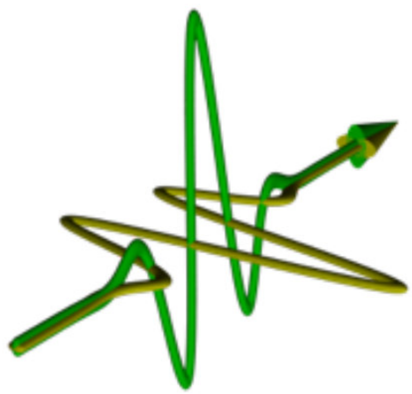
FREIA

SUFEL
STOCKHOLM-UPPSALA CENTRE FOR FREE ELECTRON LASER RESEARCH

UPPSALA UNIVERSITET

Generation of giant single-cycle pulses of THz light for controlling matter



Vitaliy Goryashko

2016

What, Why and How

Control of matter with THz light

- Overview of low-energy collective excitations
- Switching on and off spin-waves in antiferromagnets
- THz plasmons in graphene
- Control of superconducting transport
- THz dynamics in bacteriorhodopsin

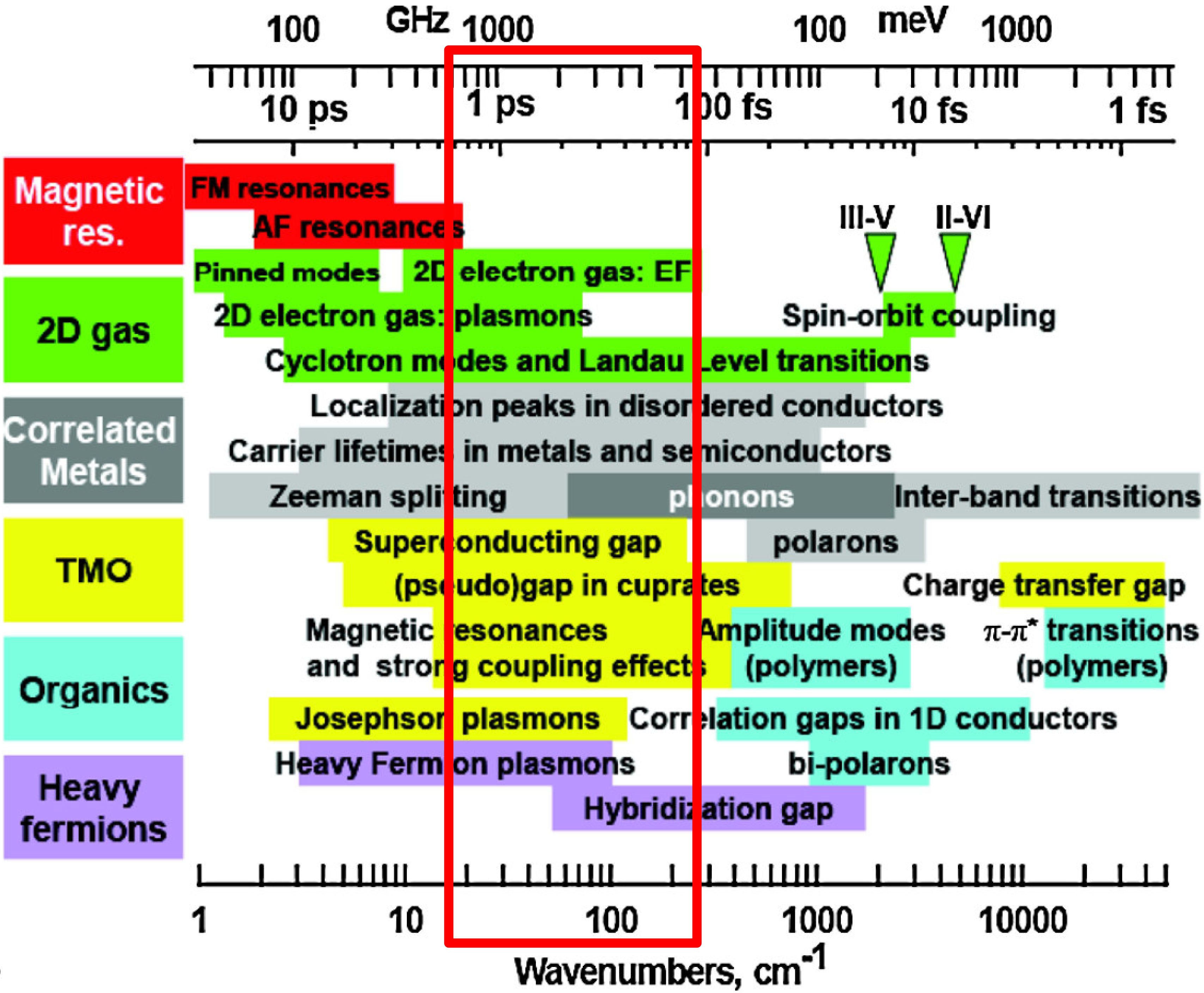
Generation of single-cycle THz pulses

- Optical rectification
- Transition THz radiation from e-bunches
- Half-cycle THz pulses from an undulator

Proposal for a THz Light at Uppsala

Control of matter with THz light

Low-energy excitations: *D. N. Basov et al., Rev. of Mod. Phys. 2011*

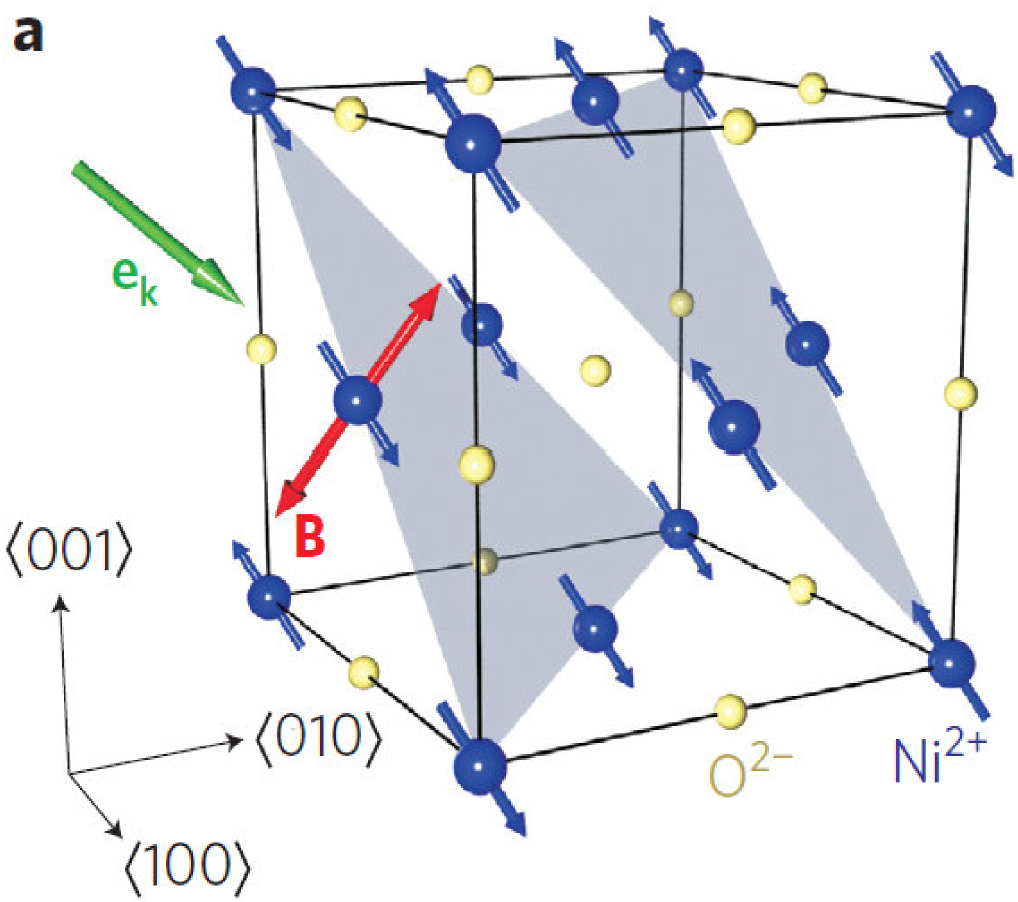


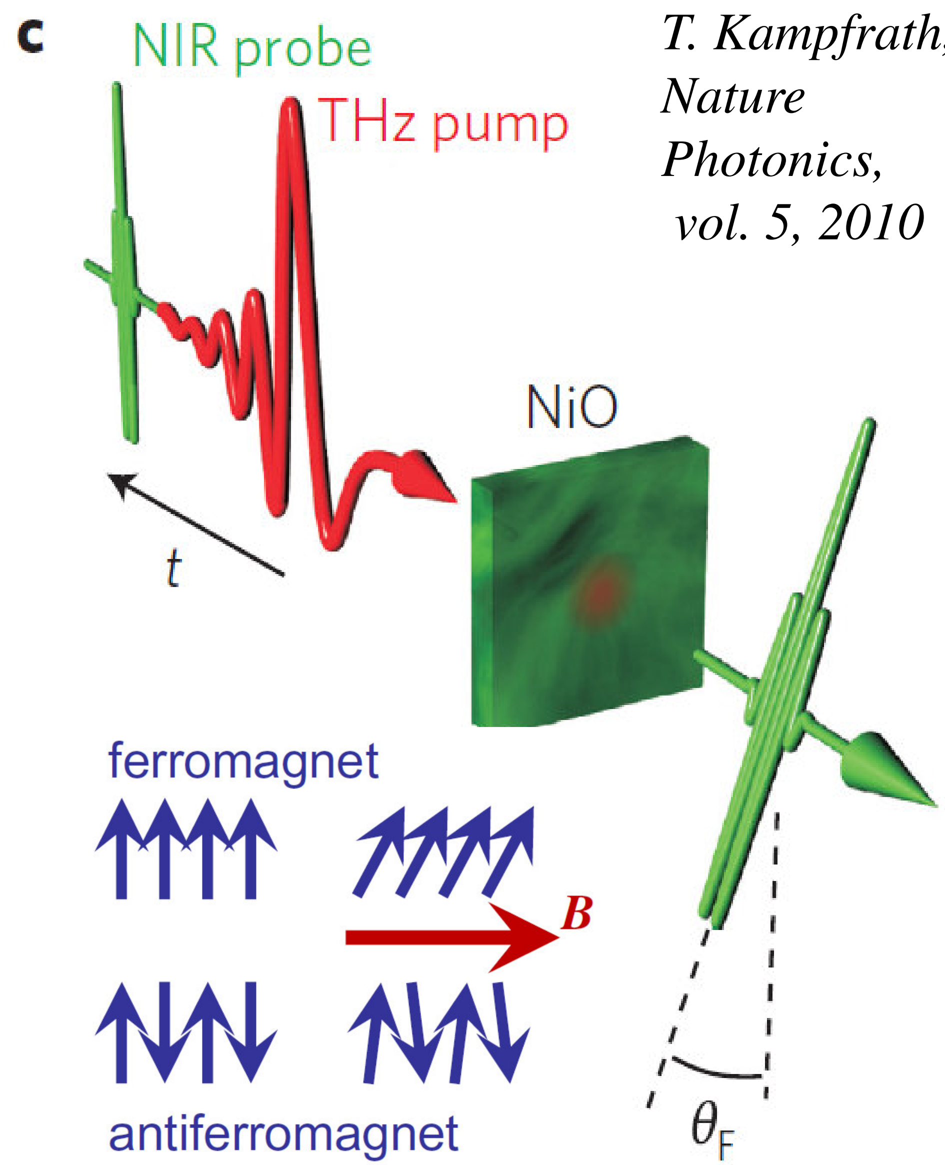
Beauty of ultra-short THz pulses

- direct access to low energy degrees of freedom in complex matter
- below optical transitions – no parasitic effects from optical pump laser pulses
- low heat deposit
- field effects directly in the time domain

1	THz	4.1	meV
1	ps	47.6	K
300	μm	0.39	kJ/mol
33	cm^{-1}	0.094	kcal/mol

THz induced magnetization dynamics in NiO



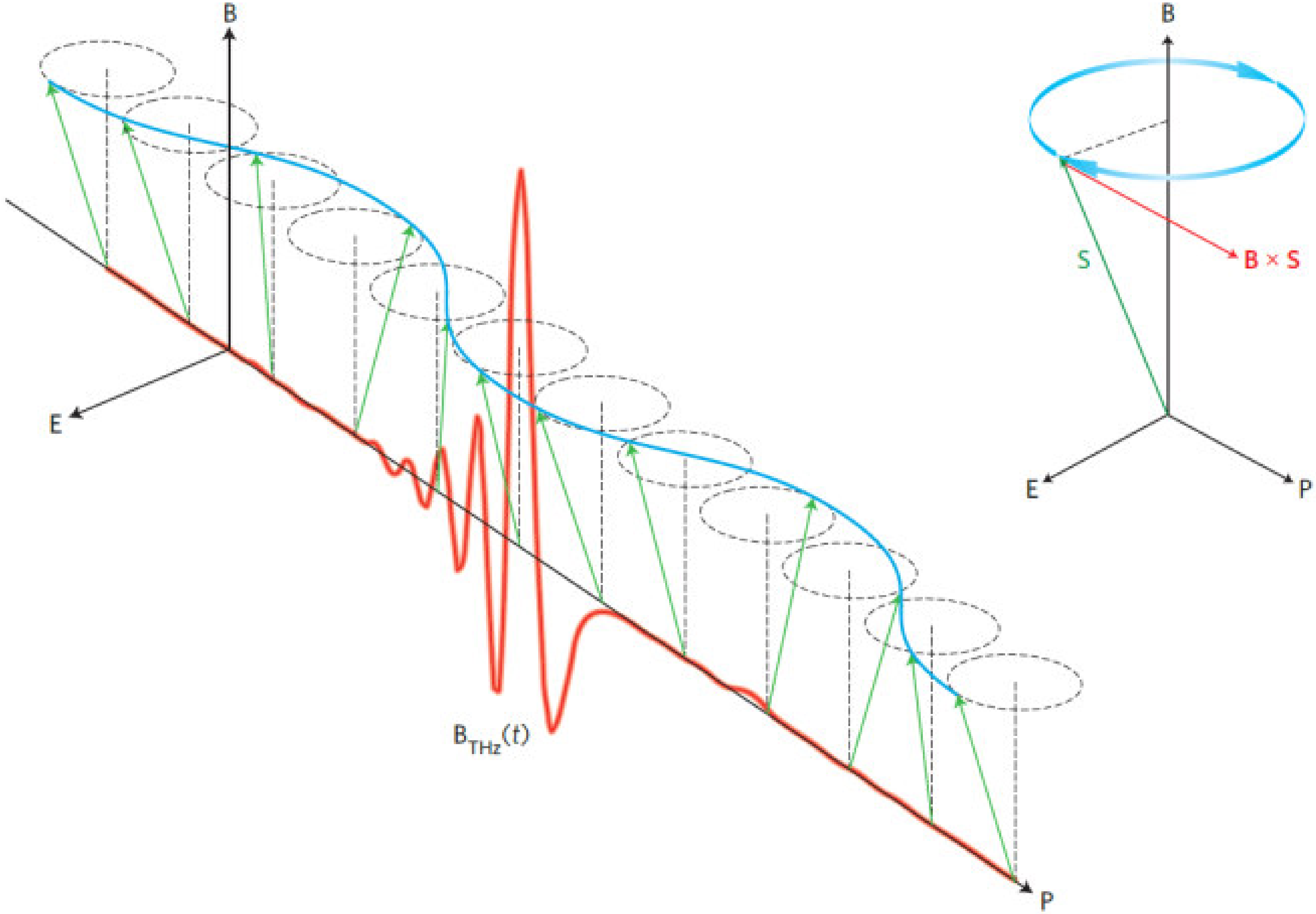


T. Kampfrath, Nature Photonics, vol. 5, 2010

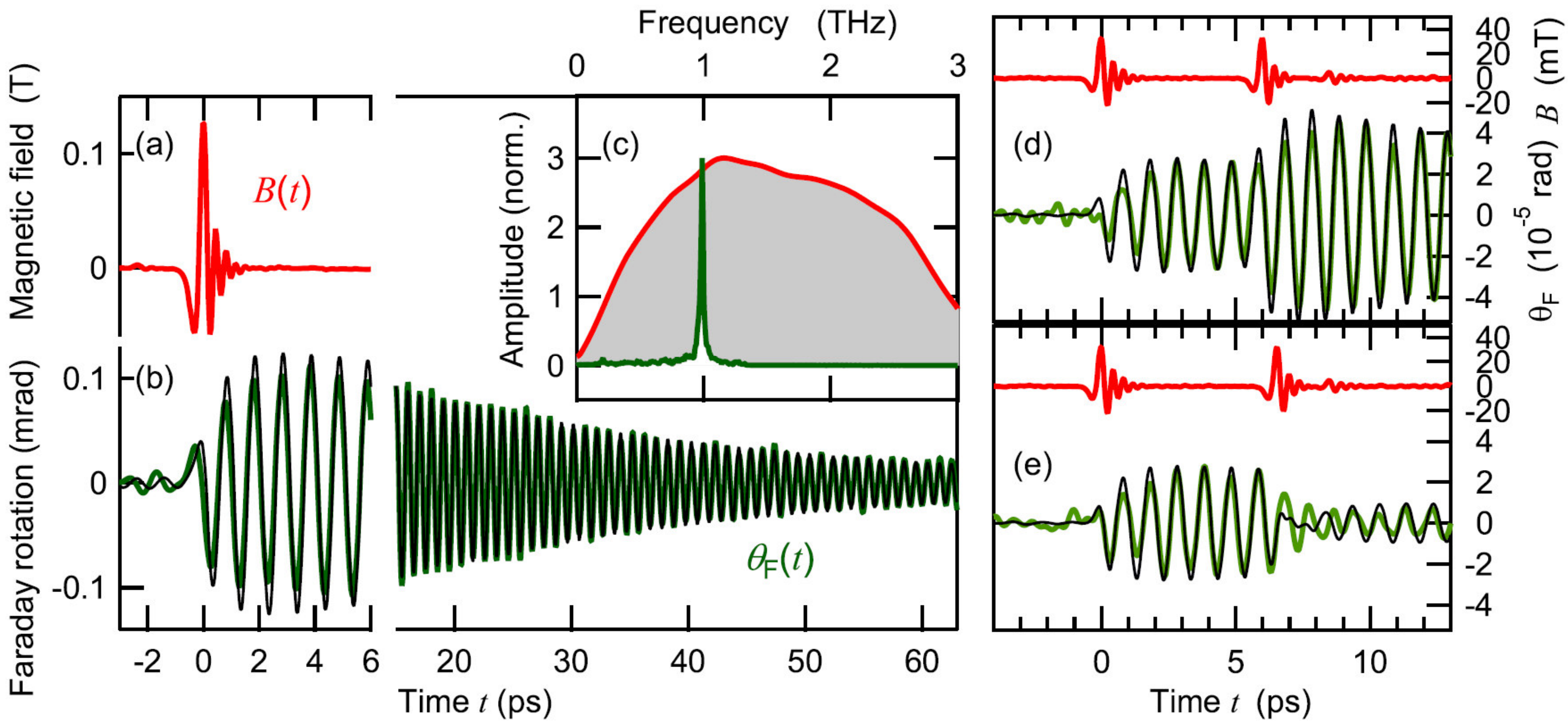
- easy axis (112)
- Neel temperature 523 K
- peak magnetic field of 0.13 T
- time resolution 8 fs

$$\vec{G} = \gamma \vec{S} \times \vec{B}$$

Dynamics of spins



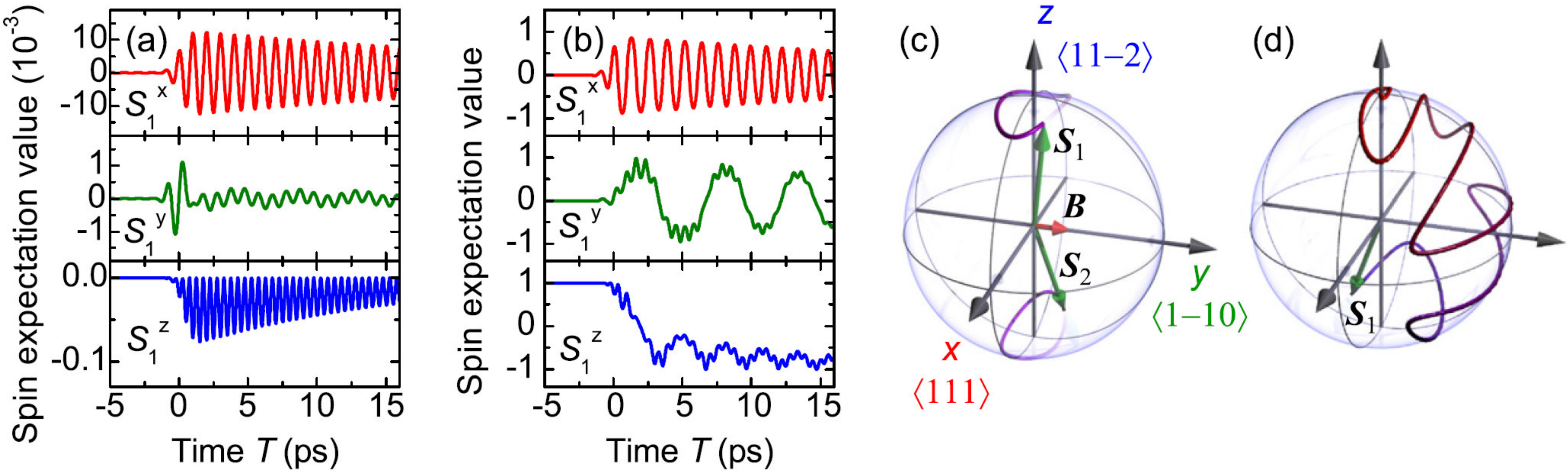
Switching on and off magnons



An induced magnetization M(t) manifests itself by the Faraday effect

$$\theta_F(t) = Vd\langle \mathbf{e_k} \cdot \mathbf{M}(t) \rangle$$

Prediction of spin flipping



Effective Hamiltonian

$$H = -J\,\boldsymbol{S}_1 \cdot \boldsymbol{S}_2 + \sum_{j=1}^{2} [D_x S_{jx}^2 + D_y S_{jy}^2] + \gamma\,\boldsymbol{B}(t) \cdot \sum_{j=1}^{2} \boldsymbol{S}_j .$$

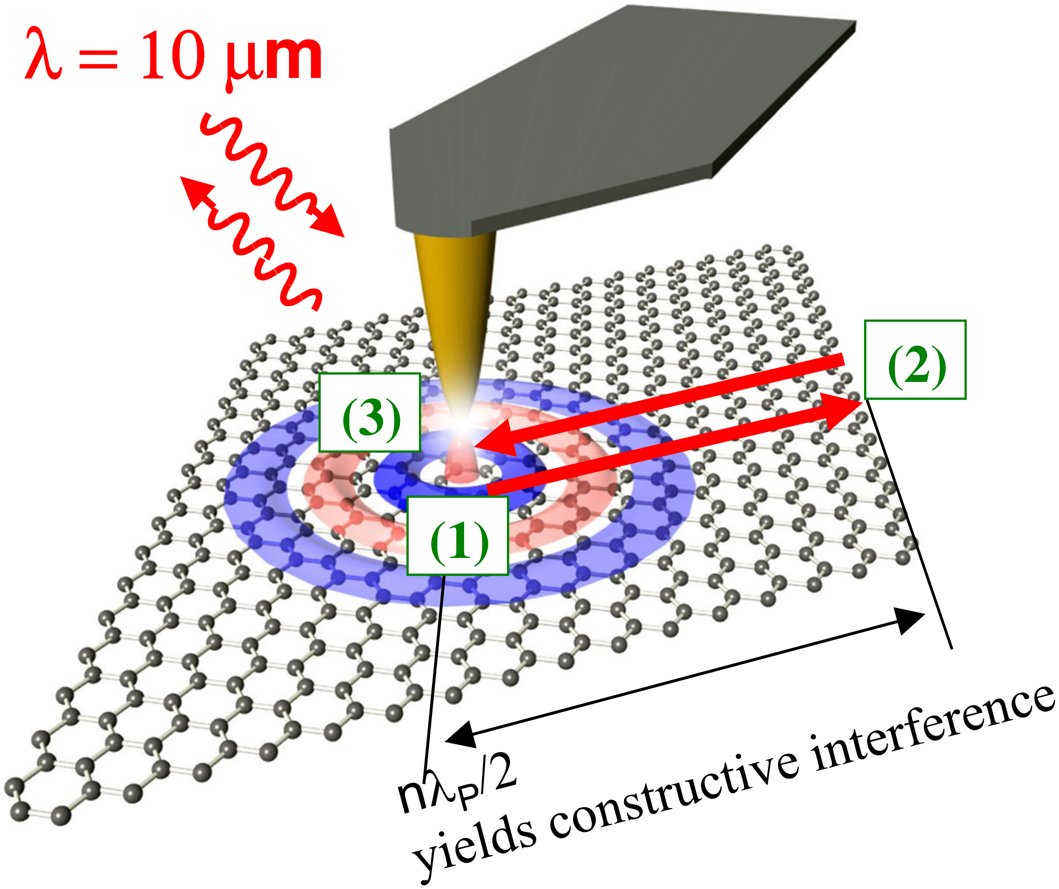
Landau-Lifshits-Gilbert eq. of motion

$$\frac{\partial}{\partial t}\boldsymbol{S}_j = -\frac{\gamma}{1+\alpha^2}\left[\boldsymbol{S}_j \times \boldsymbol{B}_j^{\mathrm{eff}} - \frac{\alpha}{|\boldsymbol{S}_j|}\boldsymbol{S}_j \times (\boldsymbol{S}_j \times \boldsymbol{B}_j^{\mathrm{eff}})\right],$$

Effective magnetic field

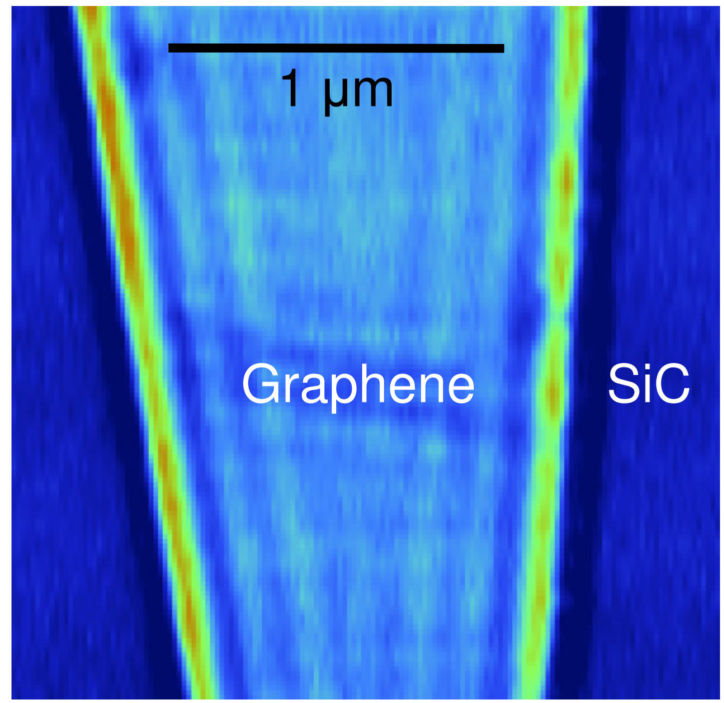
$$\boldsymbol{B}_j^{\mathrm{eff}} = \boldsymbol{B}(t) - J\,\boldsymbol{S}_{3-j}/\gamma + (D_x S_{jx}, D_y S_{jy}, 0)^{\mathrm{t}}/\gamma$$

Tip-enhanced real-space mapping of mid-IR plasmons in graphene (plasmon interferometry)



IR s-SNOM image

$\omega = 1087\ cm^{-1}$, $\lambda = 9200\ nm$



Courtesy of A. Nikitin

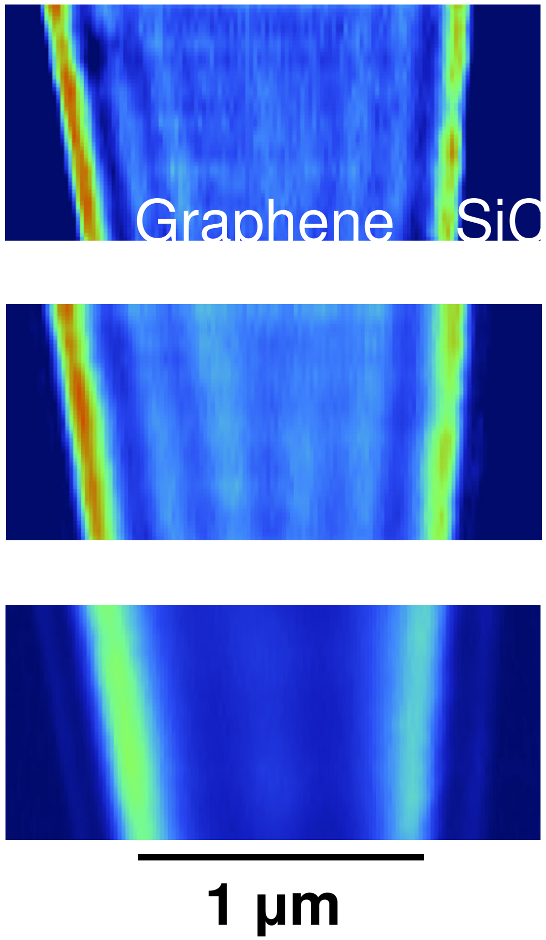
(1) near-field at tip apex excites graphene plasmons
(2) plasmons are backreflected at graphene edge
(3) tip scatteres interfering fields at tip apex

Spectroscopic mapping reveals plasmon dispersion

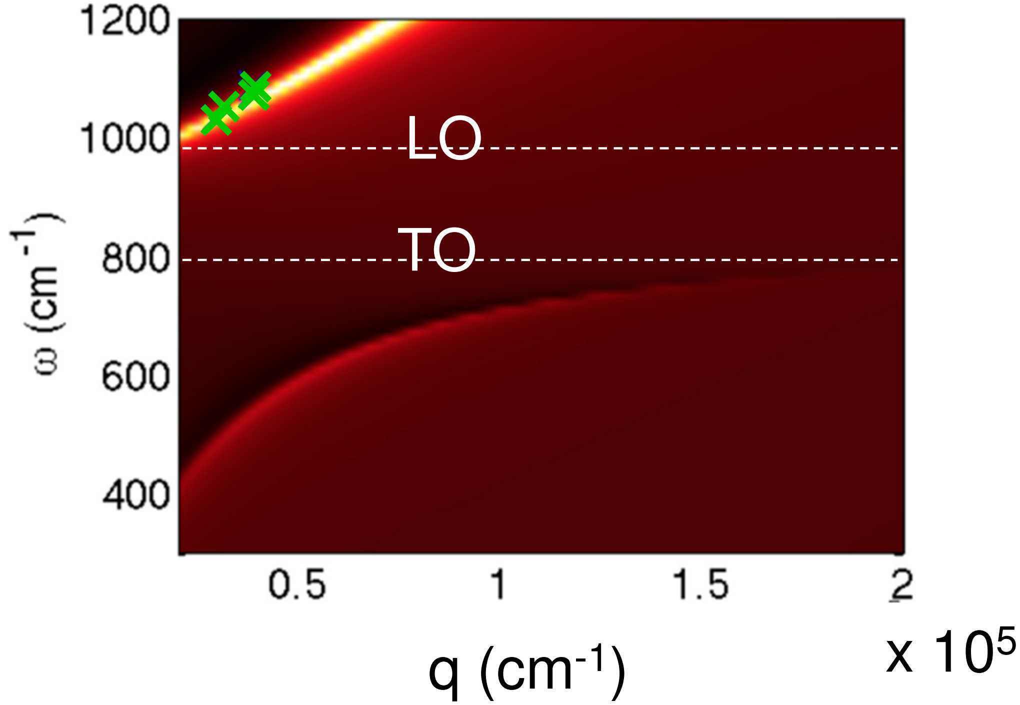
λ_0 = 9.20 μm
ε_{SiC} = 2.9

λ_0 = 9.68 μm
ε_{SiC} = 2.0

λ_0 = 10.15 μm
ε_{SiC} = 0.7



Graphene plasmon dispersion on SiC

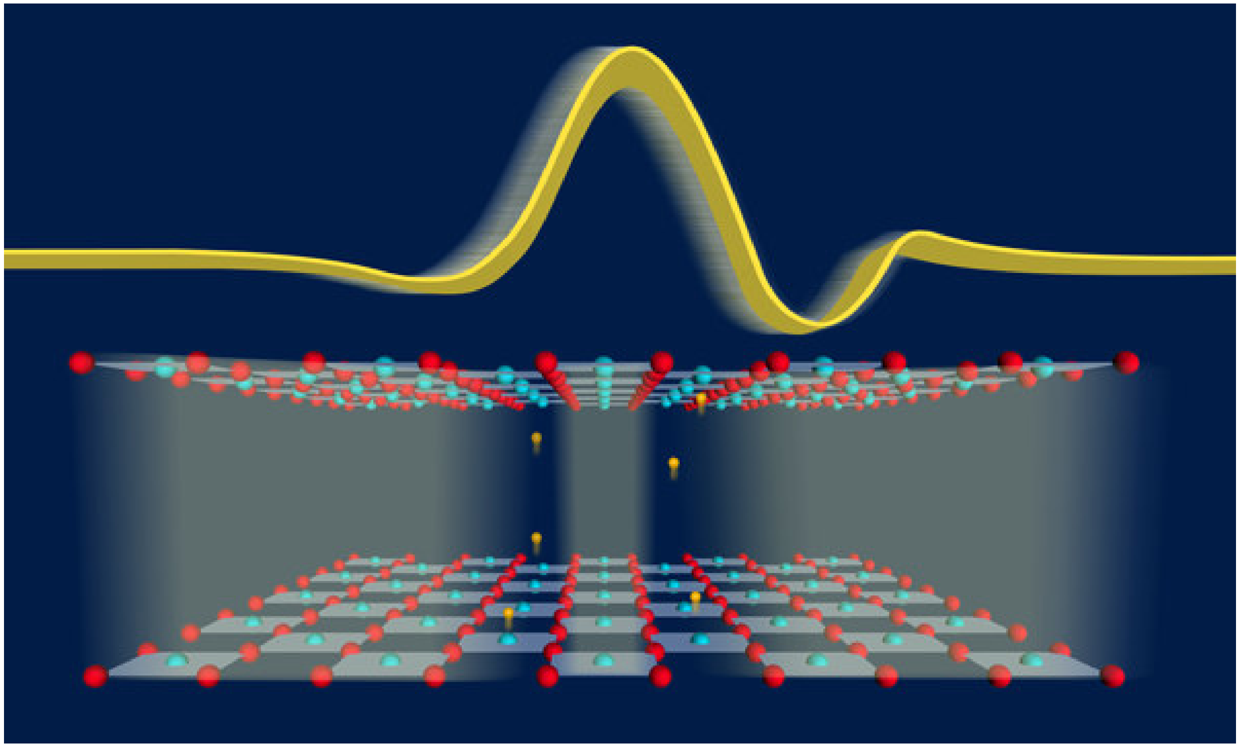


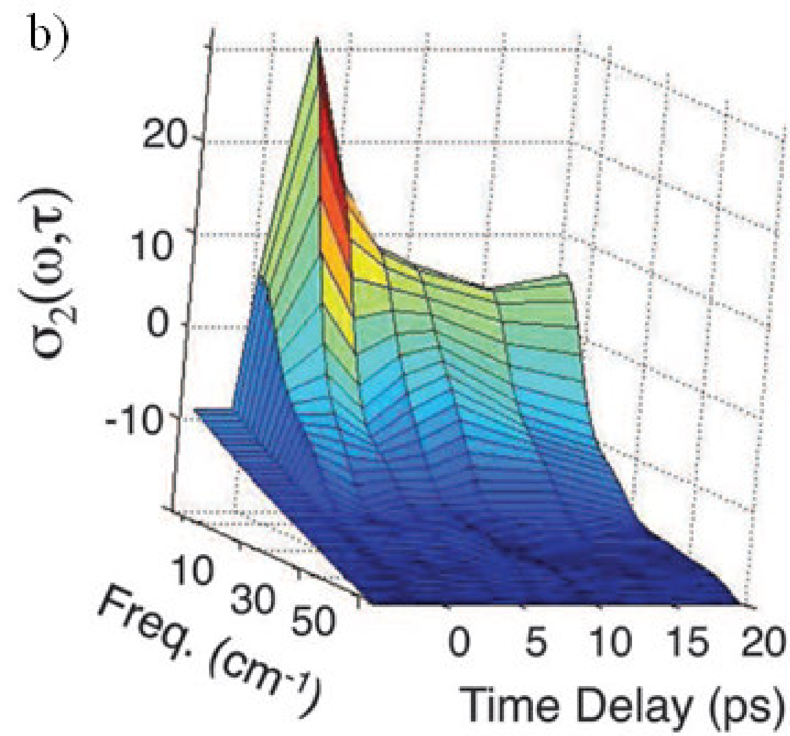
J. Chen et al., Nature **487**, 77 (2012)

➡ Interference fringes, i.e. plasmon wavelengths, increase stronger due to decreasing dielectric value of the SiC substrate ε_{SiC}

Courtesy of A. Nikitin

Light induced superconductivity



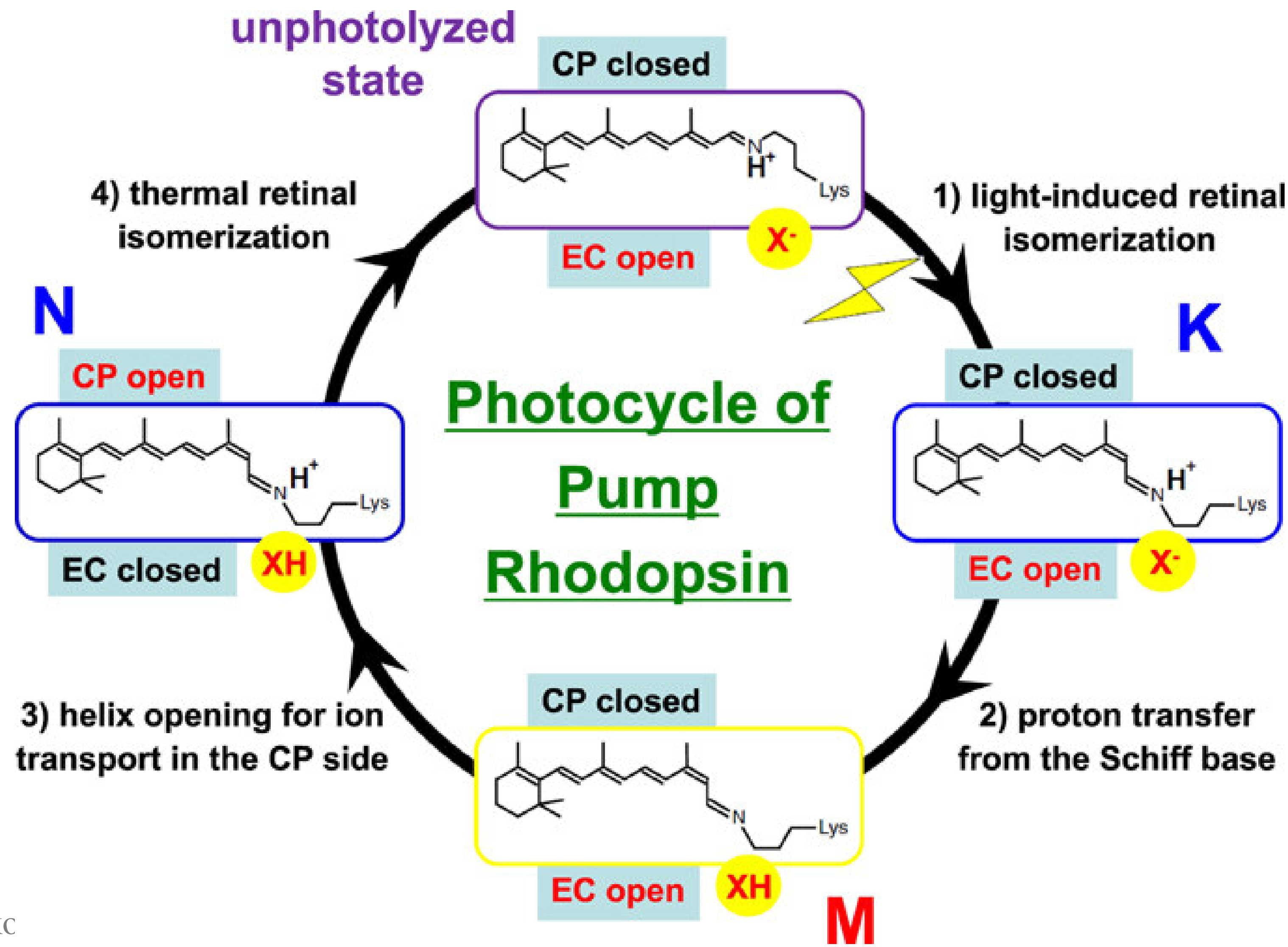


Superconducting transport between layers of a cuprate is gated with high-field terahertz pulses, leading to oscillations between superconductive and resistive states, and modulating the dimensionality of superconductivity in the material.

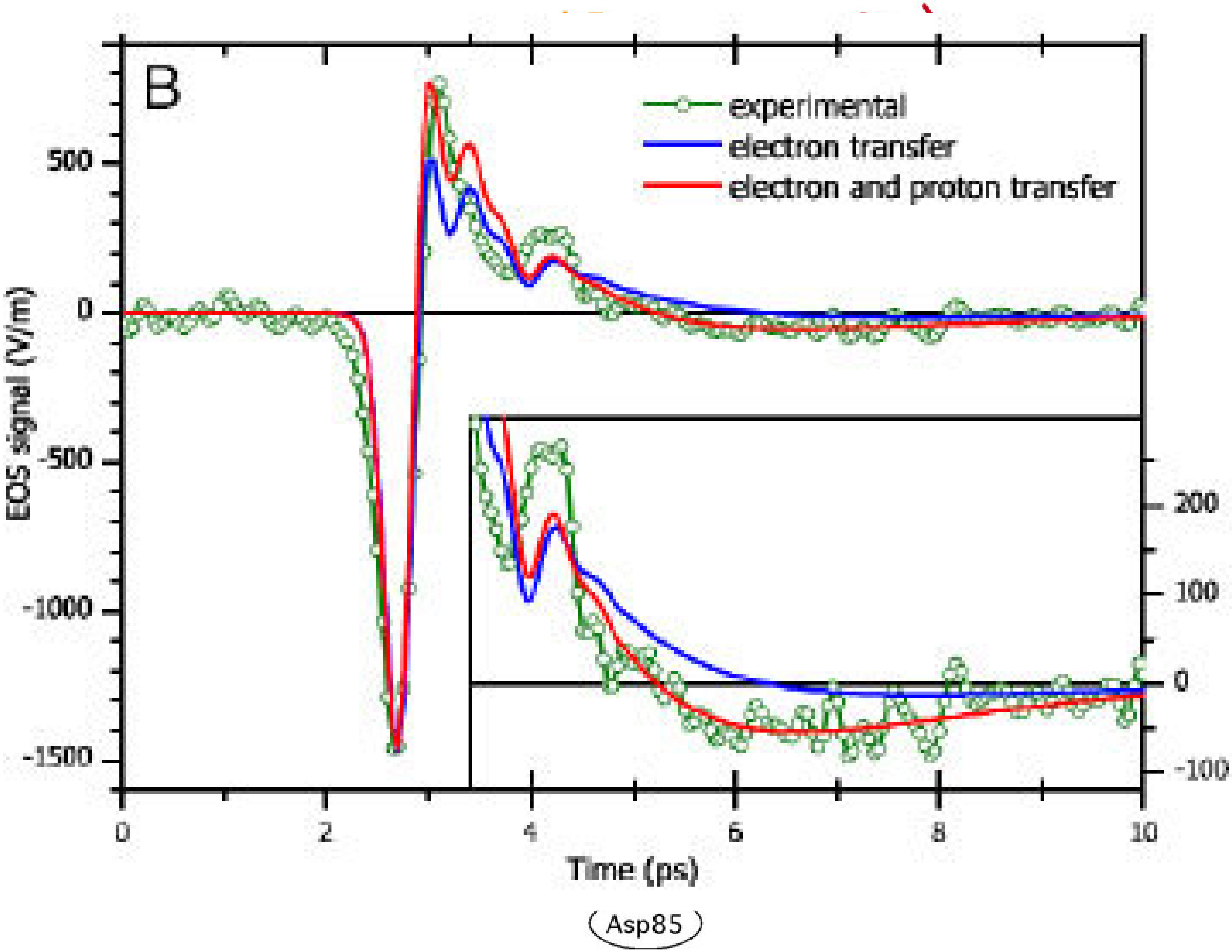
Andrea Cavalleri group

Bacteriorhodopsin is a light-driven proton pump

Bacteriorhodopsin acts as a proton pump; that is, it captures light energy and uses it to move protons across the membrane out of the cell.[2] The resulting proton gradient is subsequently converted into chemical energy.

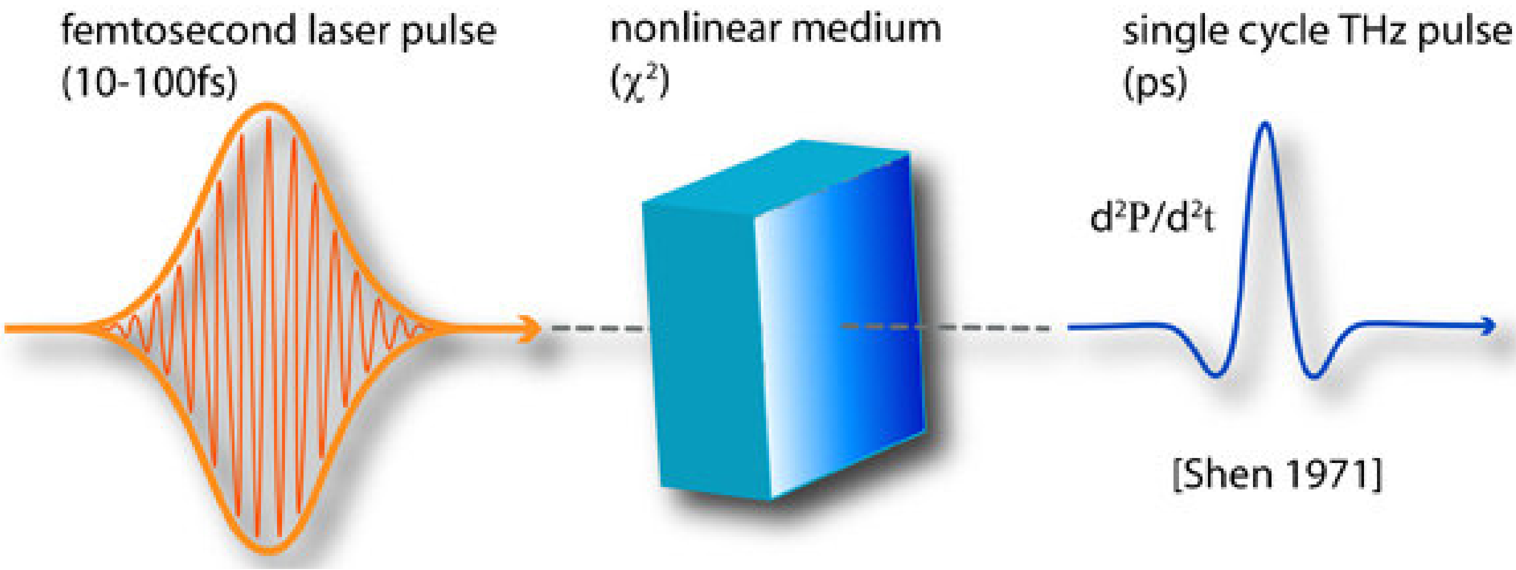


Transformation cycle of bacteriorhodopsin



Generation of single-cycle THz pulses

Generation of terahertz pulses by optical rectification



The incoming field ***E*** with frequency ω generates a nonlinear polarization ***P*** via the second order nonlinear susceptibility.

$$P_i^{(0)} = \sum_{jk} \chi^{0}_{ijk} E_j^{\omega} E_k^{\omega}$$

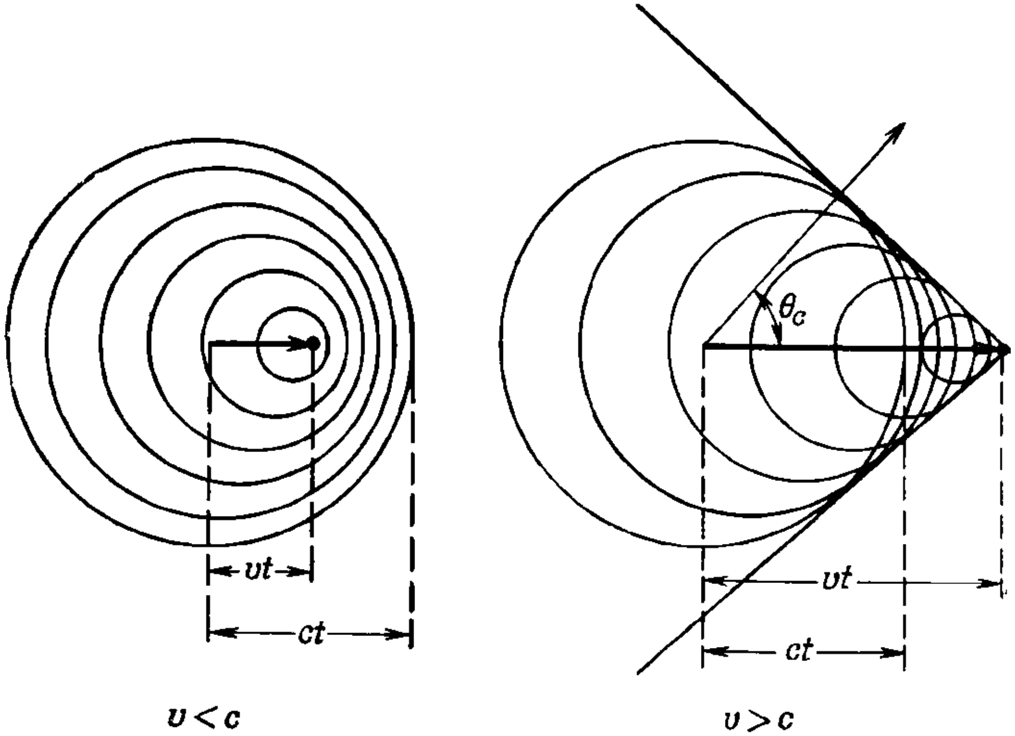
[Bass 1962]

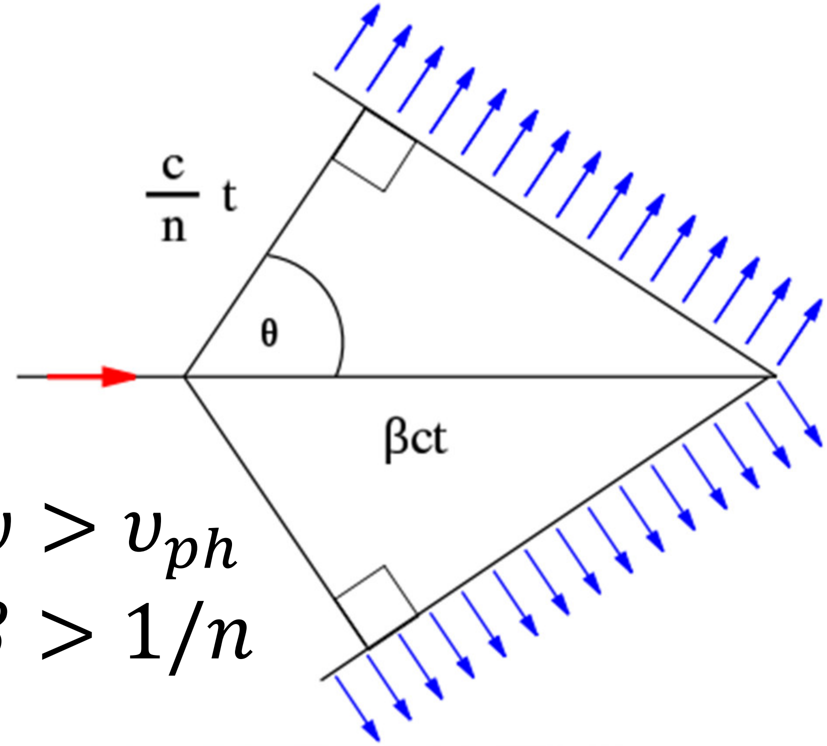
$$\nabla \times \nabla \times \vec{E} + \frac{1}{c^2}\frac{\delta^2}{\delta t^2}(\varepsilon \vec{E}) = -\frac{4\pi}{c^2}\frac{\delta^2 \vec{P}}{\delta t^2}$$

source of radiation

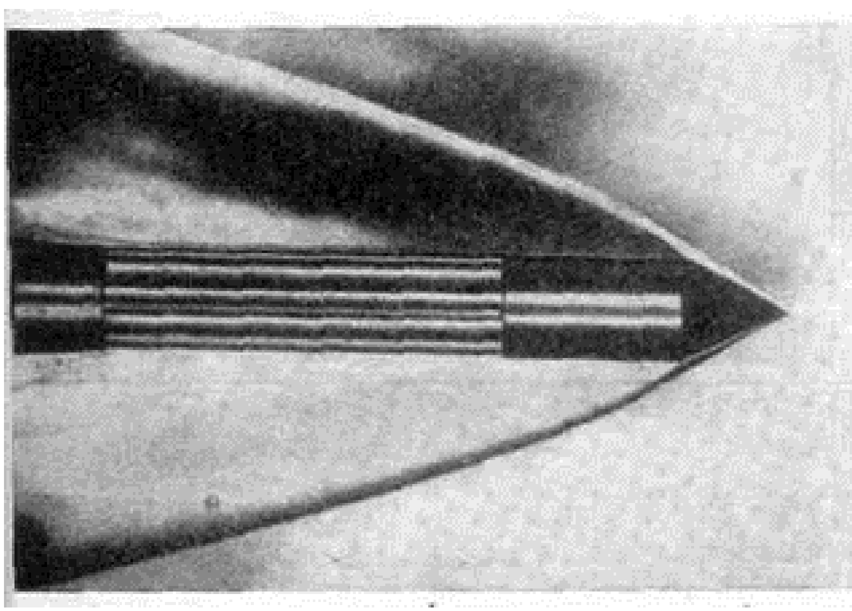
Matthias Hoffmann, http://mpsd-cmd.cfel.de/research-met-thz-optrect.html

Moving charge in a medium

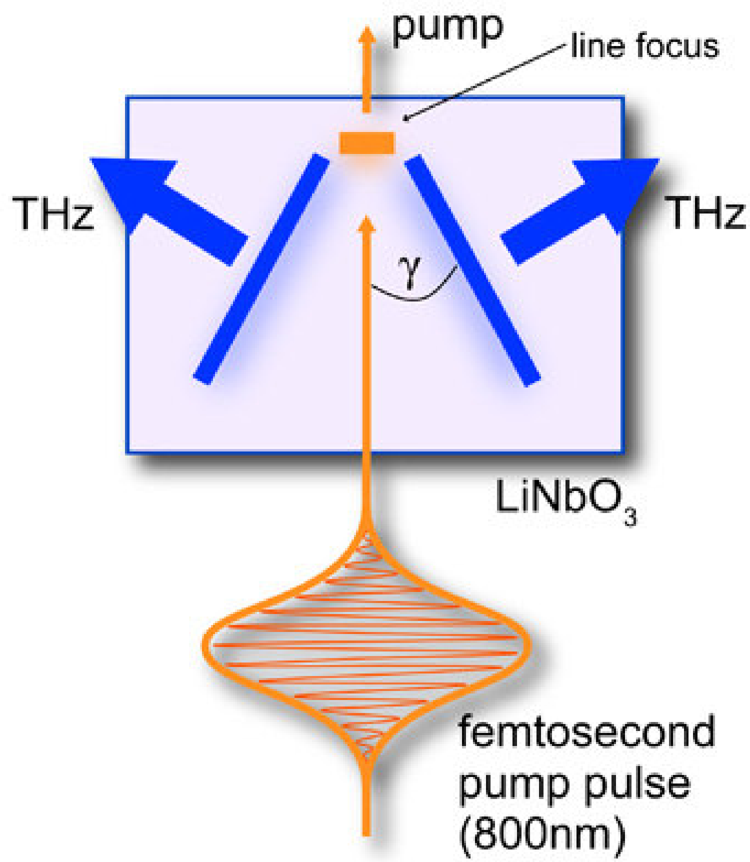


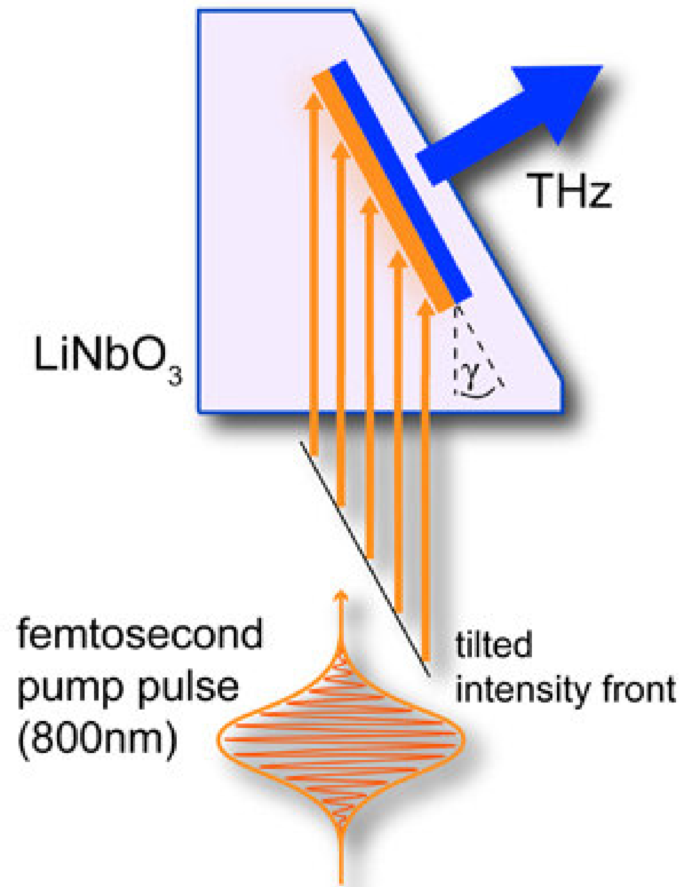


$$\upsilon > \upsilon_{ph}$$
$$\beta > 1/n$$



Phase matching





$$\cos\gamma = n_{gr}^{vis} / n_{ph}^{THz}$$

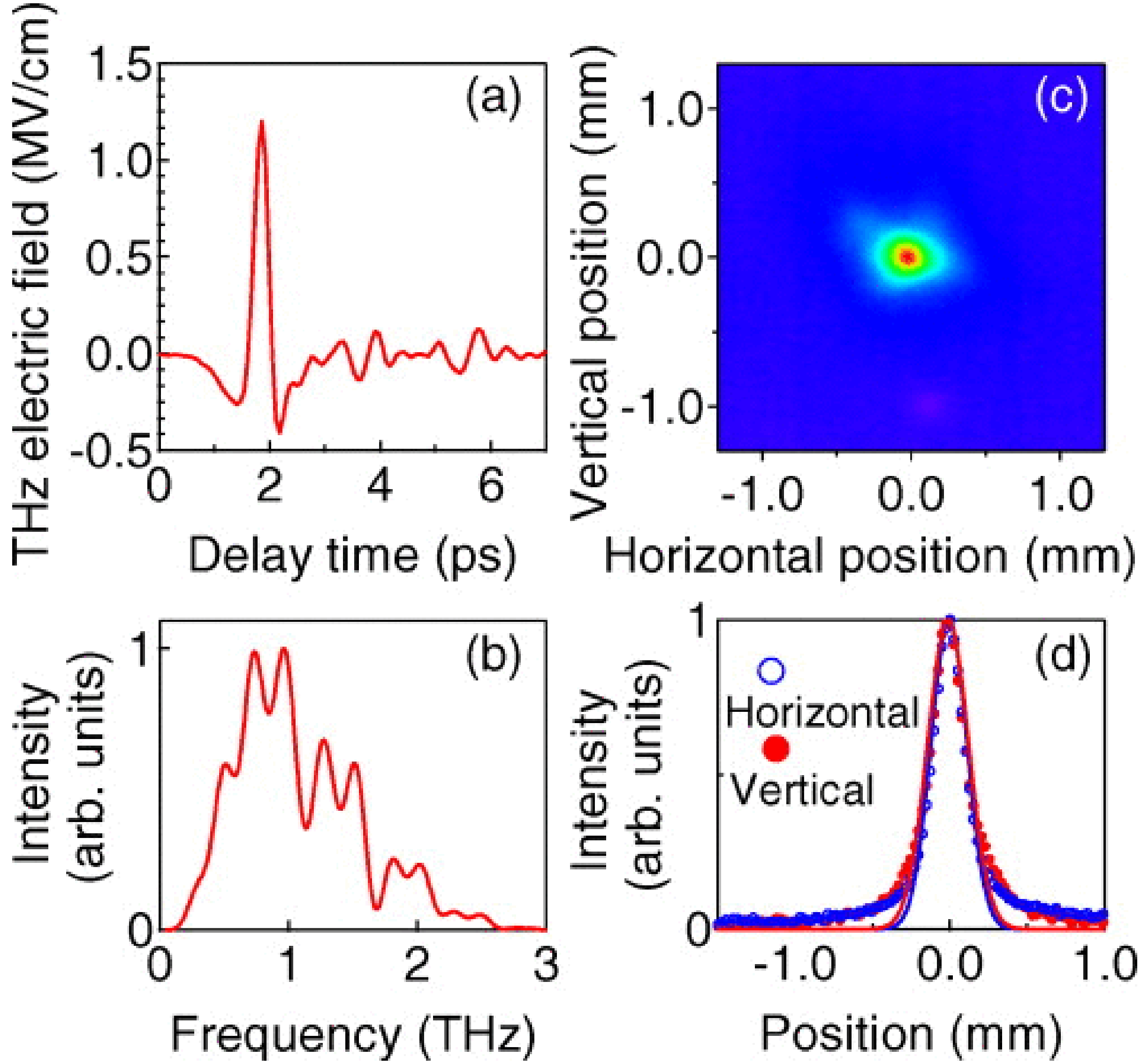
By tilting the optical pulse front, one achieves coherent build up of a THz wave with a long interaction length.

Matthias Hoffmann, http://mpsd-cmd.cfel.de/research-met-thz-optrect.html

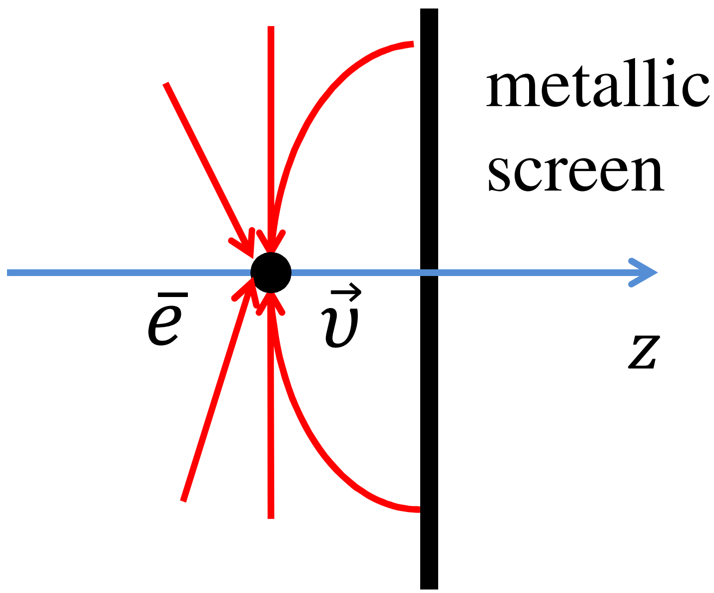
APPLIED PHYSICS LETTERS **98**, 091106 (2011)

Single-cycle terahertz pulses with amplitudes exceeding 1 MV/cm generated by optical rectification in $LiNbO_3$

H. Hirori,[1,2,a)] A. Doi,[2,3] F. Blanchard,[1,2] and K. Tanaka[1,2,4]



Generation of THz pulses through transition radiation



$$p_z = -2evt \ (t < 0),$$

$$p_z = 0 \quad \text{for} \quad t \geq 0,$$

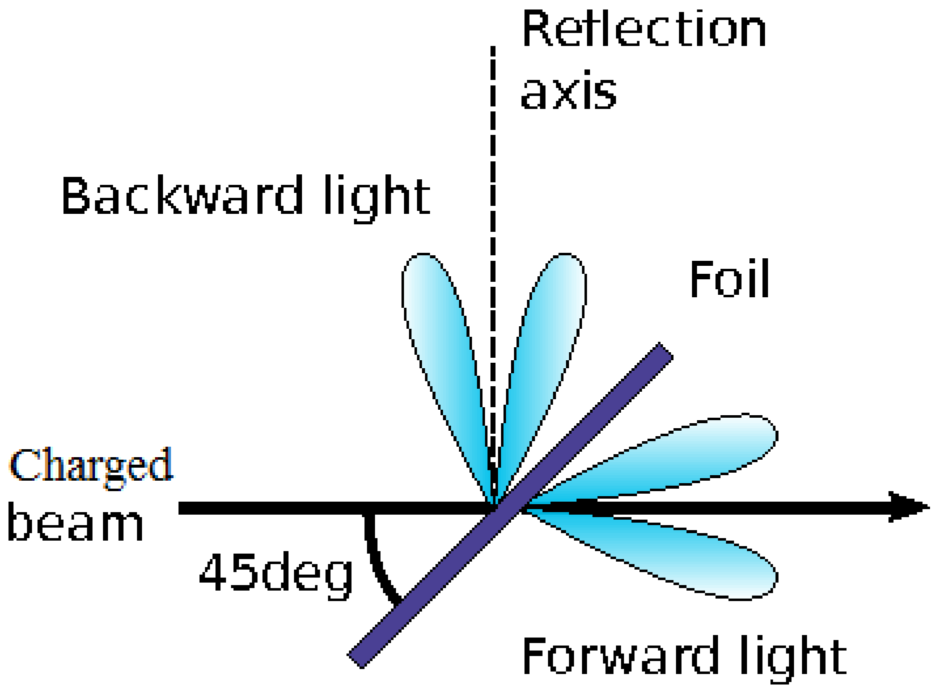
$$\ddot{p}_z = -2ev\delta(t).$$

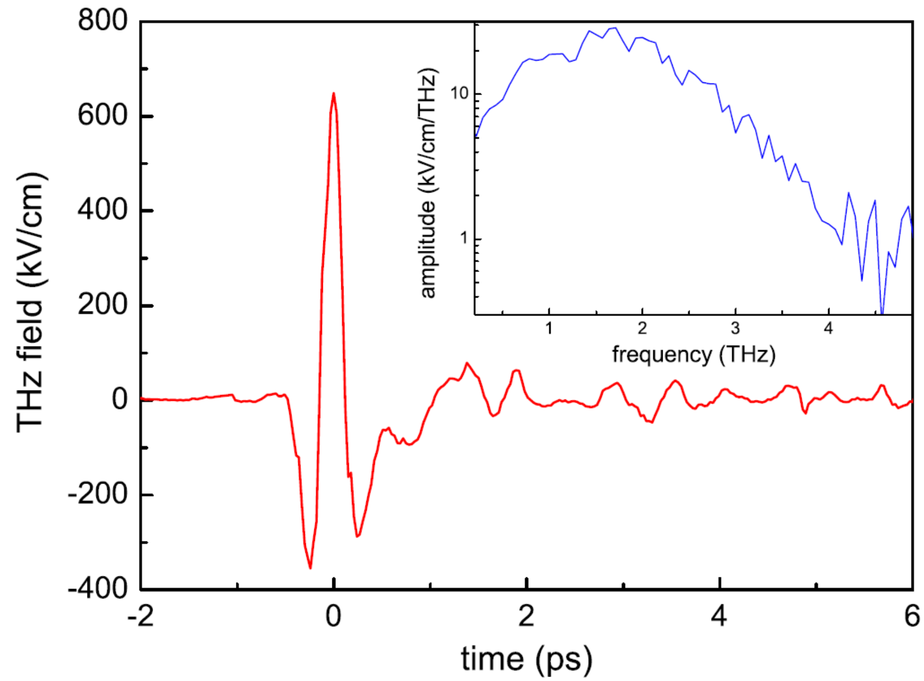
- **Transition radiation** is produced by relativistic charged particles when they cross the interface of two media of different dielectric constants.
- Since the electric field of the particle is different in each medium, *the particle has to "shake off" photons when it crosses the boundary.*

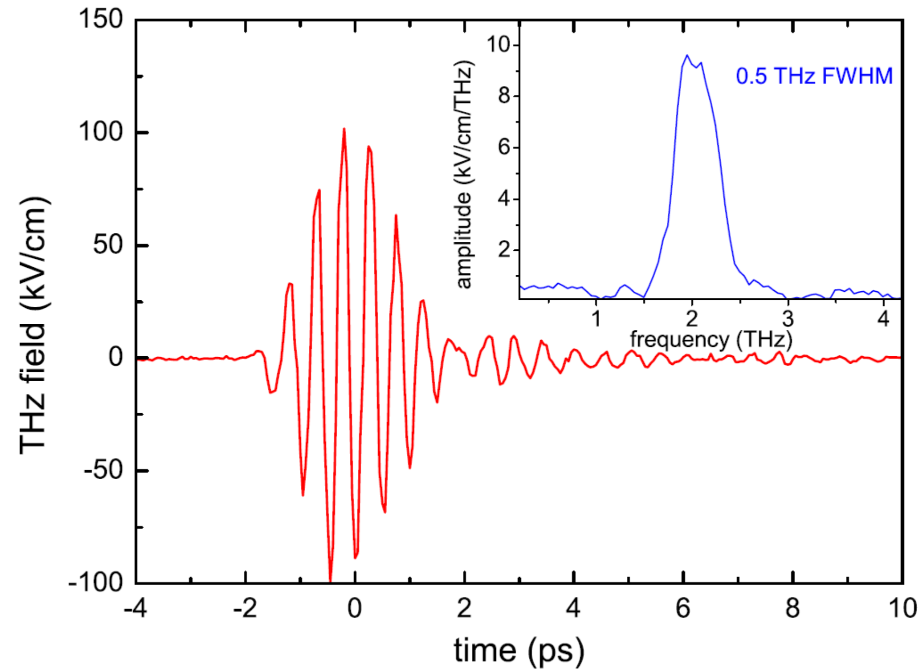
The energy emitted
in the spectral range Δf reads

$$W \approx \Delta\omega \frac{e^2}{\pi c}[2 \log 4\gamma - 1] \qquad \gamma = \frac{1}{\sqrt{1 - v^2/c^2}}$$

Single-cycle THz pulses at DESY: 1 MV/cm





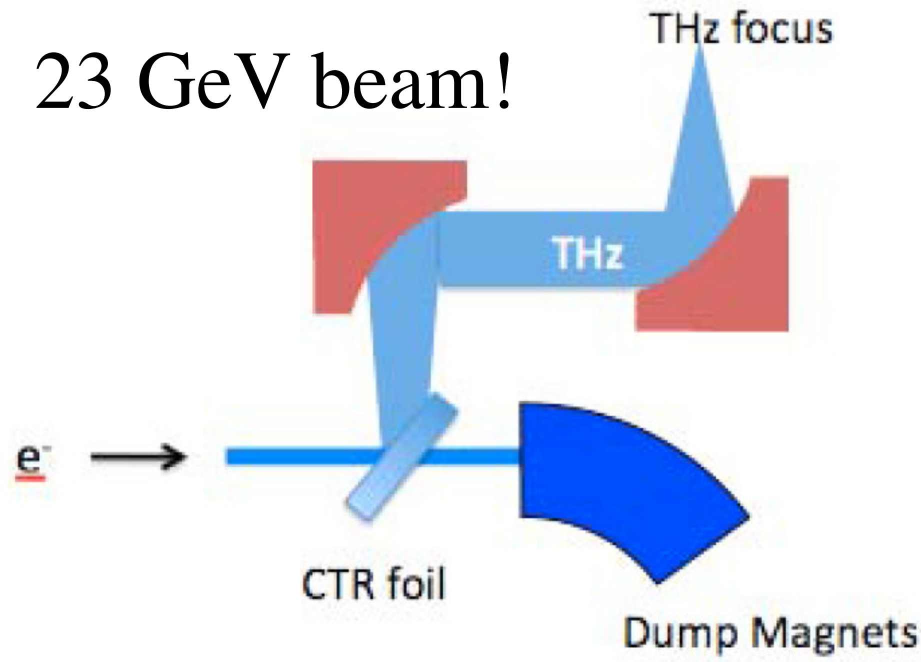


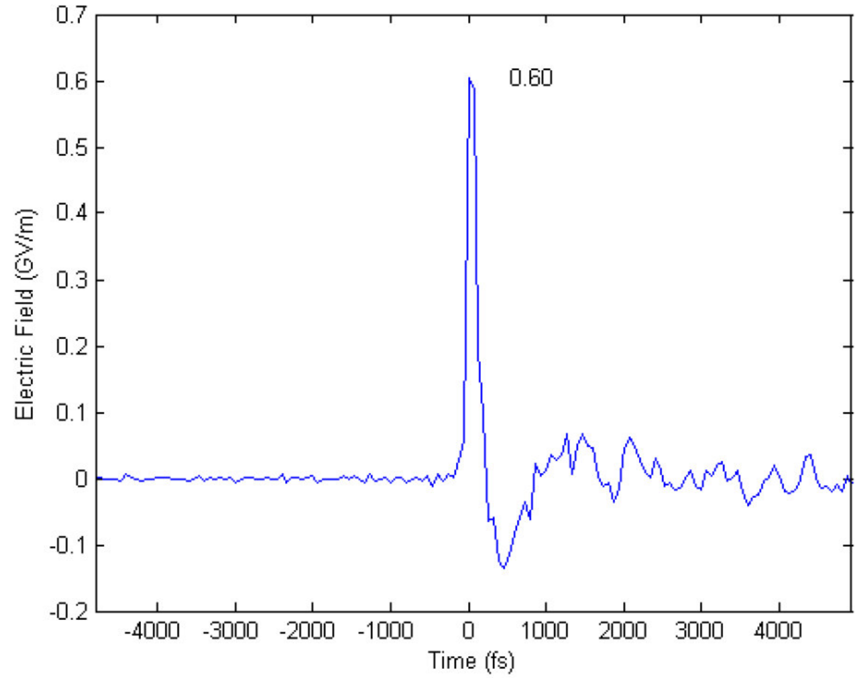
- energies up to 100 μJ
- electric fields up to 1MV/cm
- a frequency band from 200 GHz to 100 THz

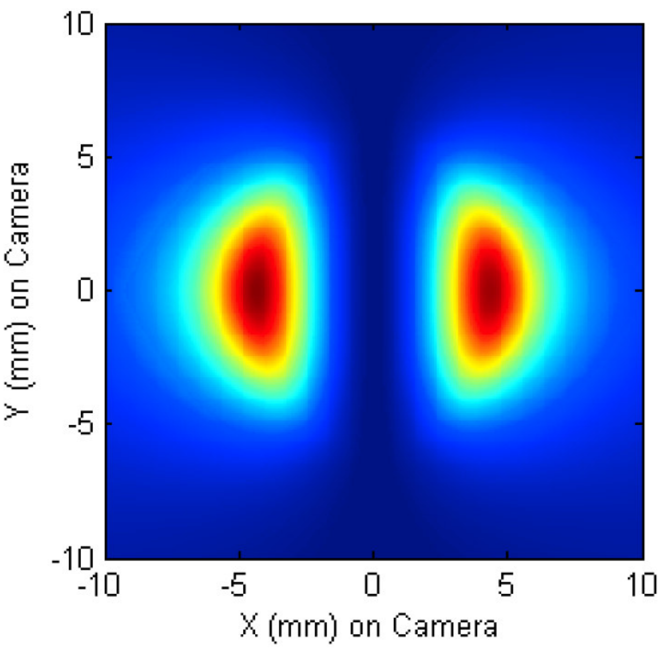
M. Hoffmann et al.,
Vol. 36, No. 23 / OPTICS LETTERS 4473

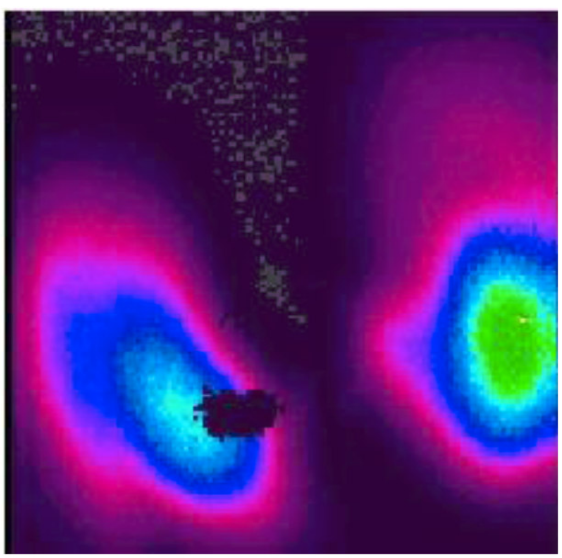
Single-cycle THz pulses at FACET/SLAC: 6 MV/cm

23 GeV beam!









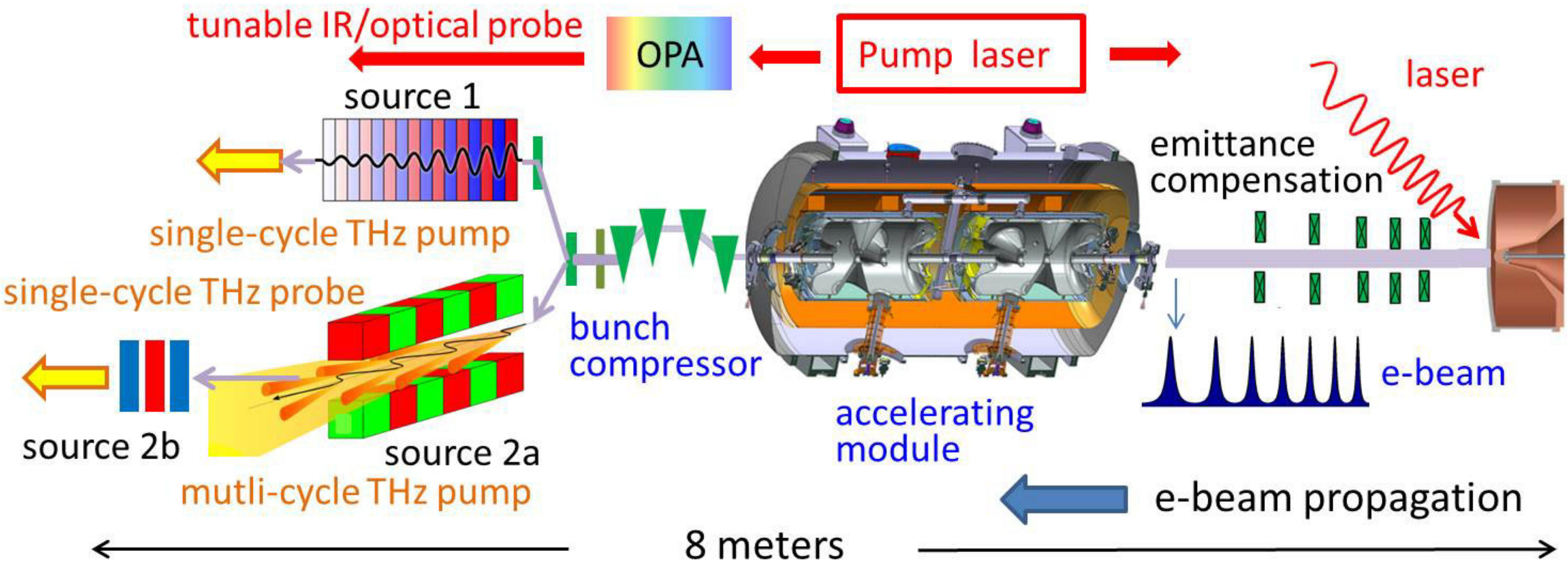
Proposal for a THz Light Source in Uppsala

Wish list for intense THz radiation.

Parameter	Quasi-half-cycle pulses for time-resolved experiments	Narrowband pulses for frequency-resolved experiments
Spectral range (THz)	1.5-15	1.5-15
Pulse duration (ps)	0.1-1	1-10
Pulse energy (mJ)	1000	100
Peak electric field (GV/m)	1	0.1
Relative bandwidth FWHM	100%	10%
Repetition rate (kHz)	1-100	1-100

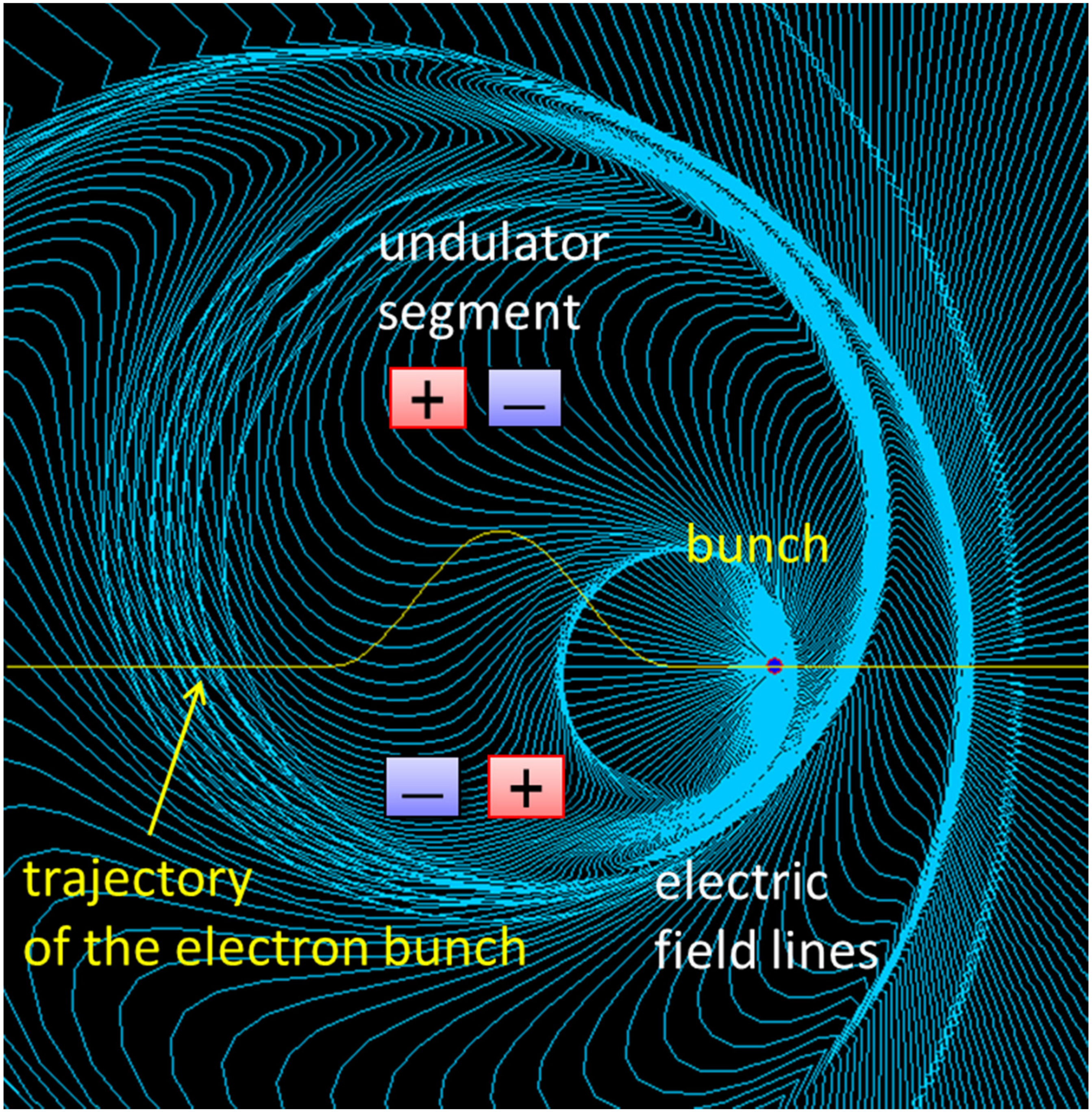
+ Polarization control, pump-probe configuration

The source

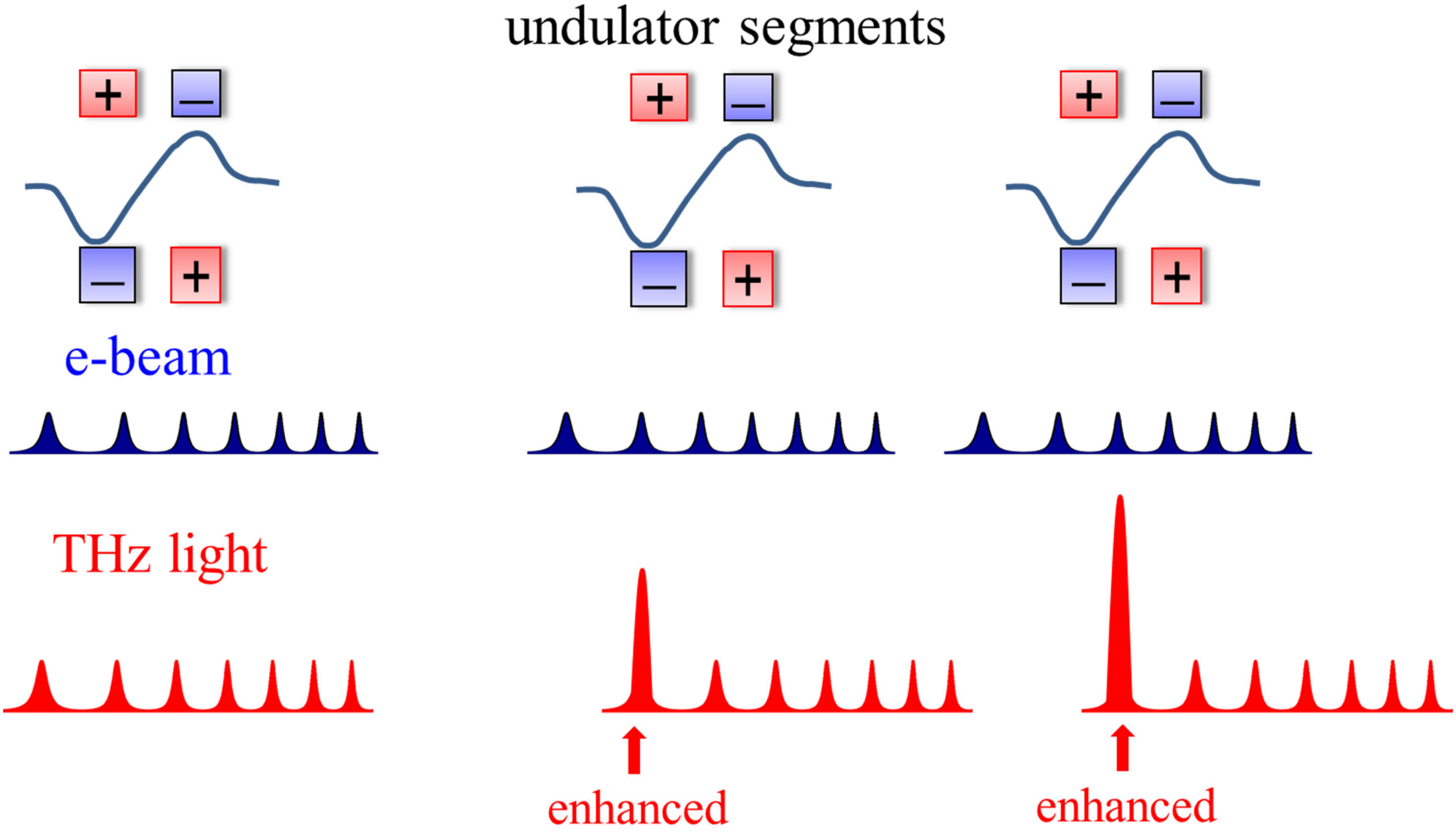


- it covers the spectral range from 5 to 15 THz, exceeding that of laser-based sources;
- polarization variable from linear to circular or elliptical;
- tunability of the central frequency and bandwidth;
- mutli-kilohertz repetition rate;
- light carrying orbital angular momentum.

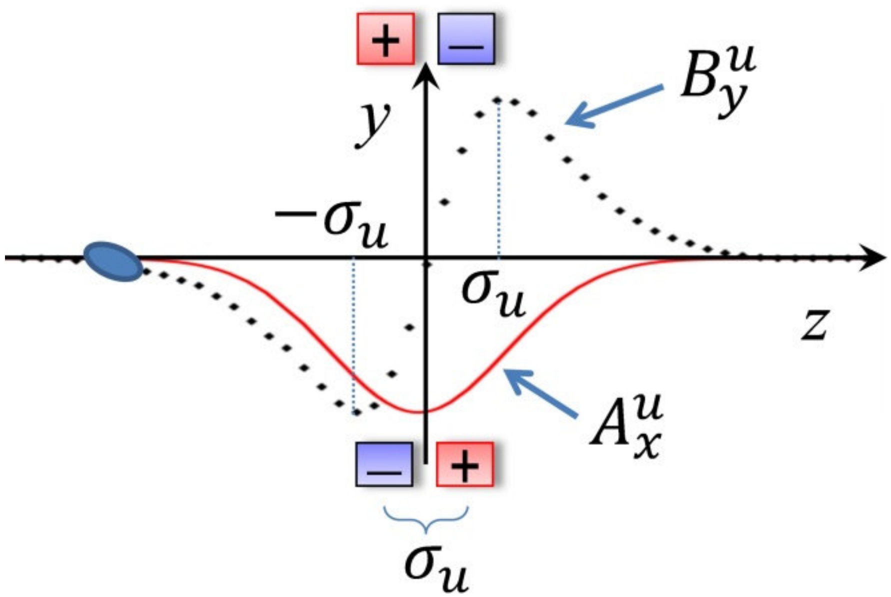
Single-cycle synchrotron radiation

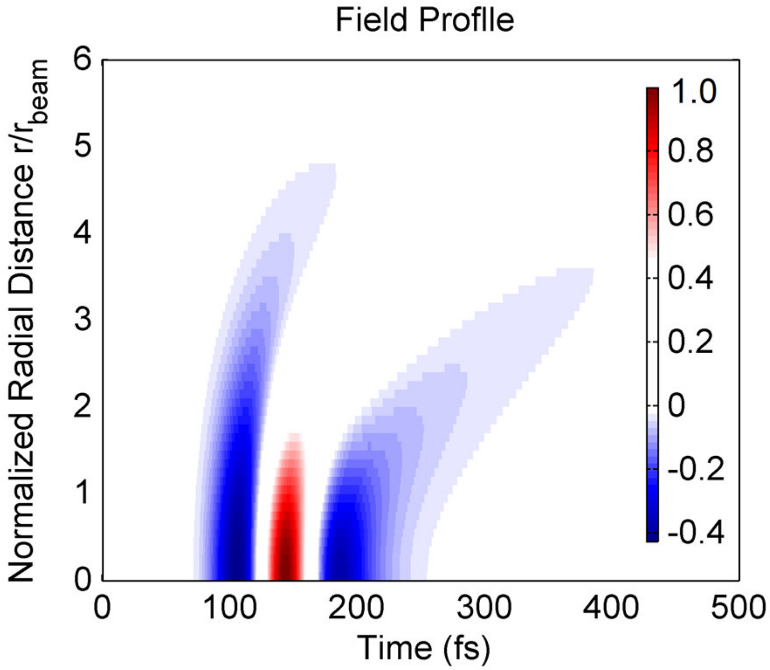


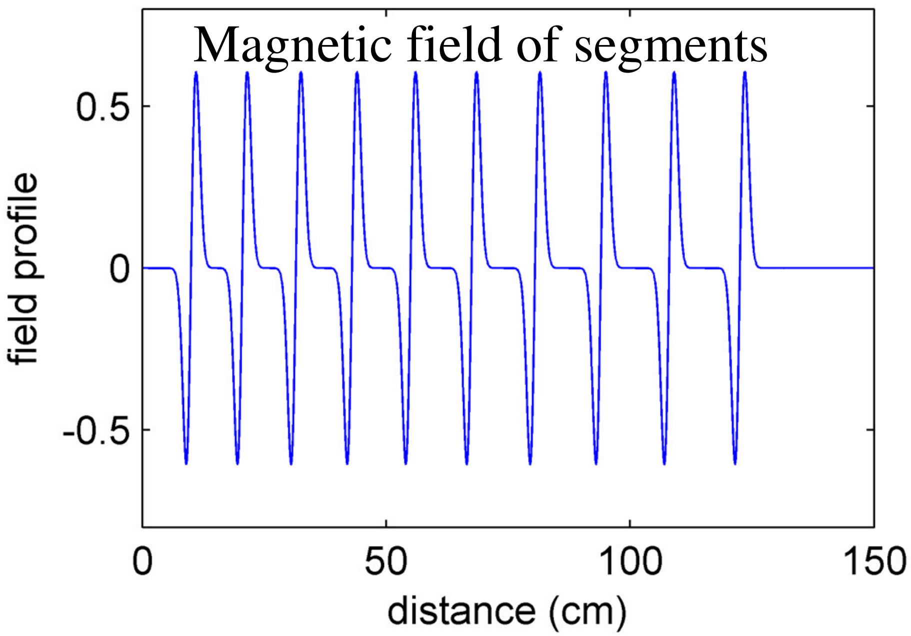
Single-cycle radiation from a segmented undulator

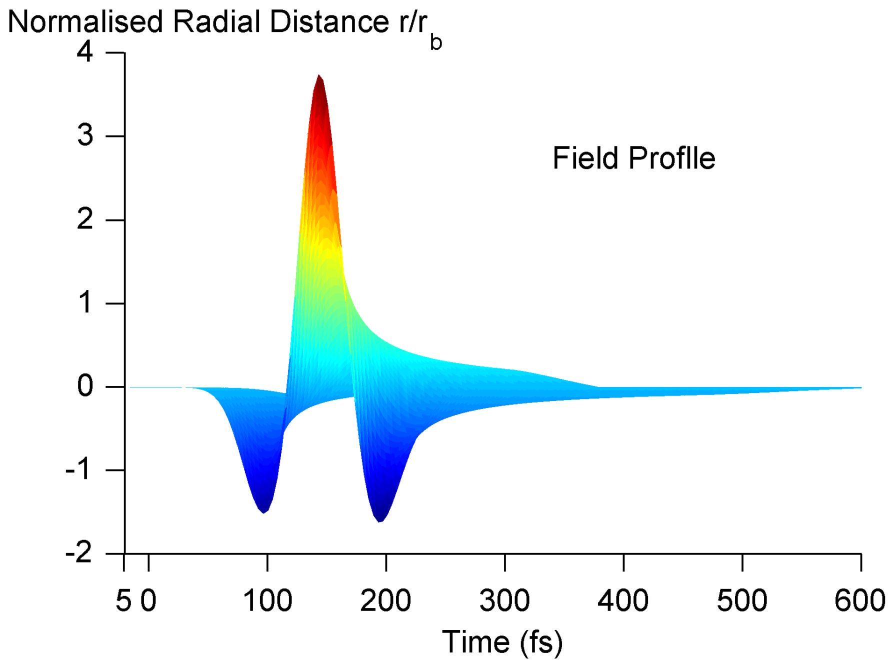


Single-cycle radiation from a segmented undulator: cont'd





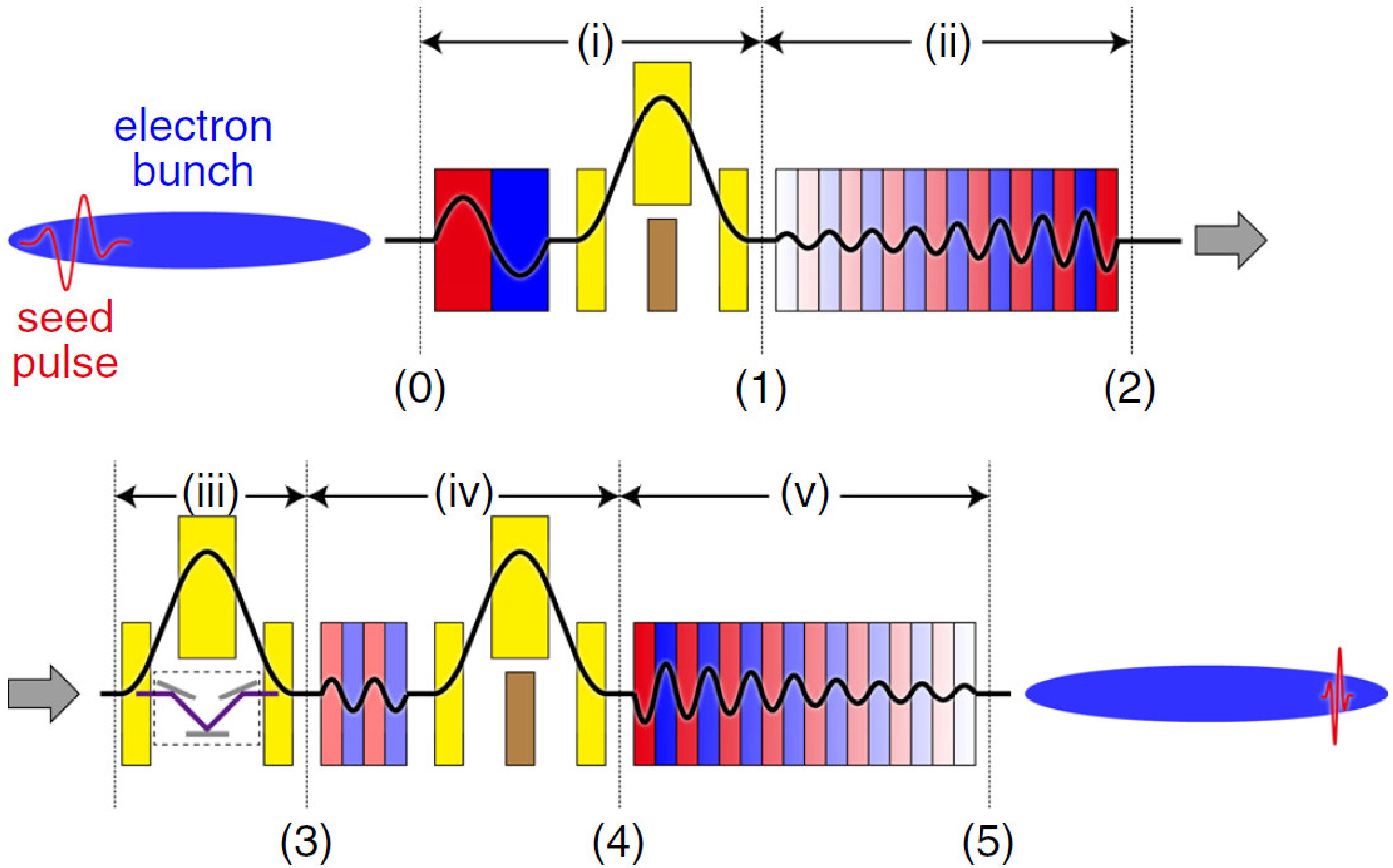




PRL 114, 044801 (2015) PHYSICAL REVIEW LETTERS week ending 30 JANUARY 2015

Proposal to Generate an Isolated Monocycle X-Ray Pulse by Counteracting the Slippage Effect in Free-Electron Lasers

Takashi Tanaka*



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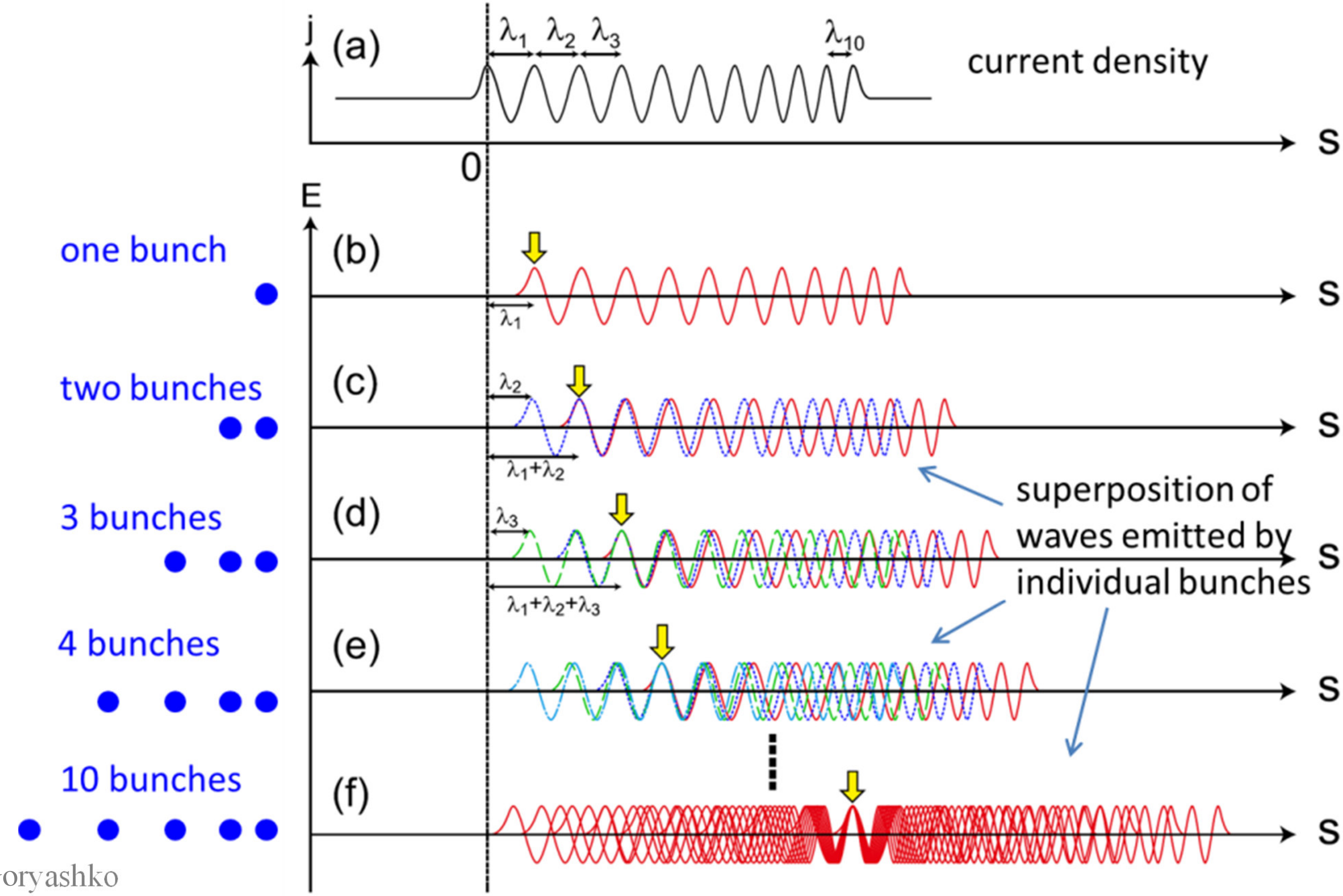
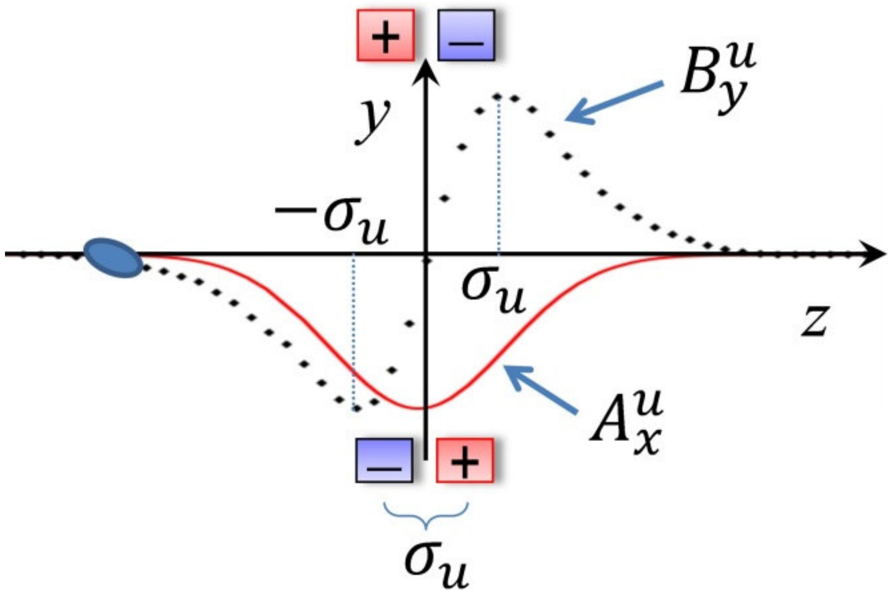
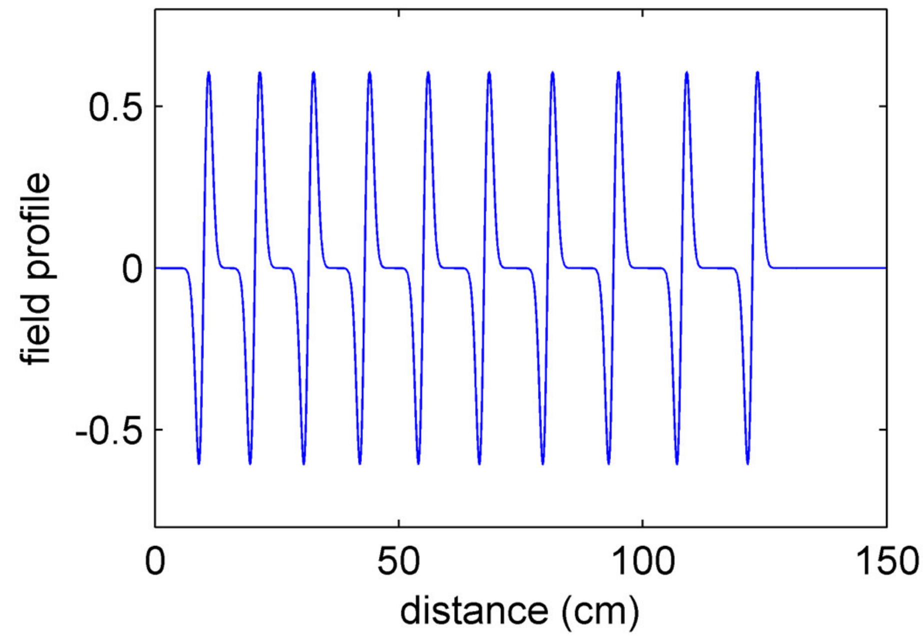
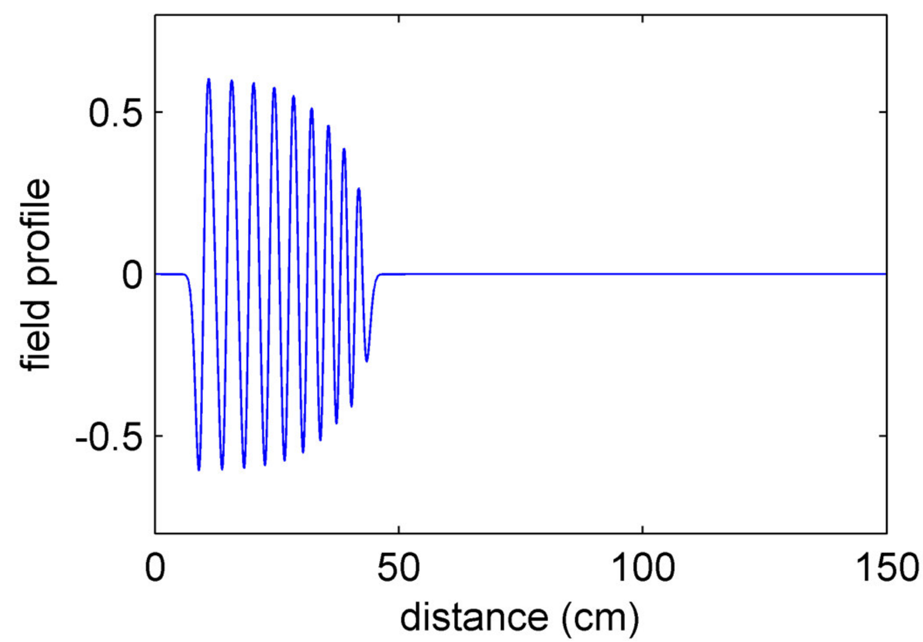


Single-cycle radiation from a segmented undulator

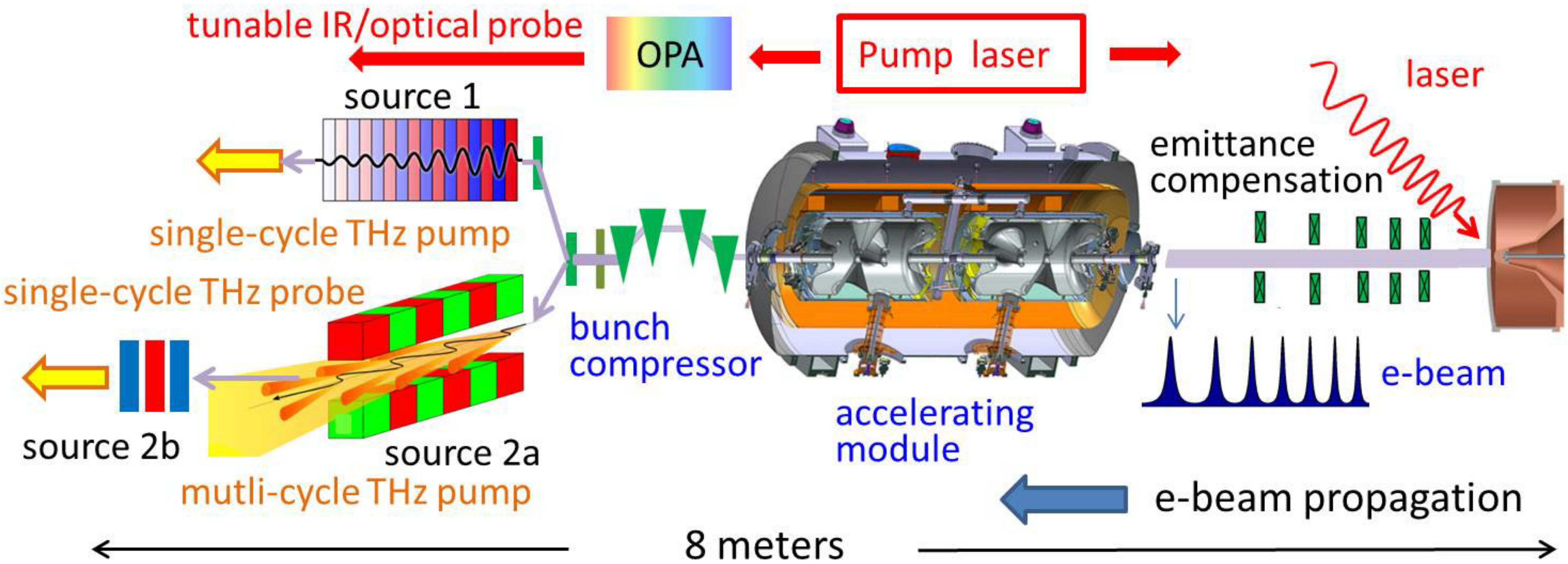




If instead of increasing the distance between the segments I will decrease it,
I will recover Takashi's tapered undulator.



The source



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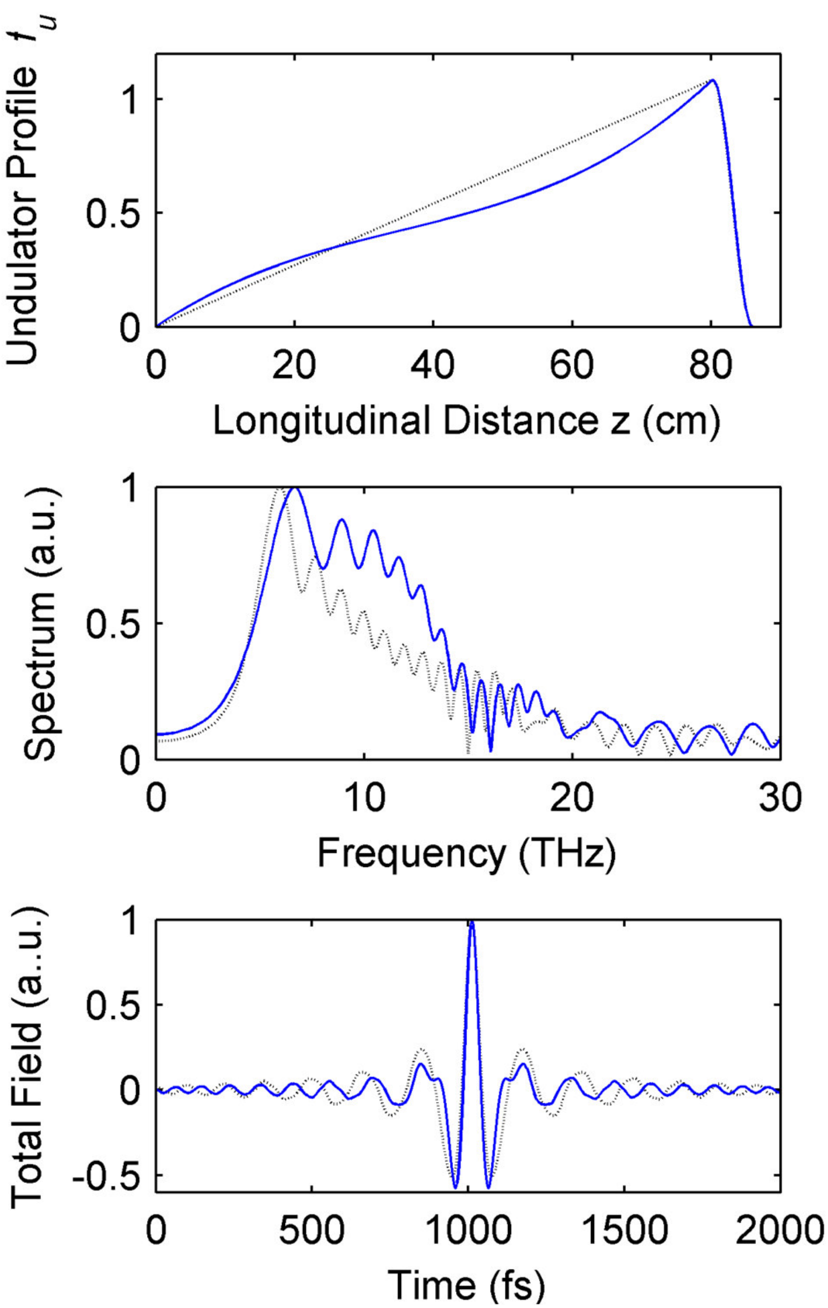
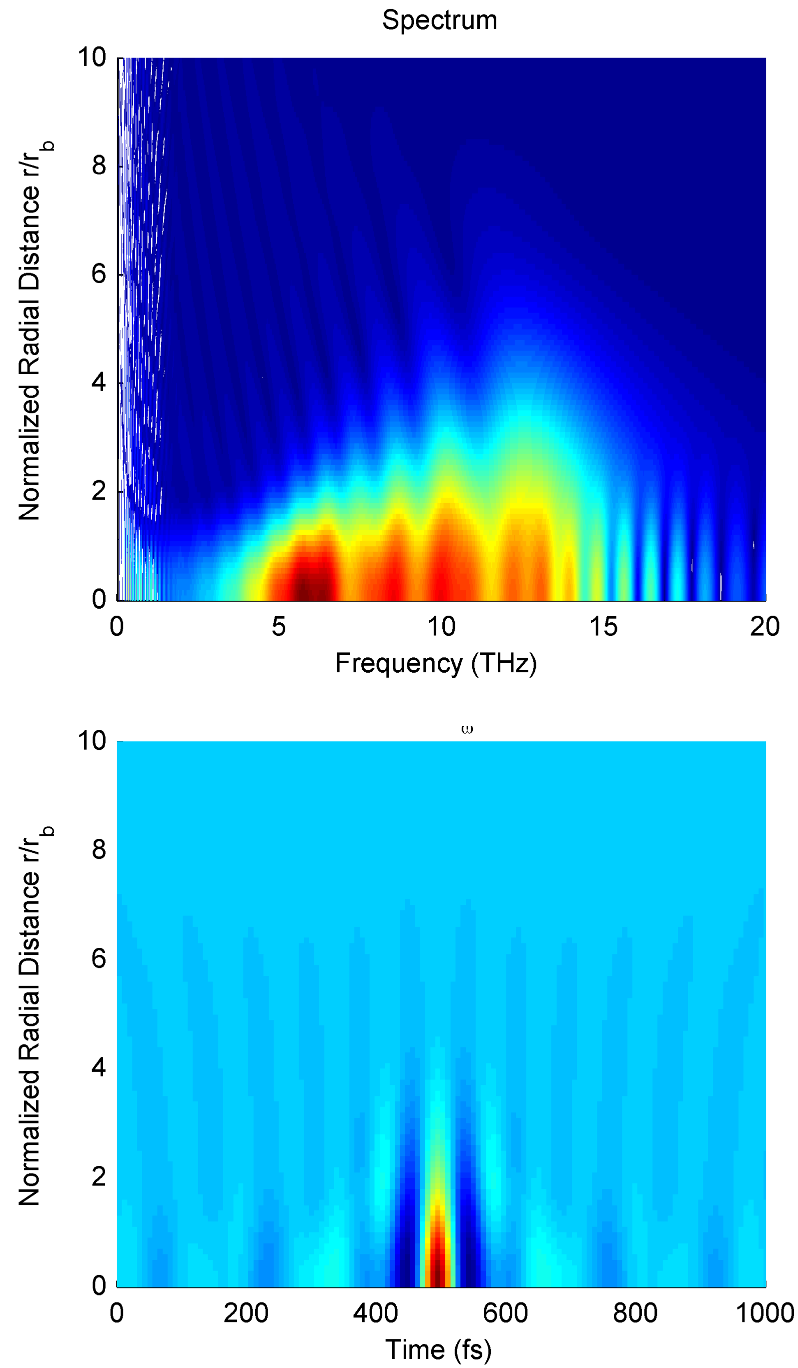
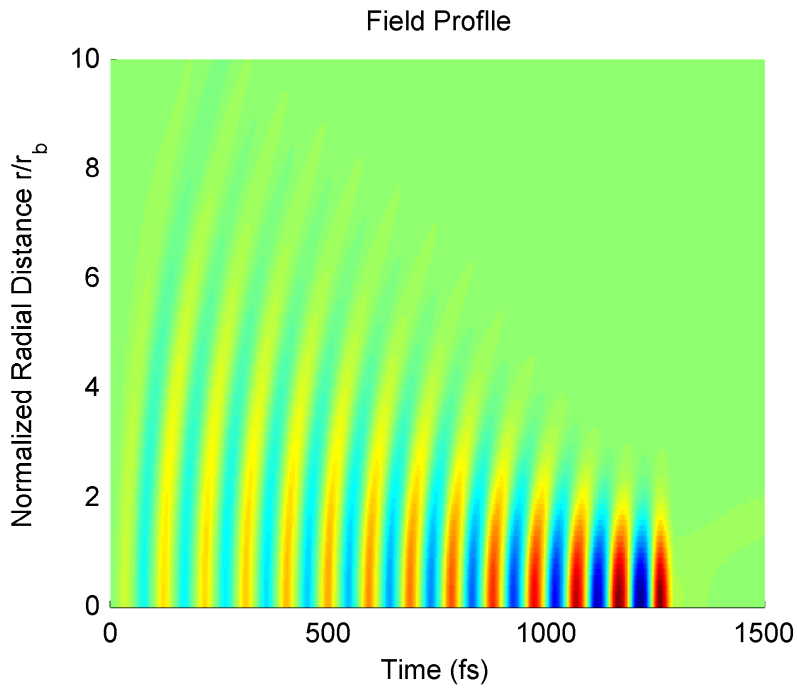
Source 1: quasi-half-cycle pulses

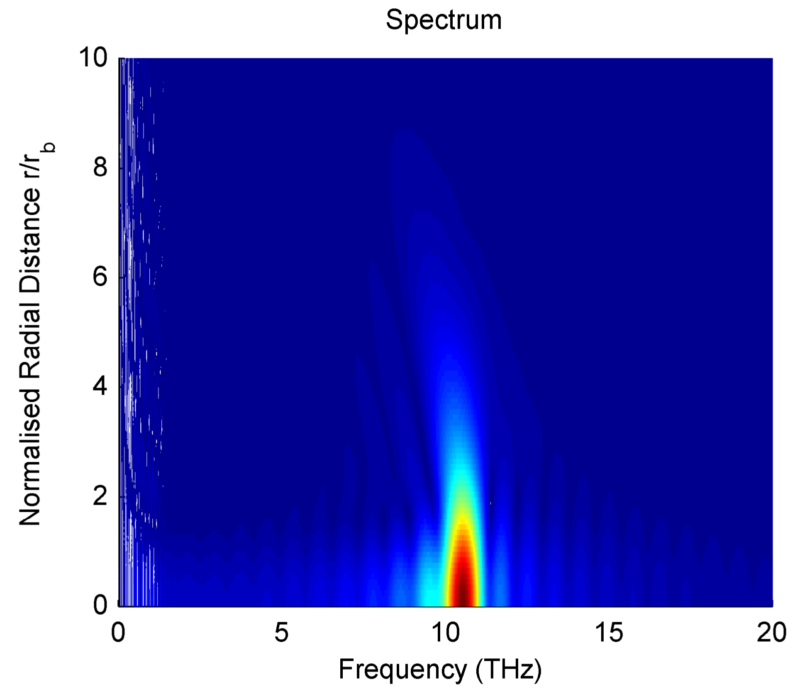




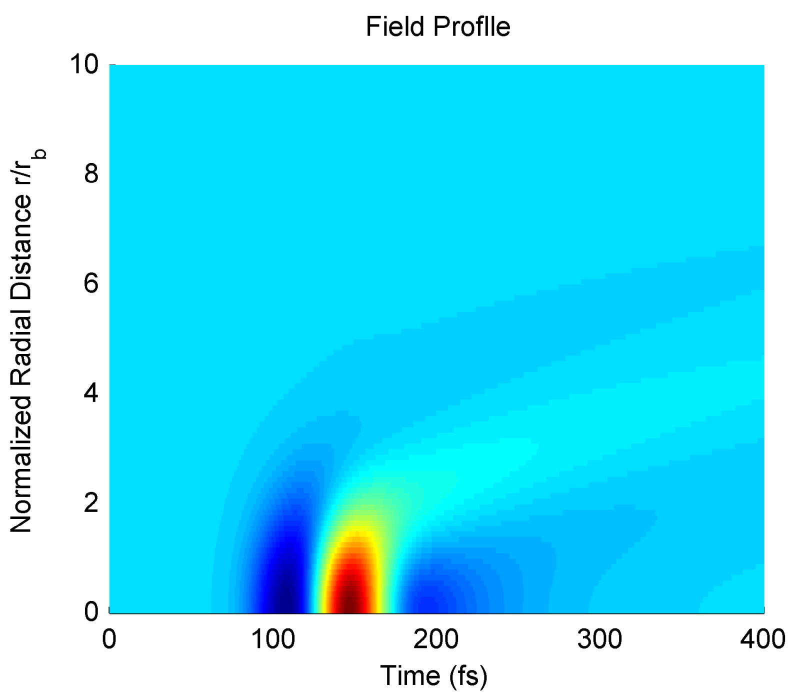
Source 2: multi-cycle pump and single-cycle probe

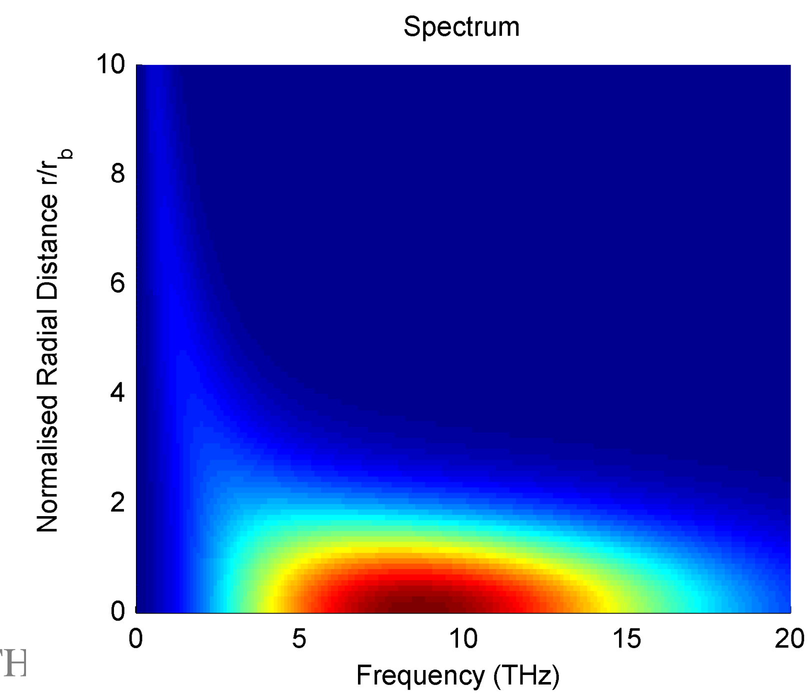
Source 2a





Source 2b





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