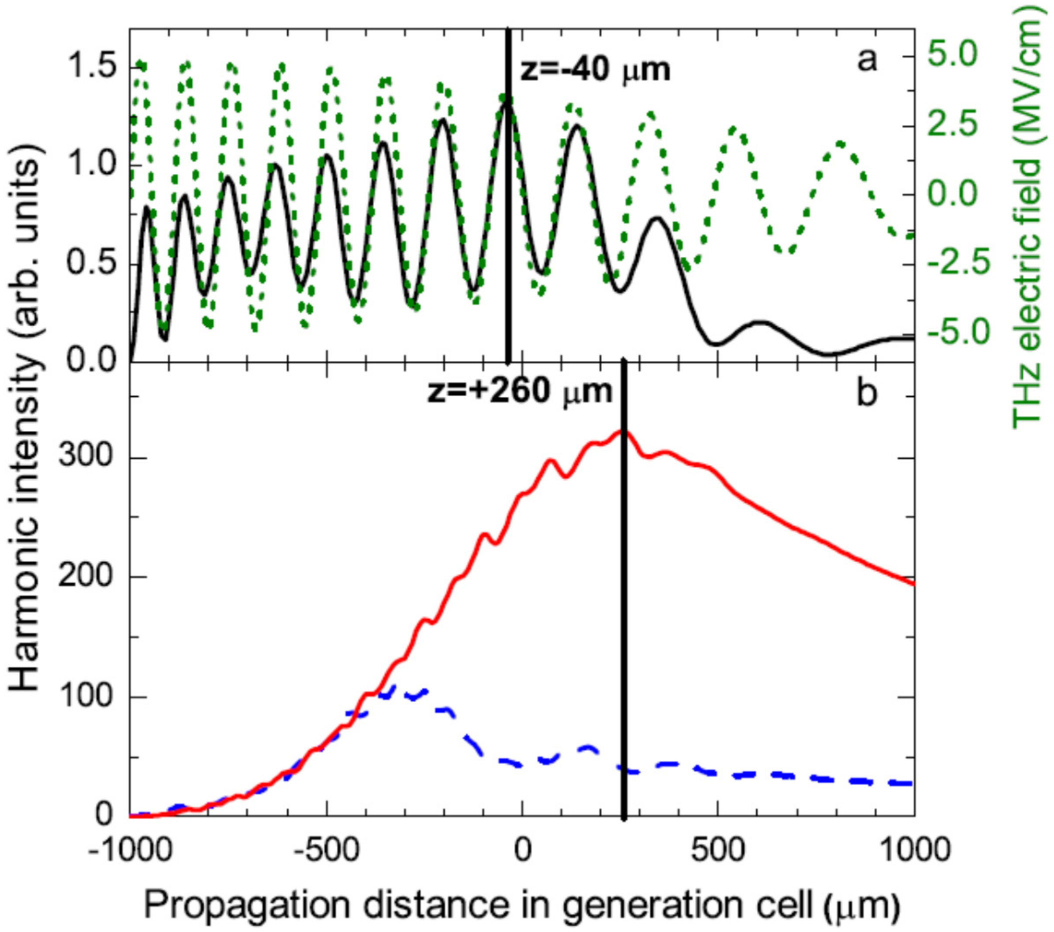
Quasi-phase-matched attosecond pulse generation



5 fs, 800 nm, Neon, 20 mbar, L=2mm

Quasi-phase-matched attosecond pulse generation

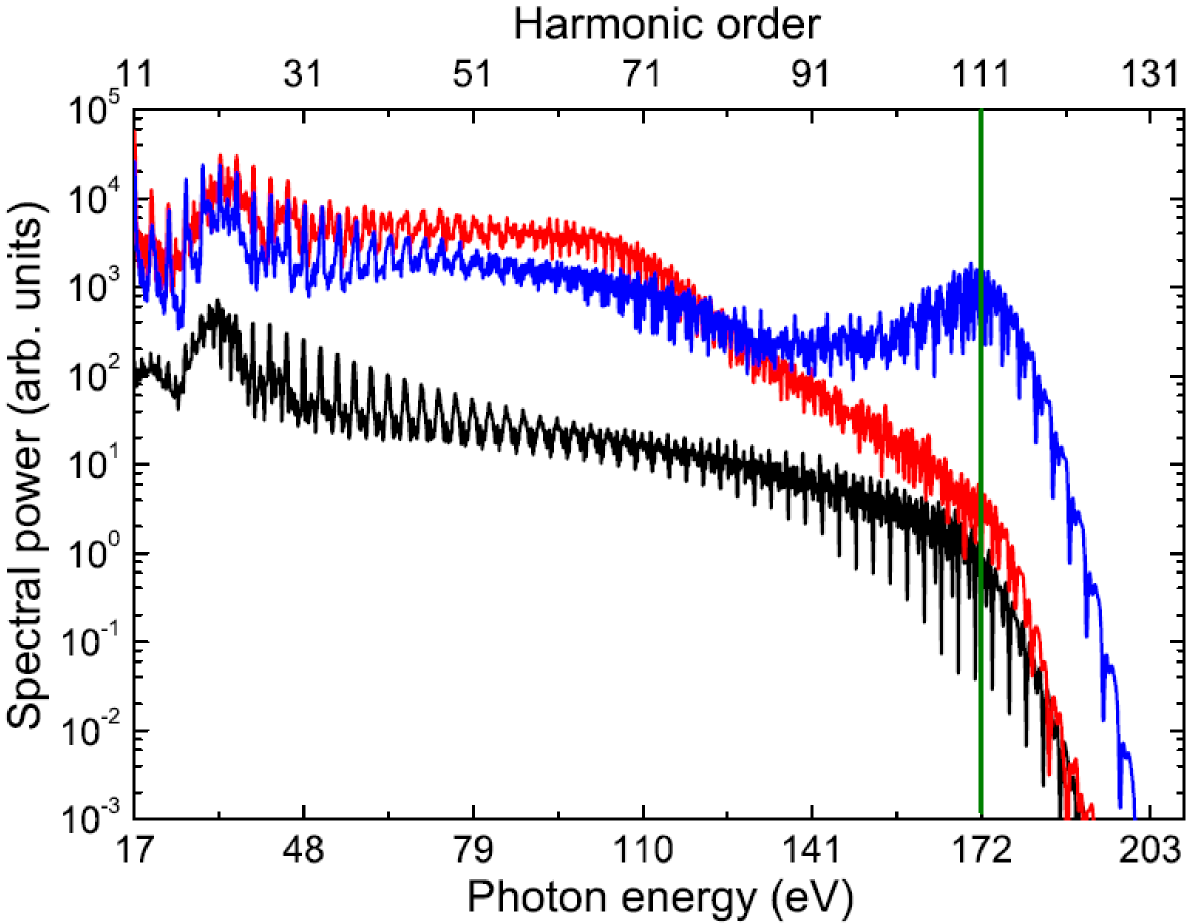
Spatial modulation by (chirped) THz pulse



K. Kovács et al.: Phys. Rev. Lett. **108**, 193903 (2012)

Quasi-phase-matched attosecond pulse generation

Spatial modulation by (chirped) THz pulse



250 times enhancement around the cut-off frequency

$E_{THz} = 2 \div 6$ MV/cm, $W_{THz} = 2 \div 20$ mJ

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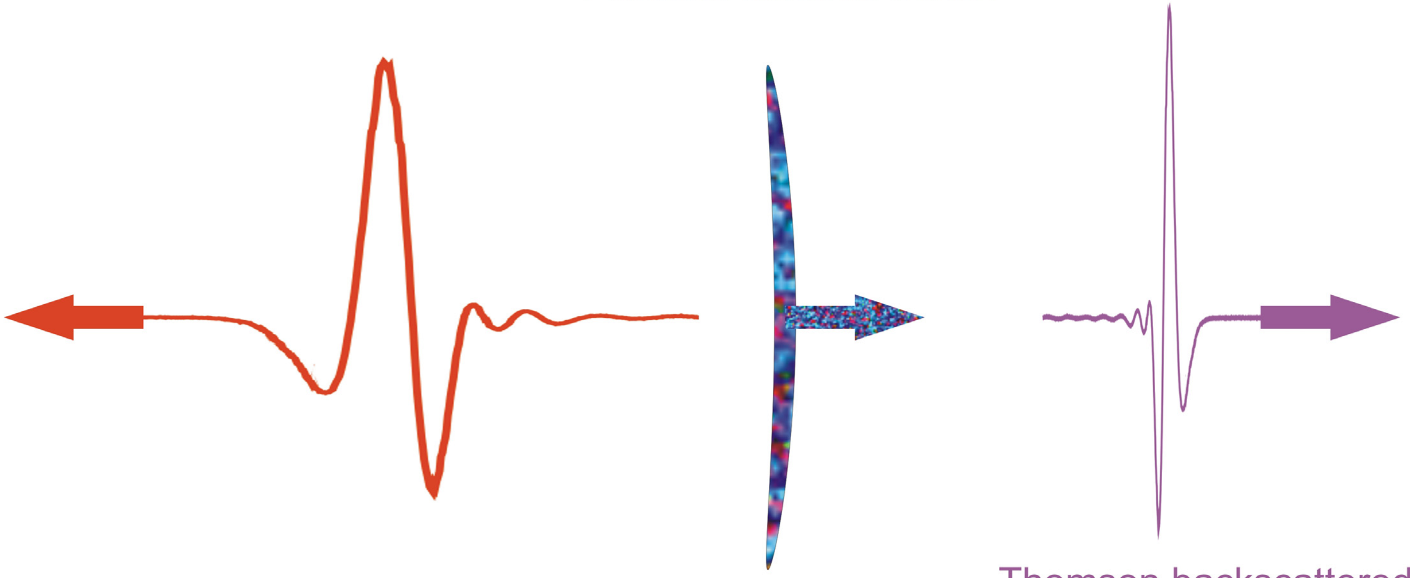
Single-cycle MIR – EUV pulse generation by „coherent” Thomson-scattering



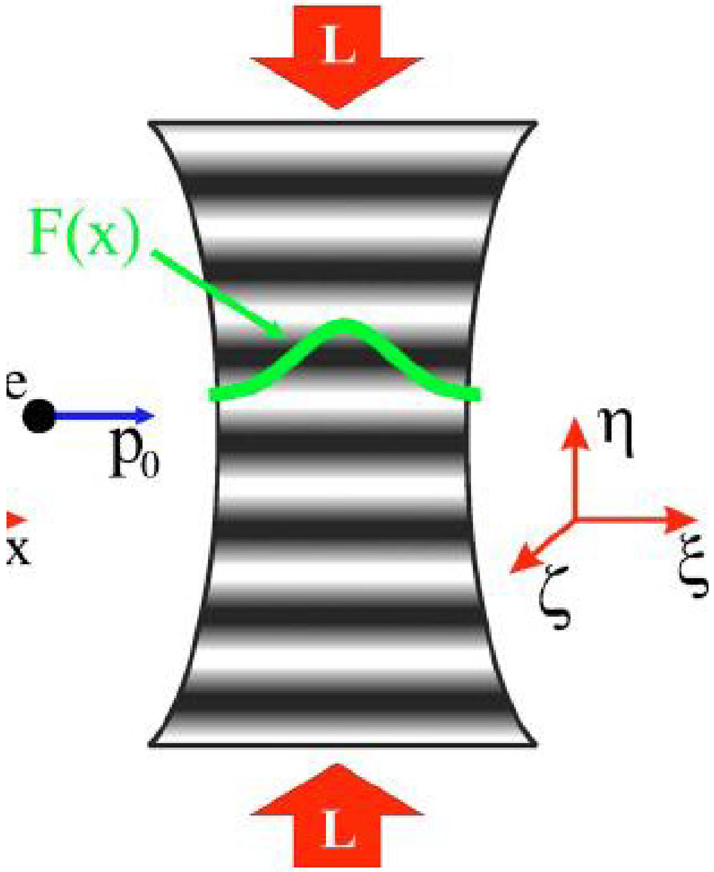
Focused electron bunch

THz pulse

Thomson backscattered coherent MIR - XUV radiation

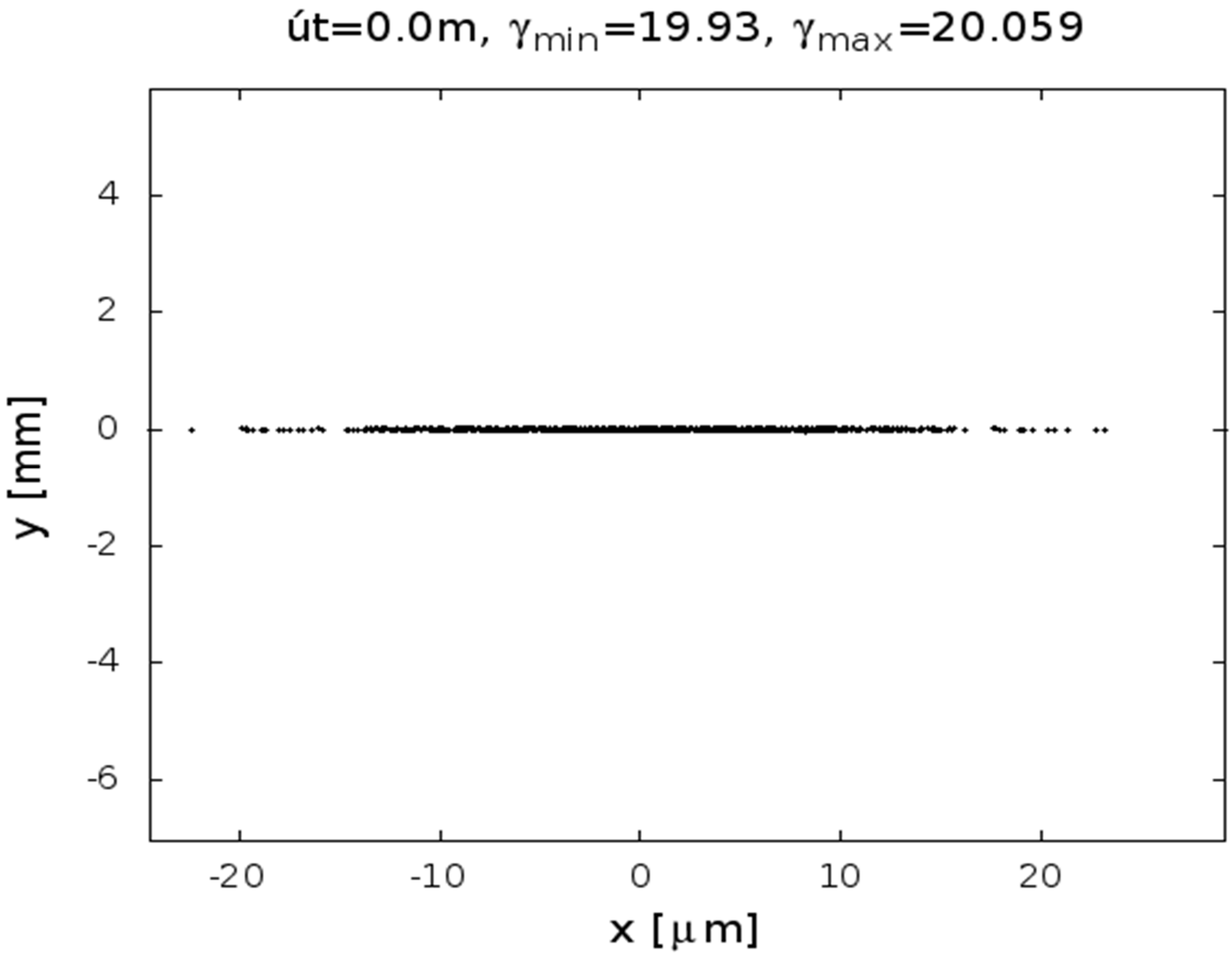
Single-cycle MIR – EUV pulse generation by „coherent" Thomson-scattering

Temporal compression of electron bunches



$\lambda = 1\ \mu\text{m}$, $\Delta t_f = 30$ zs

A. E. Kaplan, A. L. Pokrovsky: Optics Express **17**, 6194 (2009)


út=0.0m, γ_{min}=19.93, γ_{max}=20.059
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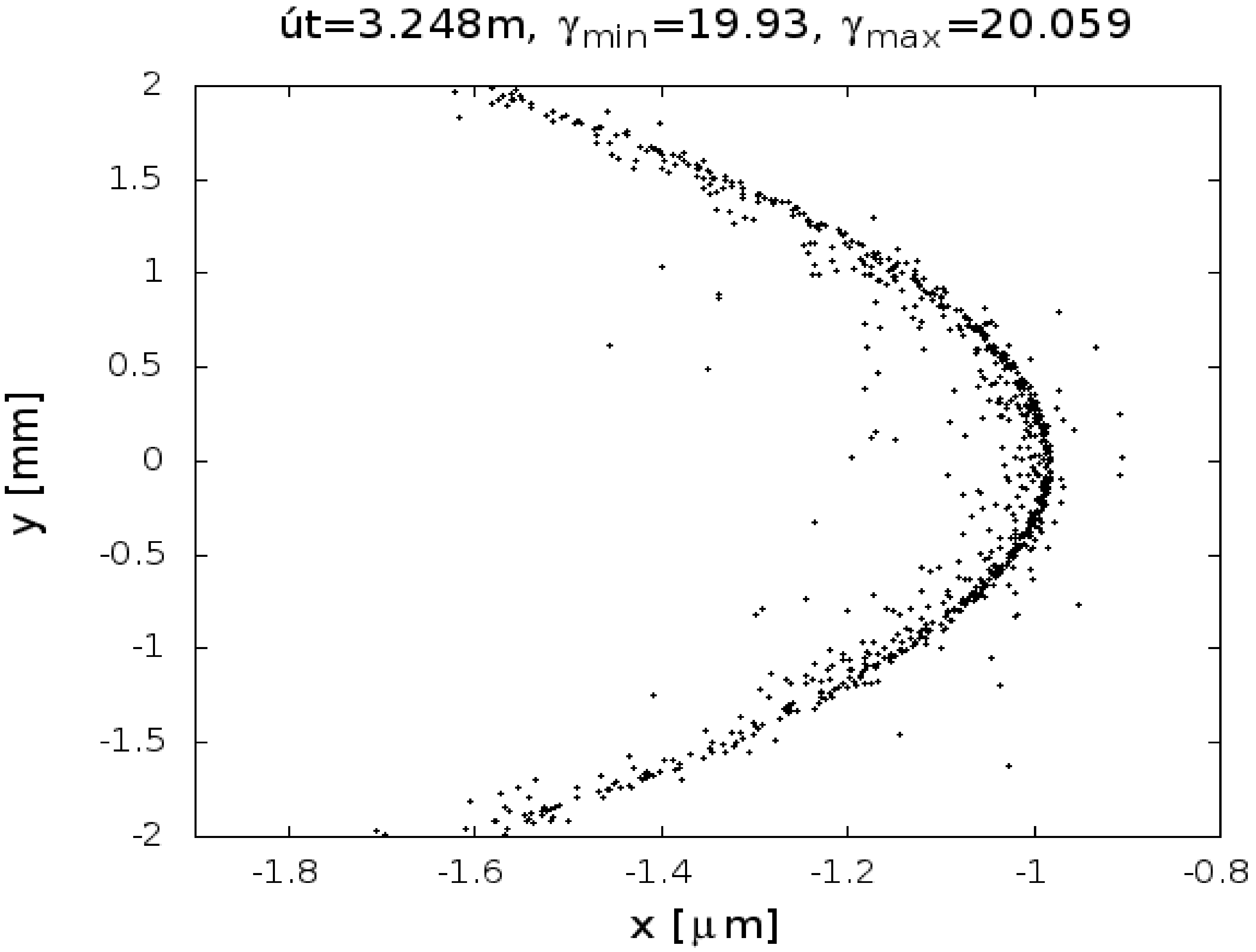
2
0
-2
-4
-6
y [mm]
-20
-10
0
10
20
x [μm]


út=3.248m, γ_{min}=19.93, γ_{max}=20.059
y [mm]
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1.5
1
0.5
0
-0.5
-1
-1.5
-2
-1.8
-1.6
-1.4
-1.2
-1
-0.8
x [μm]

Creation of ultrashort electron bunches by inverse-FEL

Simulation by GPT

parameters of e-bunch:

J. F. Yang: Jap. J. Appl. Phys. **44**, 12 (2005)

$\gamma = 62$, $\sigma_E/E = 0.04\ \%$,

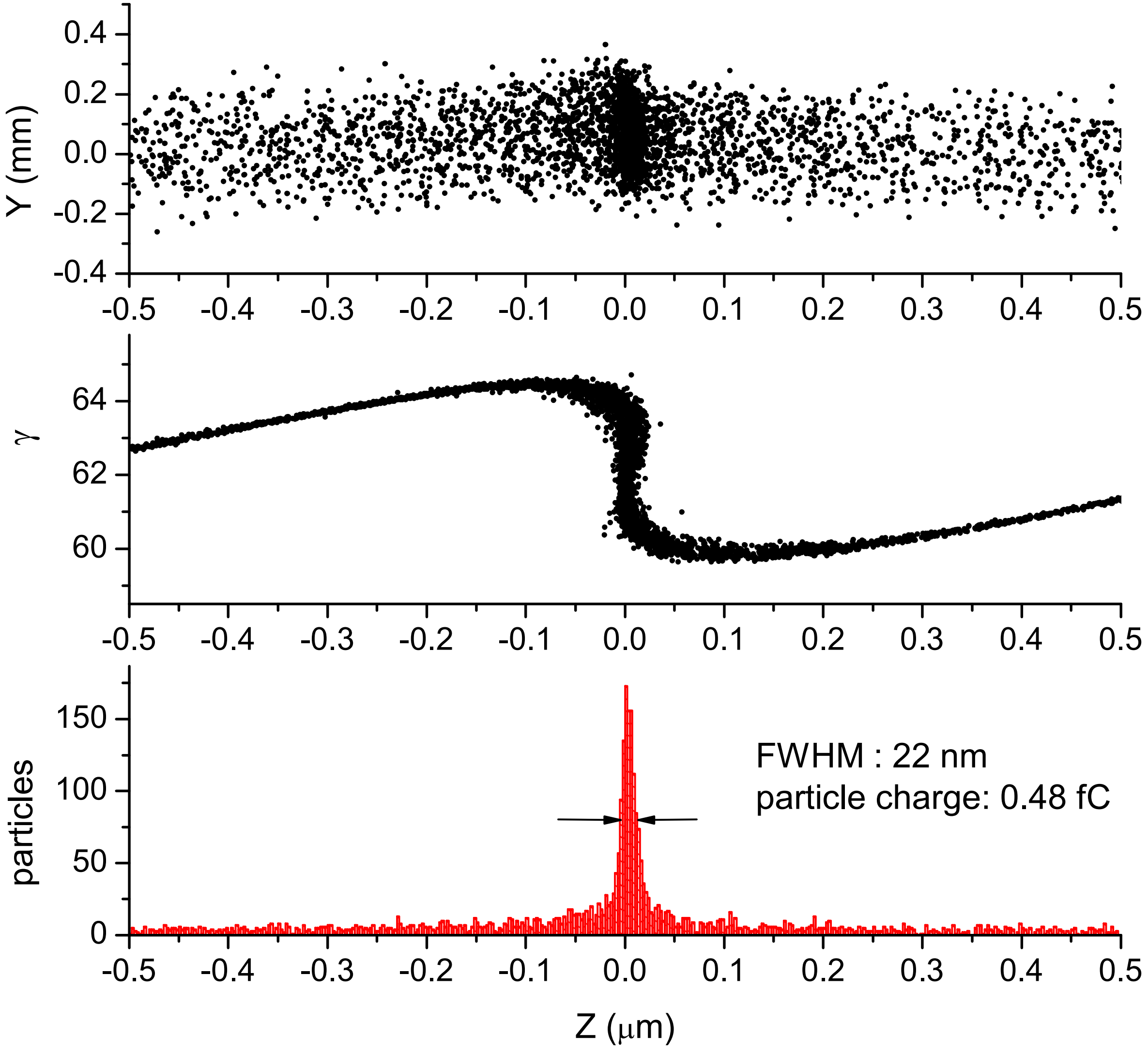
$Q_b = 1$ nC, $\Delta t_b = 1.8$ ps,

$\varepsilon_n = 3.2$ mm

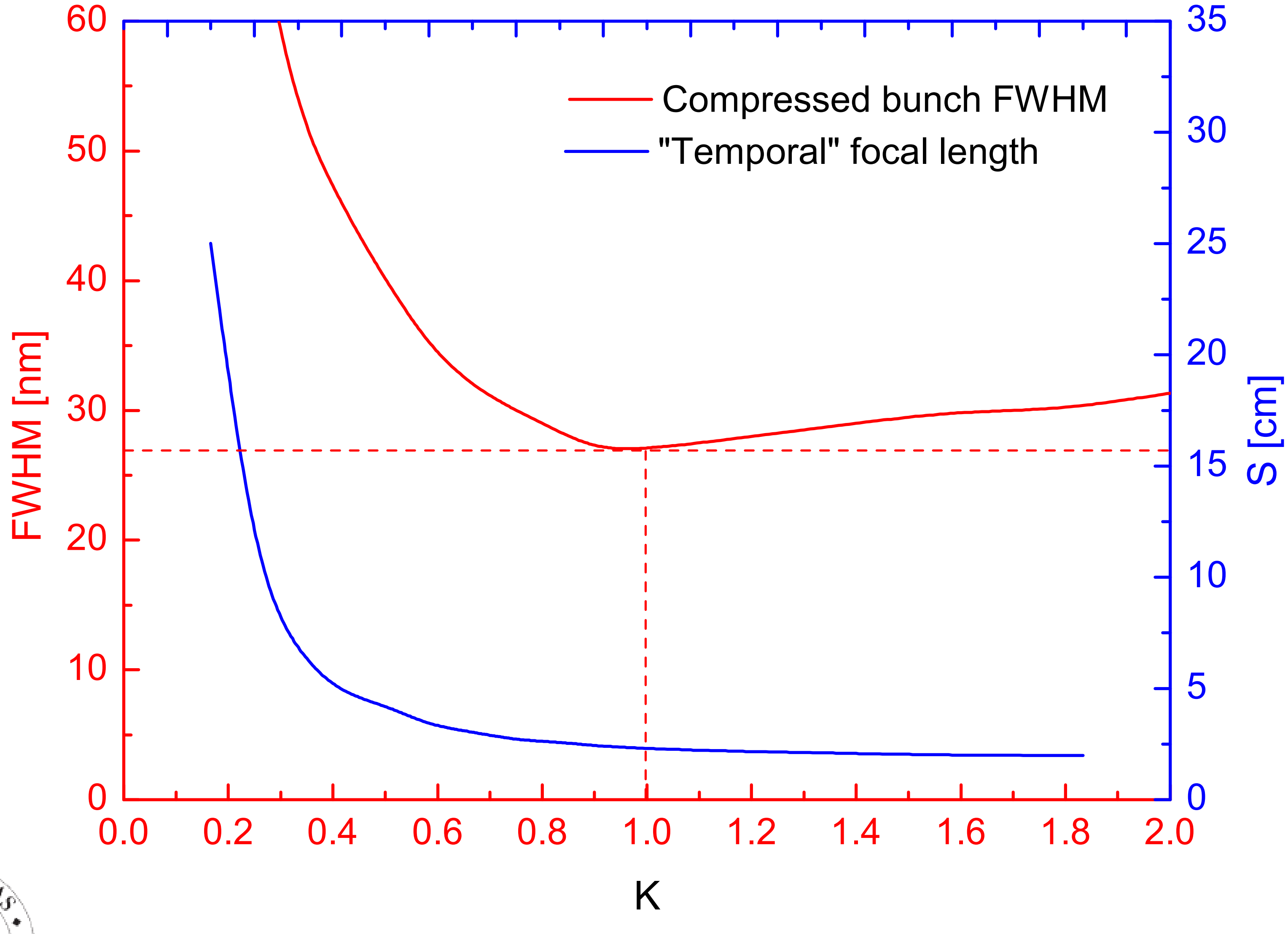
wiggler: one-period, $K = 1$

laser:

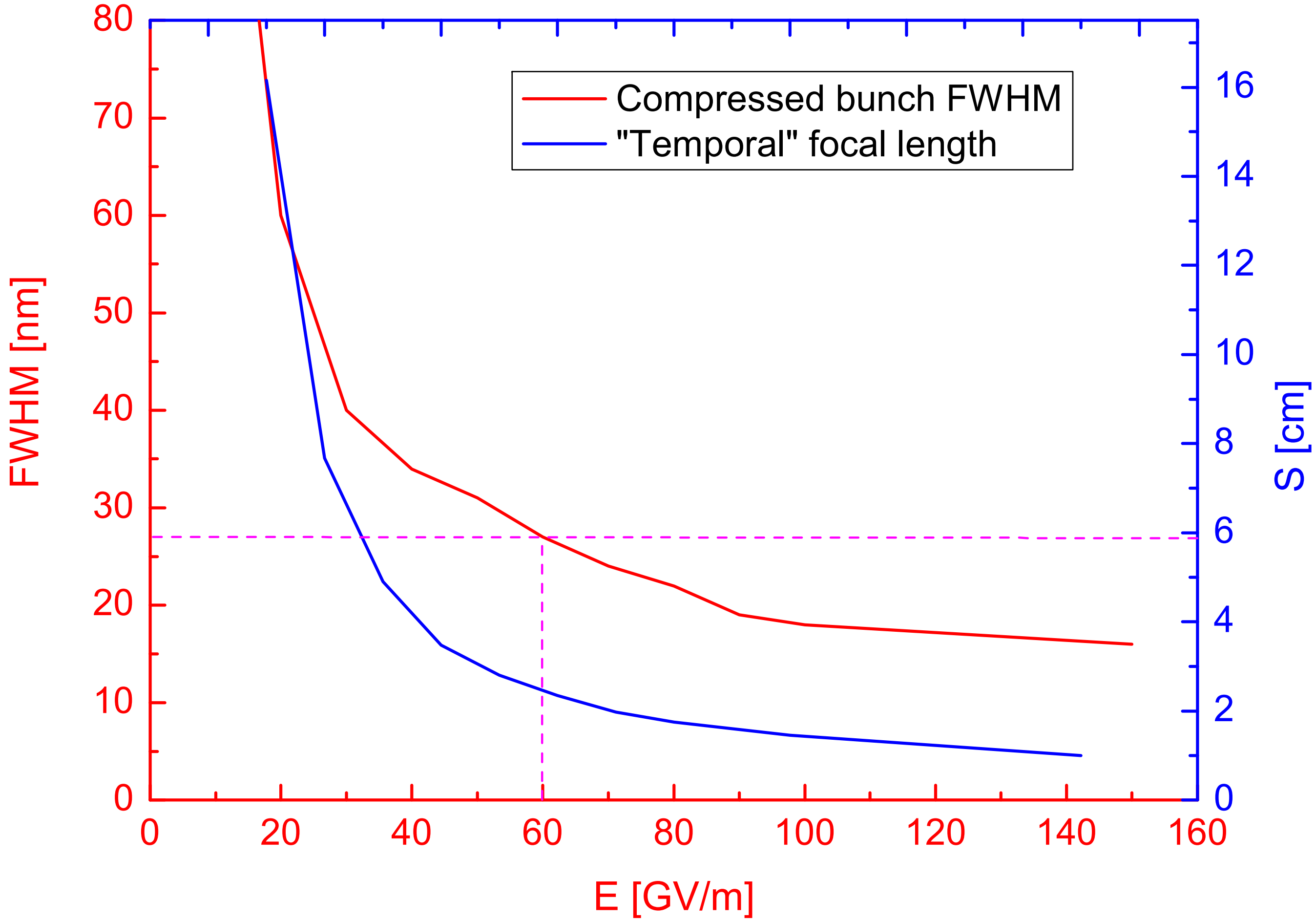
$\lambda = 1.3\ \mu$m, $P = 3.9$ TW



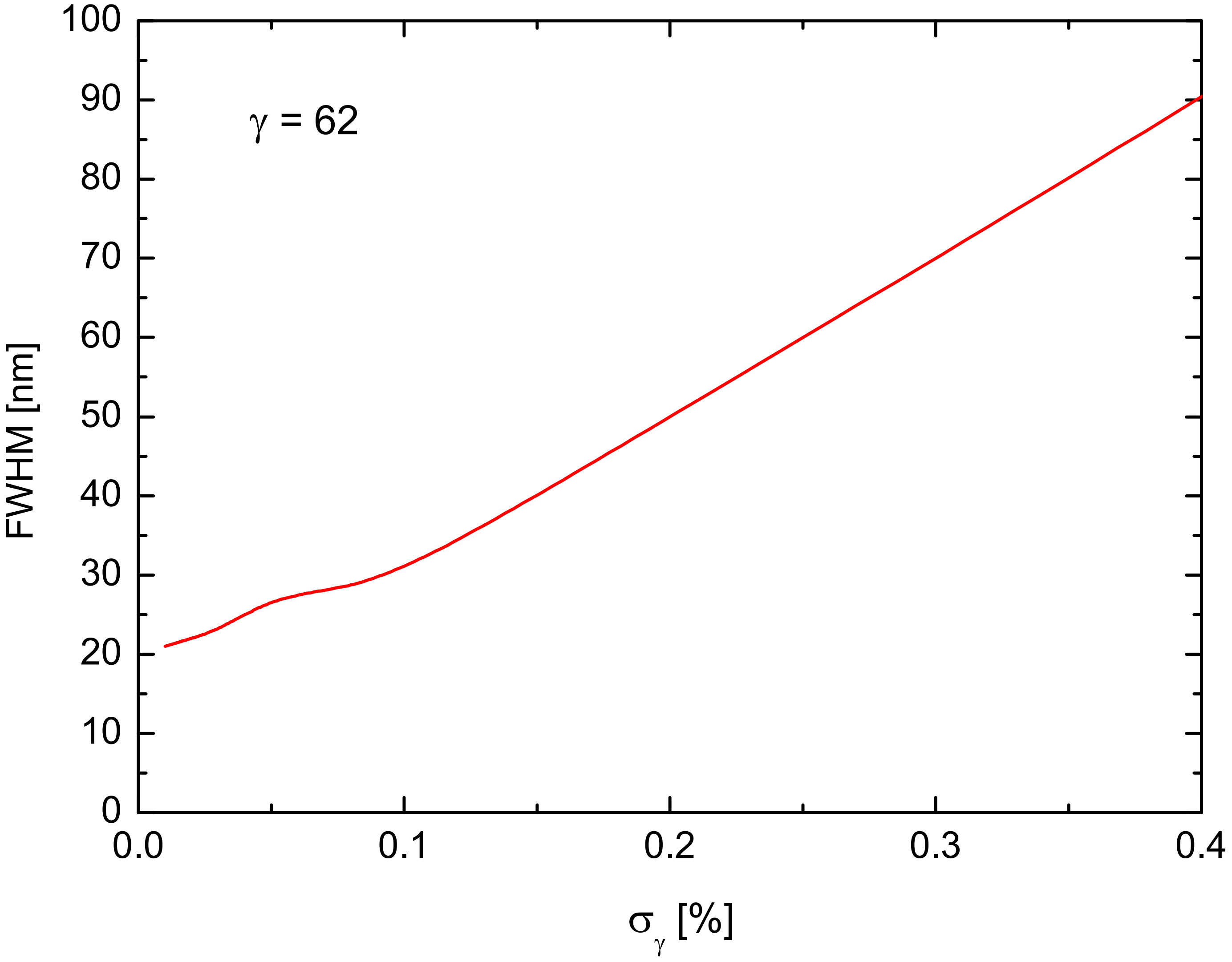
Creation of ultrashort electron bunches by inverse-FEL



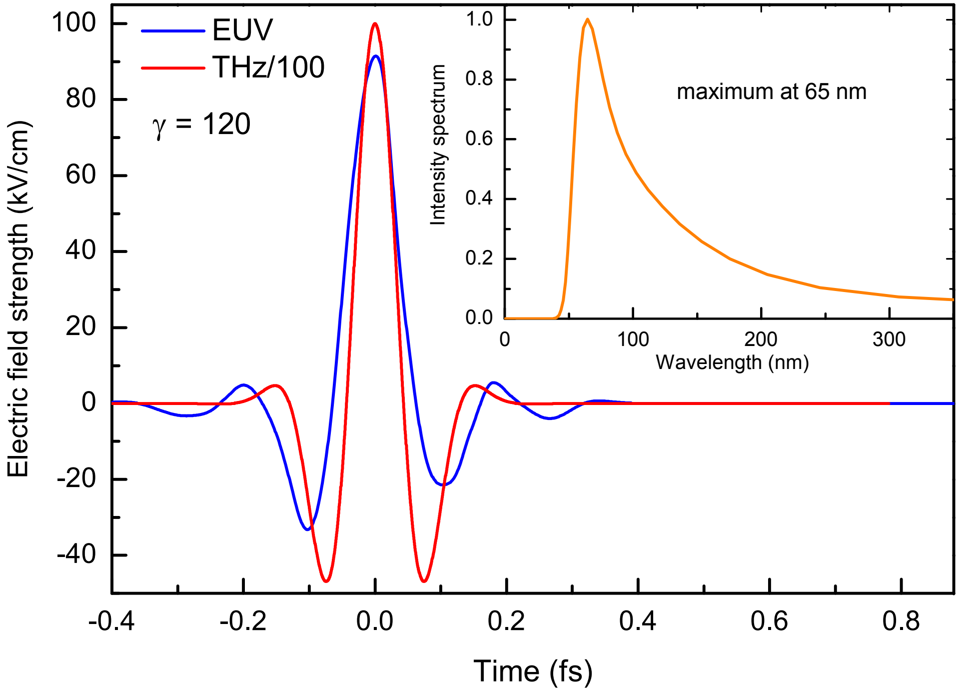
Creation of ultrashort electron bunches by inverse-FEL

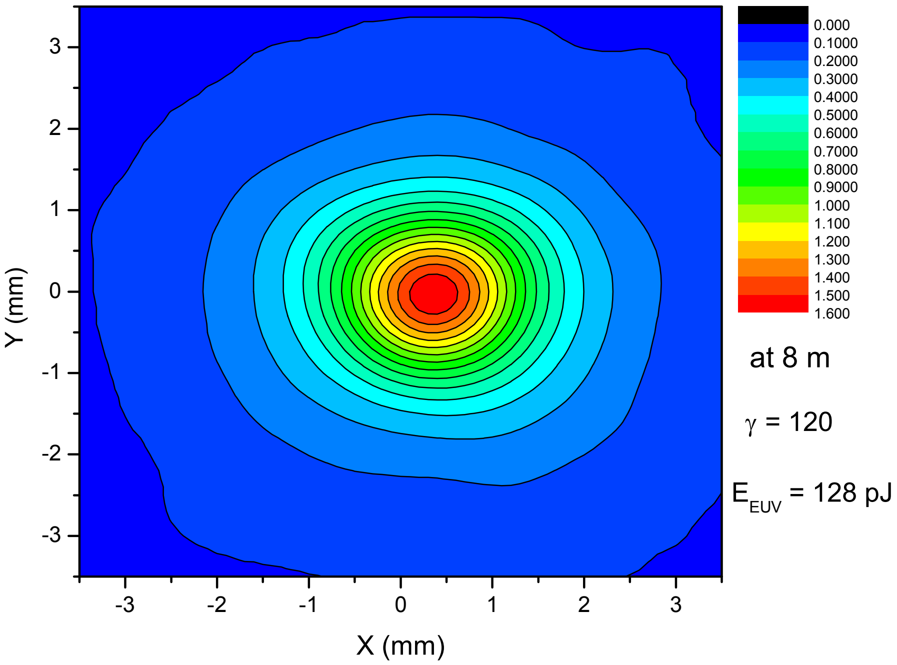


Creation of ultrashort electron bunches by inverse-FEL



Single-cycle EUV pulse generation by coherent Thomson-scattering





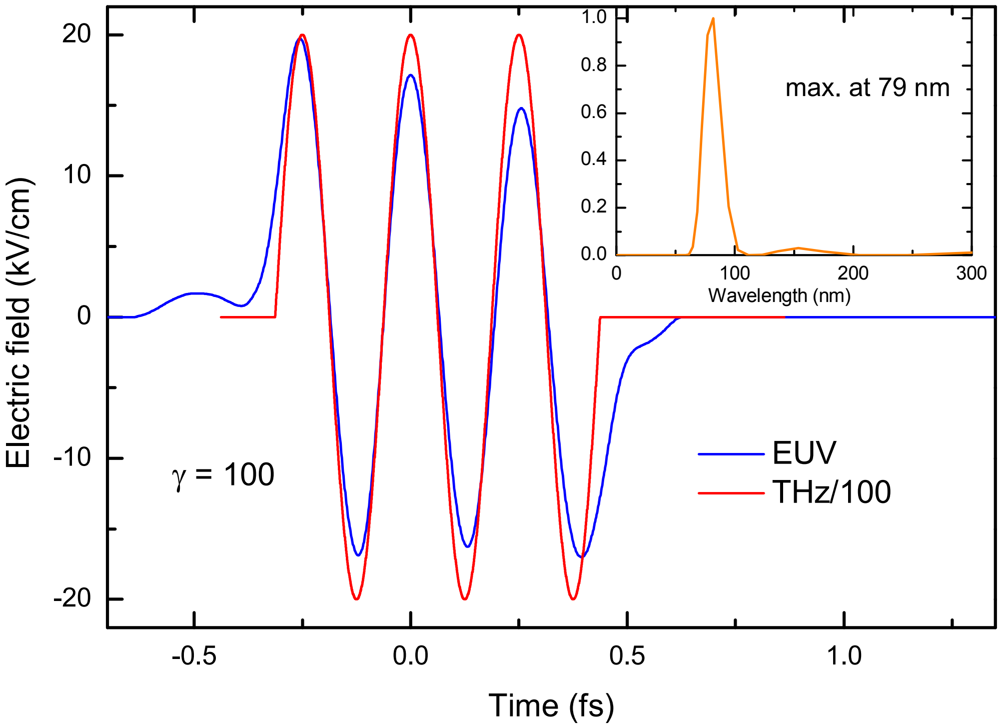
$$\frac{\mathrm{d}\vec{p}}{\mathrm{d}t} = q\vec{E} + q\vec{v}\times\vec{B}$$

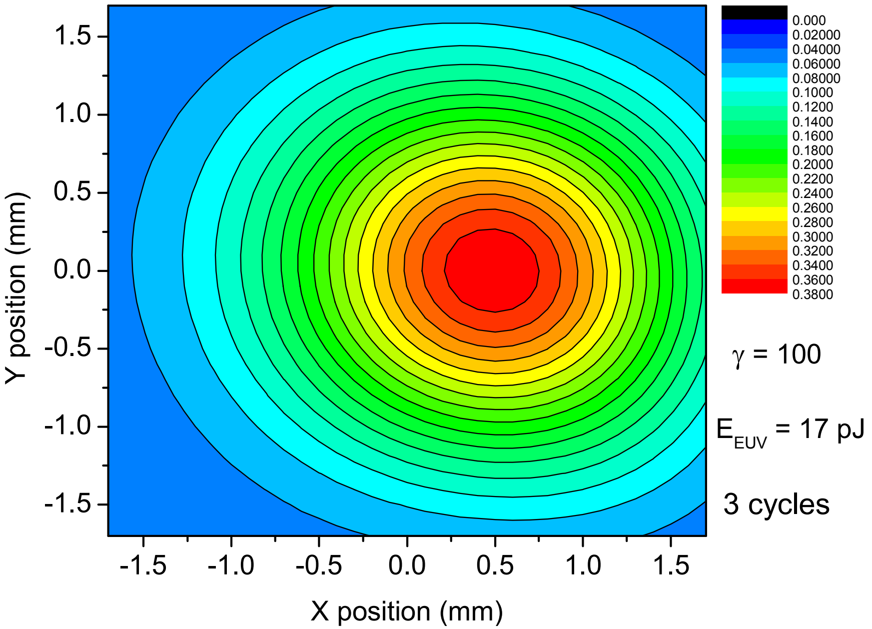
$$\vec{E} = \frac{q}{4\pi\varepsilon_0}(1-\beta)\frac{\vec{R}-R\vec{\beta}}{\left(R-\vec{R}\vec{\beta}\right)^3} + \frac{q\mu_0}{4\pi}\frac{\vec{R}\times\left(\left(\vec{R}-R\vec{\beta}\right)\times\dot{\vec{\beta}}\right)}{\left(R-\vec{R}\vec{\beta}\right)^3}$$

$$E_{THZ} = 10\ \mathrm{MV/cm}$$
$$\nu_{THz} = 0.1\ \mathrm{THz}$$
$$\gamma = 120$$
$$\mathrm{E}_{\mathrm{EUV}} = 128\ \mathrm{pJ}$$
$$\lambda_{EUV} = 65\ \mathrm{nm}$$

$$E_{THZ} = 30\ \mathrm{MV/cm}$$
$$\nu_{THz} = 0.3\ \mathrm{THz}$$
$$\gamma = 70$$
$$\mathrm{E}_{\mathrm{EUV}} = 15\ \mathrm{pJ}$$
$$\lambda_{EUV} = 85\ \mathrm{nm}$$

Three-cycle EUV pulse generation by coherent Thomson-scattering





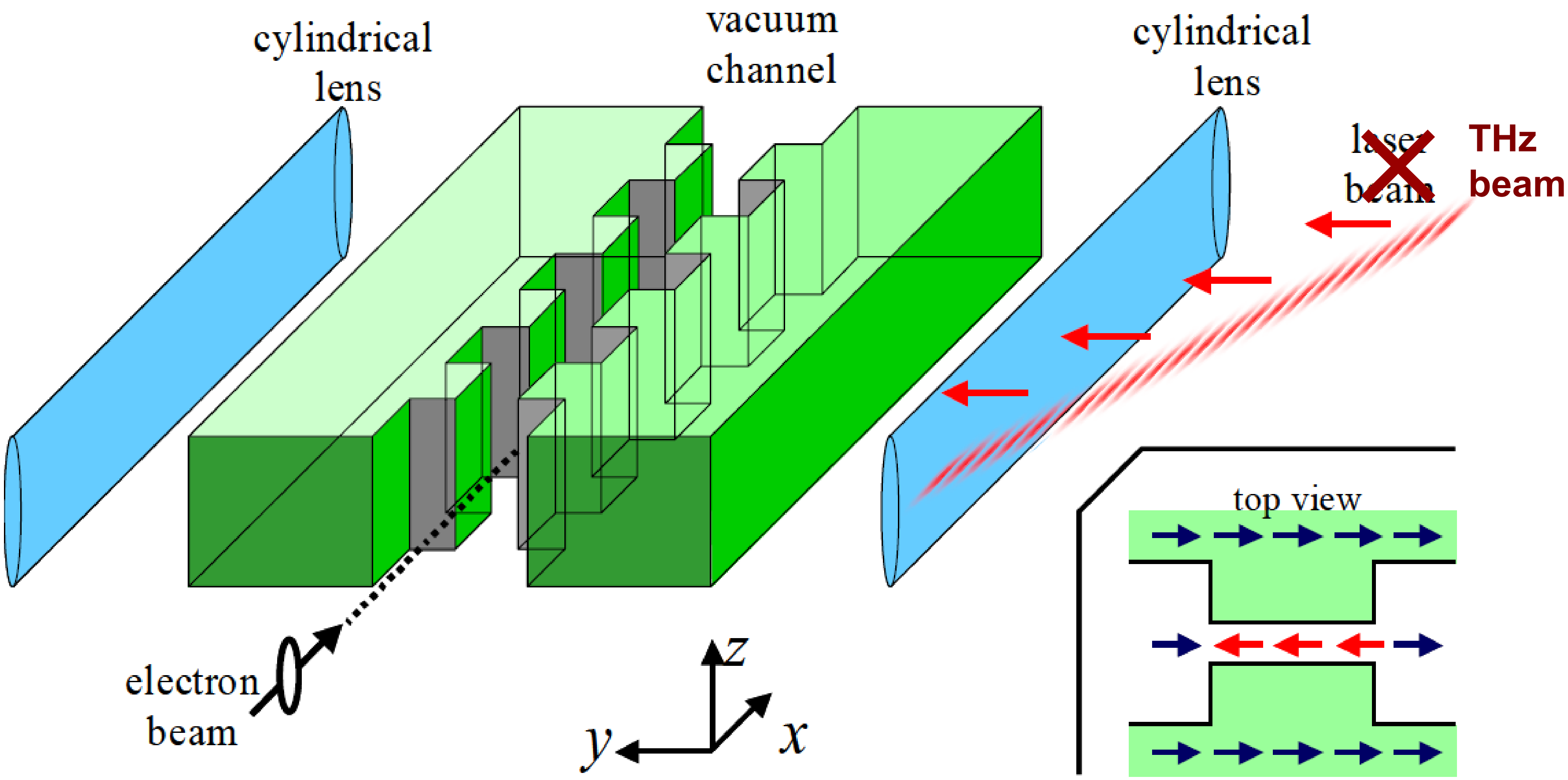
3 Å X-ray source by incoherent Thomson-scattering

Electron bunch: Q = 50 pC, γ = 800, Δt = 20 fs Leemans et al.: N. Phys. **2**, 696 (2006)

THz pulse: E = 6 MV/cm, λ = 750 μm, N = 20, Δt = 12.5 ps, W = 24 mJ

X-ray: λ = 3 Å, Δt = 20 fs, W = 5 nJ

Electron manipulation by THz pulses



Plettner et al.: Phys. Rev. Spec. Top. – Accel. and Beams **9**, 111301 (2006) acceleration
11, 030704 (2008) undulator
12, 101302 (2009) deflection, focusing

1 GV/m = 10 MV/cm peak field strength is needed!

Laser-plasma accelerator

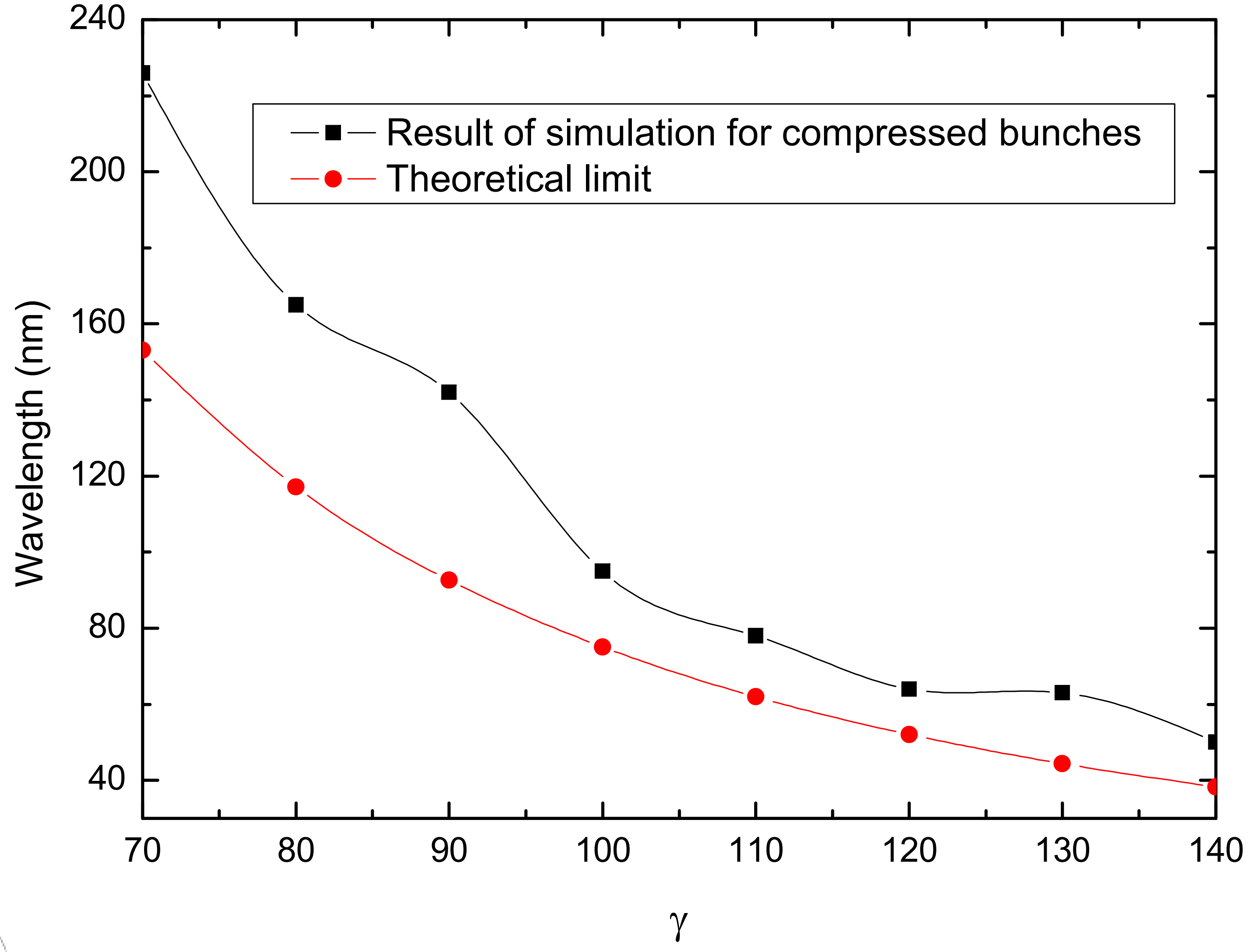
Summary

According to simple estimation and numerical simulations, -because of their appropriate wavelength and field strength-, extreme intense THz pulses are suitable for:

- improving attosecond pulse generation
- generation single-cycle or prescribed shaped EUV – VIS pulse generation
- ultrashort X-ray pulse generation
- more detailed numerical modeling
- experimental implementation
- these are only the first examples (orientation of molecules, accelerating molecules, or nanostructures, etc.)

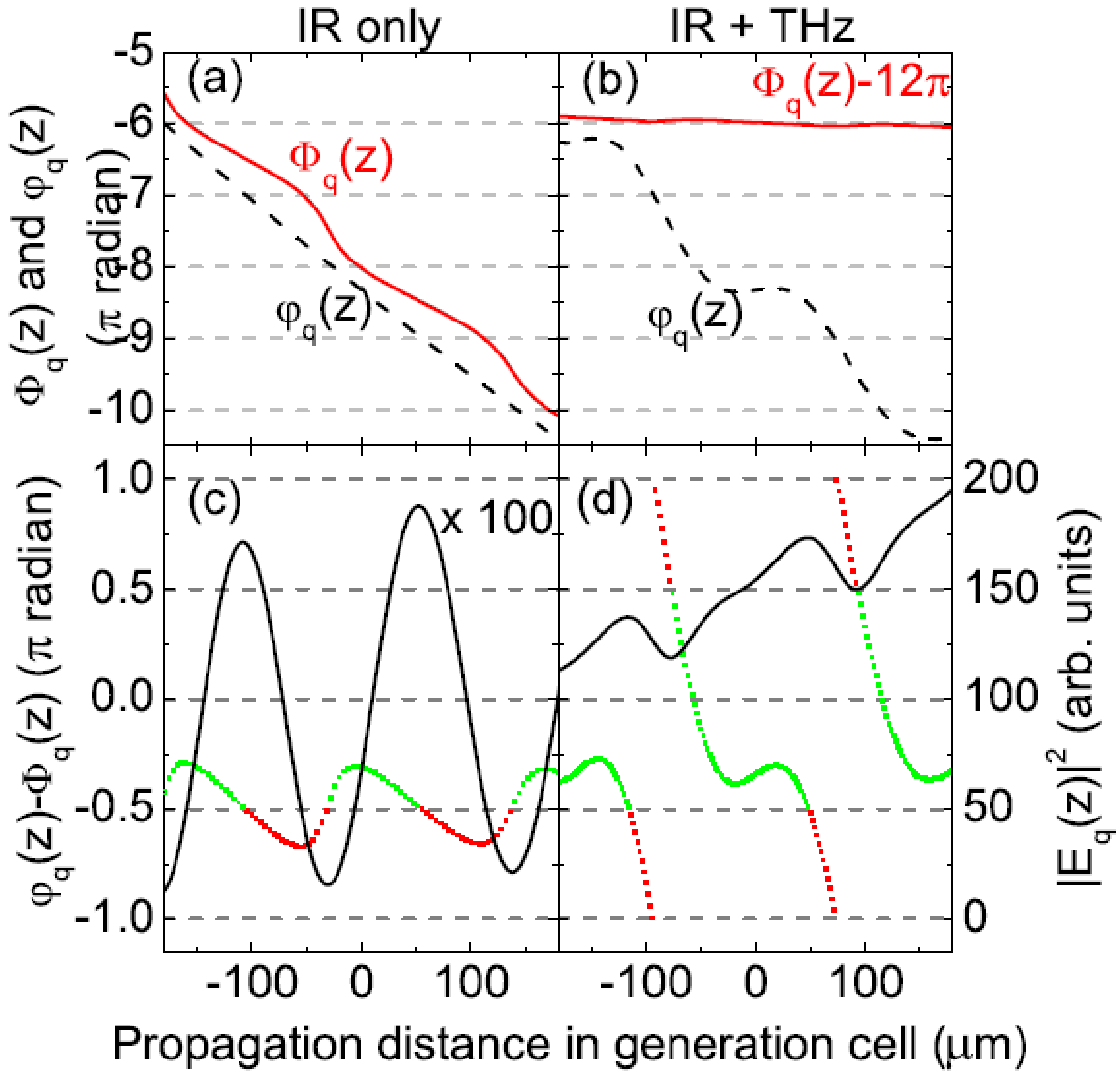
Acknowledgement: Hungarian Scientific Research Fund (OTKA), grant number 76101, 78262, 101846, SROP-4.2.1.B-10/2/KONV-2010-0002, and hELIos ELI_09-01-2010-0013

Single-cycle EUV pulse generation by coherent Thomson-scattering



Quasi-phase-matched attosecond pulse generation

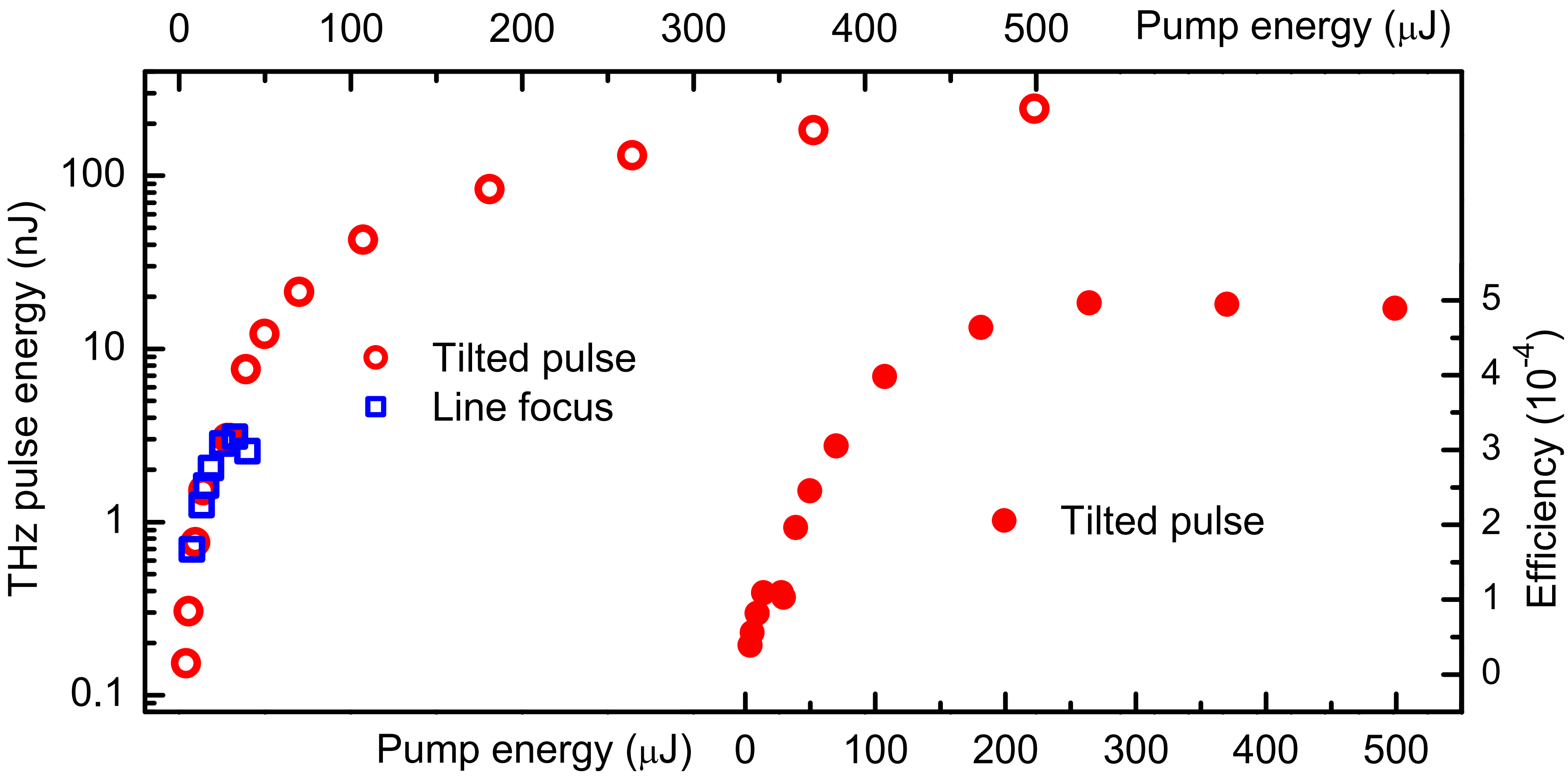
Spatial modulation by (chirped) THz pulse



Scaling-up the THz pulse energy

Opt. Express **13**, 5762 (2005)

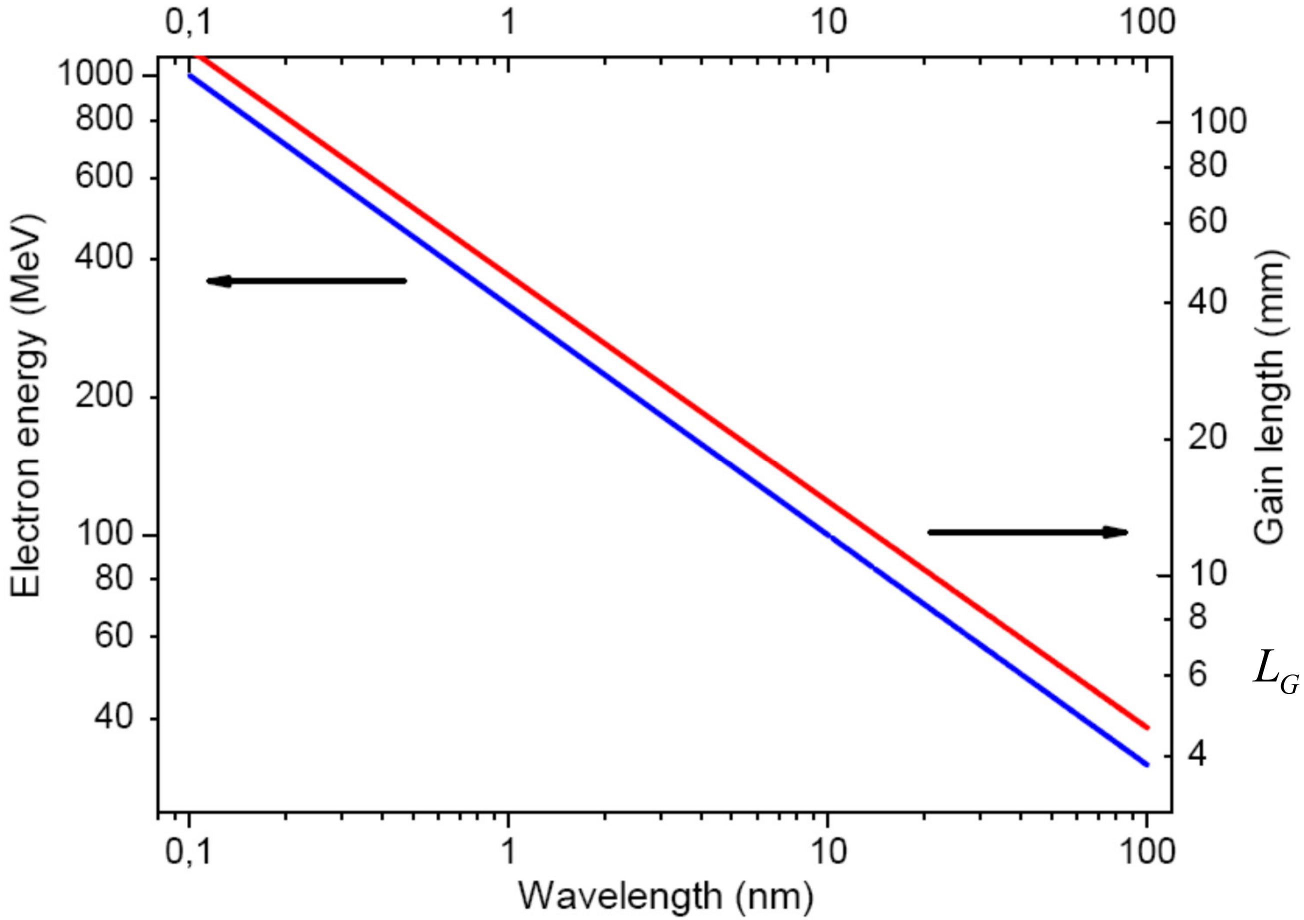
Spot diameter: 1 mm



E_{THz} = 240 nJ, η_{ph} = 10 %, electric field (unfocused) **0.1 MV/cm**

THz driven undulator for UV – X-ray generation

λ_u= 600 μm, E_{THZ}= 40 MV/cm, K= 0.747, Q = 420 pC, σ_L= 7 μm, σ_T= 30 μm



$$\lambda_r = \frac{\lambda_u}{2\gamma^2}\left[1+\frac{K^2}{2}\right]$$

$$K = \frac{\lambda_u \cdot e \cdot E_{THz}}{2\pi \cdot mc^2}$$

$$L_G \propto \lambda_u^{5/6}$$

$$L_G = \frac{\sqrt[3]{\lambda_u} \cdot \gamma \cdot \sigma_T^{2/3} \cdot (1+\Lambda)}{\sqrt[3]{\pi} \cdot \sqrt{3} \cdot K^{2/3}} \cdot \sqrt[3]{\frac{I_A}{I}}$$

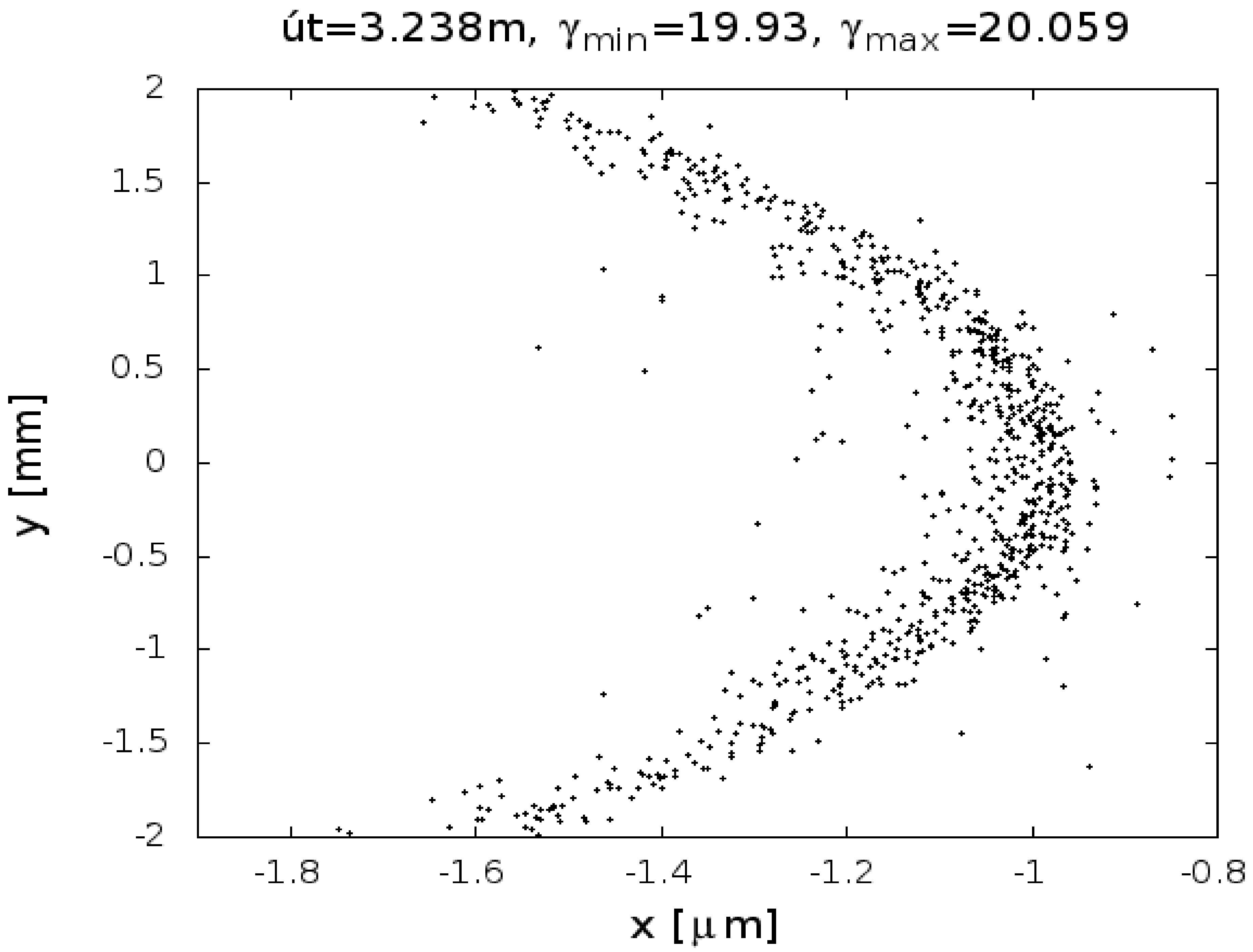
$$\Delta\gamma/\gamma \propto \sqrt[6]{\lambda_u} \qquad \varepsilon_T \propto \lambda^{3/2}$$

J. Hebling et al.: arXiv 1109.6852 (2011)

W_{THz} = 14 J !!

ELI-ALPS light sources

Primary sources	Peak /average power	Repetition rate	Pulse Energy	Pulse Duration	Spectral Range	Secondary sources
ALPS-WB	**2-3TW / 300-500W**	**100kHz**	**3-5mJ**	**1.5-3fs**	**0.3-1.3µm**	**-T0 FIR/THz** 0.3-3THz, 100µm-1mm, 1.24-12.4meV / 0.1-1 mJ, 10-30 MV/cm **-T1 MIR** 3-30THz, 10-100µm, 12.4-124meV / 10-100µJ, 3-300 MV/cm **-T2 NIR** 30-300THz, 1-10µm, 0.12-1.24eV / >100µJ, 0.3-30 GV/cm; as an alternative an IR OPCPA system can provide similar parameters **-P1 UV/XUV** 1-25PHz, 12-300nm 4-100eV / 100-10nJ **-P2 SXR** 25-100PHz, 3-12nm,100-400eV / >1nJ
SYLOS ***(Single-cycle OPCPA System)***	**100TW / 300-1000W**	**1kHz**	**0.3-1J**	**3-5fs**	**0.5-1.3µm**	**-S1** 10-100eV, 12-120nm / 100-1µJ **-S2** 100-1000eV, 1.2-12nm / 1-0.1µJ **-H1** 1-10keV, 0.12-1.2nm / 100-1nJ **-H2** 10-100keV, 0.12-1.2A / >1nJ
ALPS-HF	**1-3PW / 10-100W** (>2PW / >400W)	**1-10Hz** (10Hz)	**3-10J** (>40J)	**3-5fs** (<20fs)	**0.5-1µm/ 0.7-1.3µm** (0.7-0.9µm)	**Controlled electric field:** (3-5)x10^{14} V/m **Normalized vector potential:** 60-110/80-140 **Peak intensity:** (1-3)x10^{22} W/cm^2 **Ponderomotive potential:** (0.6-2)x10^{22} / (1-3)x10^{22} W/cm^2 × $\mu\mathrm{m}^2$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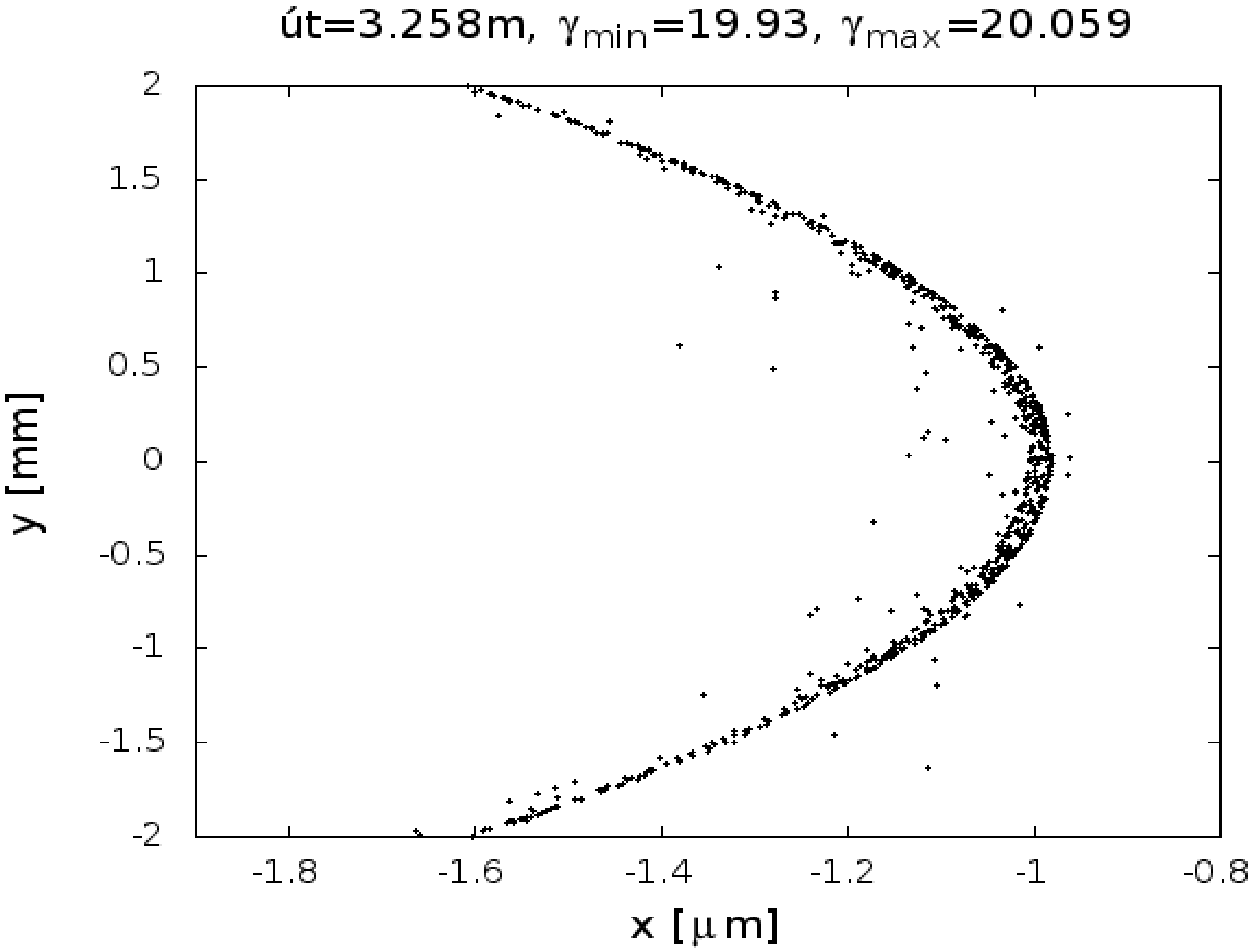
1
0.5
0
-0.5
-1
-1.5
-2
x [μm]
-1.8
-1.6
-1.4
-1.2
-1
-0.8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0
-0.5
-1
-1.5
-2
-1.8
-1.6
-1.4
-1.2
-1
-0.8
x [μm]

Optical rectification

Conversion efficiency depends on:

- ω_{THz} ($\eta \sim \omega^2_{THz}$)
- material parameters
- phase-matching → velocity matching: $v_{vis}^{gr} = v_{THz}^{ph}$

$$\eta_{THz} = \frac{2\omega^2 d_{eff}^2 L^2 I}{\varepsilon_0 n_v^2 n_{THz} c^3} \cdot \exp\left[-\alpha_{THz} L \big/ 2\right] \cdot \frac{\sinh^2\left[\alpha_{THz} L \big/ 4\right]}{\left[\alpha_{THz} L \big/ 4\right]^2}$$

$\alpha_{THz} L << 1$

$$\eta_{THz} = \frac{2\omega^2 d_{eff}^2 L^2 I}{\varepsilon_0 n_v^2 n_{THz} c^3} \qquad FOM_{NA} = \frac{d_{eff}^2 L^2}{n_v^2 n_{THz}}$$

$\alpha_{THz} L >> 1$

$$\eta_{THz} = \frac{8\omega^2 d_{eff}^2 I}{\varepsilon_0 n_v^2 n_{THz} \alpha_{THz}^2 c^3} \qquad FOM_{A} = \frac{4 d_{eff}^2}{n_v^2 n_{THz} \alpha_{THz}^2}$$

Figure of merits (FOMs) supposing 2 mm long crystals

Material	d_{eff} (pm/V)	$n^{gr}_{800\,nm}$	n_{THz}	$n^{gr}_{1.55\,\mu m}$	α_{THz} (cm^{-1})	*FOM* (pm^{2}cm^2/V^2)
CdTe	81.8		3.24	2.81	4.8	11.0
GaAs	65.6	4.18	3.59	3.56	0.5	4.21
GaP	24.8	3.67	3.34	3.16	0.2	0.72
ZnTe	68.5	3.13	3.17	2.81	1.3	7.27
GaSe	28.0	3.13	3.27	2.82	0.5	1.18
sLiNbO$_3$ sLN 100K	168	2.25	4.96	2.18	17 4.8	18.2 48.6
DAST	615	3.39	2.58	2.25	50	41.5

Velocity matching condition: $v^{gr}_{NIR} = v^{ph}_{THz} \Rightarrow n^{gr}_{NIR} = n_{THz}$

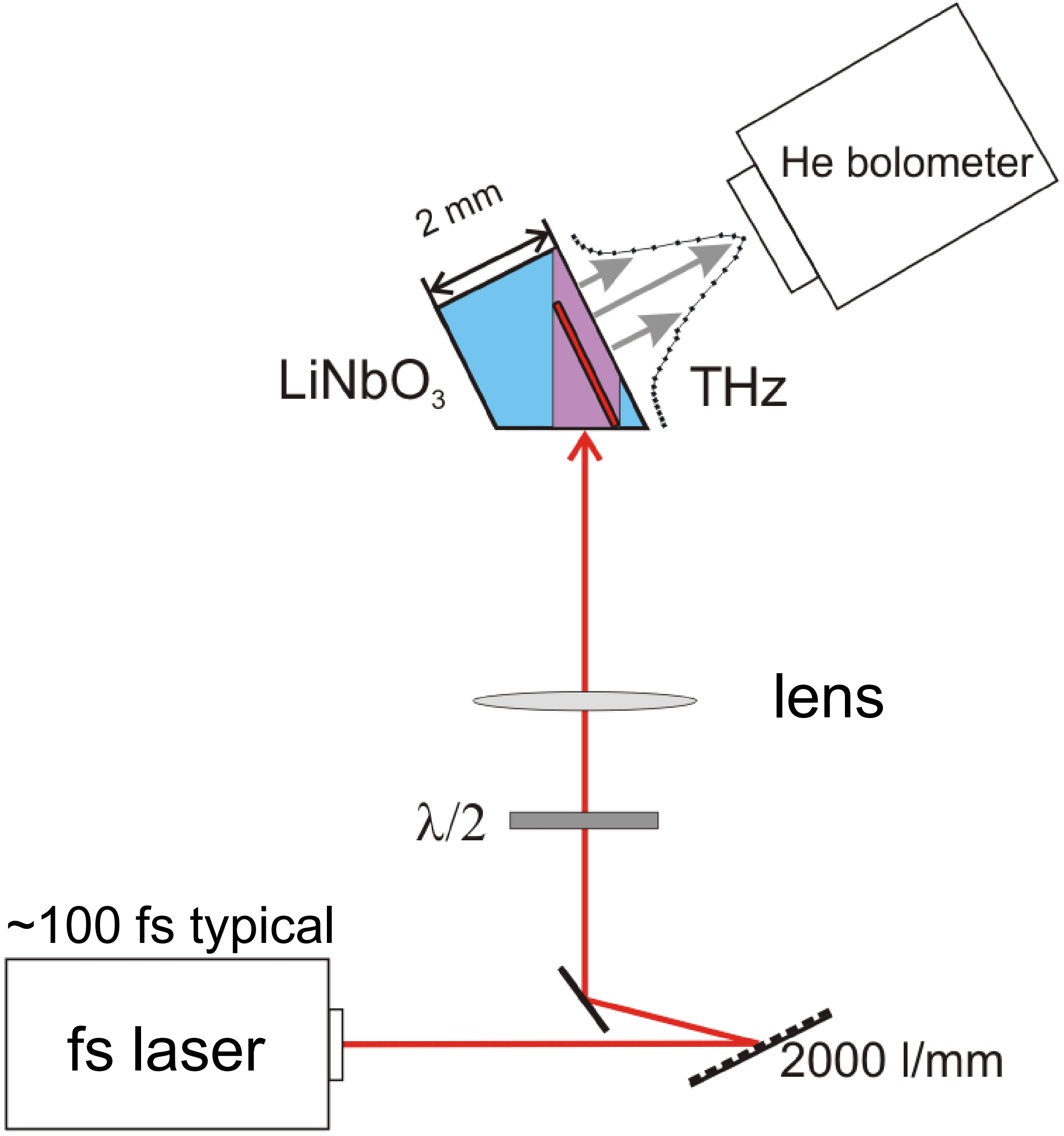
Tilted-Pulse-Front Pumping (TPFP) Setup

Fülöp & Hebling,
in: Recent Optical and
Photonic Technologies, 2010

$$\tan\gamma = -\frac{n}{n_{\mathrm{g}}}\lambda\frac{\mathrm{d}\varepsilon}{\mathrm{d}\lambda}$$

pulse front tilt

angular dispersion



THz
La