STOCKHOLM-UPPSALA CENTRE FOR FREE ELECTRON LASER RESEARCH

UPPSALA UNIVERSITET

Controlling matter with single-cycle pulses of THz light

Vitaliy Goryashko

2017

What, Why and How

Accelerator physics in Uppsala

Control of matter with THz light

- Overview of low-energy collective excitations
- Switching on and off spin-waves in antiferromagnets
- Switching between conducting and insolating states
- 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

Uppsala University

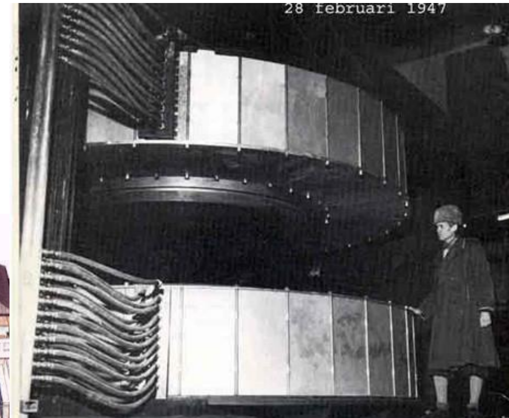
Oldest university in Scandinavia (1477)

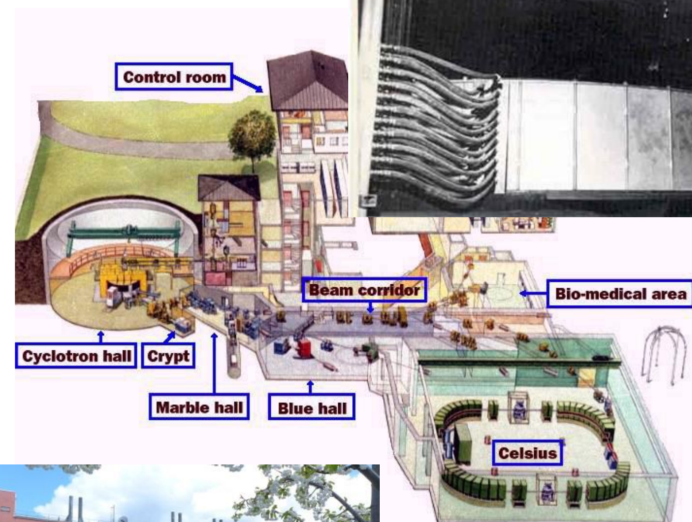
- Sweden
  - 10 million (pop.), 450'000 km^2, 500 GEur (BNP)
- Uppsala
  - 25'000 students, 9'000 staff, 630 MEur annual budget
  - faculties of theology, law, medicin, pharmacy, arts, social sciences, languages, educational sciences,
    science and technology
  - university library and hospital
- Science and technology
  - 10'000 students, 1'800 staff
  - historical profiles: Linnaeus, Rudbeck, Celsius, Ångström, Siegbahn, Svedberg
  - R&D areas
    - physics, chemistry, biology, earth sciences, engineering, mathematics, IT

Accelerator physics in Uppsala

1940's: Theodore Svedberg proposes to build a cyclotron

- Gustaf Werner synchro-cyclotron (1947 – present)
  - nuclear physics & cancer treatment
- CELSIUS ring (1984 – 2005)
  - nuclear physics
- External
  - CTF3/CLIC at CERN (since 2005)
  - FLASH/XFEL at DESY (since 2008)
  - ESS (since 2009)
- FREIA laboratory (since 2011)
- Skandion clinic (2015)
  - cancer treatment





European Spallation Source (ESS), Sweden

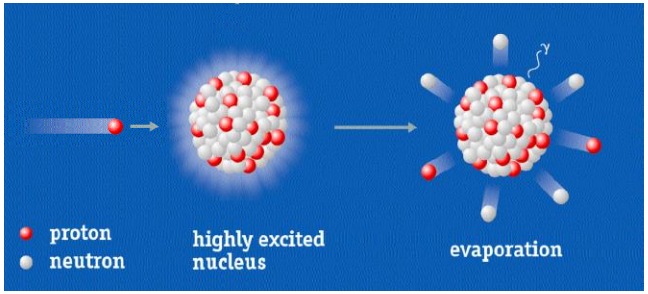
The European Spallation Source (ESS)

- Lund, Sweden, next to MAX-IV
  - to replace aging research reactors
  - 2019 first neutrons
  - 2019 – 2025 consolidation and operation
  - 2025 – 2040 operation

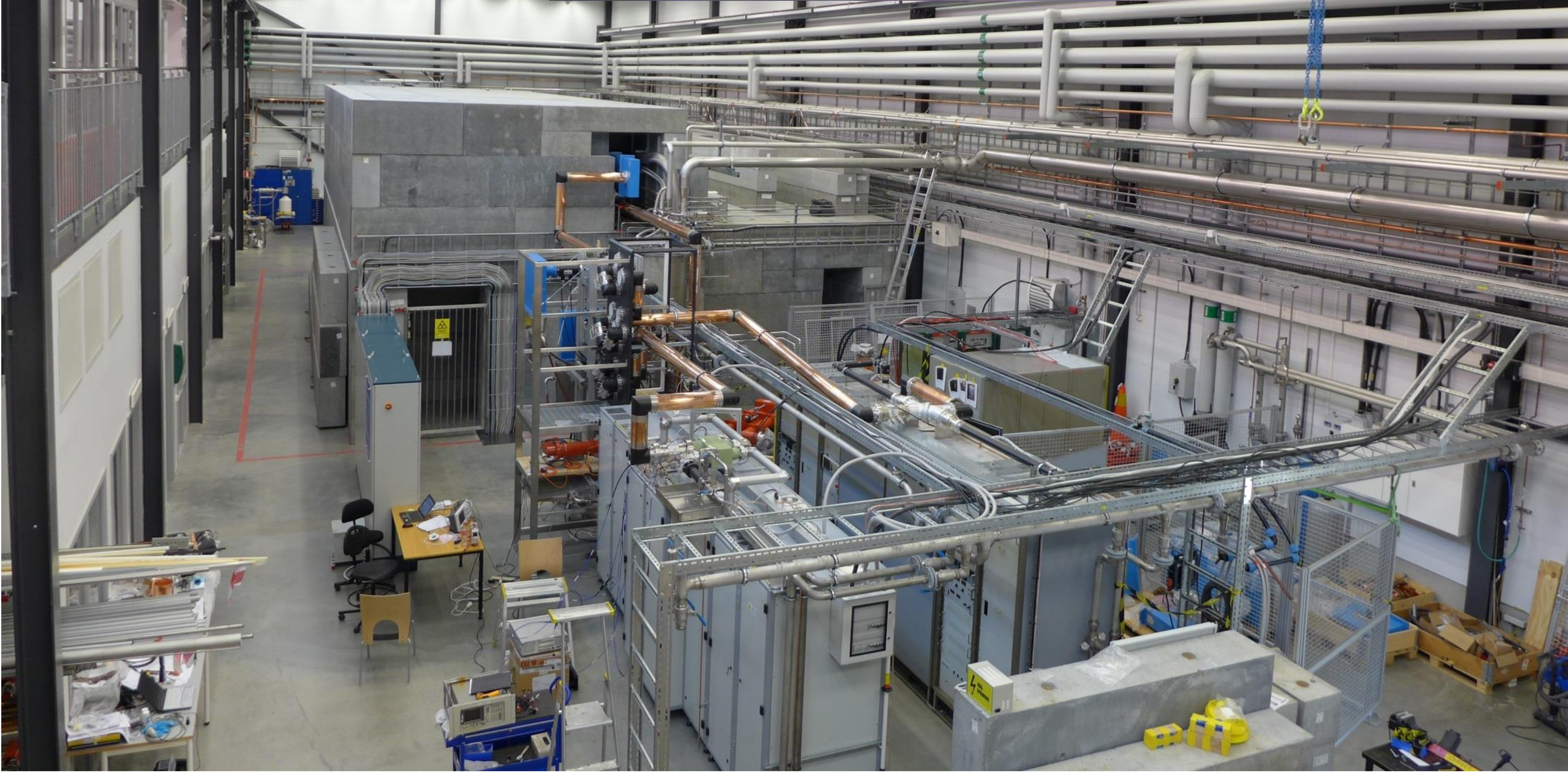
- 5 MW pulsed cold neutron source, long pulse
  - 14 Hz rep. rate, 4% duty factor
  - >95% reliability for user time
  - short pulse requires ring, but user demand satisfied by existing facilities (ISIS, SNS, J-PARC)

- High intensity allows studies of
  - complex materials, weak signals, time dependent phenomena

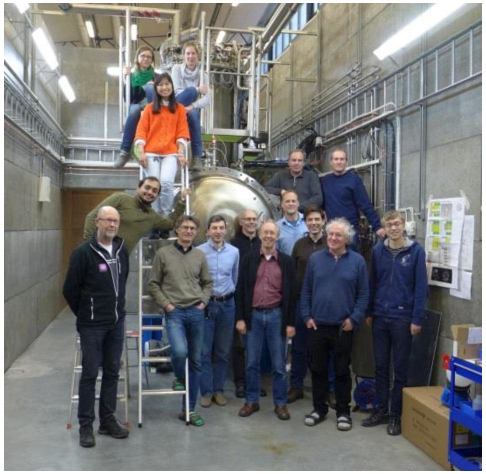
- Cost estimates (2008 prices)
  - 1,5 G€ / 10 years
  - 50% by Sweden, Denmark, Norway



FREIA



FREIA: Facility for Research Instrumentation & Accelerator Development



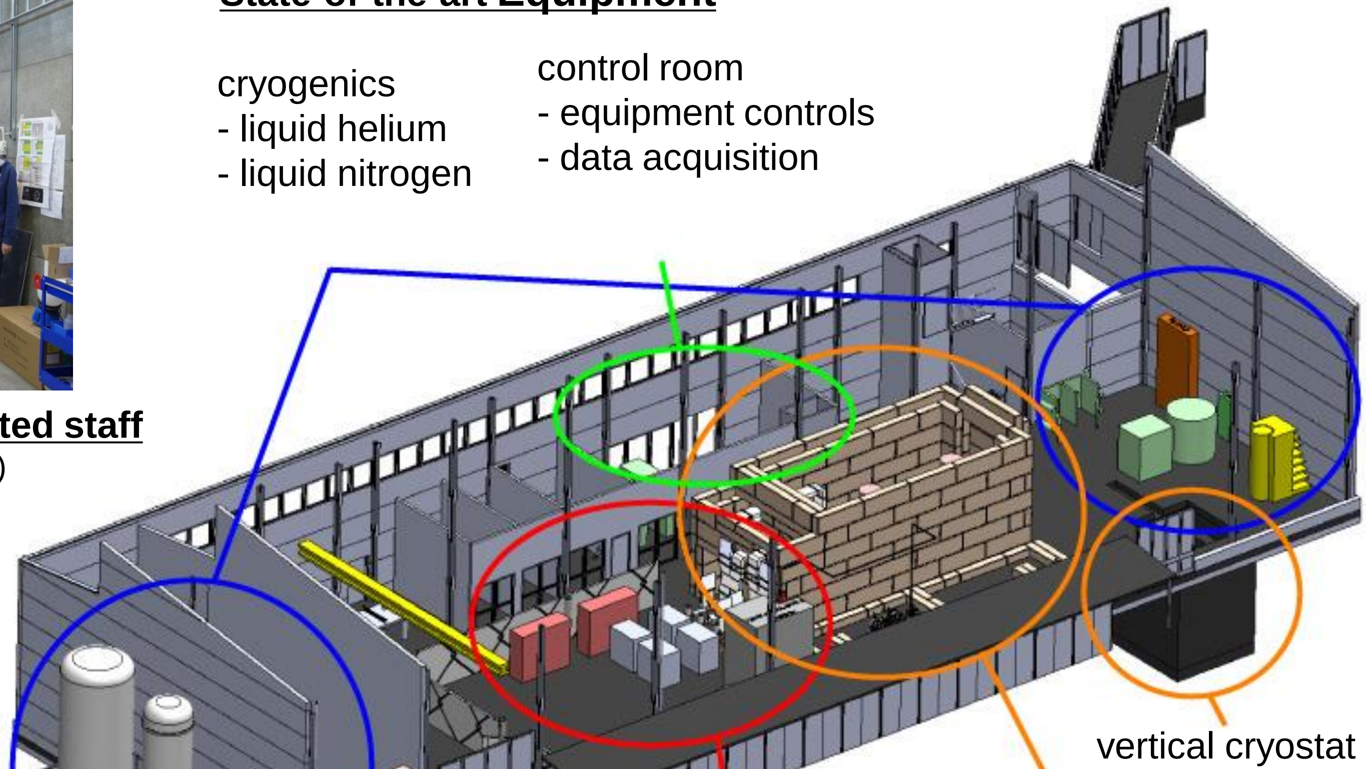
Competent and motivated staff
collaboration of physics (IFA)
and engineering (Teknikum).

Funded by KAWS, Government, Uppsala Univ.

State-of-the-art Equipment

cryogenics
- liquid helium
- liquid nitrogen

control room
- equipment controls
- data acquisition



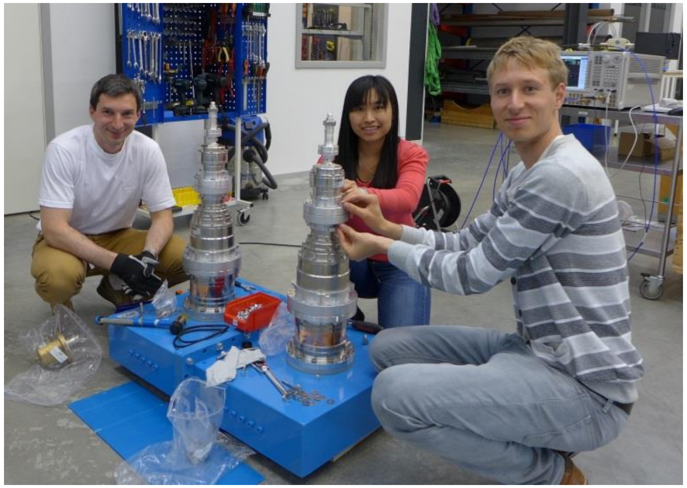
radio-frequency (RF) power sources

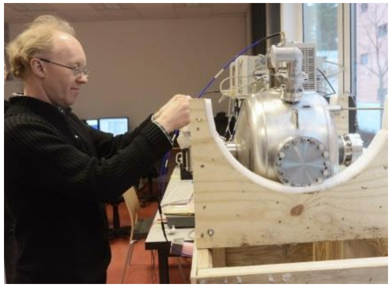
3 bunkers with test stands

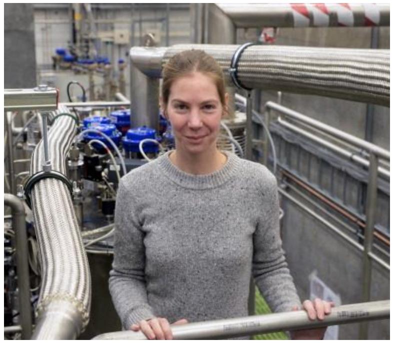
vertical cryostat

horizontal cryostat

Research and fun







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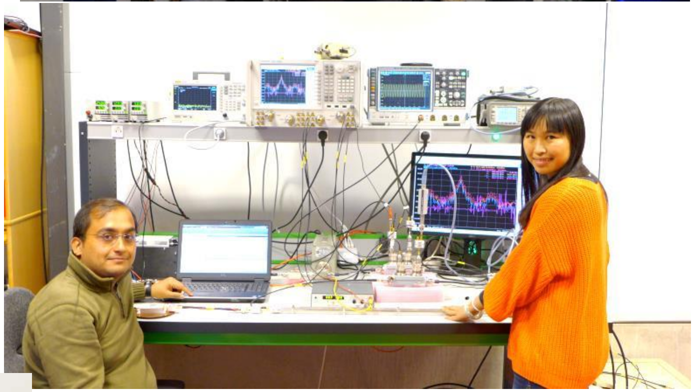
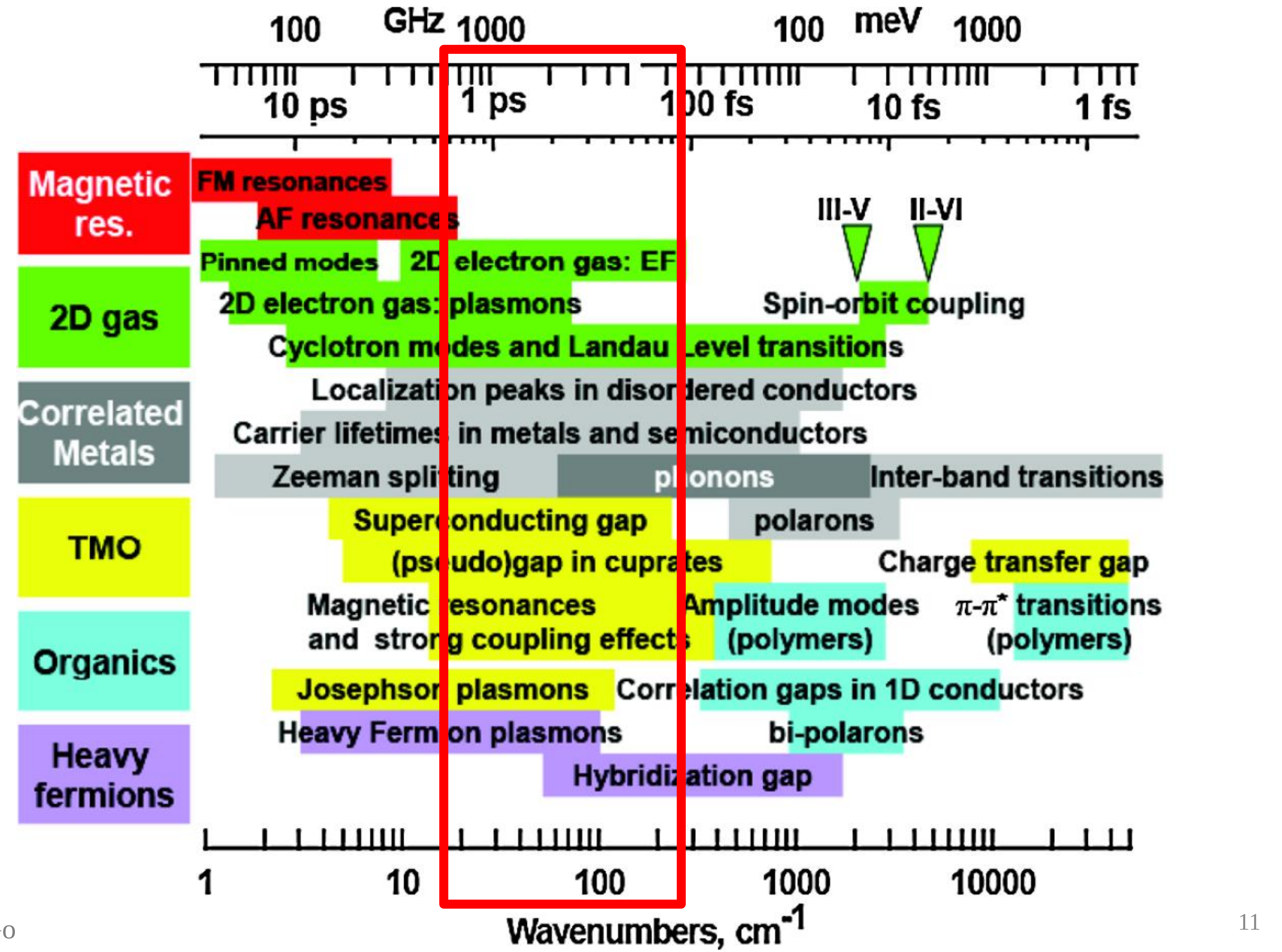


Control of matter with THz light

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

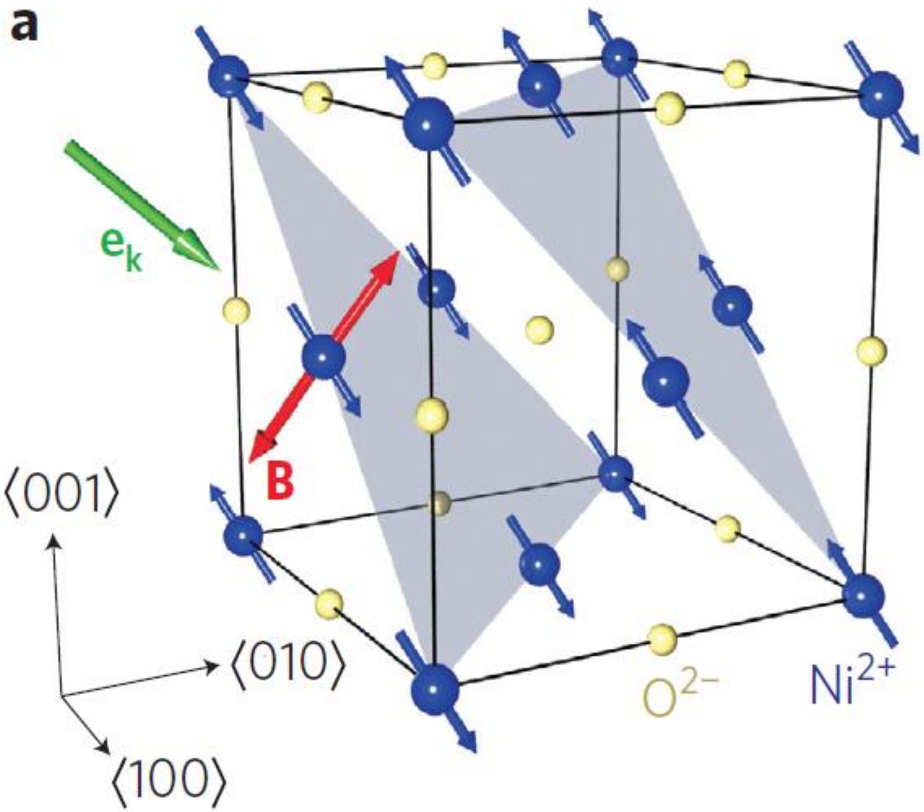


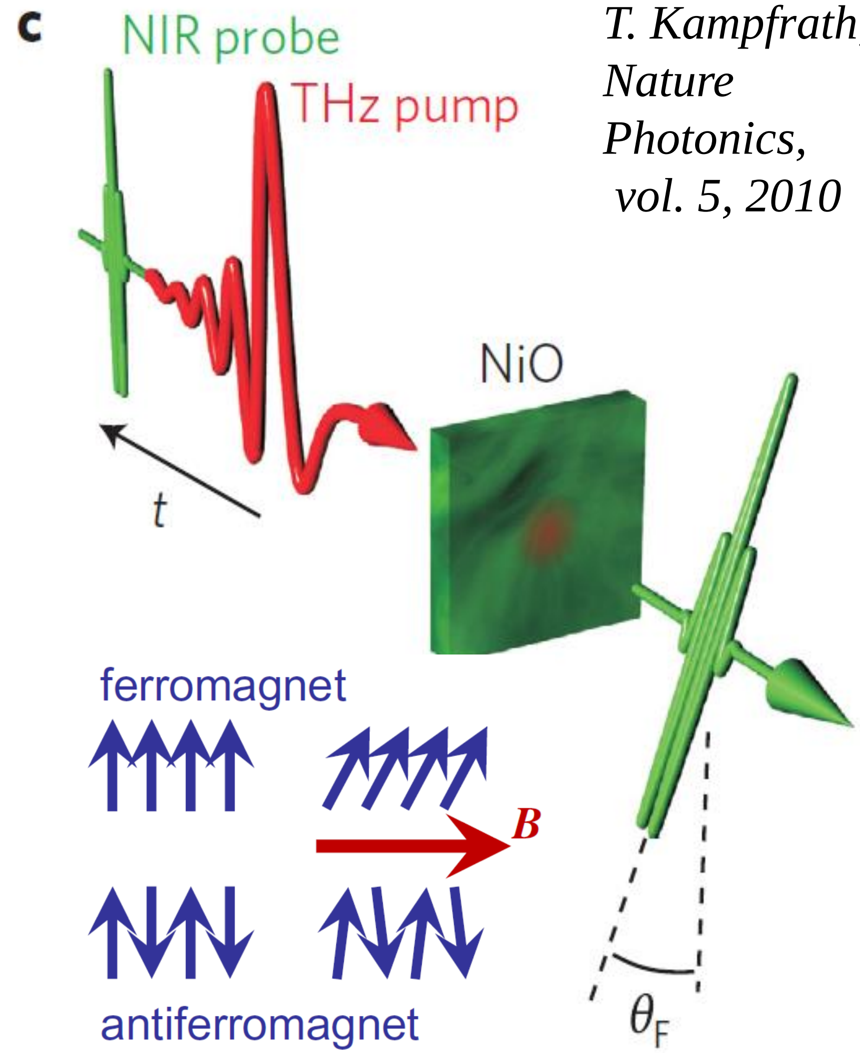
Beauty of ultra-short THz pulses

- 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



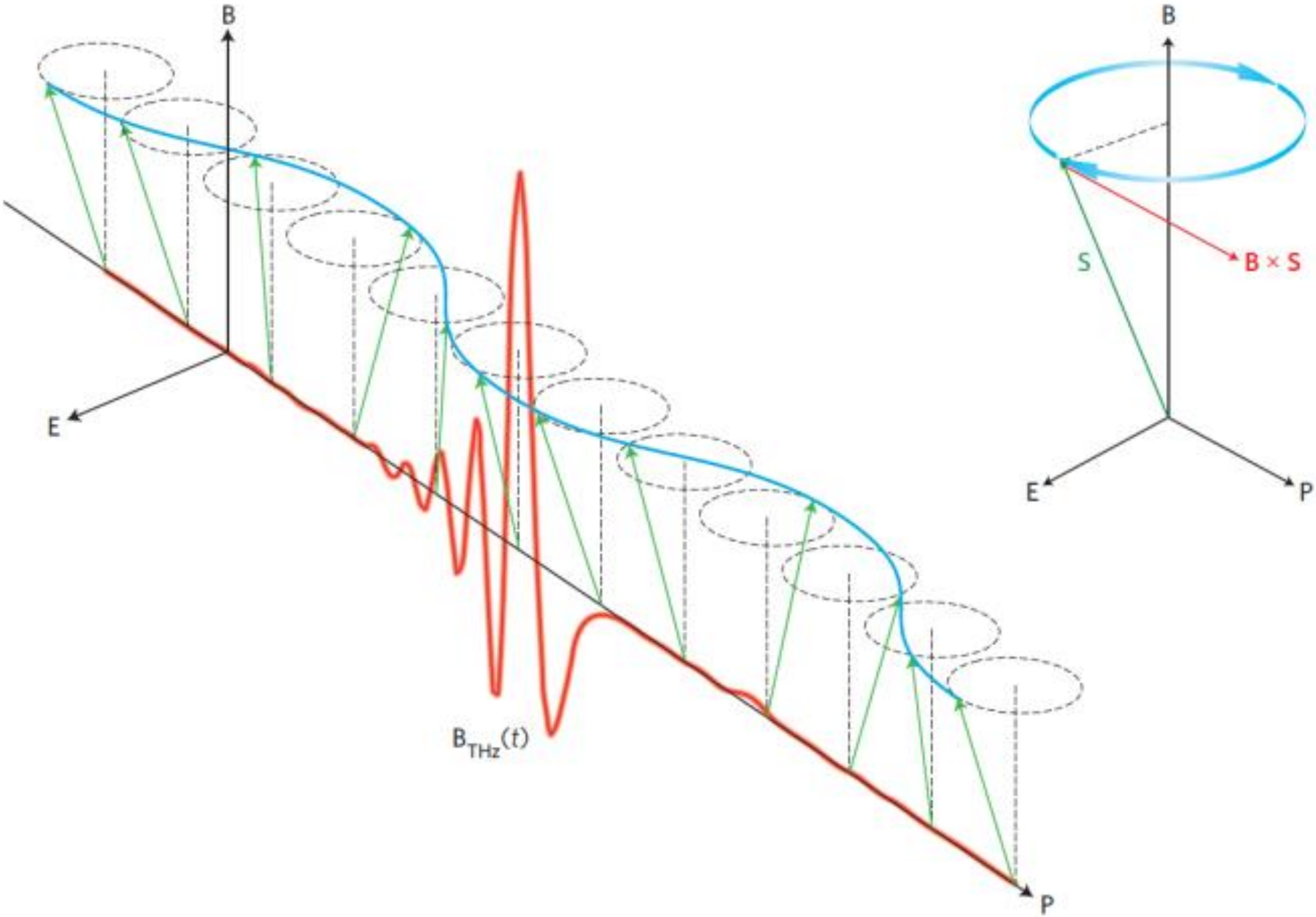


T. Kampfrath, Nature Photonics, vol. 5, 2010

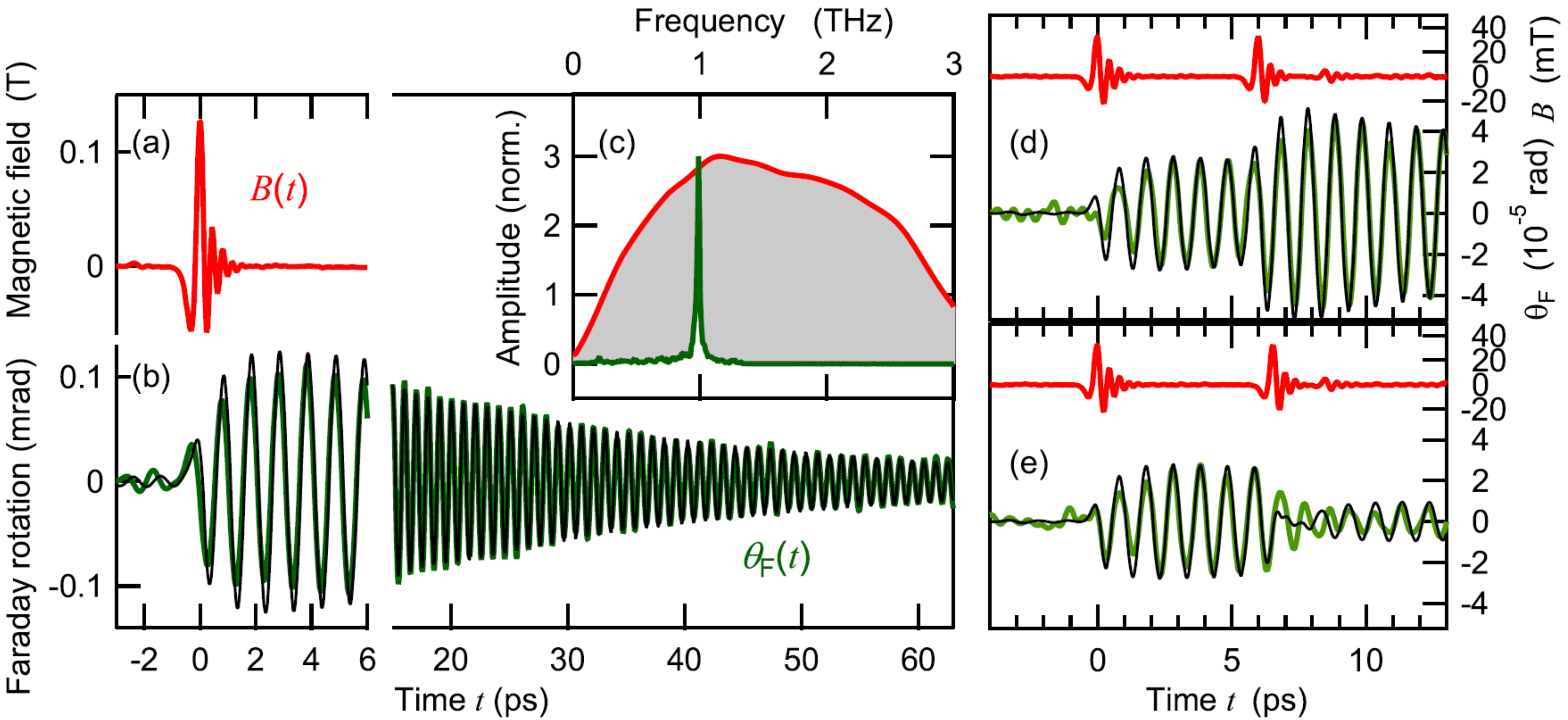
- easy axis (112)
- Neel temperature 523 K
- peak magnetic field of 0.13 T
- time resolution 8 fs

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

Dynamics of spins



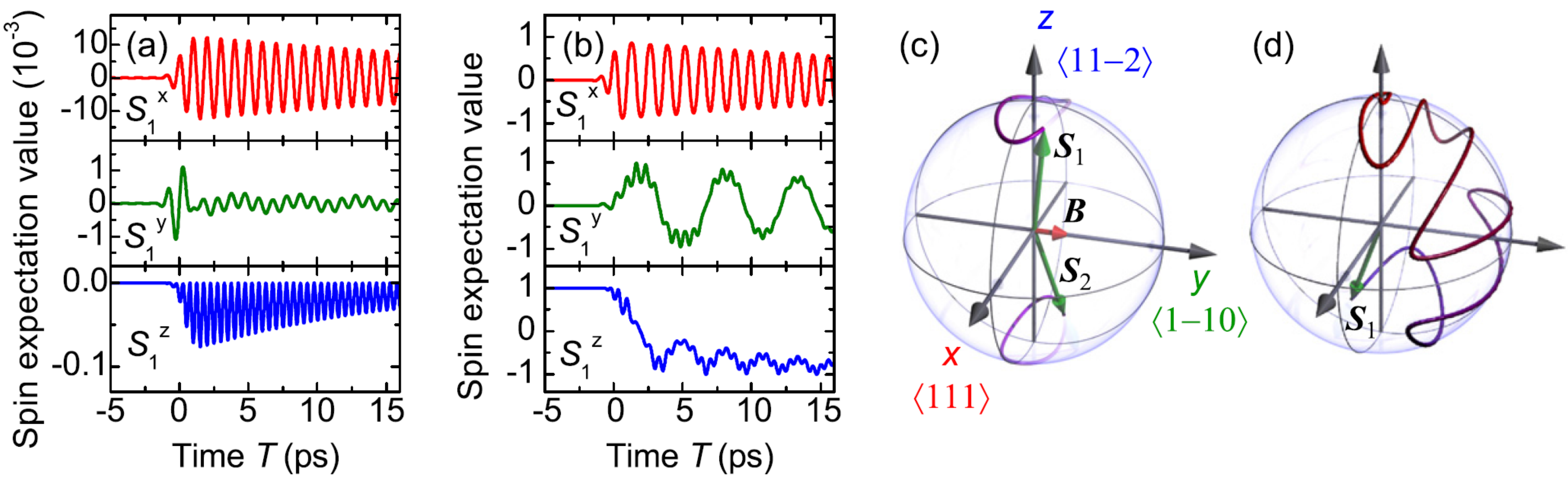
Switching on and off magnons



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

$$\theta_{\mathrm{F}}(t) = Vd\langle \mathbf{e_k} \cdot \mathbf{M}(t) \rangle$$

Prediction of spin flipping



Effective Hamiltonian

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

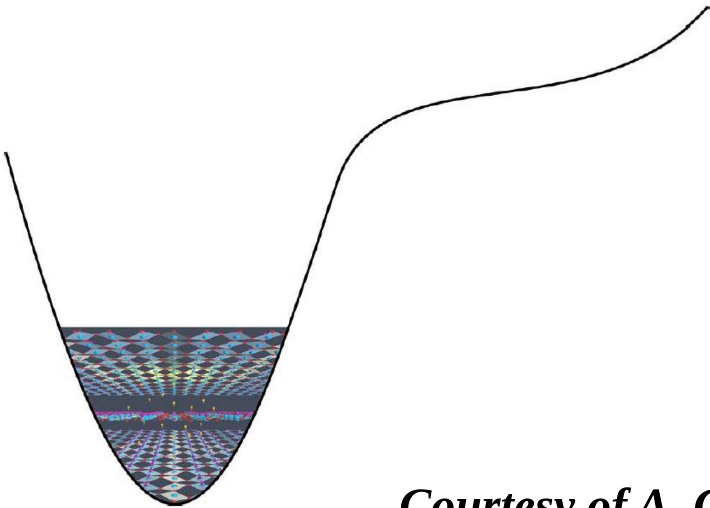
Landau-Lifshits-Gilbert eq. of motion

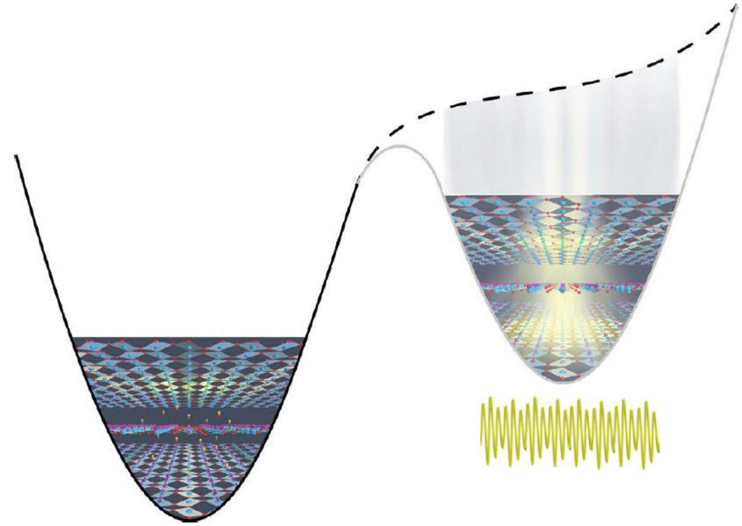
$$\frac{\partial}{\partial t}\boldsymbol{S}_j = -\frac{\gamma}{1+\alpha^2}\left[\boldsymbol{S}_j\times\boldsymbol{B}_j^{\mathrm{eff}} - \frac{\alpha}{|\boldsymbol{S}_j|}\boldsymbol{S}_j\times(\boldsymbol{S}_j\times\boldsymbol{B}_j^{\mathrm{eff}})\right],$$

Effective magnetic field

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

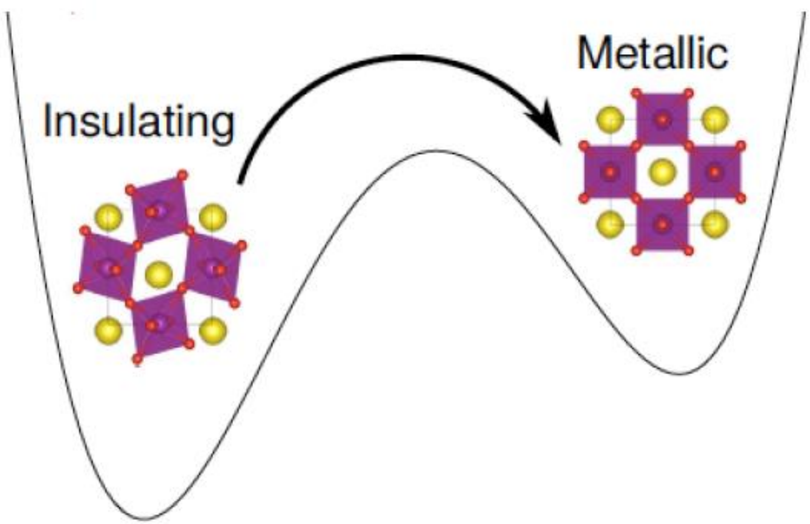
Creating new dynamics states of matter by THz light

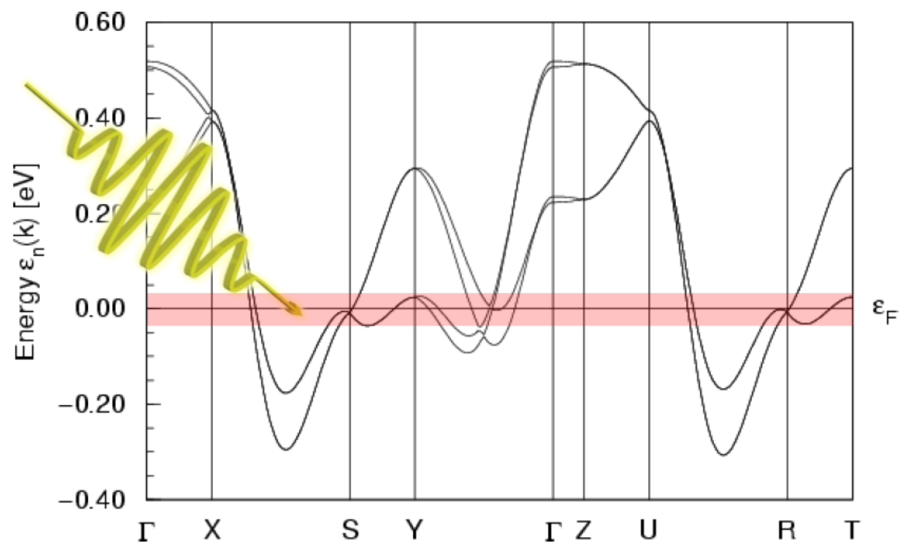




Courtesy of A. Cavalleri

1 THz ~ 50 K ~ 4 meV

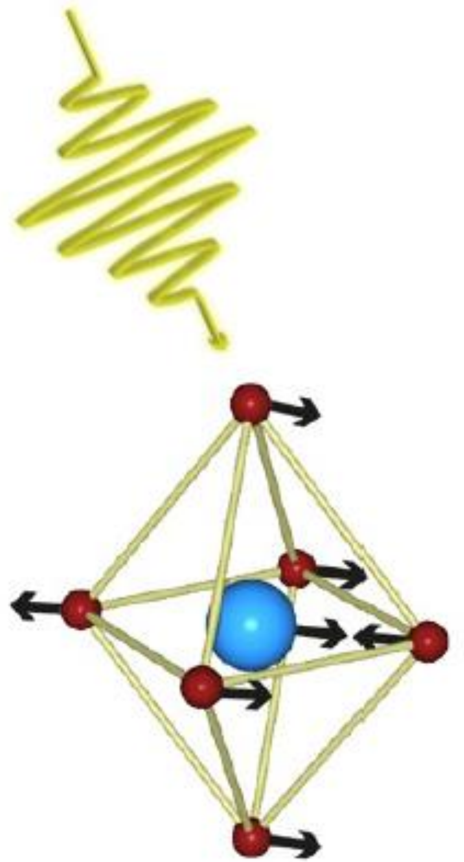


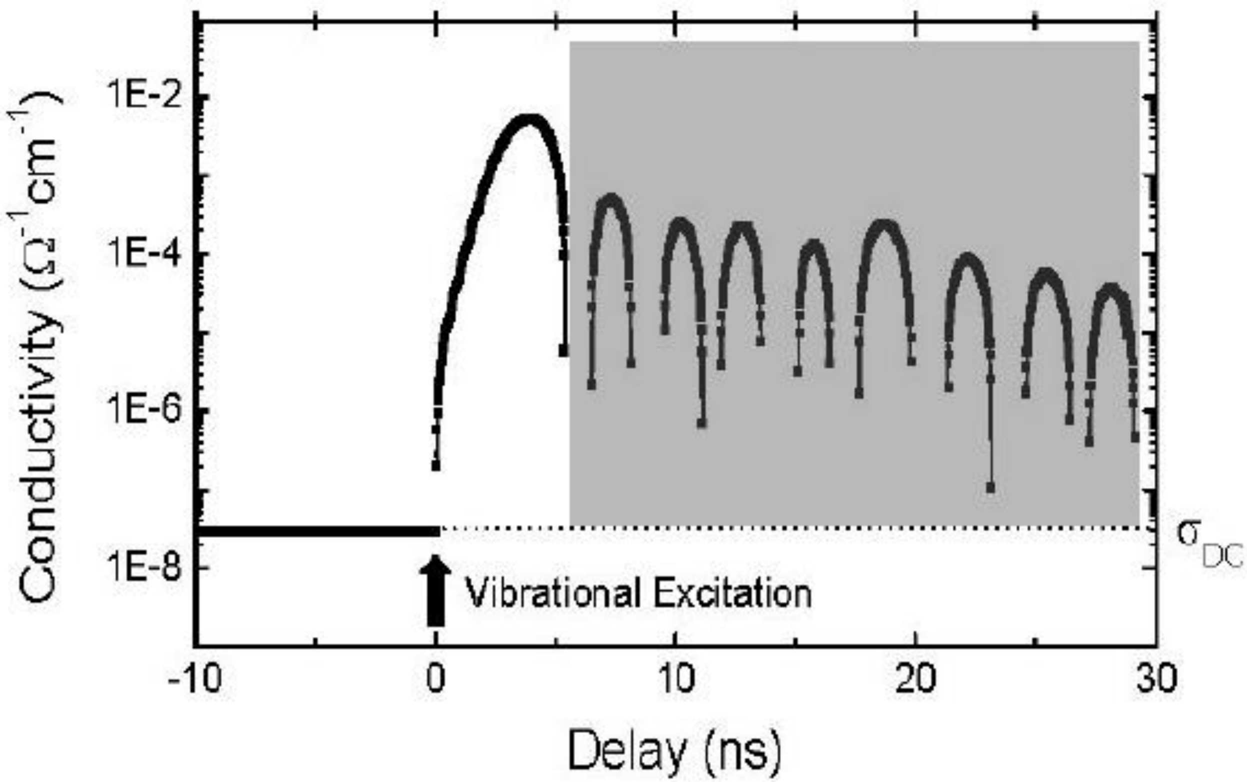


Phonon Driven I-M Transition

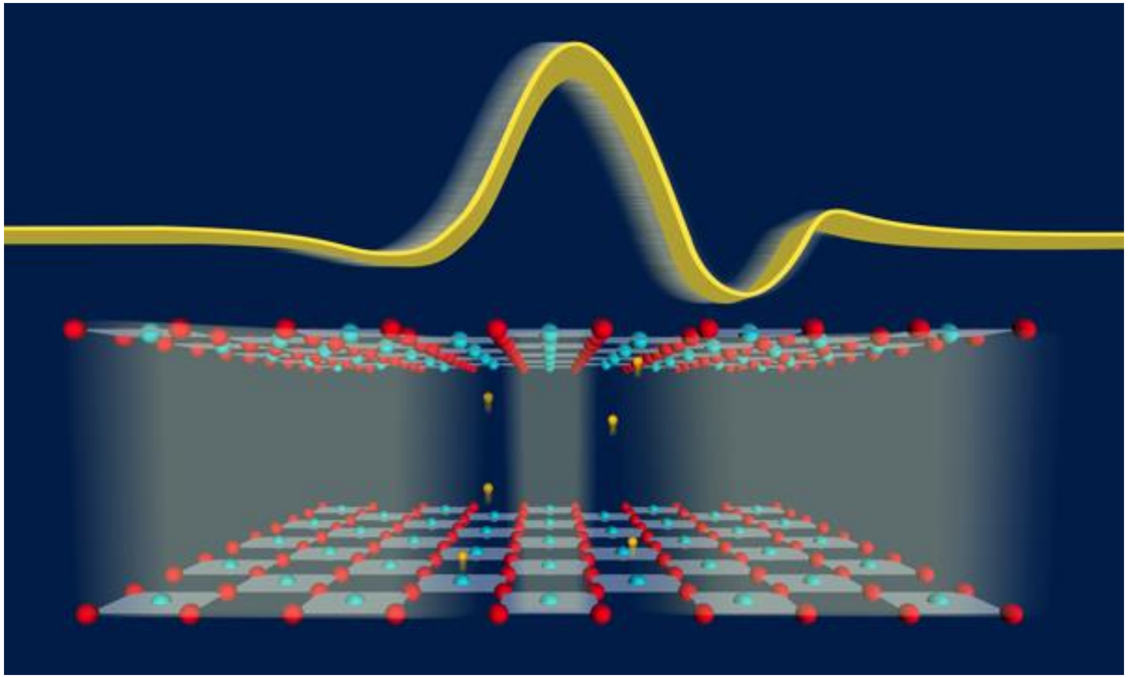
$Pr_{0.7}Ca_{0.3}MnO_3$

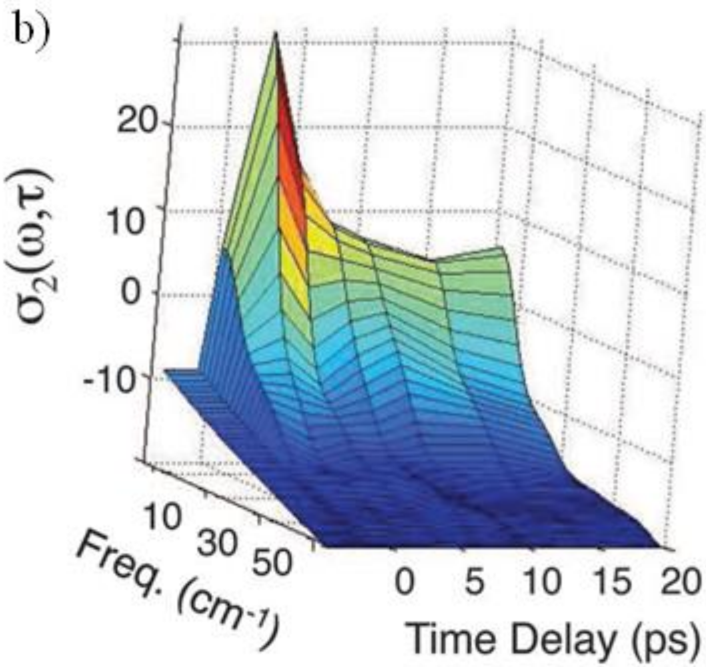
M. Rini et al., Nature 449, 72 (2007)





Light induced superconductivity



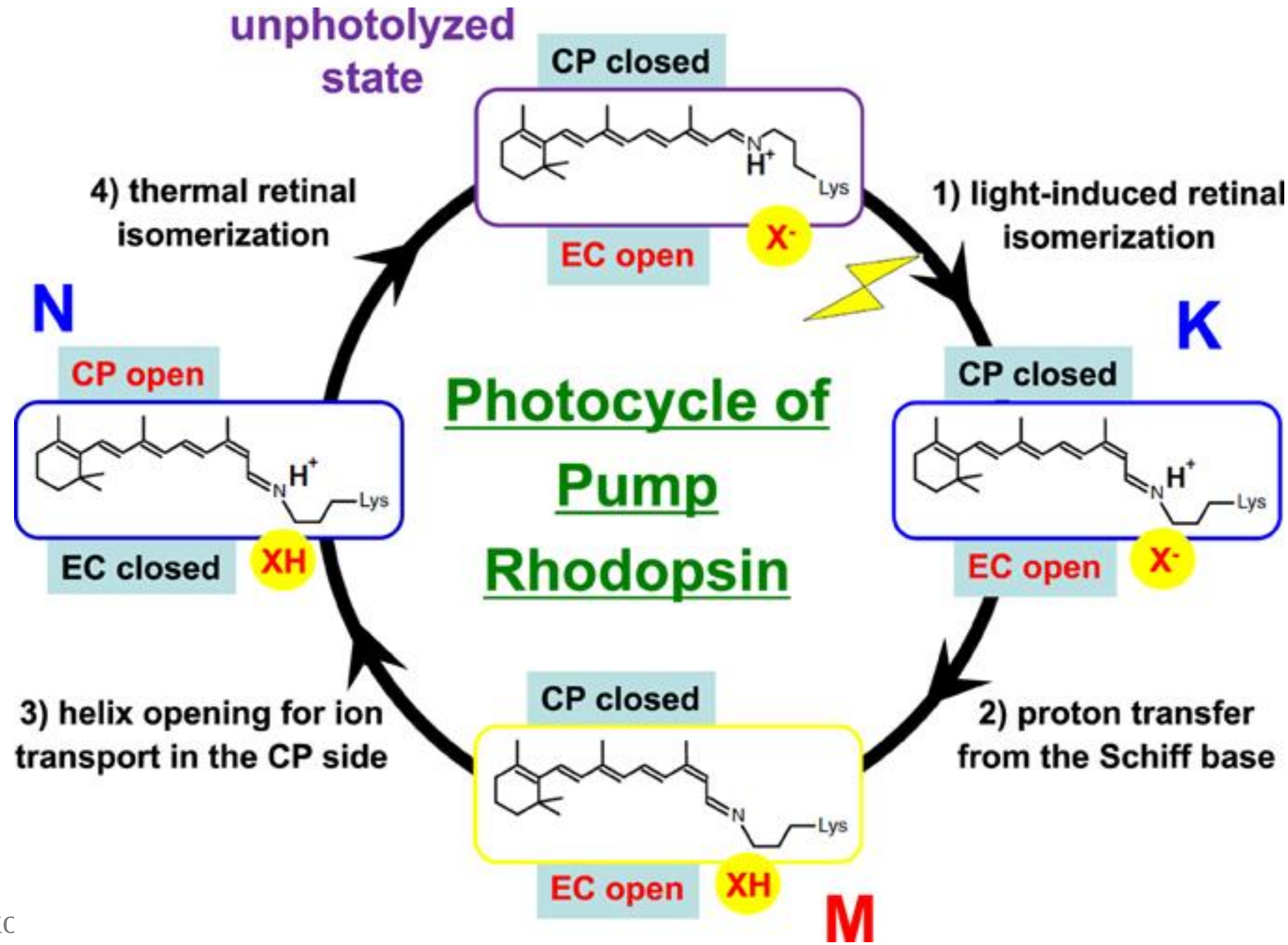


Superconducting transport between layers of a cuprate is gated with high-field terahertz pulses, leading to oscillations between superconductive and resistive states, and modulating the dimensionality of superconductivity in the material.

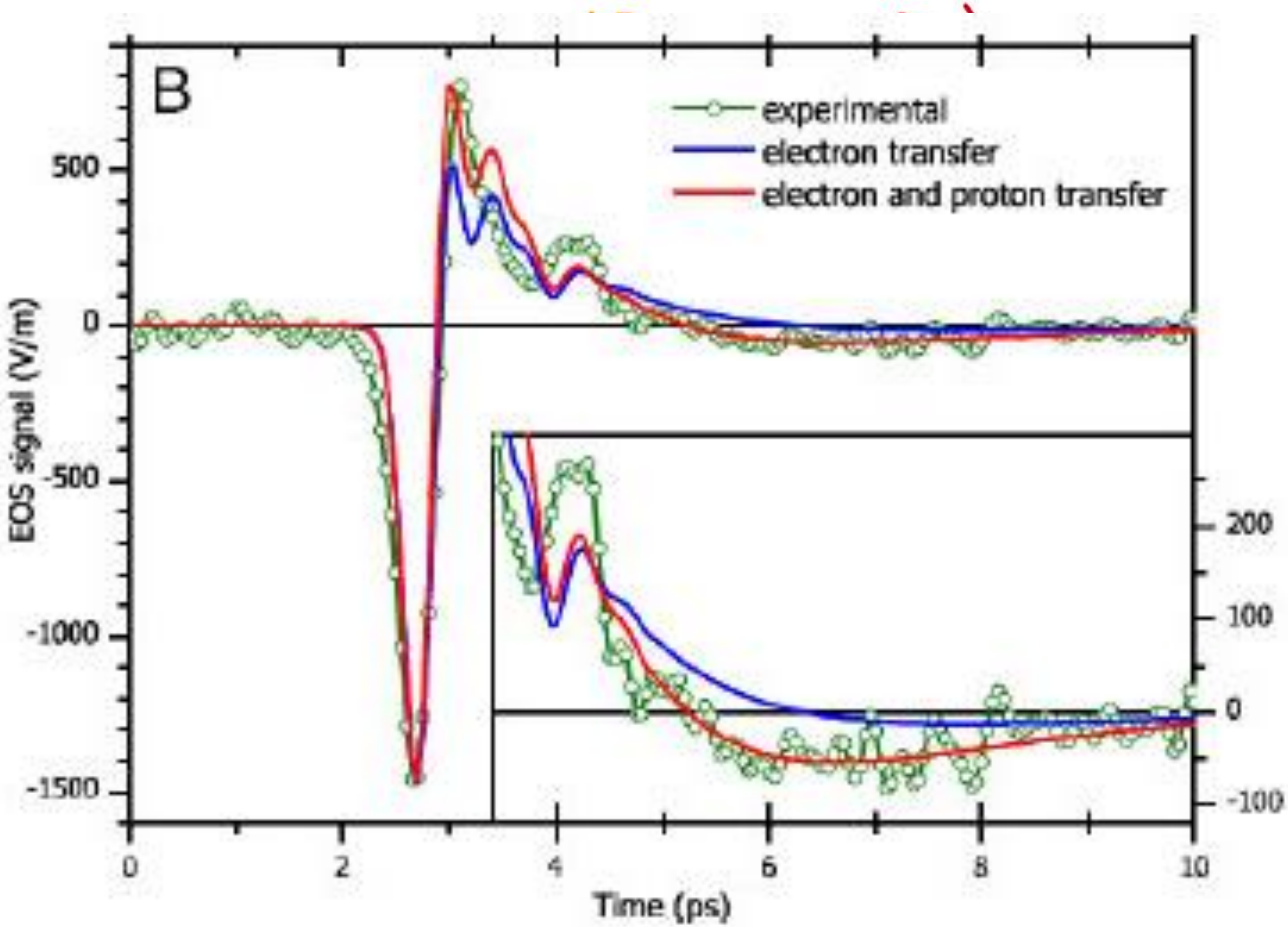
Andrea Cavalleri group

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.



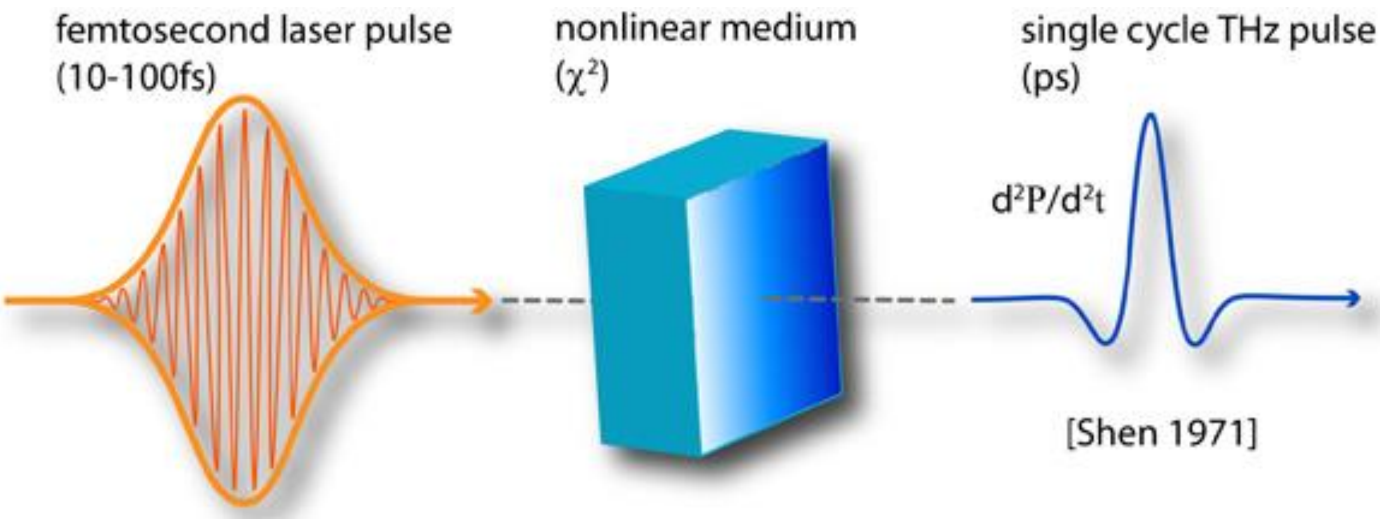
Transformation cycle of bacteriorhodopsin



Asp85

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.

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

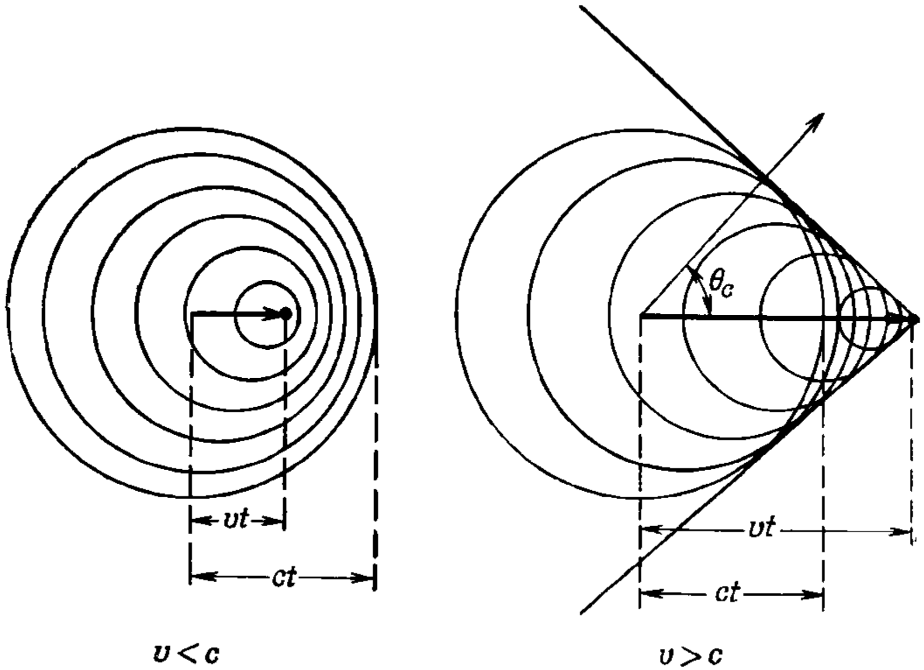
[Bass 1962]

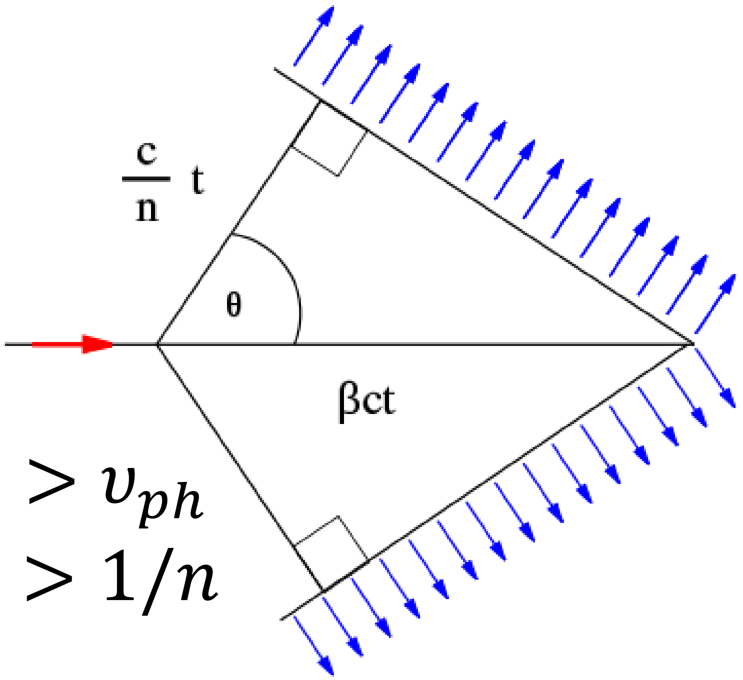
$$\nabla \times \nabla \times \vec{E} + \frac{1}{c^2}\frac{\delta^2}{\delta t^2}(\varepsilon\vec{E}) = -\frac{4\pi}{c^2}\frac{\delta^2\vec{P}}{\delta t^2}$$

source of radiation

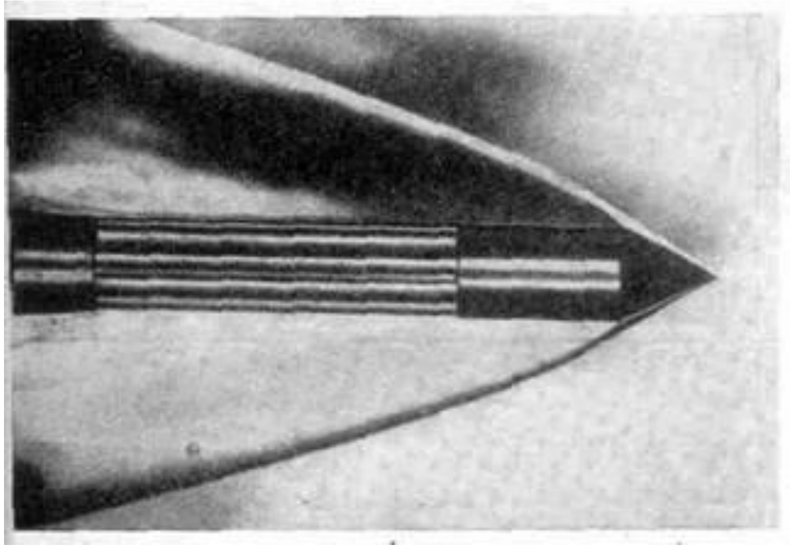
Matthias Hoffmann, http://mpsd-cmd.cfel.de/research-met-thz-optrect.html

Moving charge in a medium

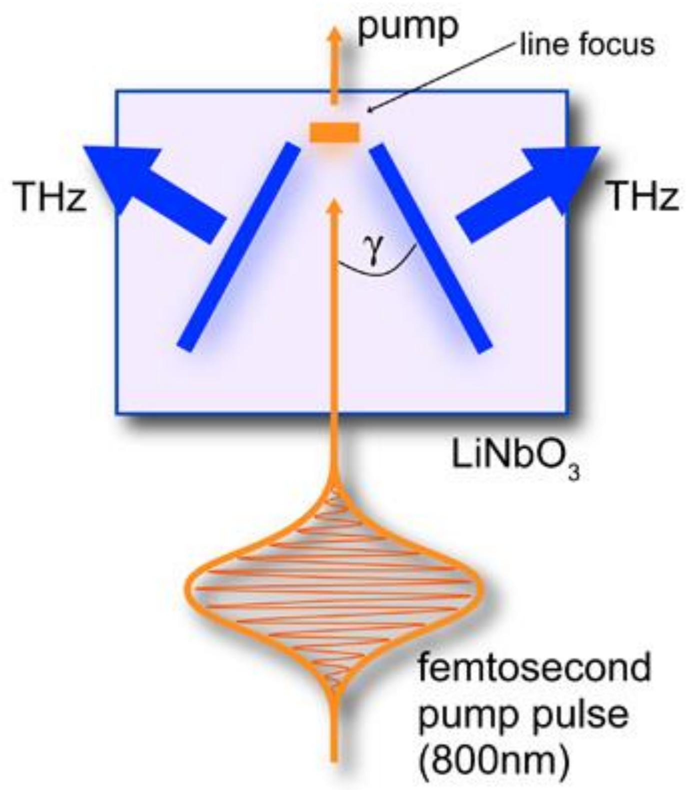


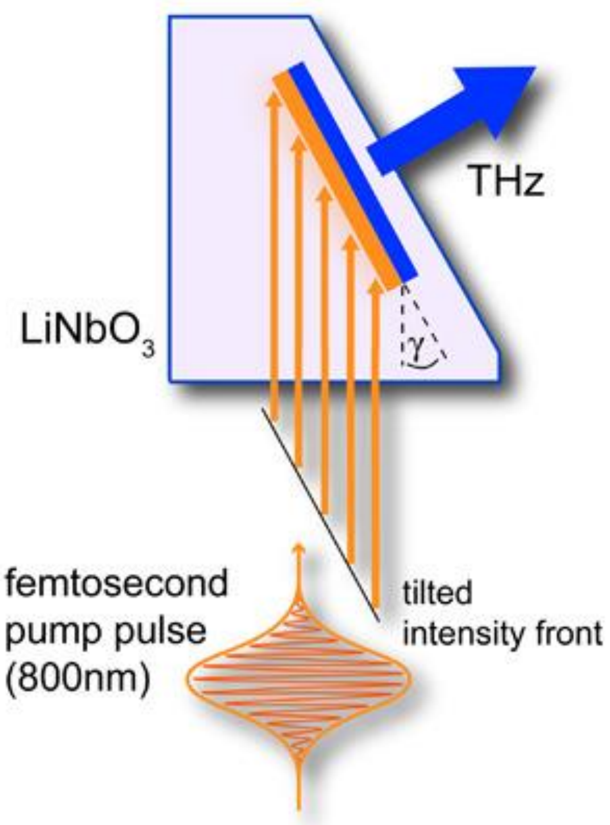


$$v > v_{ph}$$
$$\beta > 1/n$$



Phase matching





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

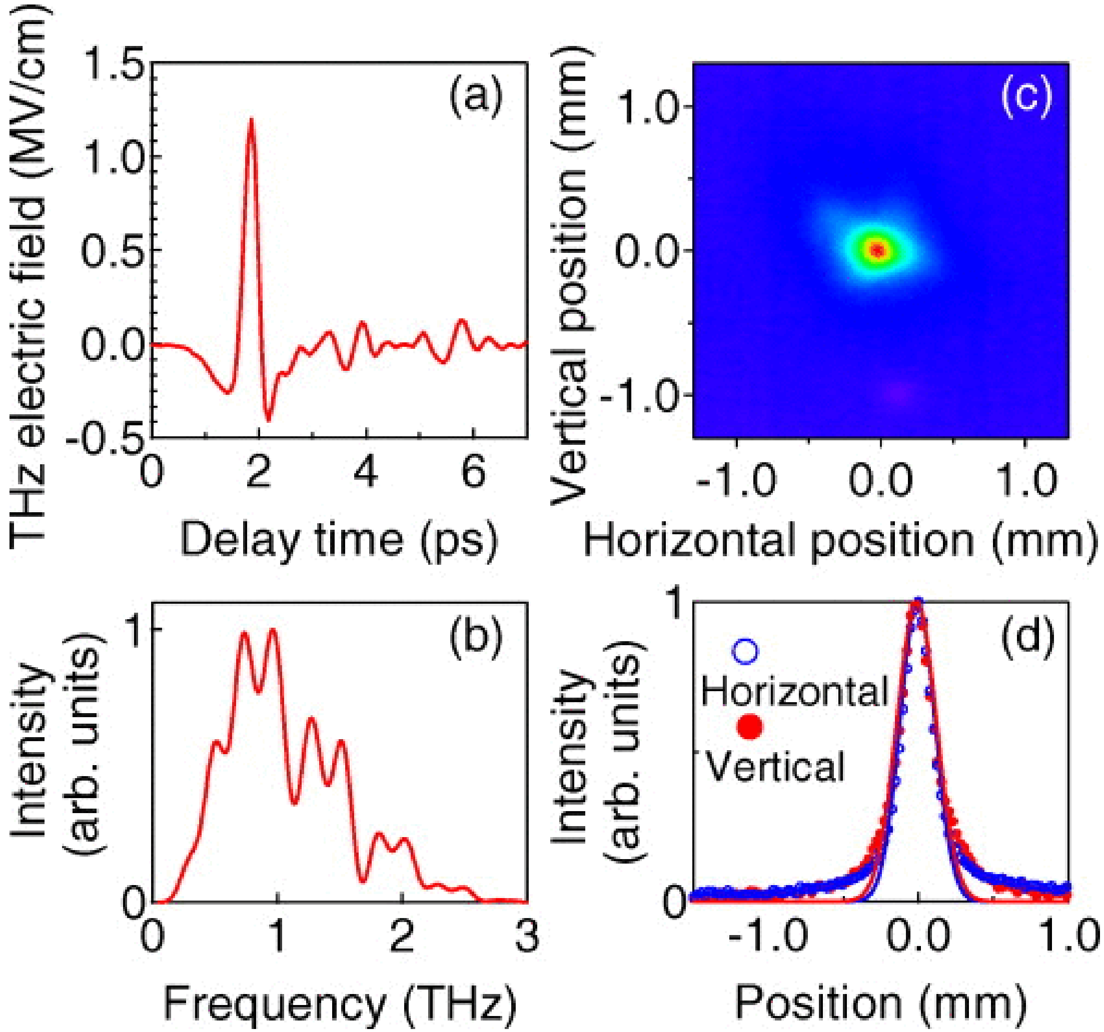
By tilting the optical pulse front, one achieves coherent build up of a THz wave with a long interaction length.

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

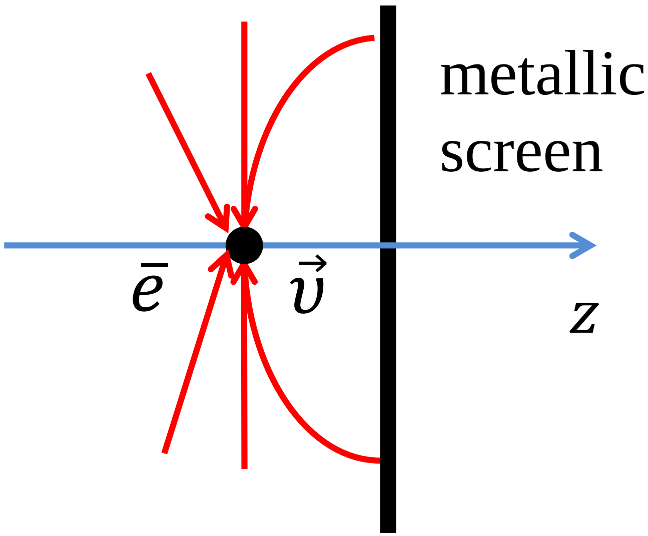
APPLIED PHYSICS LETTERS **98**, 091106 (2011)

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



- **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.*

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

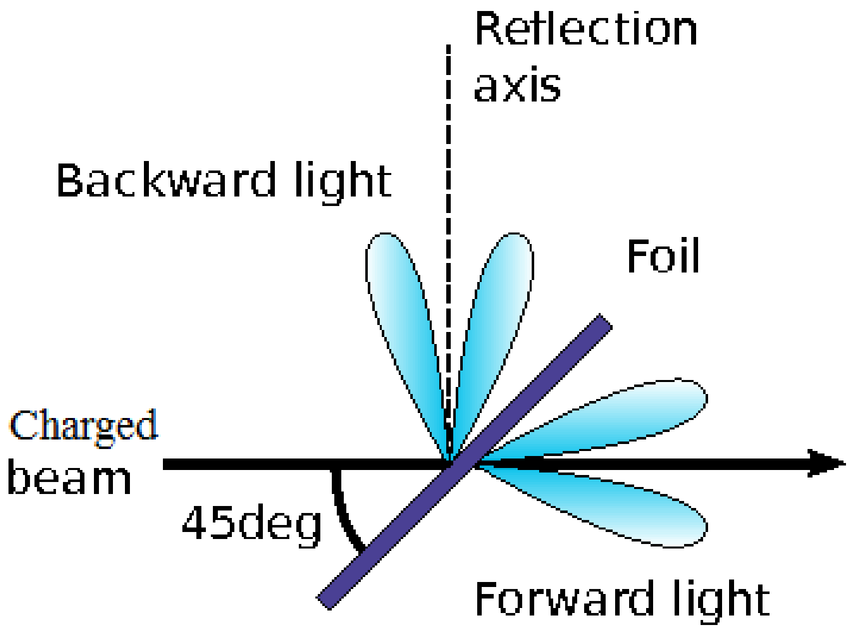
$$p_z = 0 \quad \text{for} \quad t \geq 0,$$

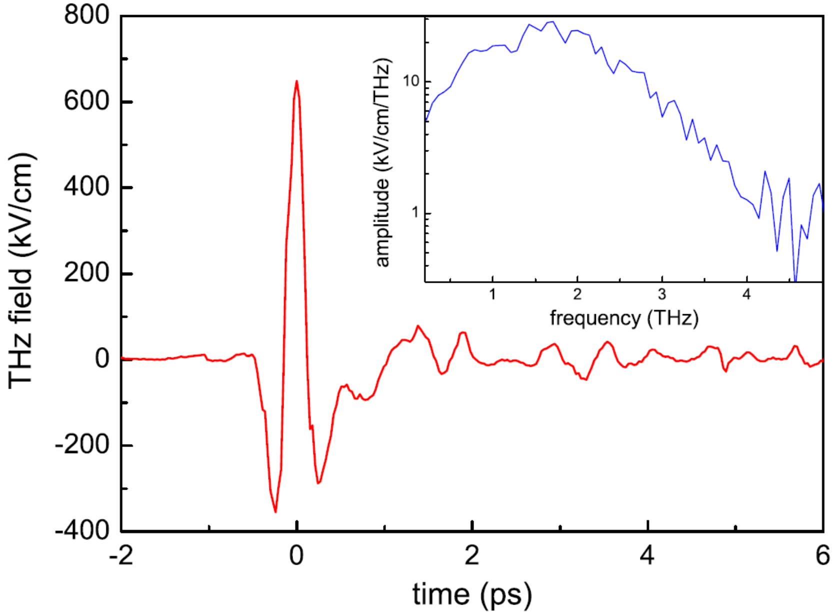
$$\ddot{p}_z = -2ev\delta(t).$$

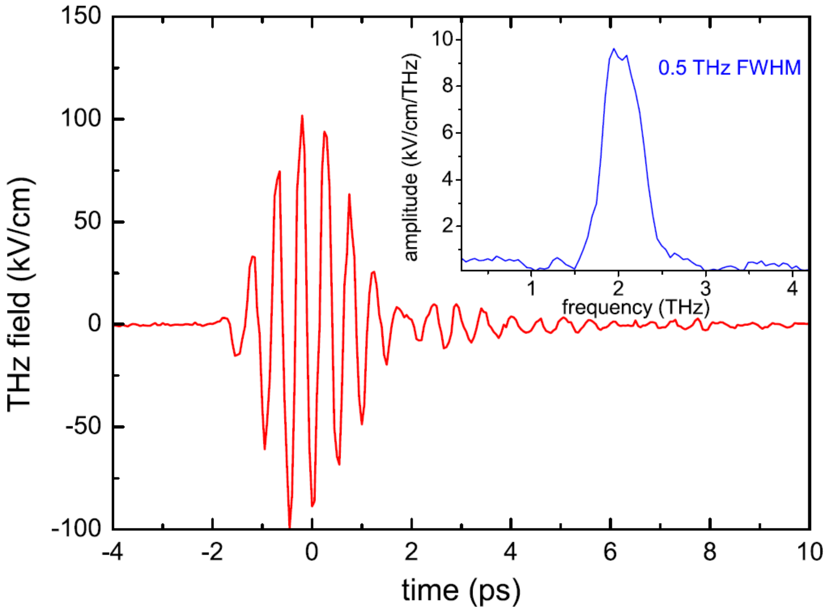
The energy emitted in the spectral range Δf reads

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

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





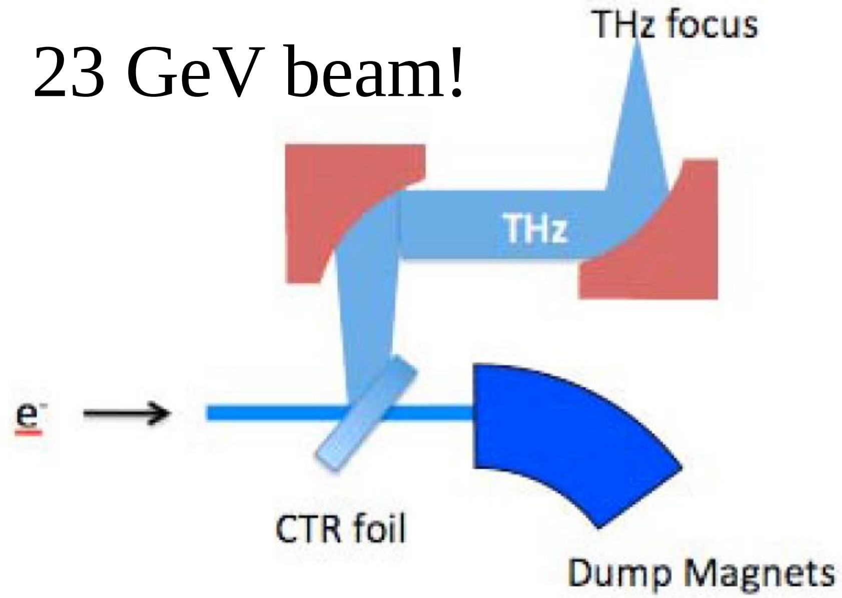


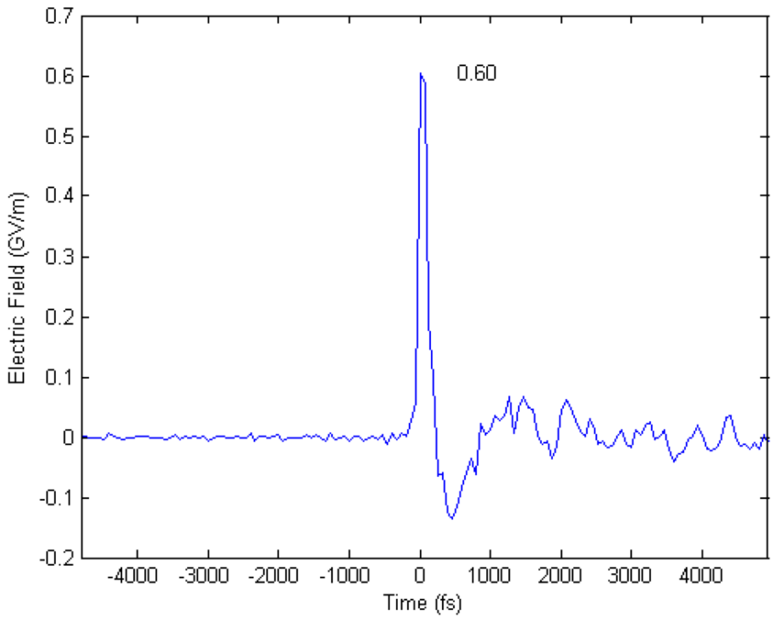
- energies up to 100 μJ
- electric fields up to 1MV/cm
- a frequency band from 200 GHz to 100 THz

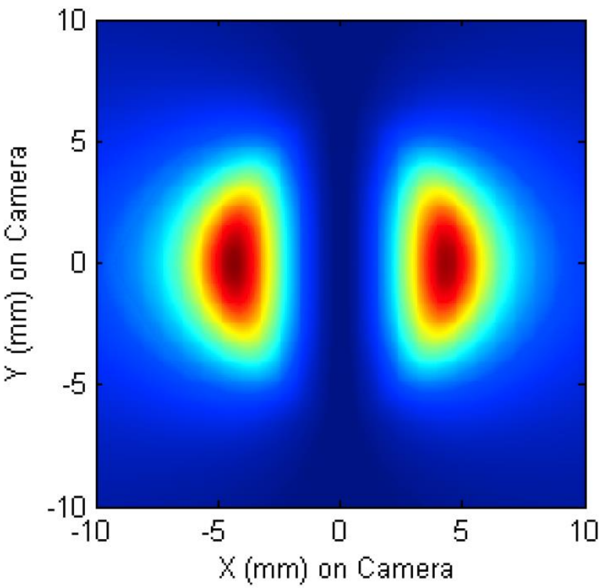
M. Hoffmann et al.,
Vol. 36, No. 23 / OPTICS LETTERS 4473

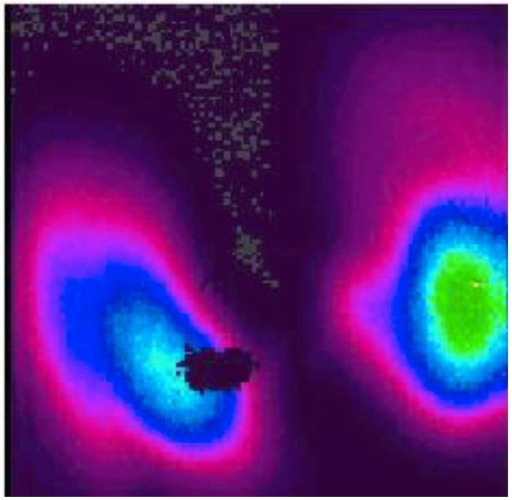
Single-cycle THz pulses at FACET/SLAC: 6 MV/cm

23 GeV beam!









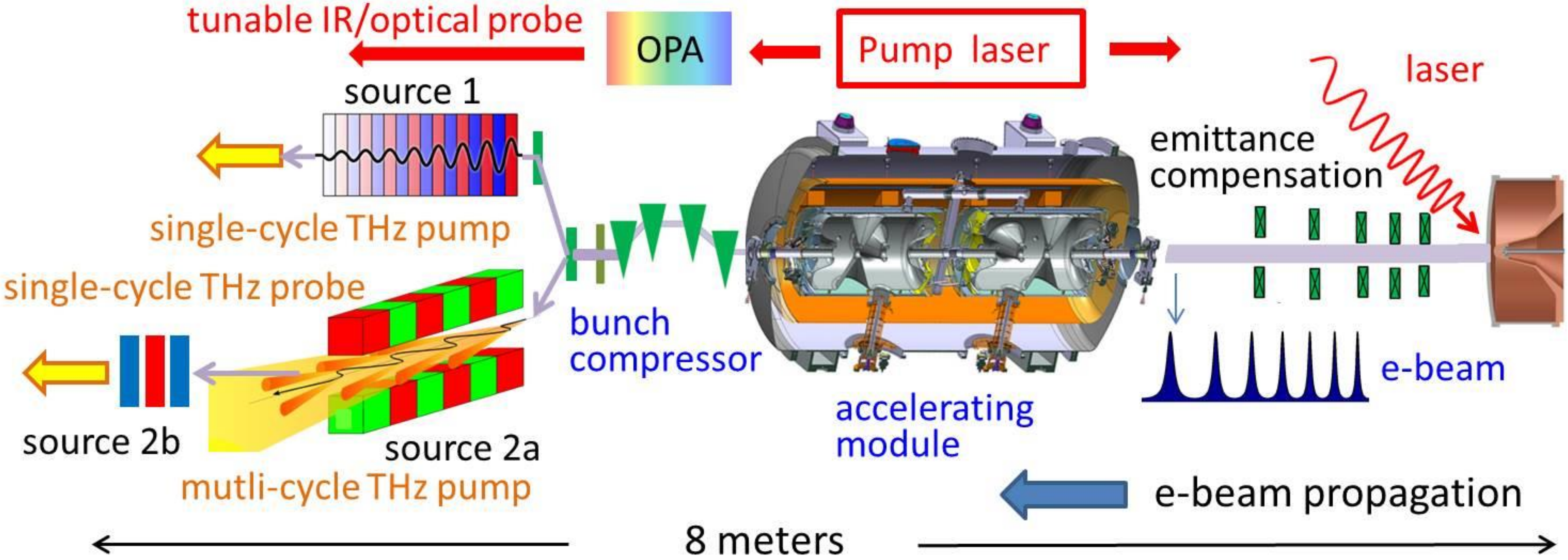
Proposal for a THz Light Source in Uppsala

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

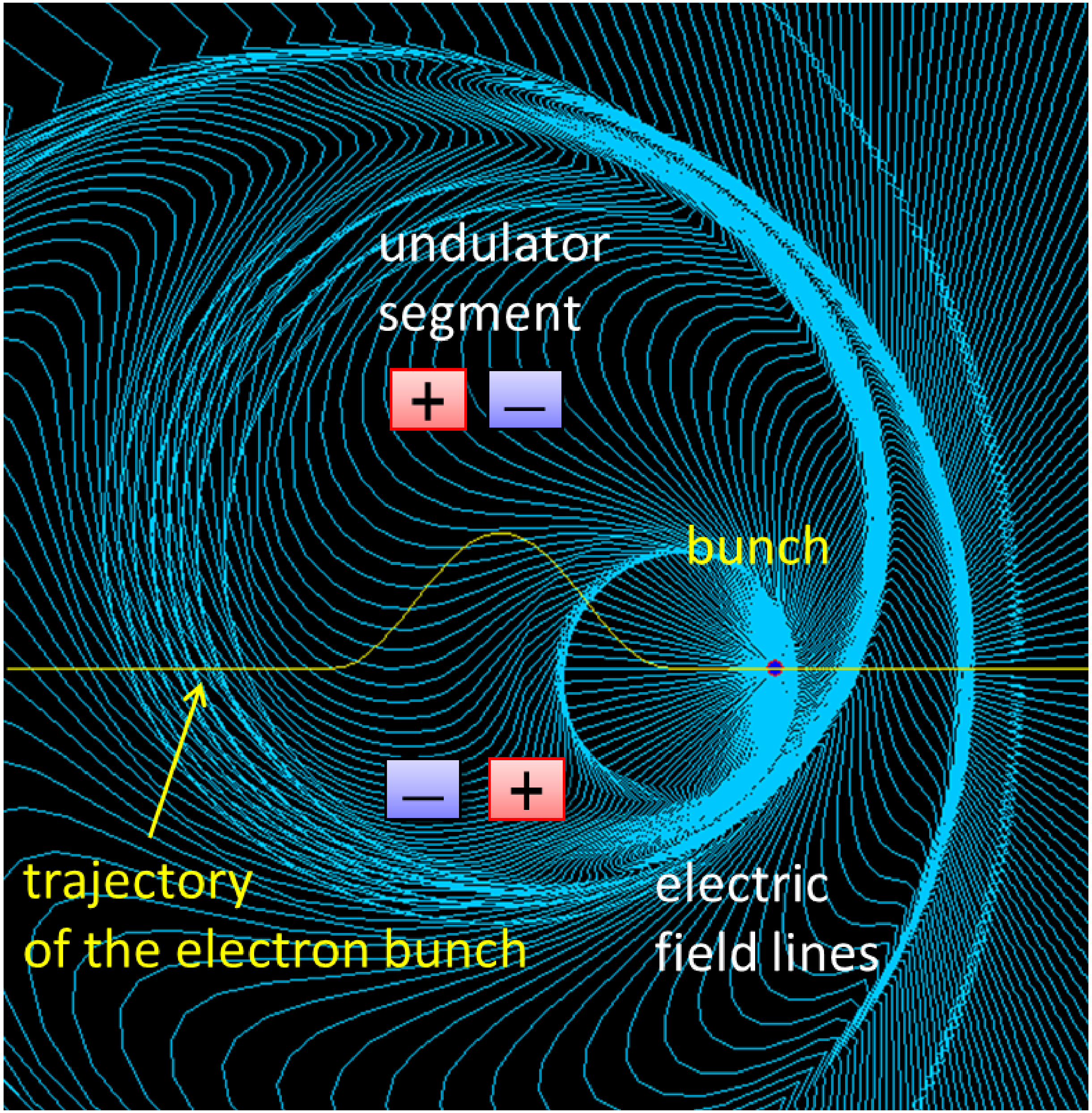
+ Polarization control, pump-probe configuration

The source

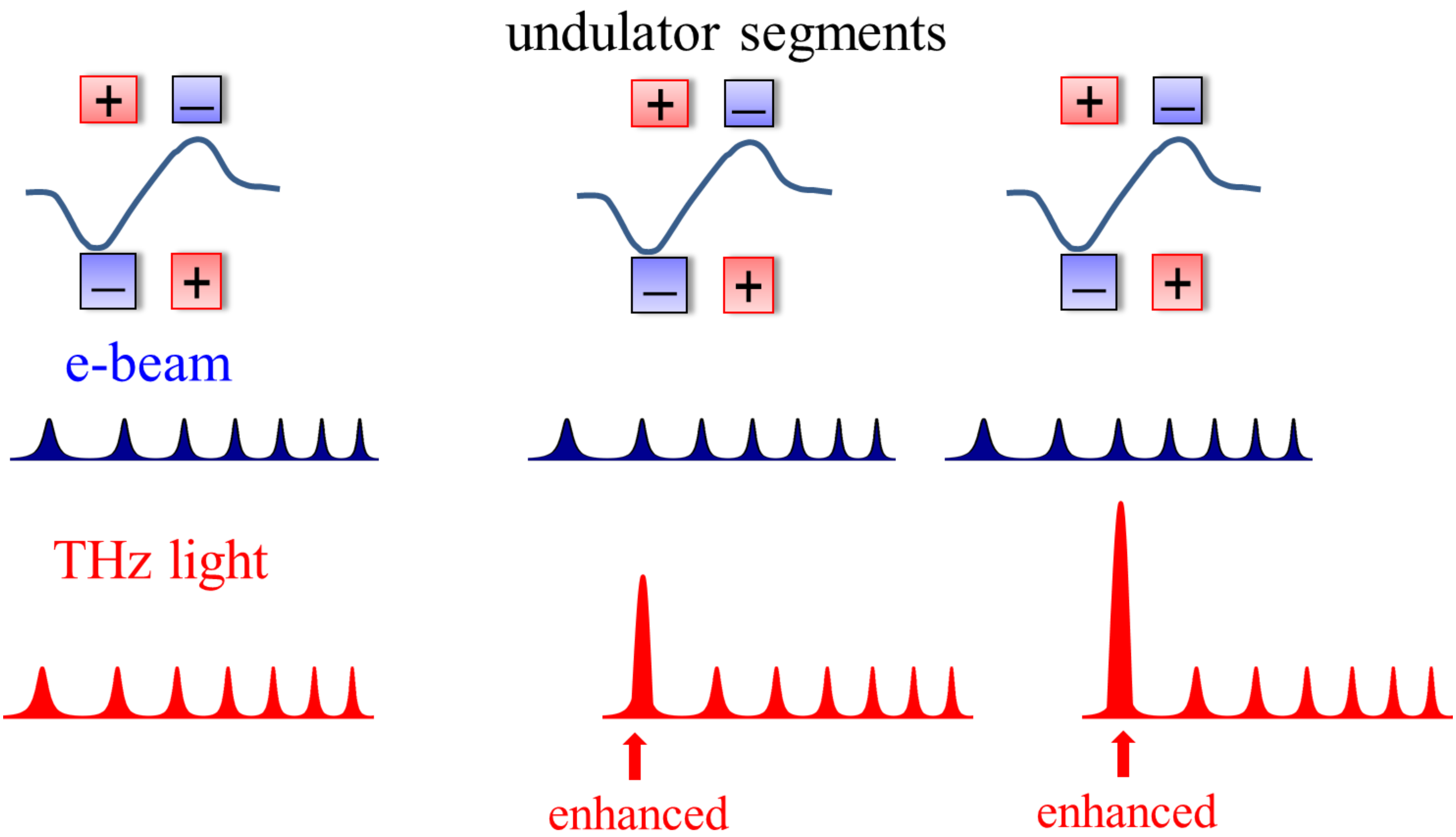


- it covers the spectral range from 5 to 15 THz;
- polarization variable from linear to circular or elliptical;
- tunability of the central frequency and bandwidth;
- mutli-kilohertz repetition rate;
- light carrying orbital angular momentum.

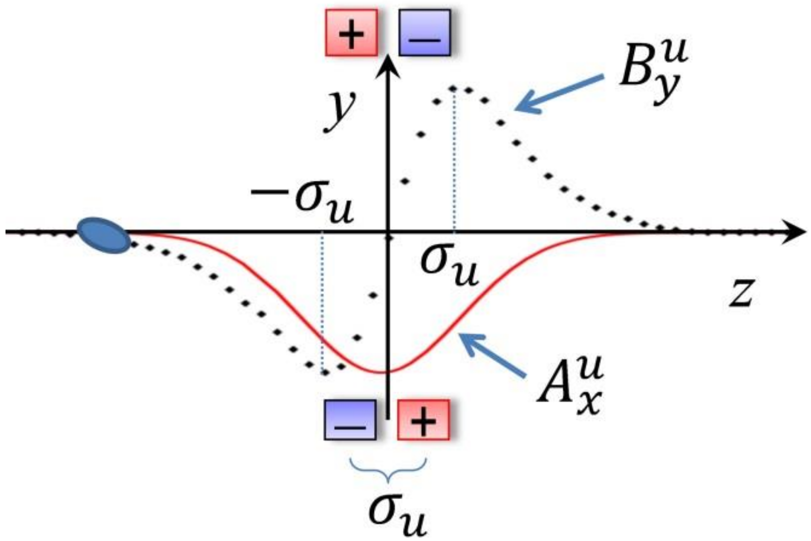
Single-cycle synchrotron radiation

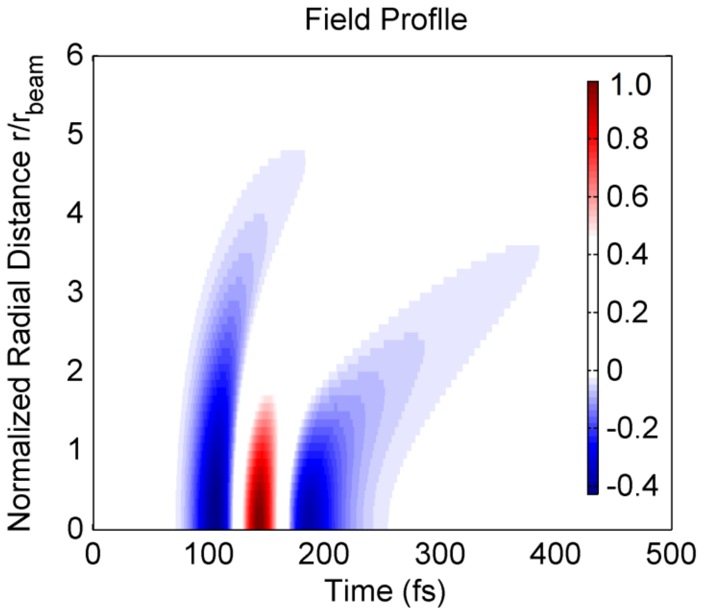


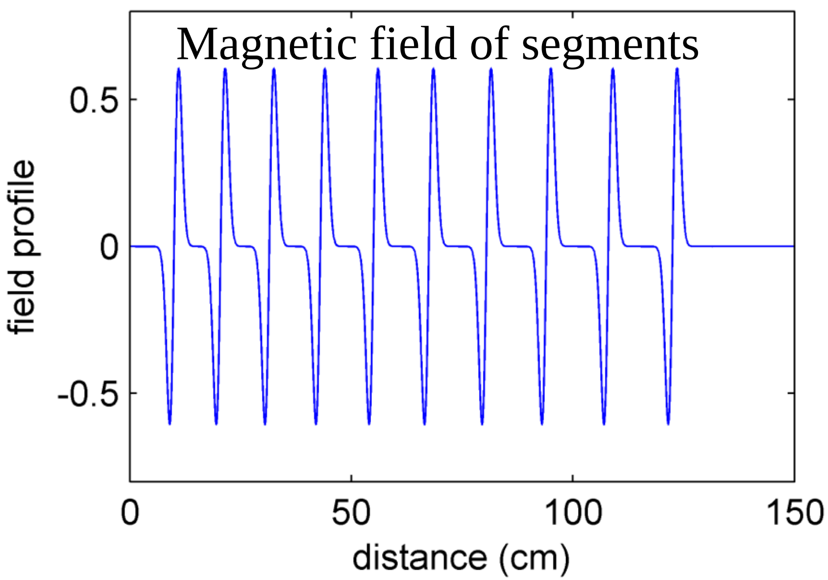
Single-cycle radiation from a segmented undulator

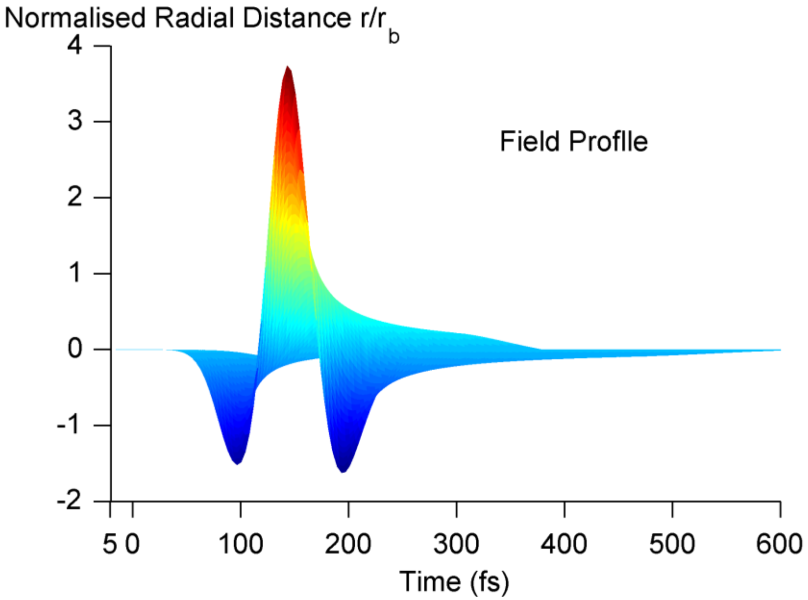


Single-cycle radiation from a segmented undulator: cont’d

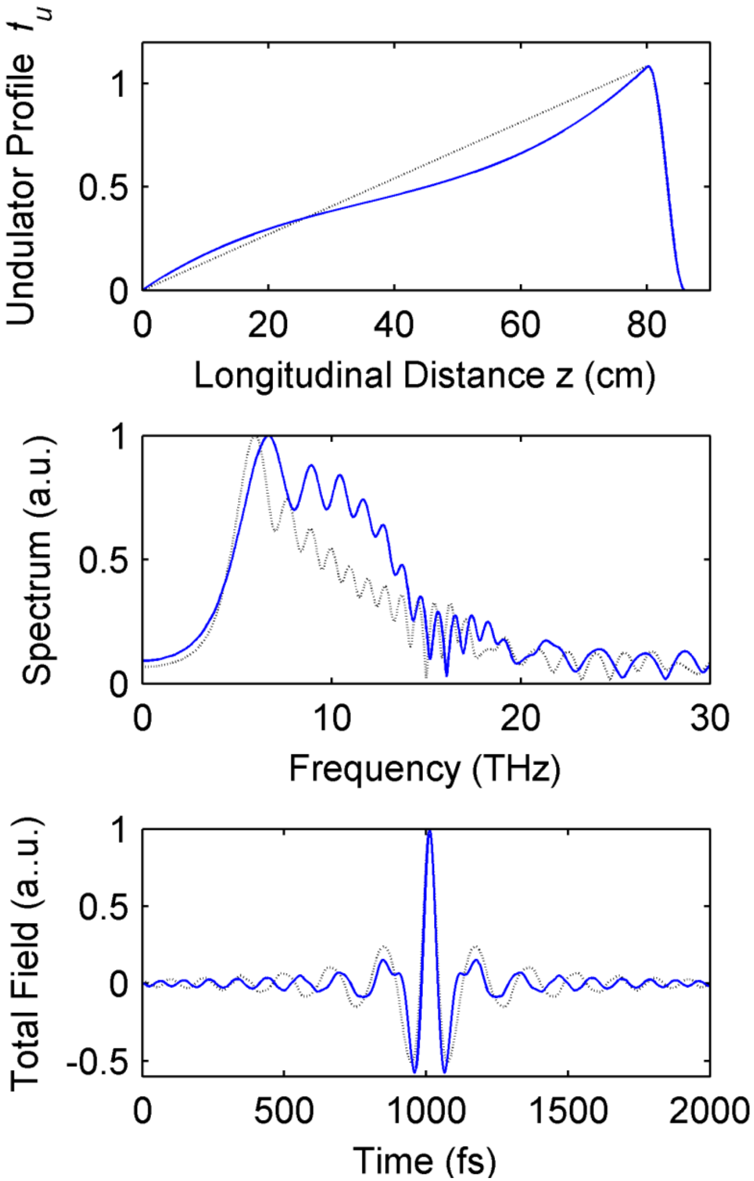


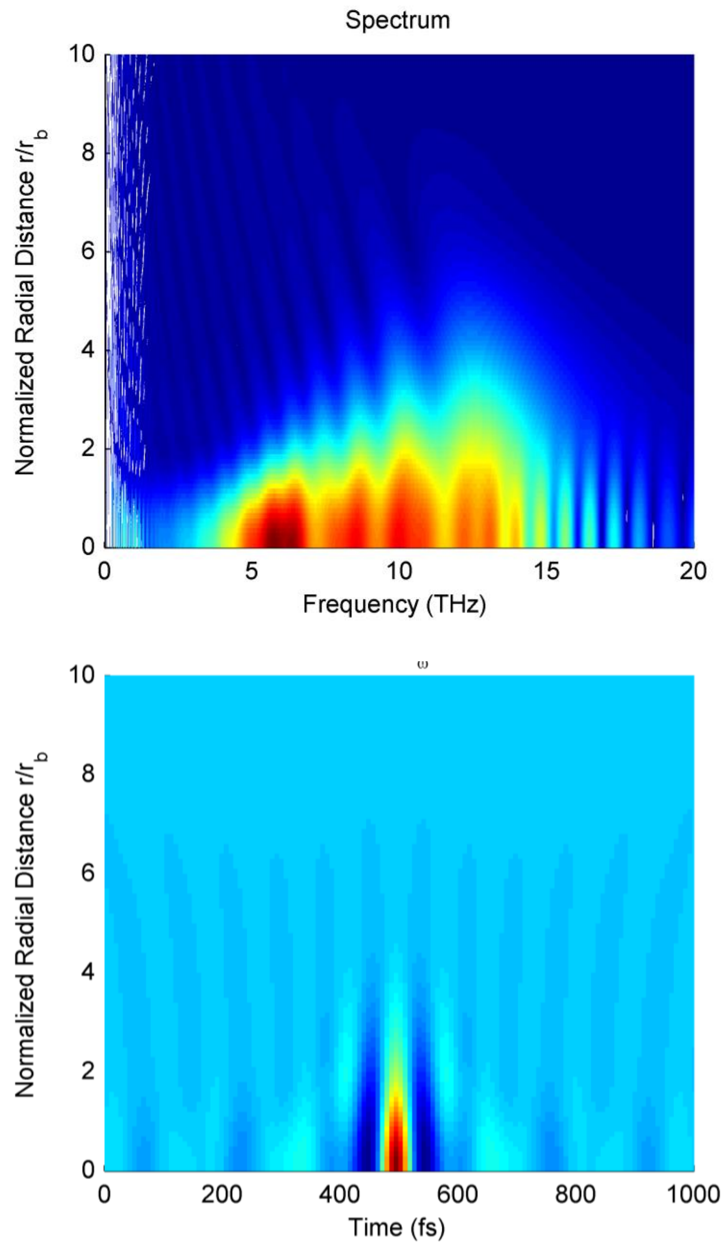






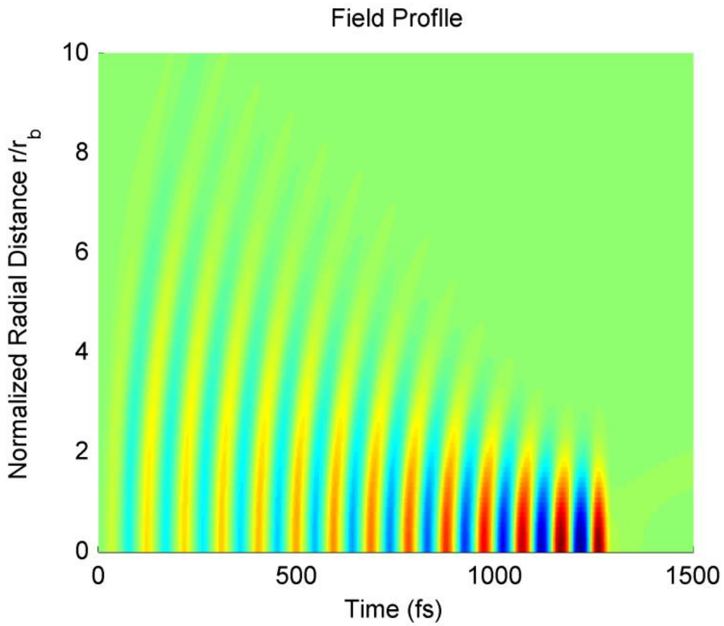
Source 1: quasi-half-cycle pulses

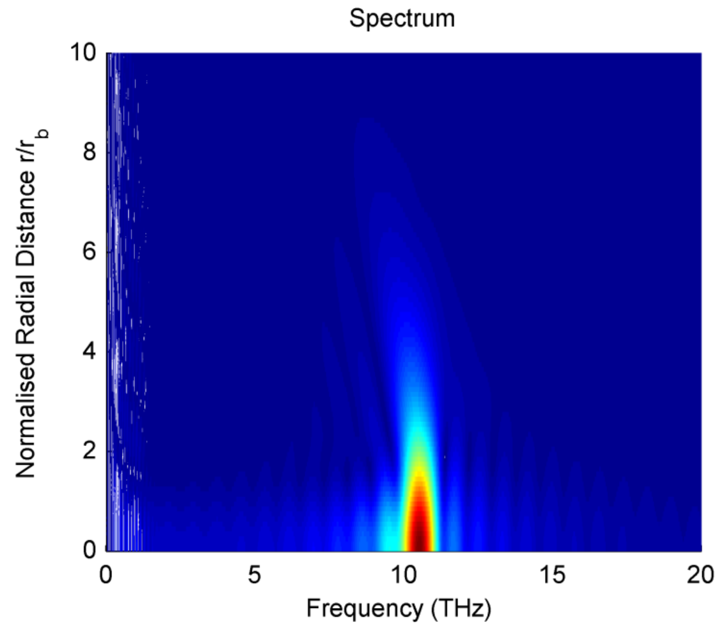




Source 2: multi-cycle pump and single-cycle probe

Source 2a





Source 2b