Coherent Synchrotron Radiation Studies and Applications at the NSLS

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in collaboration with

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NSLS / Brookhaven National Laboratory

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UVSOR Workshop on Terahertz Coherent Synchrotron Radiation

Inst. for Molecular Science, Nat'l Inst. of Nat. Science, Okazaki, Sept. 23-25, 2007

Outline

- Coherent synchrotron radiation from the NSLS VUV/IR storage ring:
  - Far-infrared spectroscopy at beamline U12IR
  - CSR bursts in the ~ 100 GHz spectral range.
- Coherent transition radiation from the NSLS Source Development Laboratory linac:
  - large THz radiation pulses.
  - electro-optic measurement setup to sense waveforms/fields
  - issues when fields are large (time-dependence)
  - non-linear optics application:
    phase modulation to control spectral content, chirping, etc.
- Potential application:
  - switching behavior in ferroelectrics, ferromagnets, superconductors.

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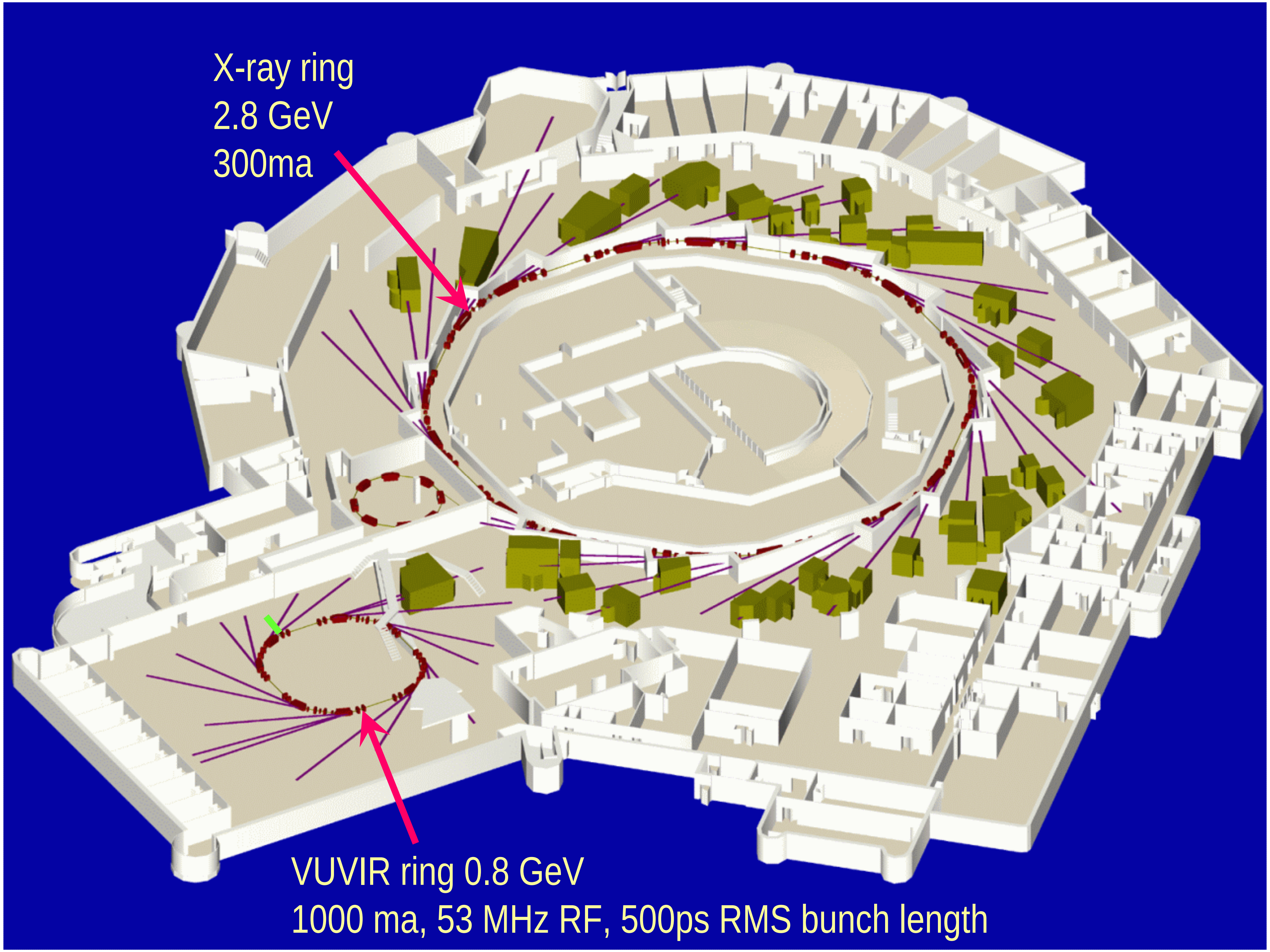
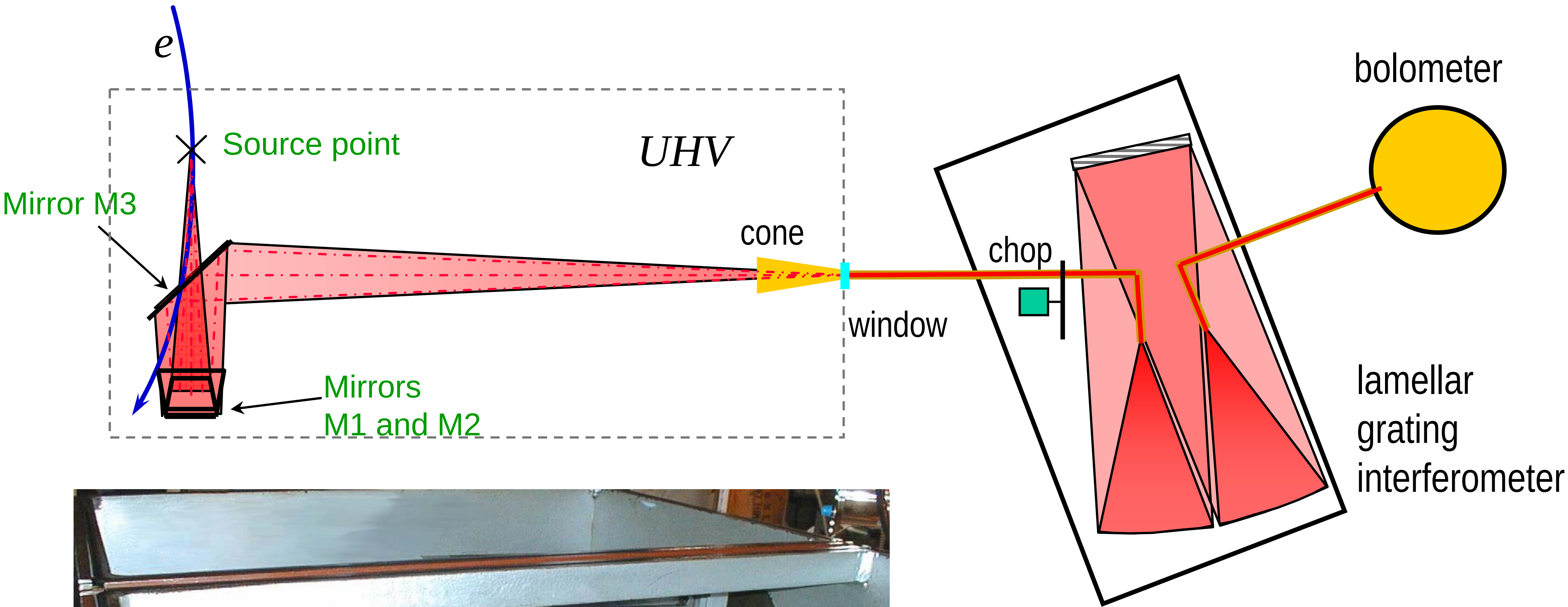
Coherent Synchrotron Radiation (CSR)

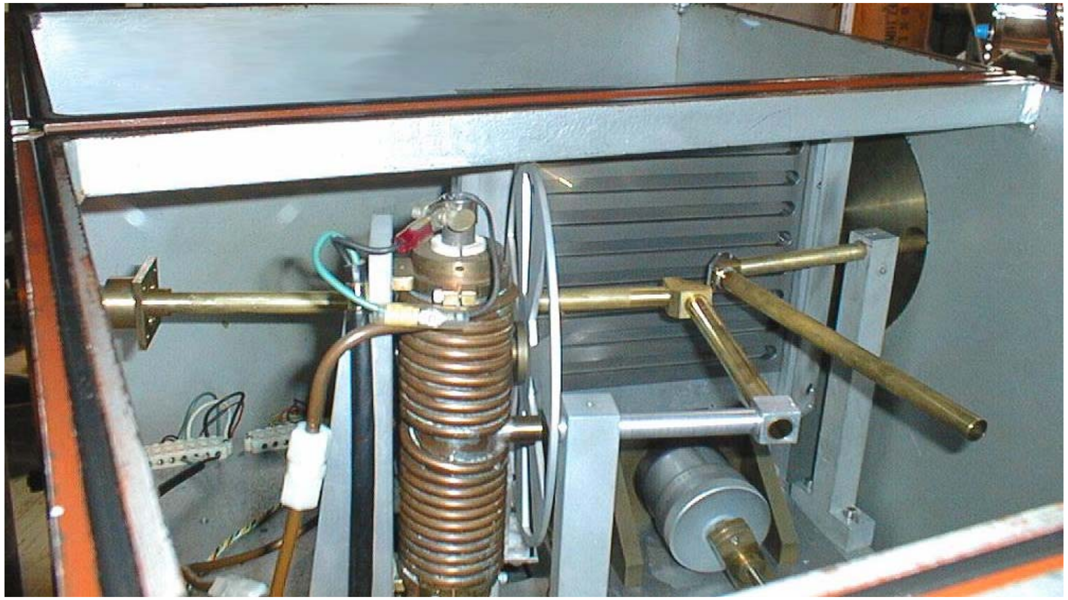
- 1st observations in linacs:
  - Nakazato et al (PRL ‘89), Happek et al (PRL ‘91)
- As a linac bunch diagnostic:
  - Shibata et al (PRE ‘94), Lai et al (PRE ‘94), Yan et al (PRL ‘00)
- As a THz source
  - Ishi et al (PRA ‘91), Takahashi et al (RSI ‘98), Carr et al., (Nature ‘02)
- CSR also from storage rings
  - Arpe et al, Carr et al, Anderson et al, Abo-Bakr et al., ALS, SPRing-8, MIT/Bates, ...

NSLS Storage Rings



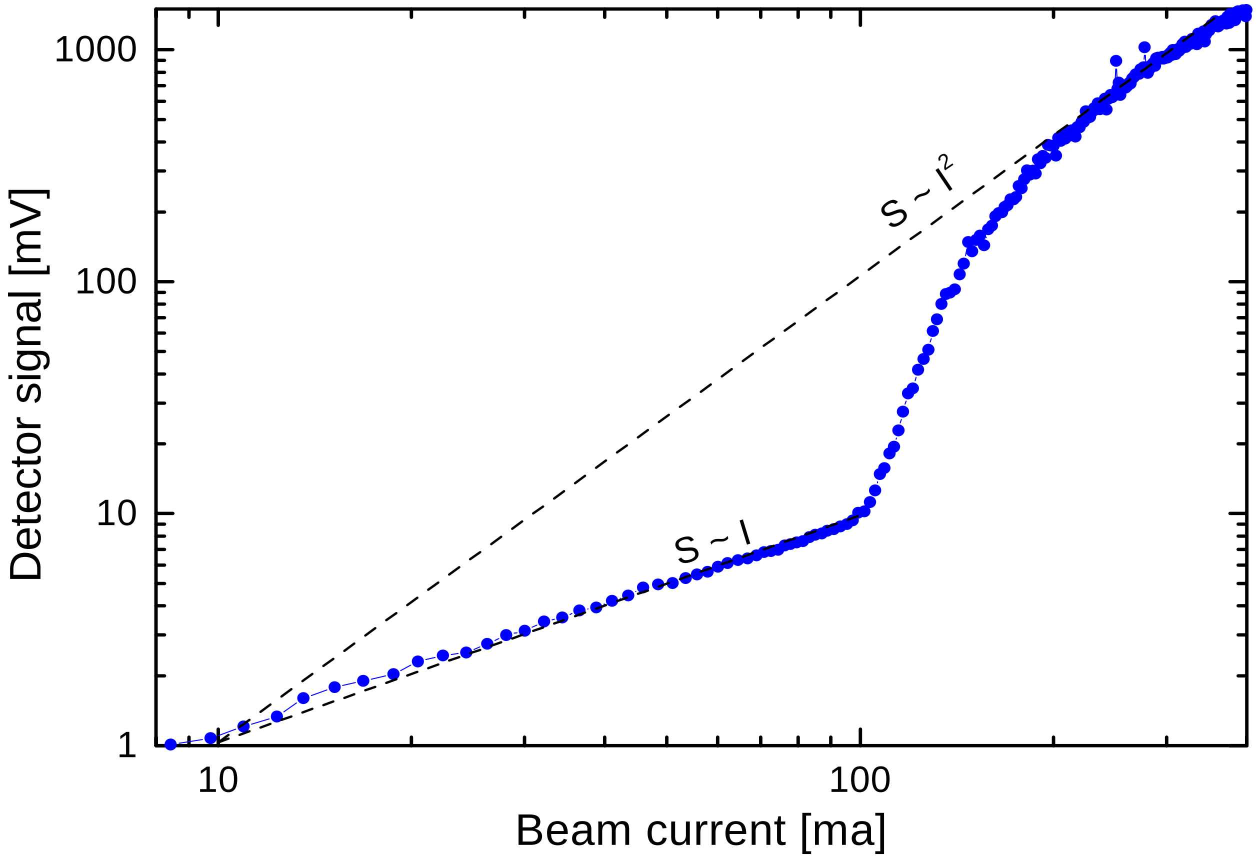
U12IR - beamline / spectrometer



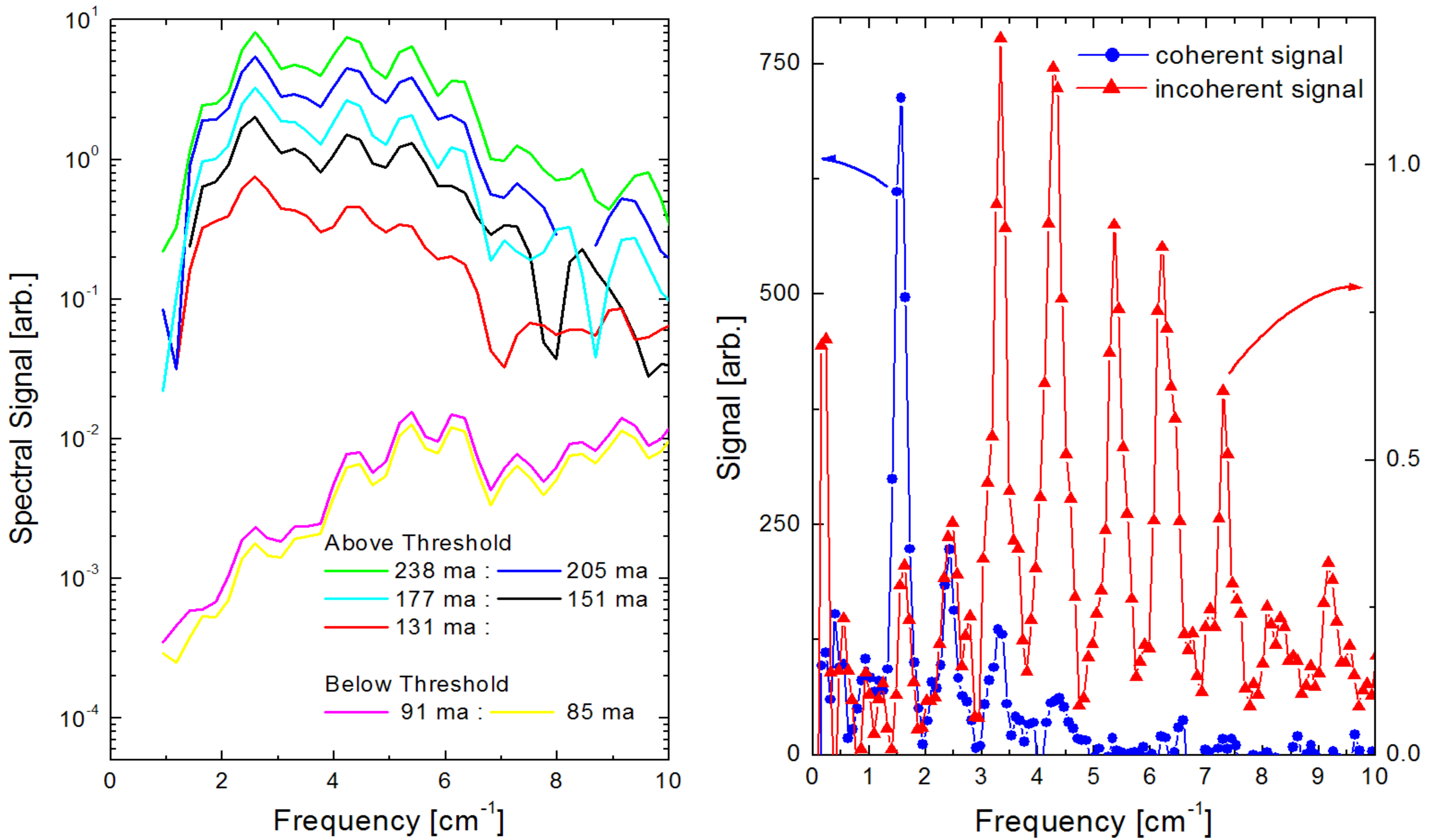


Coherent synchrotron radiation: Beam current dependence

- First observed: October 1997.
- I^2 dependence beyond threshold.
- threshold depends on operating parameters (E, bunch stretching, α).
  - *G.L. Carr et al, PAC-99, SPIE: vol.* ***3775*** *p.88 (1999),*
    Nucl. Instrum. & Meth. Phys. Res. A **463**, 387 (2001)

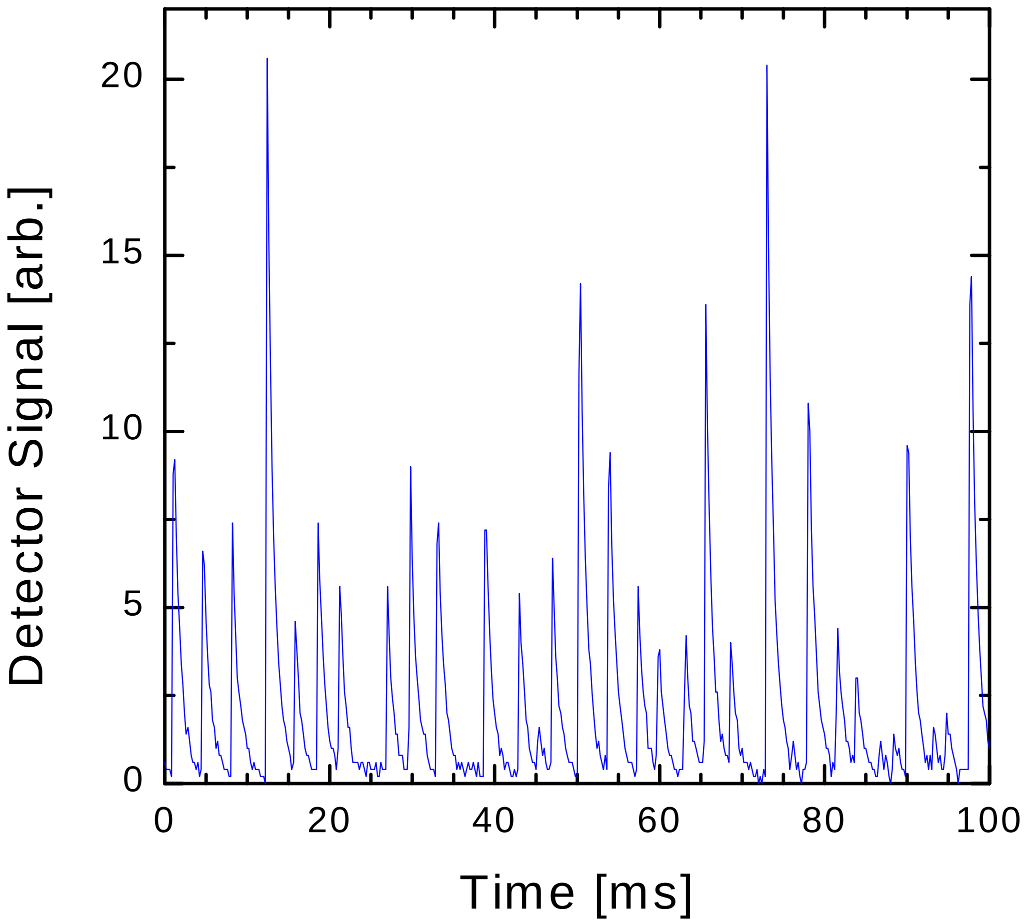


VUV Ring Coherent SR: Relative Spectral Intensity

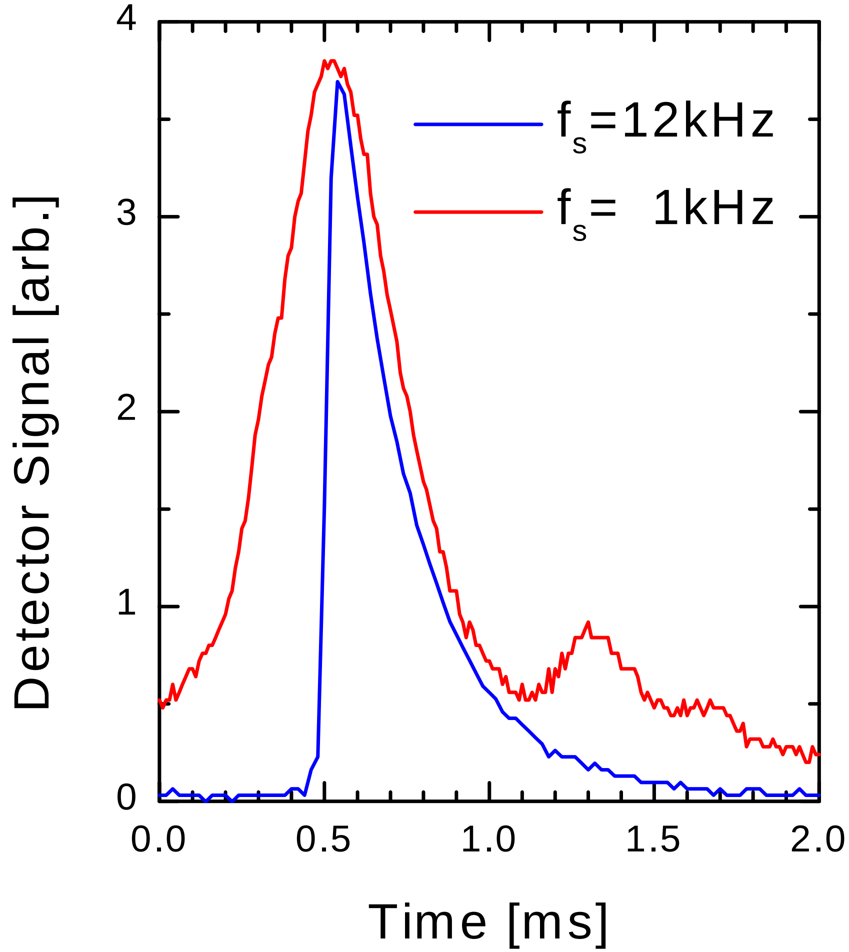


CSR Emission Bursts

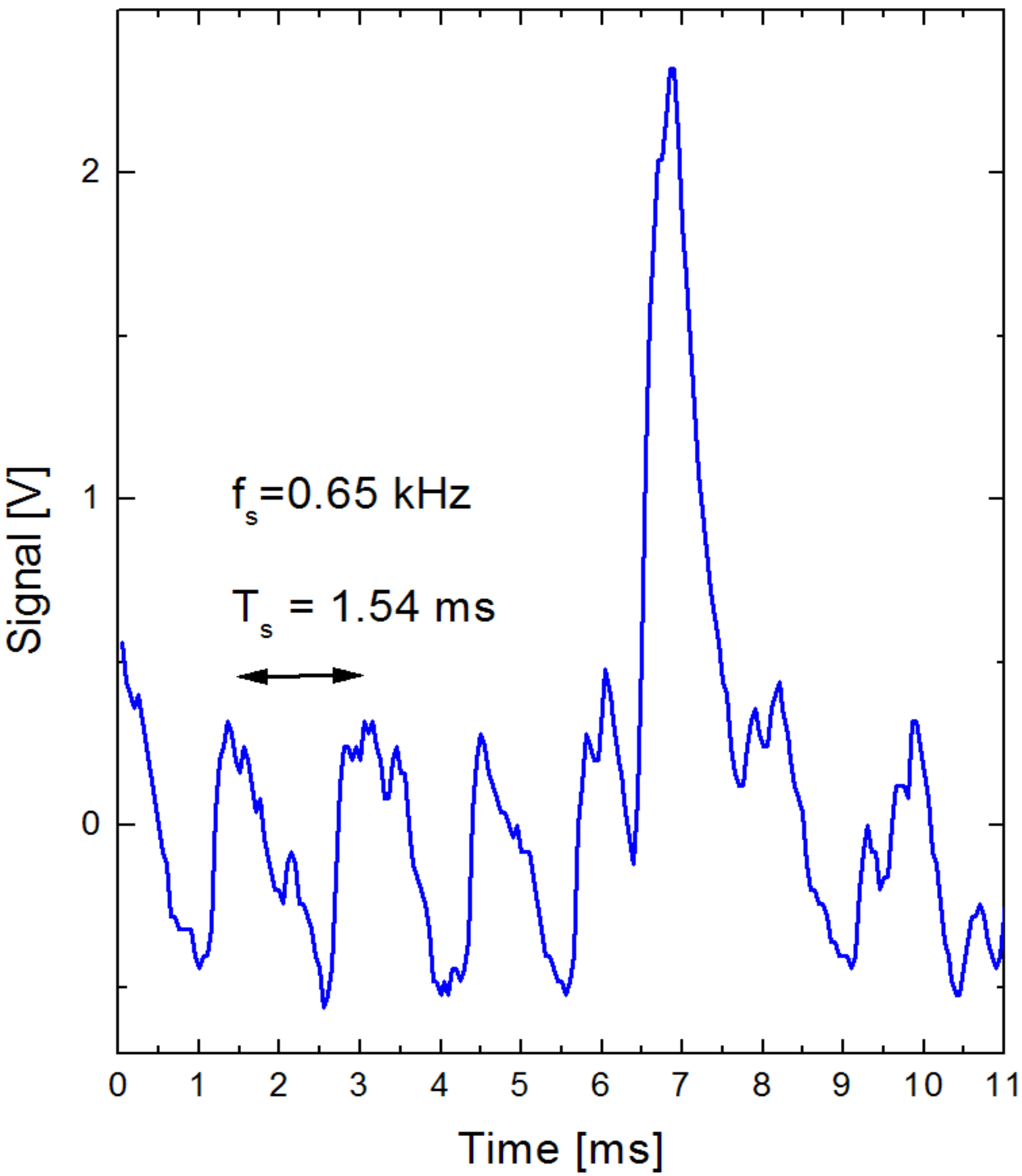
- *Quasi-periodic bursts*
- *T ~ 1 to 10 ms*
- *detector-limited fall time*

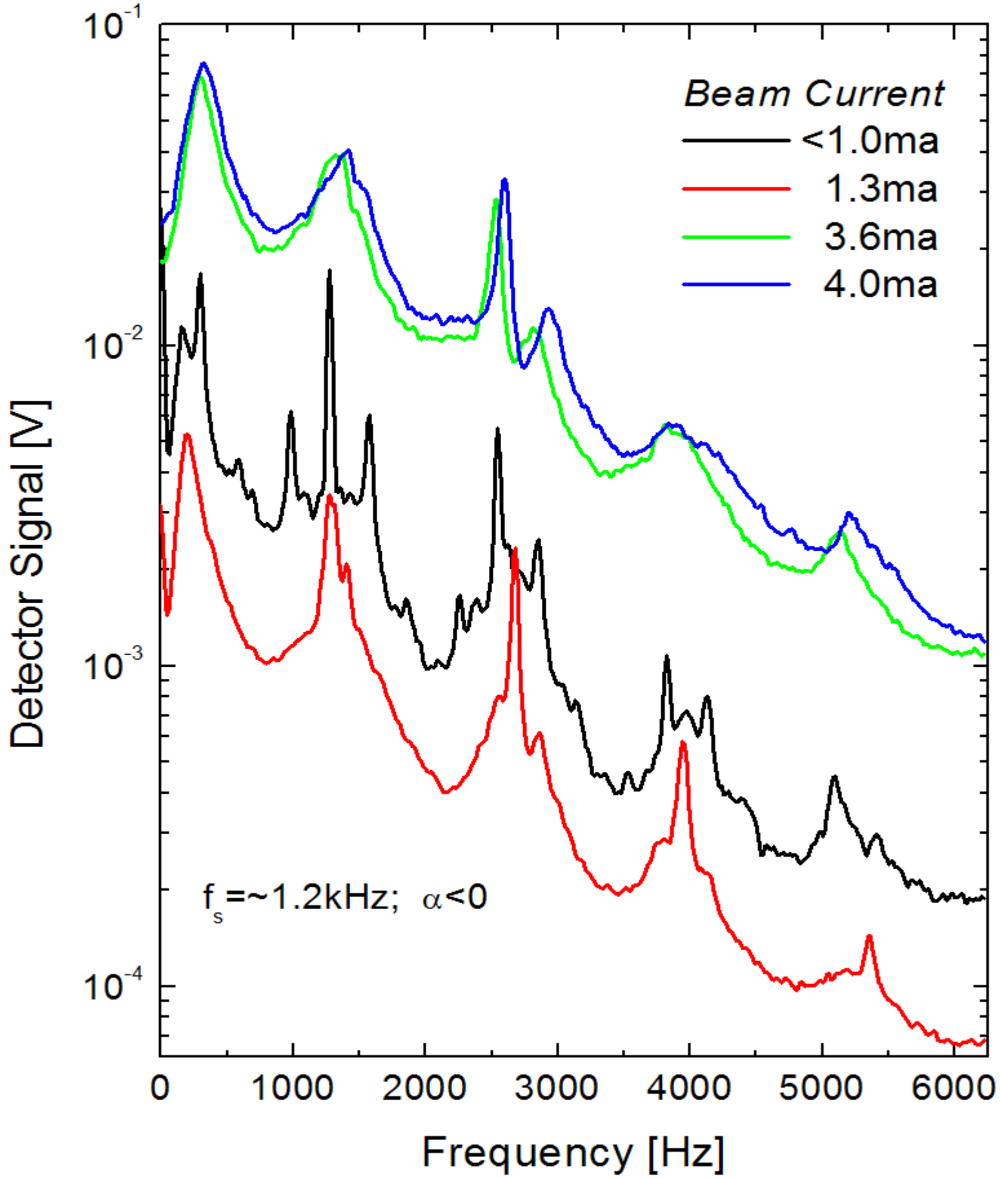


- *Risetime < 100 μs for $\alpha = \alpha_o$*
- *increases with decreasing α*



Coherent Bursts: Time Structure (spectrum analysis)





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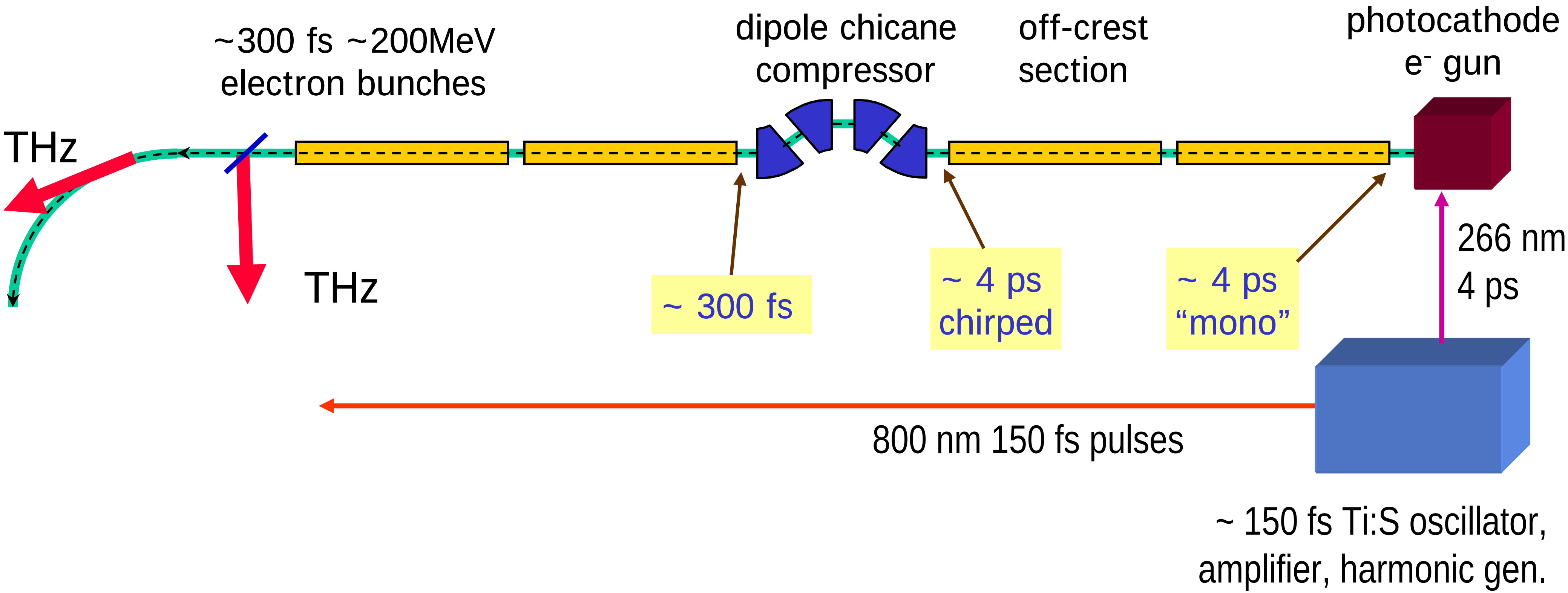
The NSLS Source Development Lab Linac

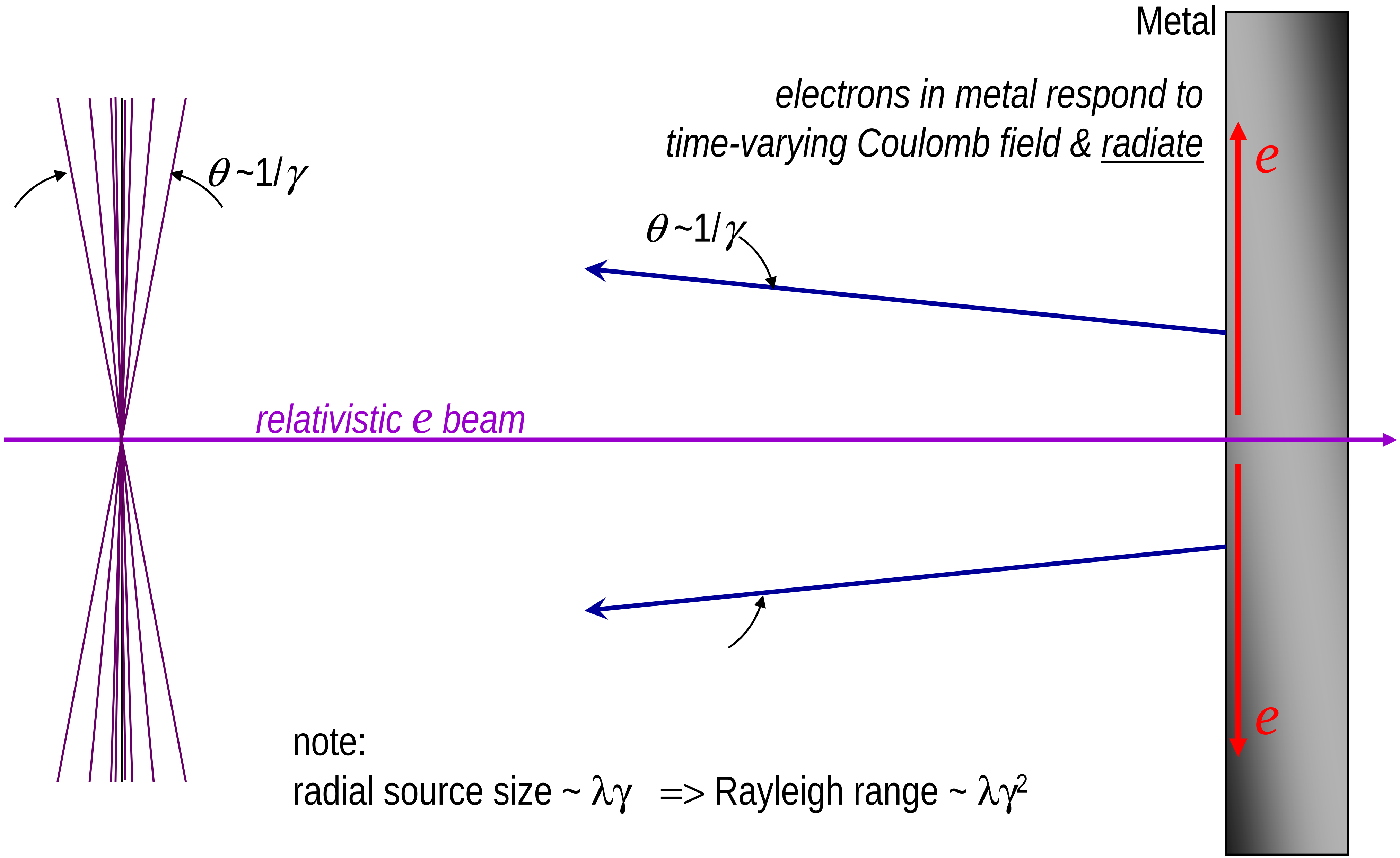
X.-J. Wang et al

- Photocathode gun produces ~ 0.84nC ($5x10^9$ electrons) per "shot"



- Coherent output to over 1 THz. Potential for shorter bunches with less charge.
- Low rep. rate (1 to 10 Hz)

Transition Radiation from Relativistic Electrons



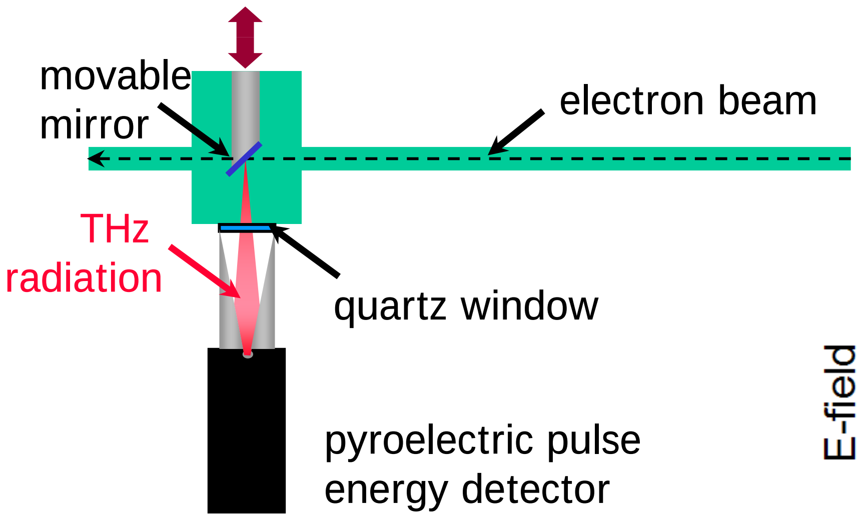
note:
radial source size ~ $\lambda\gamma$ => Rayleigh range ~ $\lambda\gamma^2$

Coherent THz Pulses

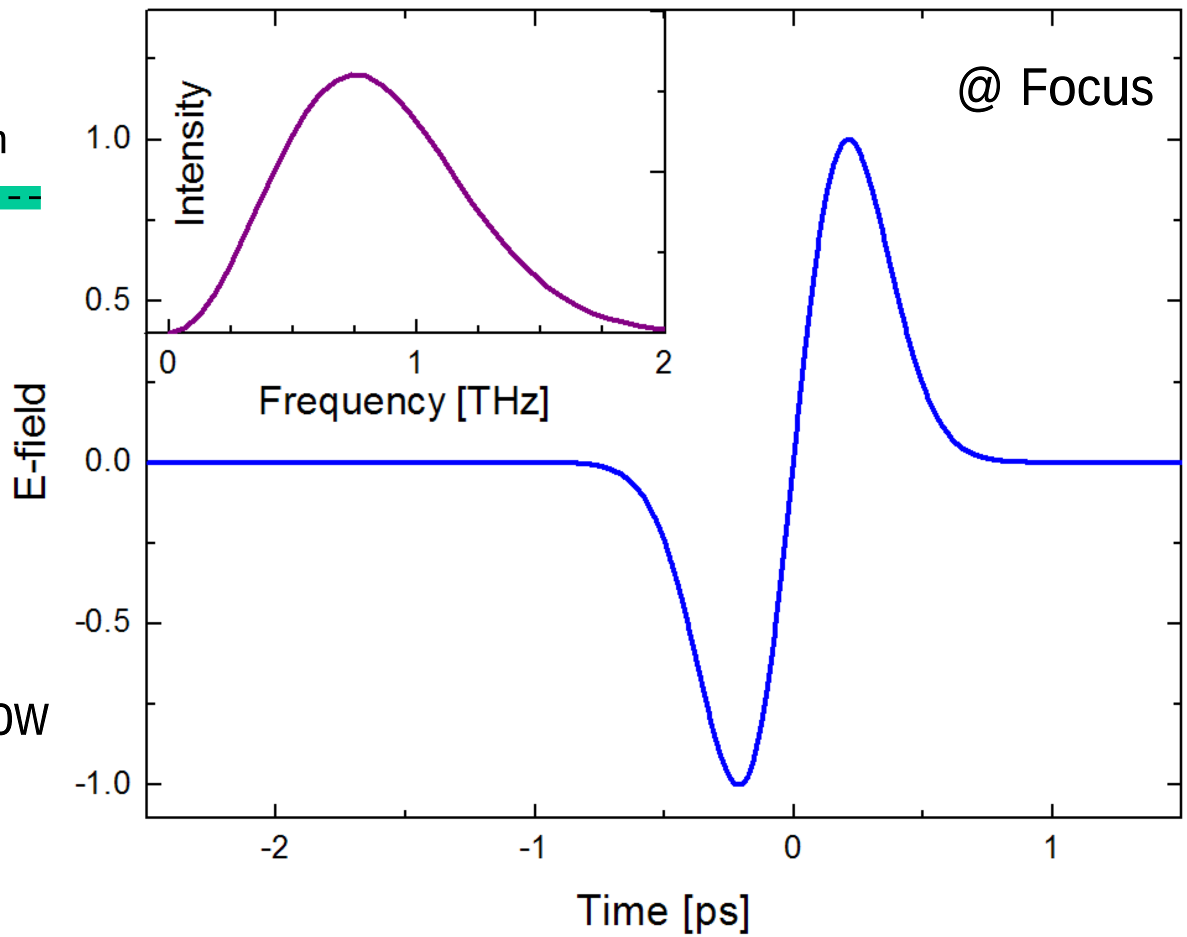
Transition Radiation: Energy per electron per $\omega \rightarrow$ $E = \frac{e^2}{\pi c}\left[\ln\left(\frac{2}{1-\beta}\right)-1\right]$

(Happek et al, PRL)

10^{10} electrons, 116 MeV coherent to 1 THz
=> pulse energy of 400 μJ



Expected behavior



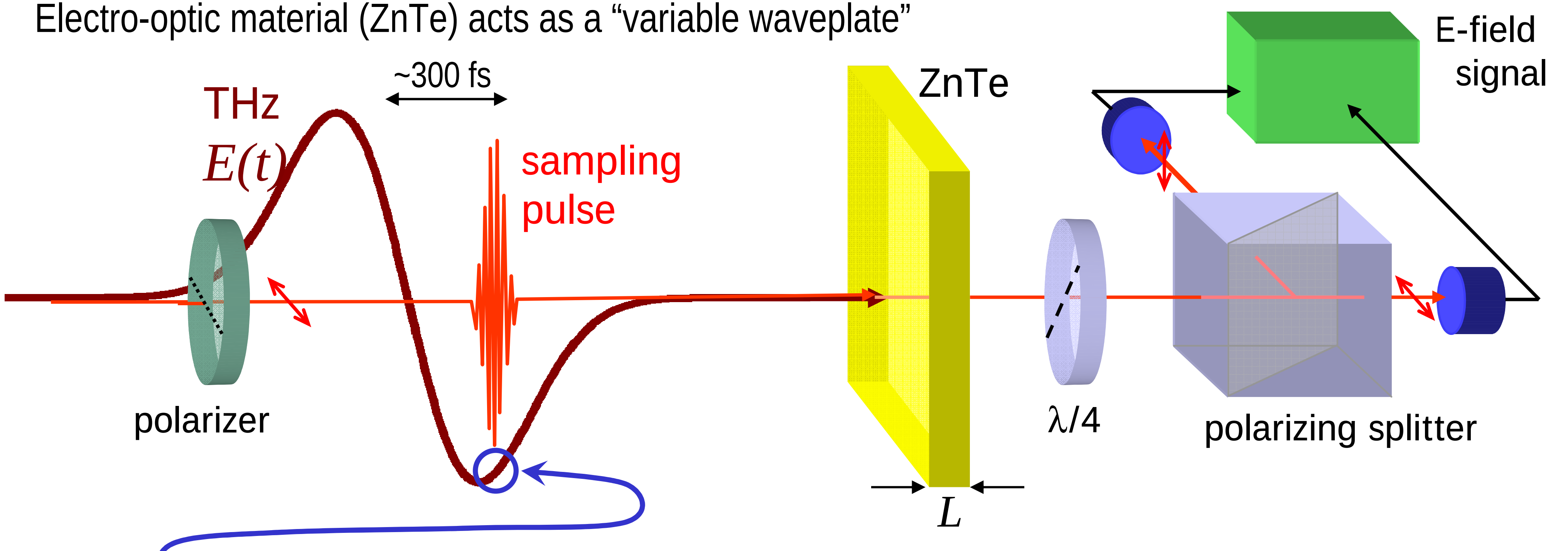
Finite source and aperture, quartz window reflection => ~ 35% efficient or 140 μJ.
We have measured 100 μJ per pulse.

THz Characterizion: Electro-Optic Methods

Coherent detection setup for measuring THz waveforms using Pockels Effect: "THz Electro-Optic switch" (*Zhang et al, Heinz et al*)

$$E_{laser} \sim \cos\left[\left(\frac{2\pi n}{\lambda_0}\right) z - \omega_0 t + \Delta\phi_E(t)\right] \quad \text{where} \quad \Delta\phi_E(t) = \left(\frac{2\pi L}{\lambda_0}\right)\Delta n[E_{THz}(t)]$$

Electro-optic material (ZnTe) acts as a "variable waveplate"



$$E(t) = E(t_0) + \frac{dE}{dt}(t - t_o) + \frac{1}{2}\frac{d^2E}{dt^2}(t - t_o)^2 + \ldots$$

Result: Detector signal gives instantaneous THz E-field.

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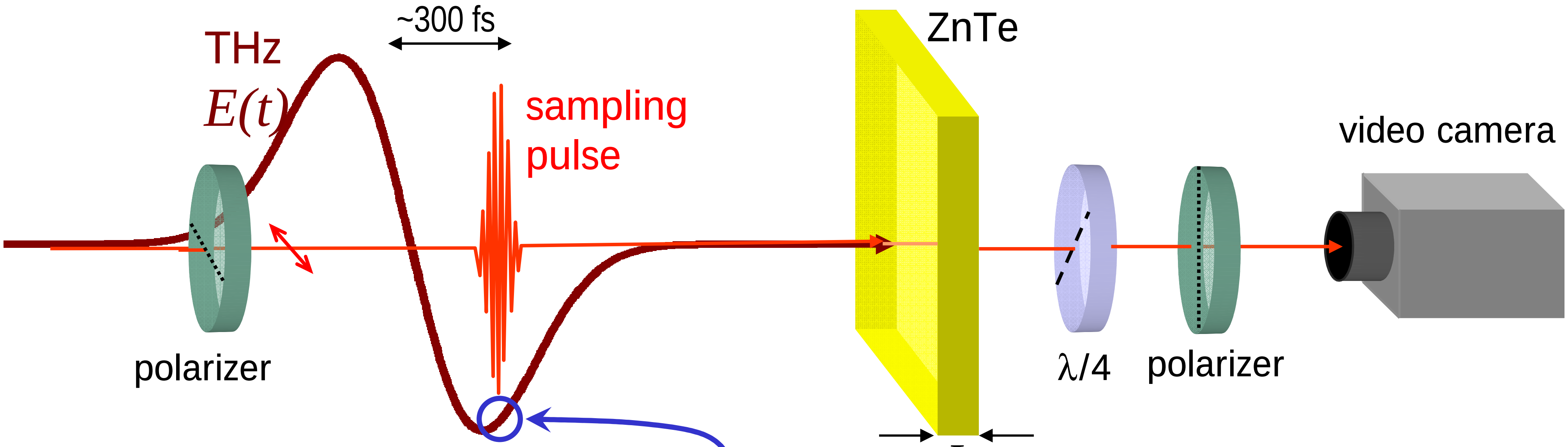


Result: Snapshot of instantaneous THz E-field.

$$E(t) = E(t_0) + dE/dt\,(t - t_o) + ½\, d^2E/dt^2\,(t - t_o)^2 + \ldots$$

Electro-optic sampling of SDL Linac Coherent THz Pulses

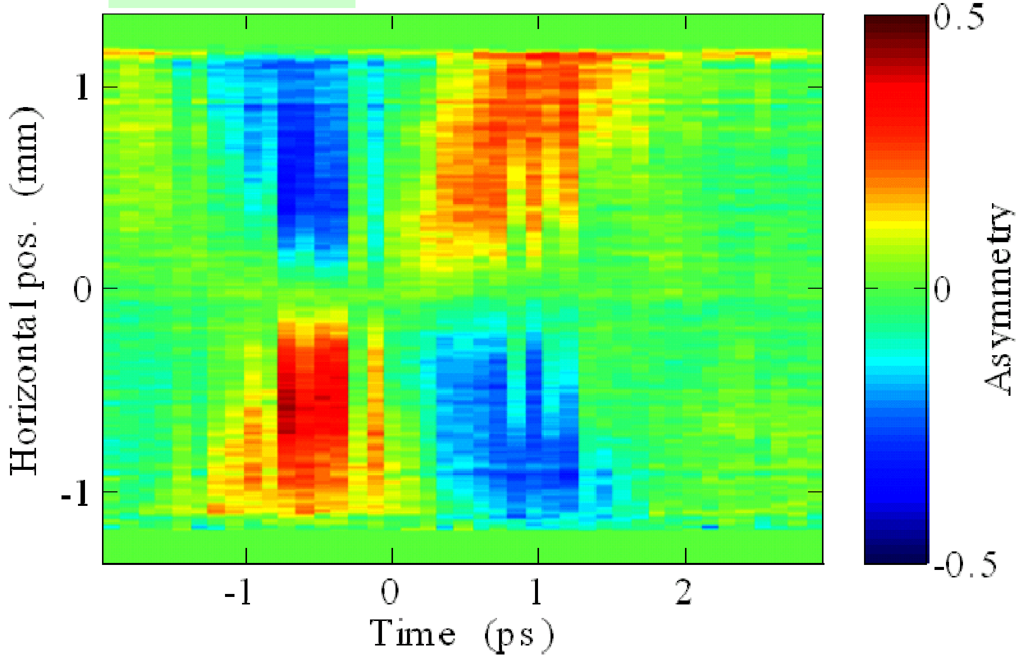
Low charge (intensity) measurement:

Single-cycle at focus: note that Transition Radiation is radially polarized

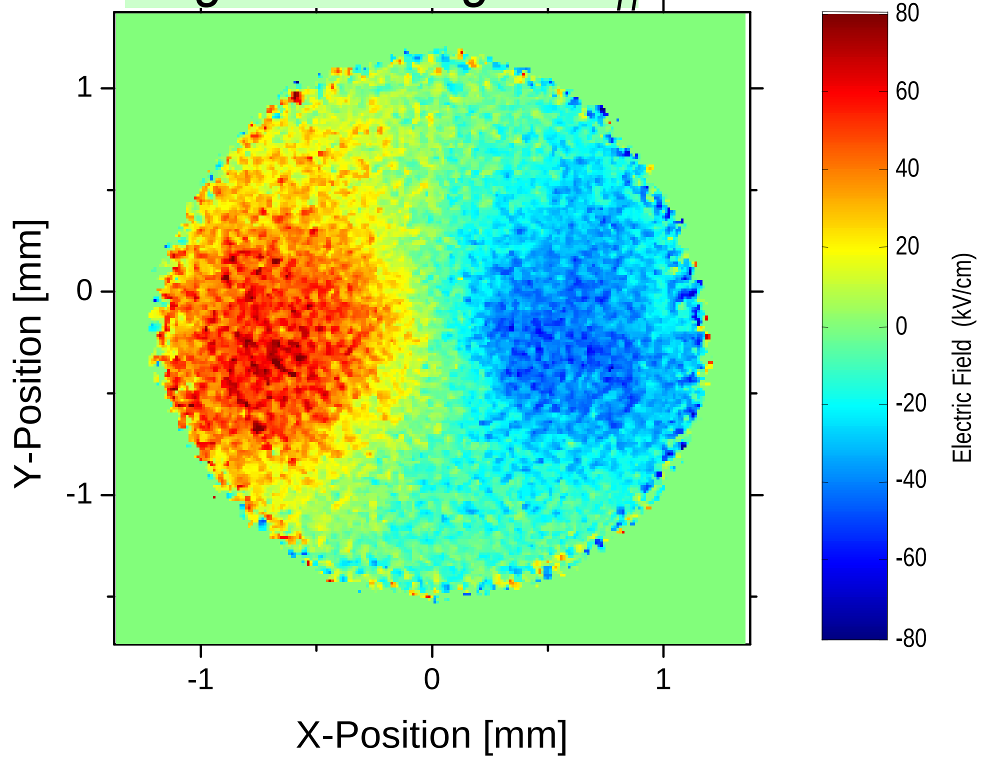
Jitter (~ 150 fs) limits ability to extract detailed waveforms & spectra.

Need a "single-shot" method

Time slices



Single shot image of E_H



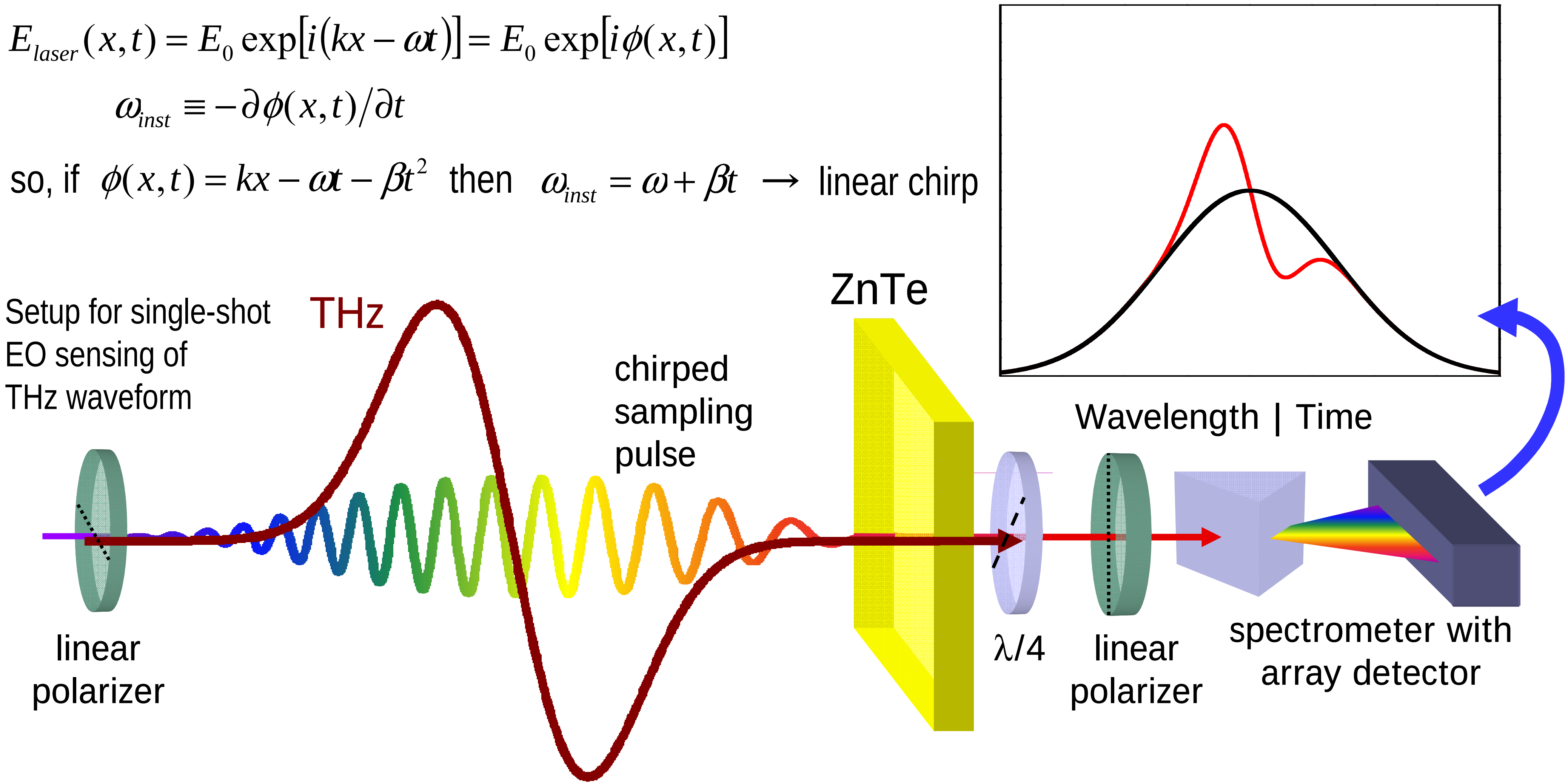
Single-Shot Electro-Optic Method

Use chirped sampling laser to encode waveform's entire time-dependence onto different wavelengths of laser in a single pulse. Avoids need for multiple sampling.
[Jiang and Zhang, *Appl. Phys. Lett.* **72**, 1945 (1998)].

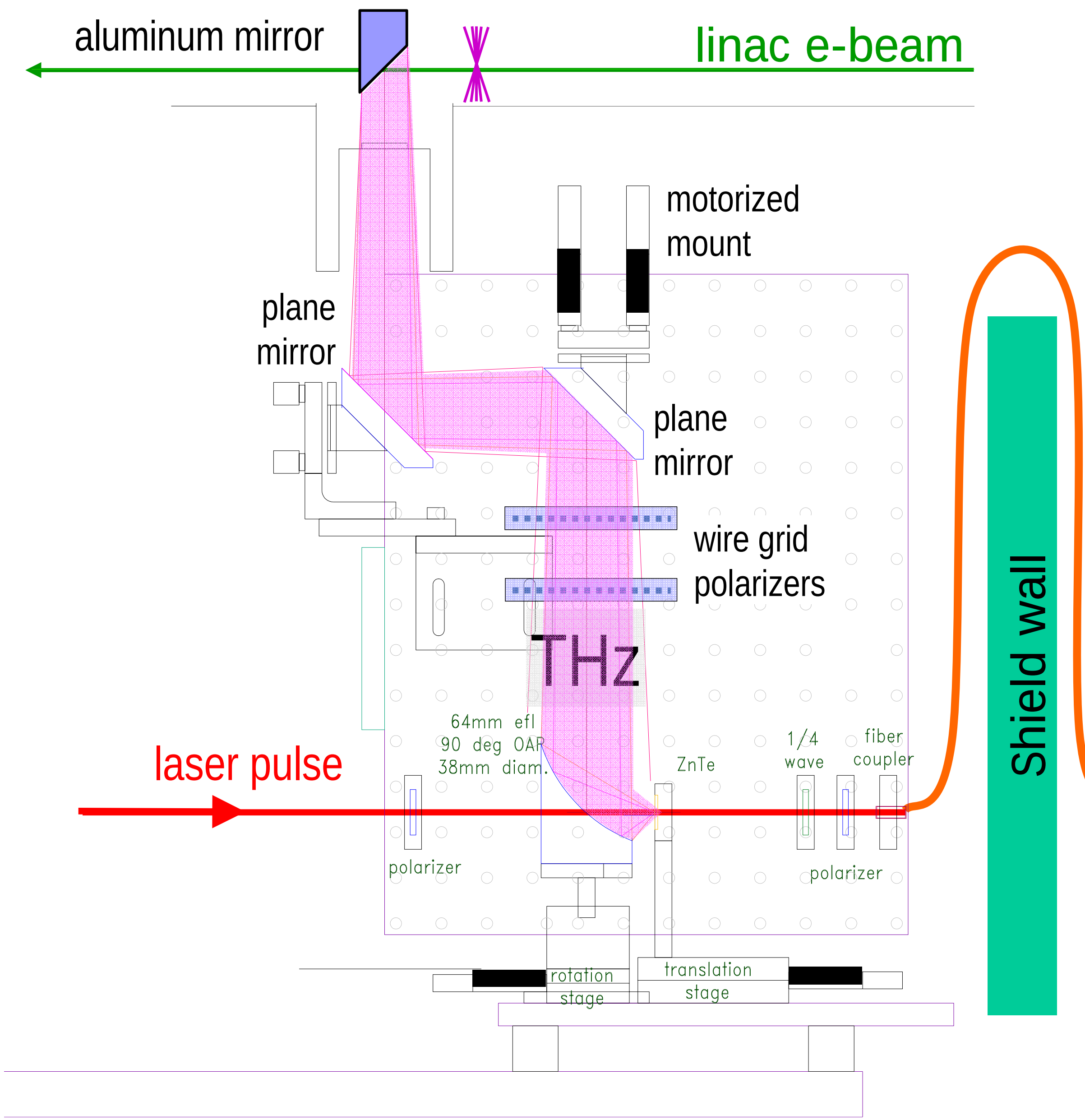
$$E_{laser}(x,t) = E_0 \exp[i(kx - \omega t)] = E_0 \exp[i\phi(x,t)]$$

$$\omega_{inst} \equiv -\partial\phi(x,t)/\partial t$$

so, if $\phi(x,t) = kx - \omega t - \beta t^2$ then $\omega_{inst} = \omega + \beta t$ → linear chirp

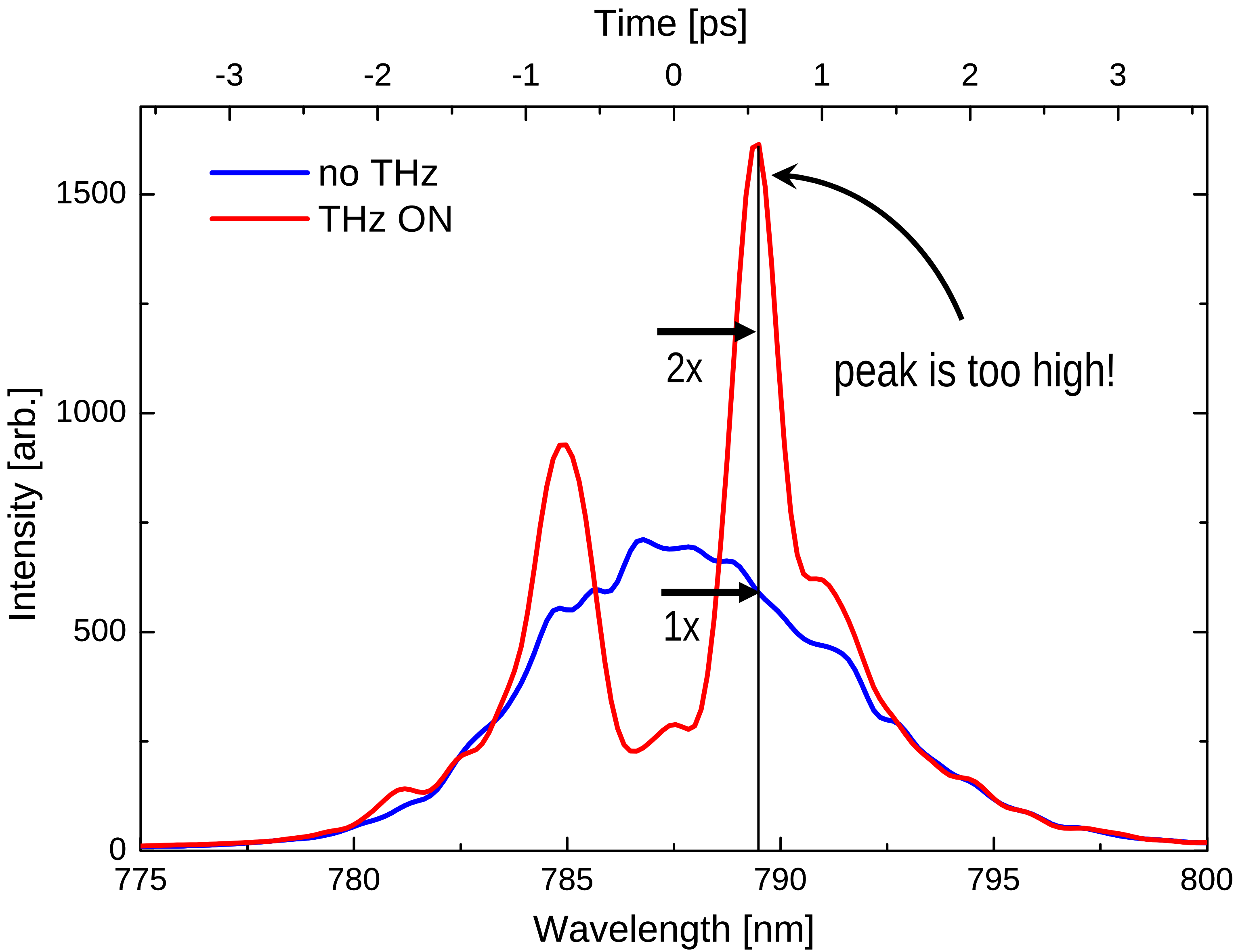


Layout for Characterizing THz Waveforms

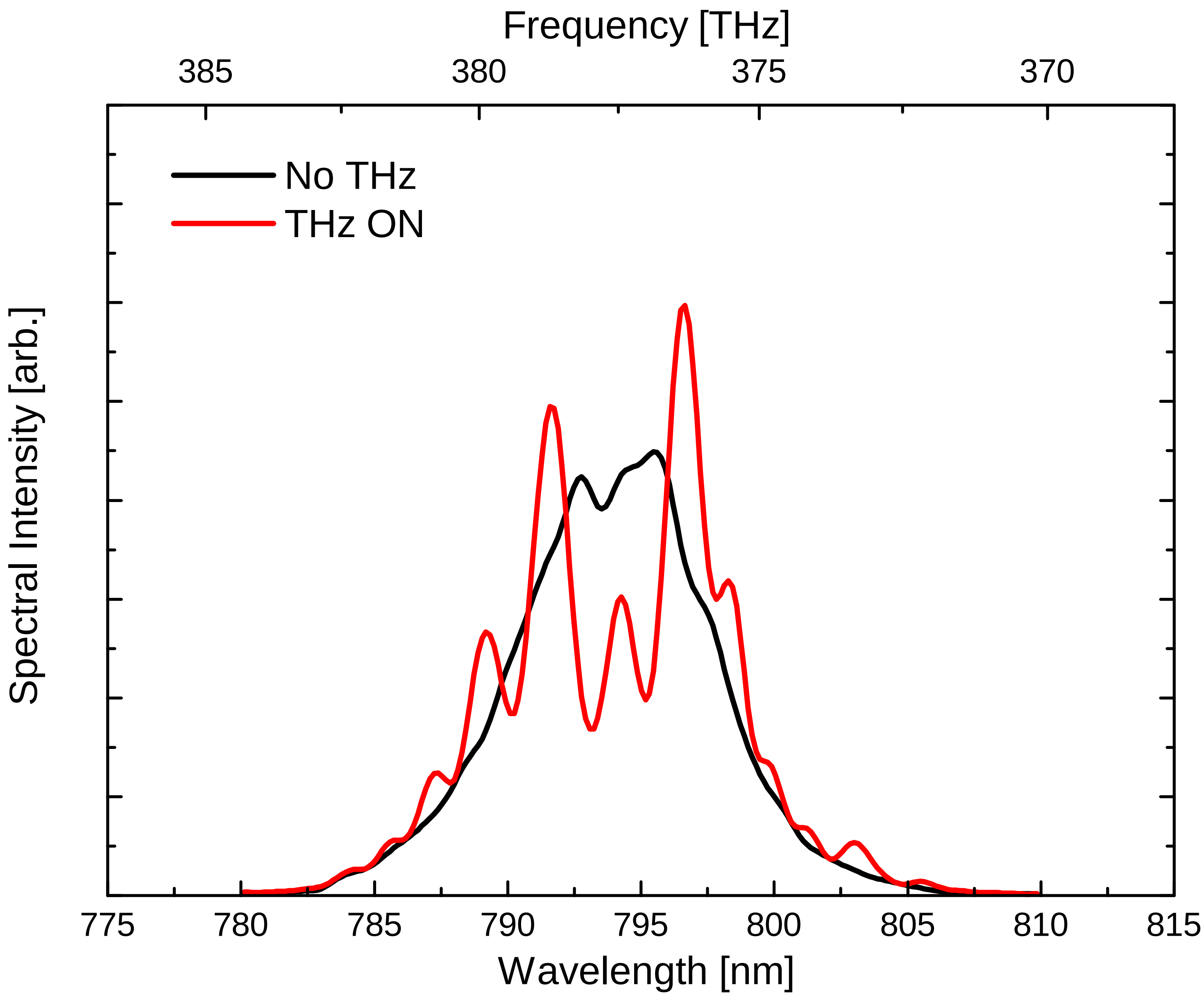


Fiber coupled spectrometer

Single-Shot EO Sampling of SDL THz Pulse using Chirped Laser



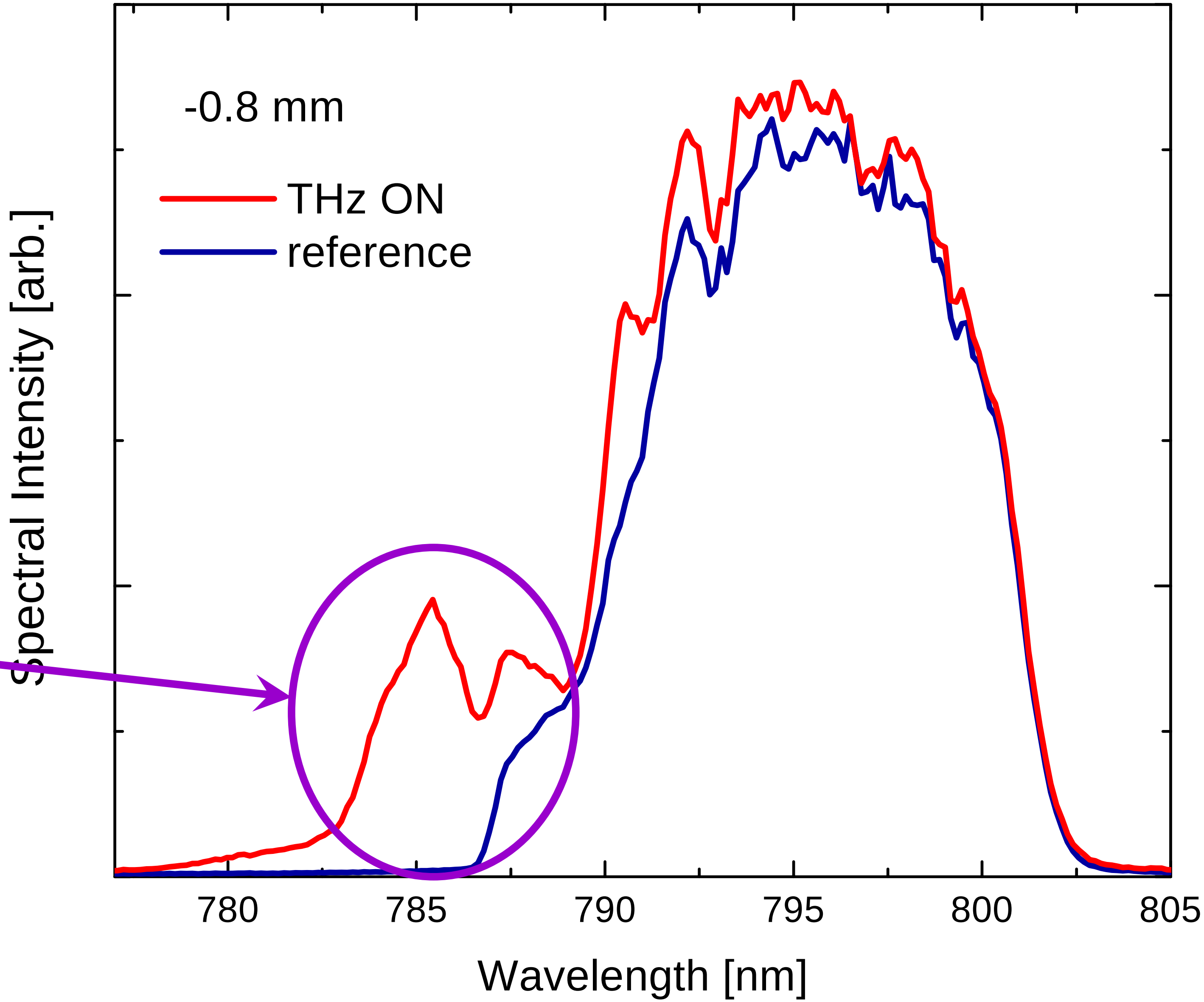
Single-Shot EO Sampling of SDL THz Pulse: Higher intensity



Spectral Distribution

Now, shift relative timing between the THz and chirped laser pulse by 0.8mm (places THz nearer to the short wavelength end of the chirped laser's spectrum).

"New" spectral intensity appears in the sampling laser.



Time-Dependent THz E-field and Phase Modulation Effects

- Return to details of Pockels electro-optic effect in terms of the induced phase $\phi[E_{THz}(t)]$ for the sampling laser:

$$E_{laser} \sim \cos[\phi_0 + \phi(t)]; \qquad \phi(t) = \frac{2\pi L}{\lambda_0} n[E_{THz}(t)] - \omega t$$

- Return to Taylor series expansion (this time for phase):

$$\phi(t) = \underbrace{\eta\, E(0)}_{\substack{\text{conventional}\\ \text{EO effect}}} + \left[\underbrace{\eta \left(dE_{THz}/dt \right)}_{\substack{\text{freq.}\\ \text{shift}}} - \omega \right] t + \underbrace{\left[\eta \left(d^2E_{THz}/dt^2 \right) \right]}_{\substack{\text{linear}\\ \text{chirp}}} t^2 + \ldots \quad \text{where} \quad \eta = \frac{2}{1+\sqrt{\varepsilon}} \frac{2\pi L}{\lambda_0} n_0{}^3 r_{41}$$

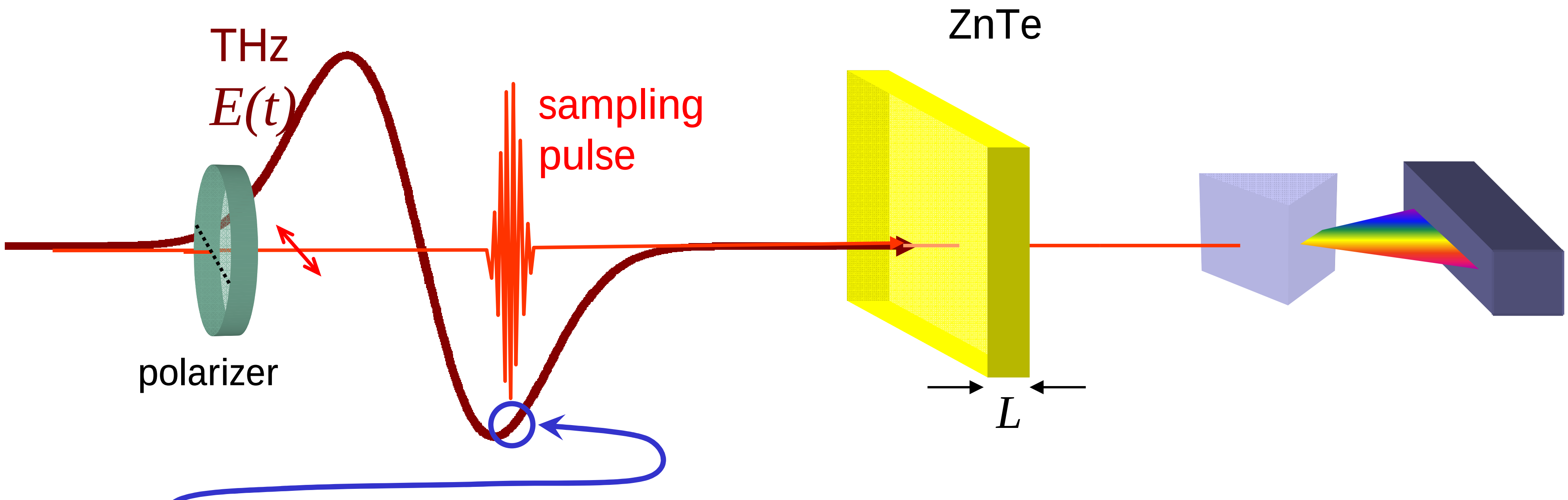
- Different terms in phase correspond to simple phase shifts, spectral shifts and even spectral chirping.
- Result: When THz is sufficiently strong, it modifies the spectral content of the Ti:S laser.
- Note: for 1% wavelength shift at λ=800nm with 0.5mm ZnTe, need dE/dt = 1.3 MV/cm/ps
- Application: THz *control* of ultra-fast laser pulses (tuning, chirp+compression, lensing, …)
- Effects simplified using an unchirped laser (to sample just a small segment of THz waveform).

THz Characterizion: Electro-Optic Methods

"Simple" EO setup to observe time-dependent phase modulation

$$E_{laser} \sim \cos\left[kz + \Delta\phi_E(t) - \omega t\right] \quad \text{where} \quad \Delta\phi_E(t) = \left(2\pi\, L/\lambda_0\right)\Delta n\left[E_{THz}(t)\right]$$

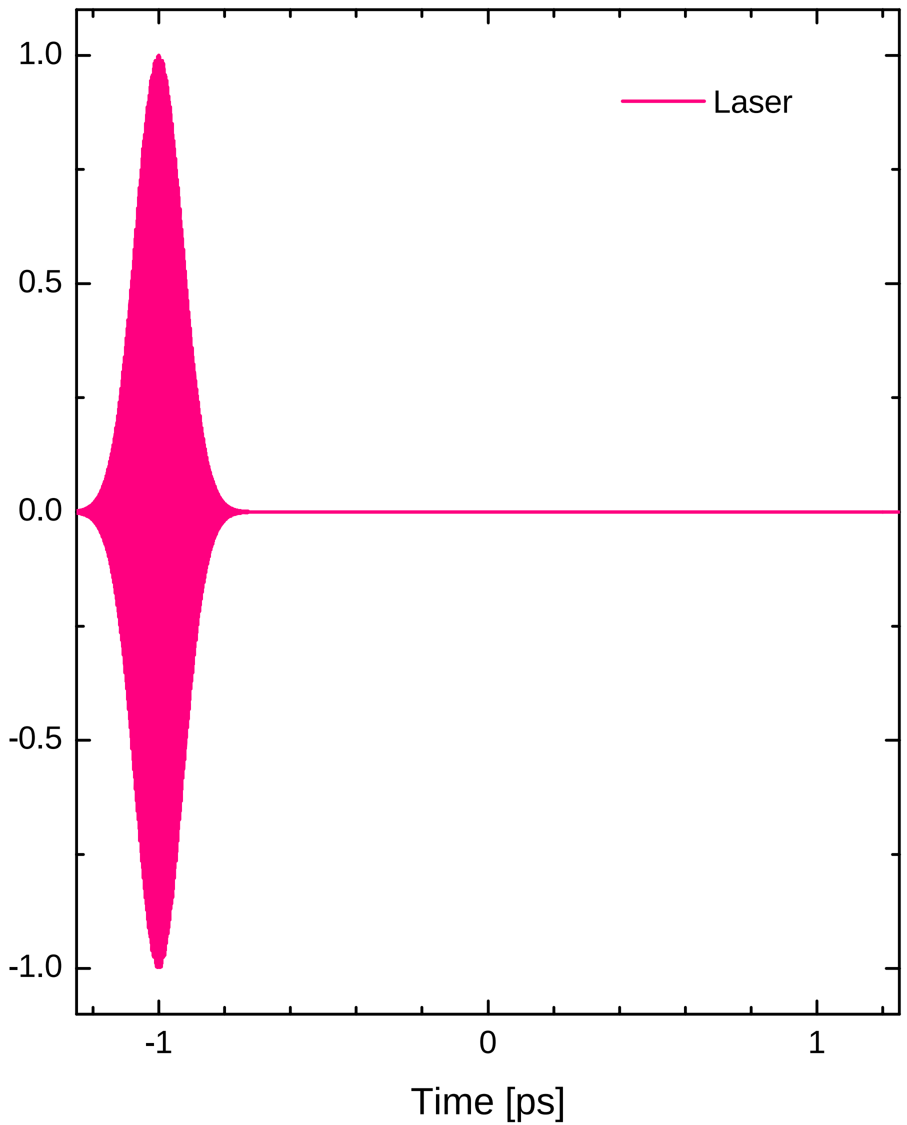
Electro-optic material (ZnTe) acts cross phase modulator

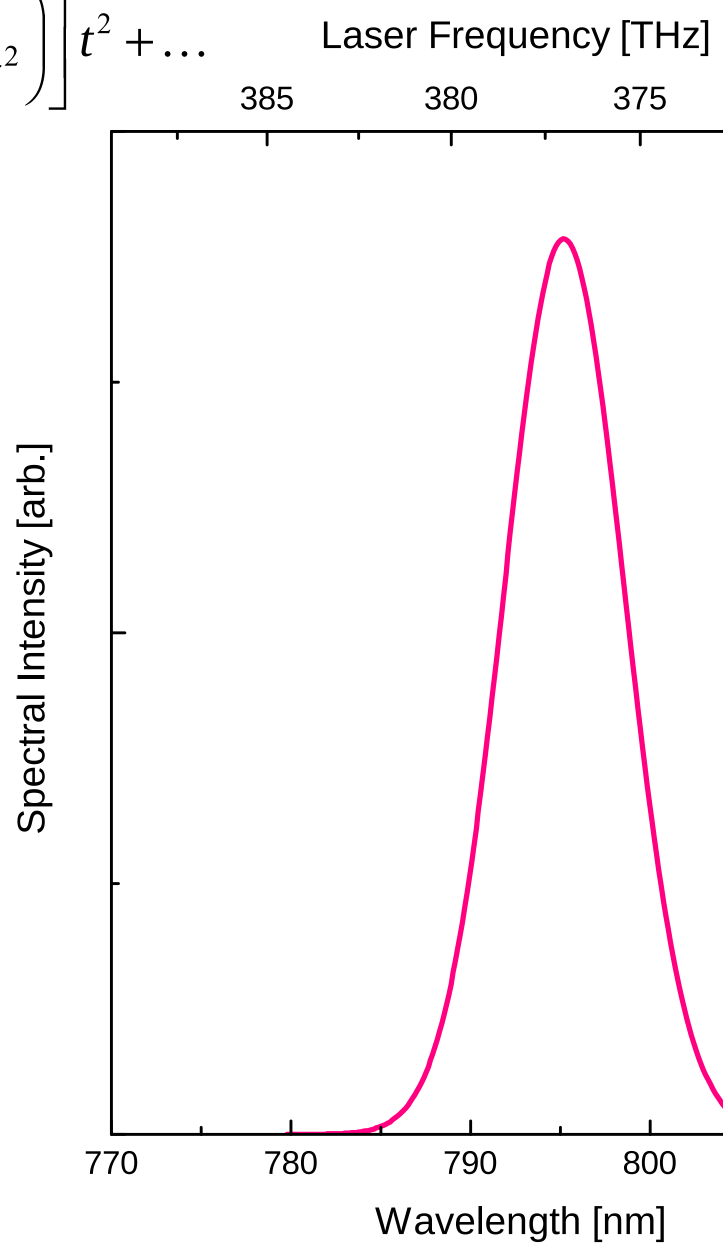


$$E(t) = E(t_0) + dE/dt\,(t - t_o) + ½\, d^2E/dt^2\,(t - t_o)^2 + \ldots$$

Sampling Laser Pulse & Spectral Content

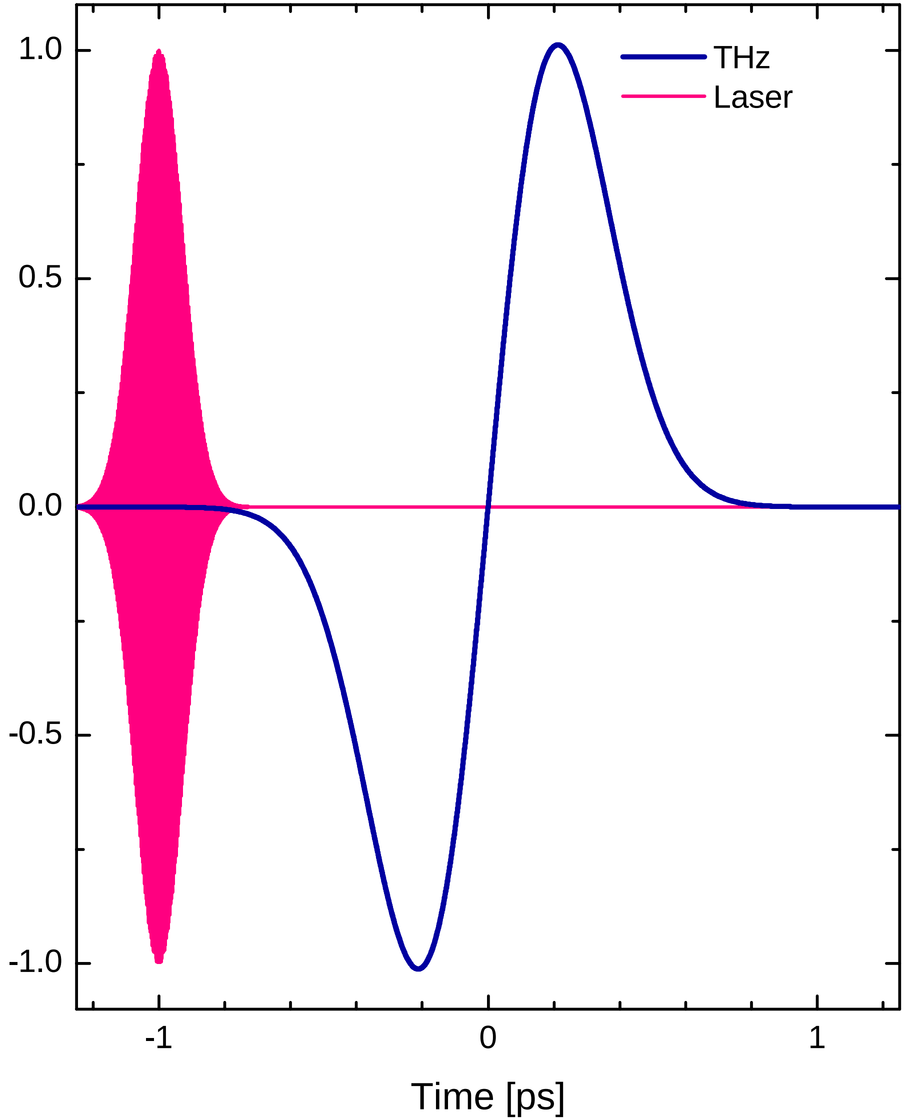
$$\phi(t) = \eta\, E(0) + \left[\eta\left(\frac{dE_{THz}}{dt}\right) - \omega\right] t + \left[\eta\left(\frac{d^2E_{THz}}{dt^2}\right)\right] t^2 + \ldots$$

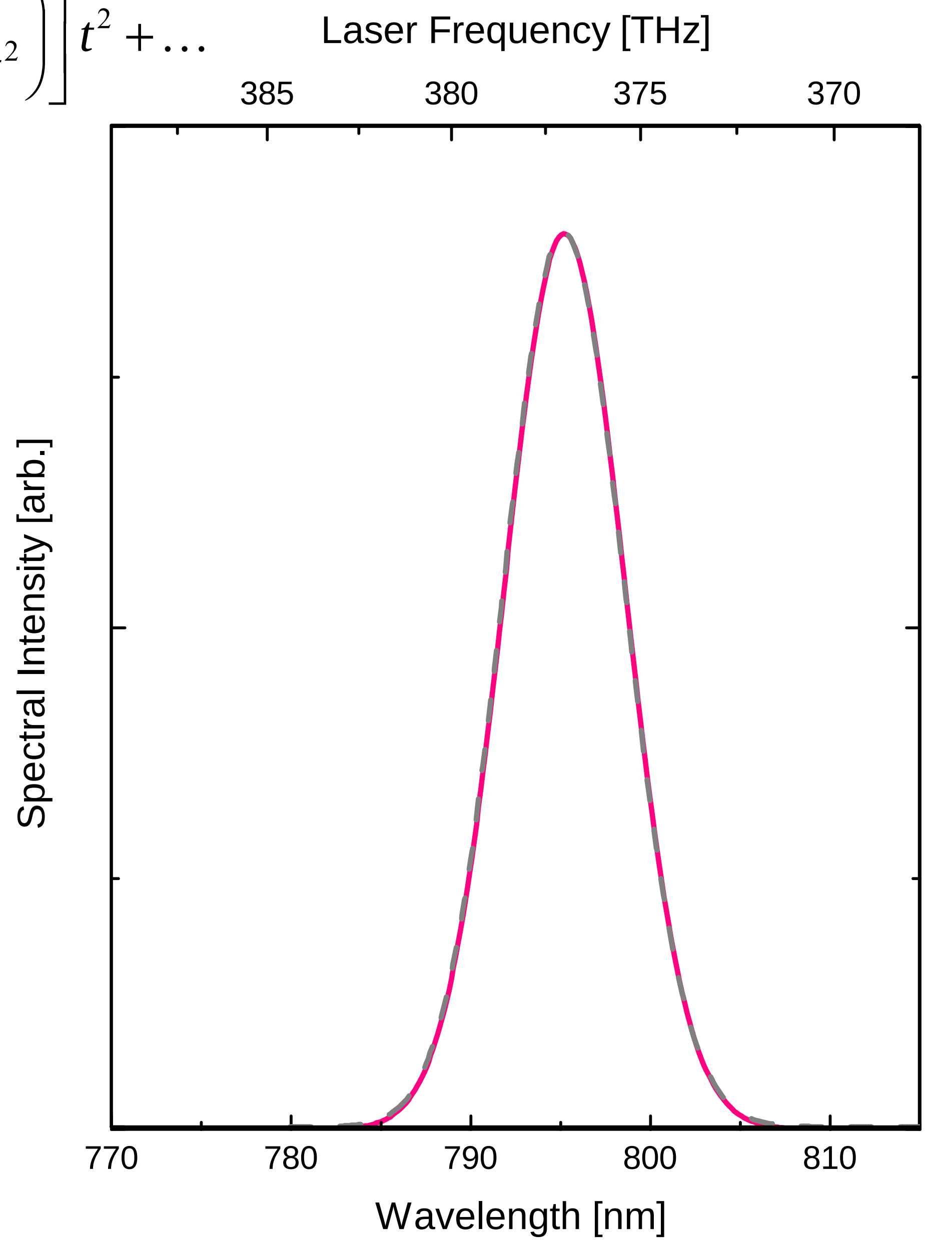




THz Phase Modulation of Sampling Laser

$$\phi(t) = \eta\, E(0) + \left[\eta\left(\frac{dE_{THz}}{dt}\right) - \omega\right]t + \left[\eta\left(\frac{d^2E_{THz}}{dt^2}\right)\right]t^2 + \ldots$$





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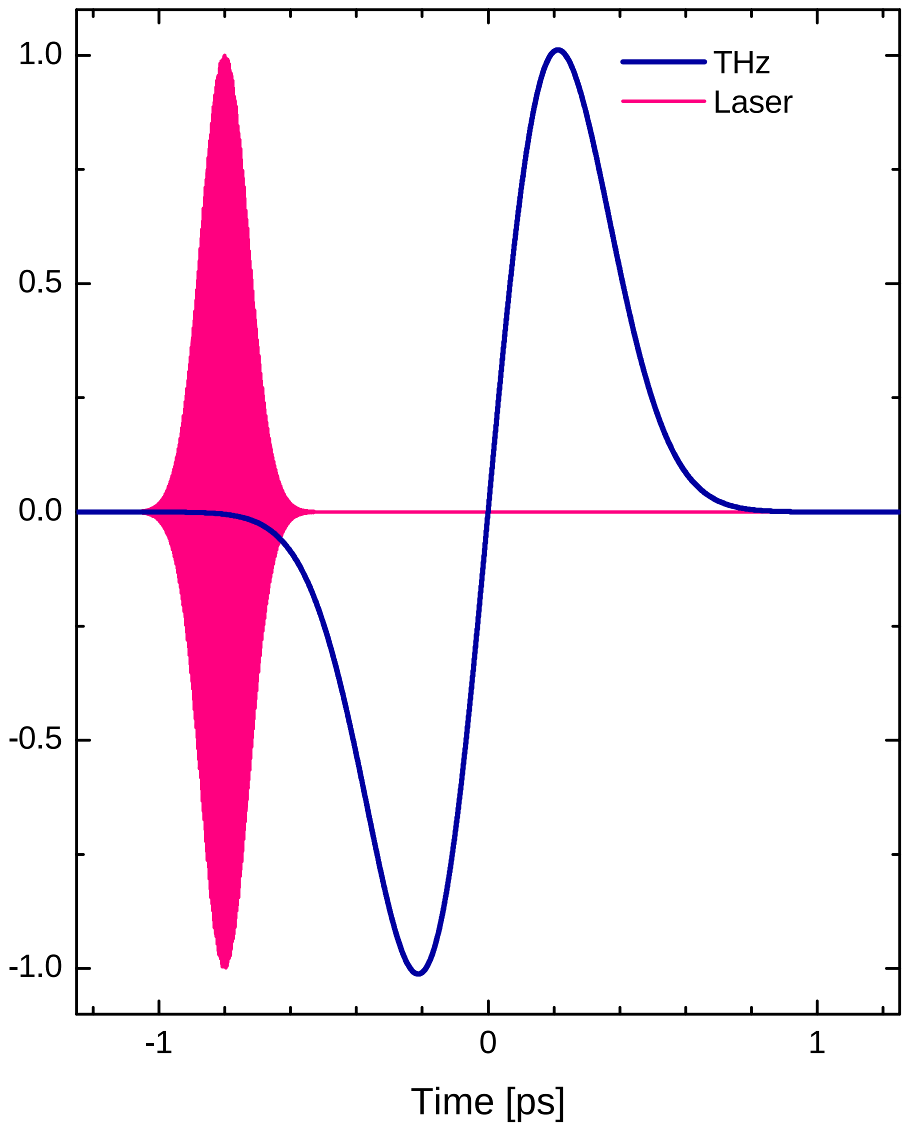
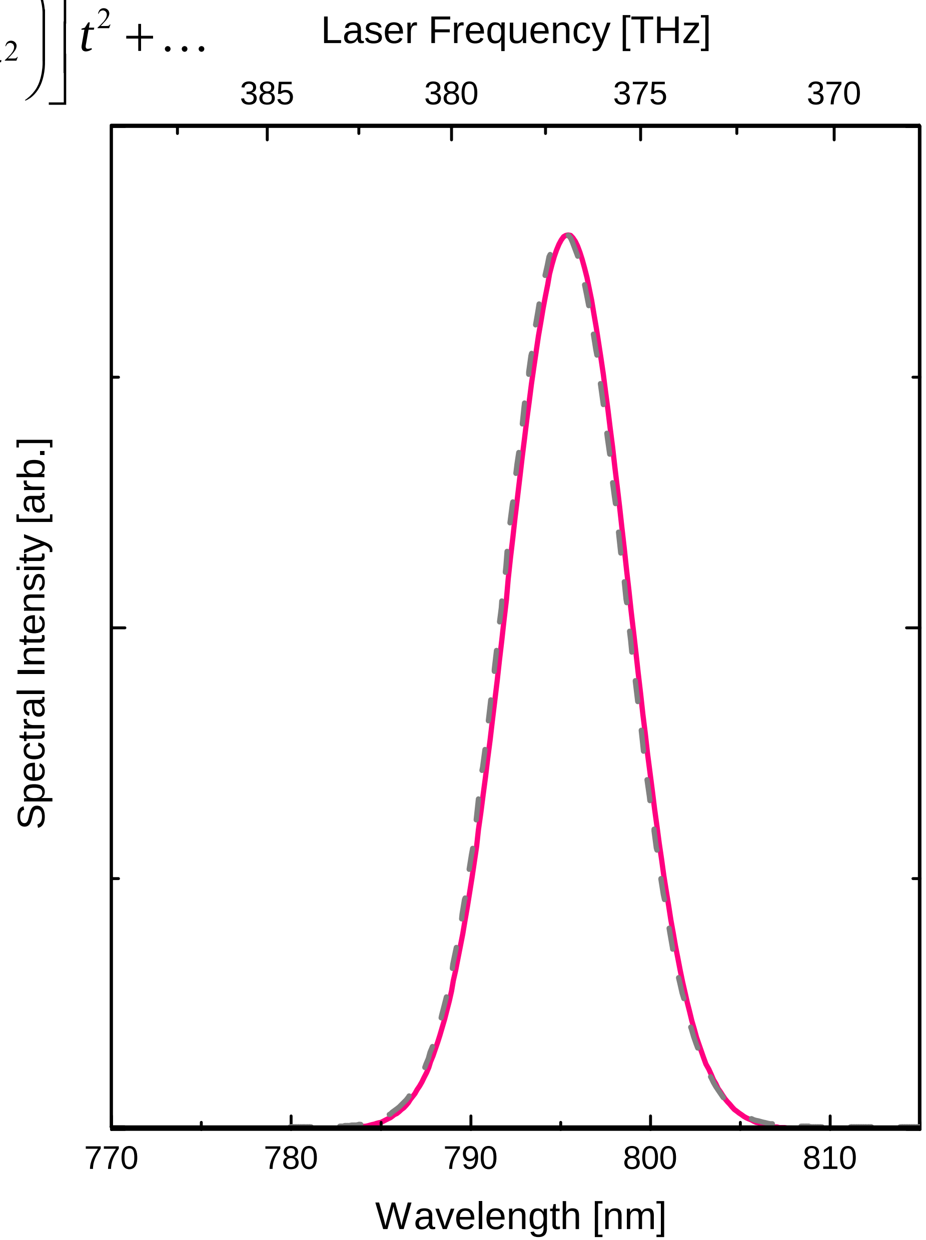
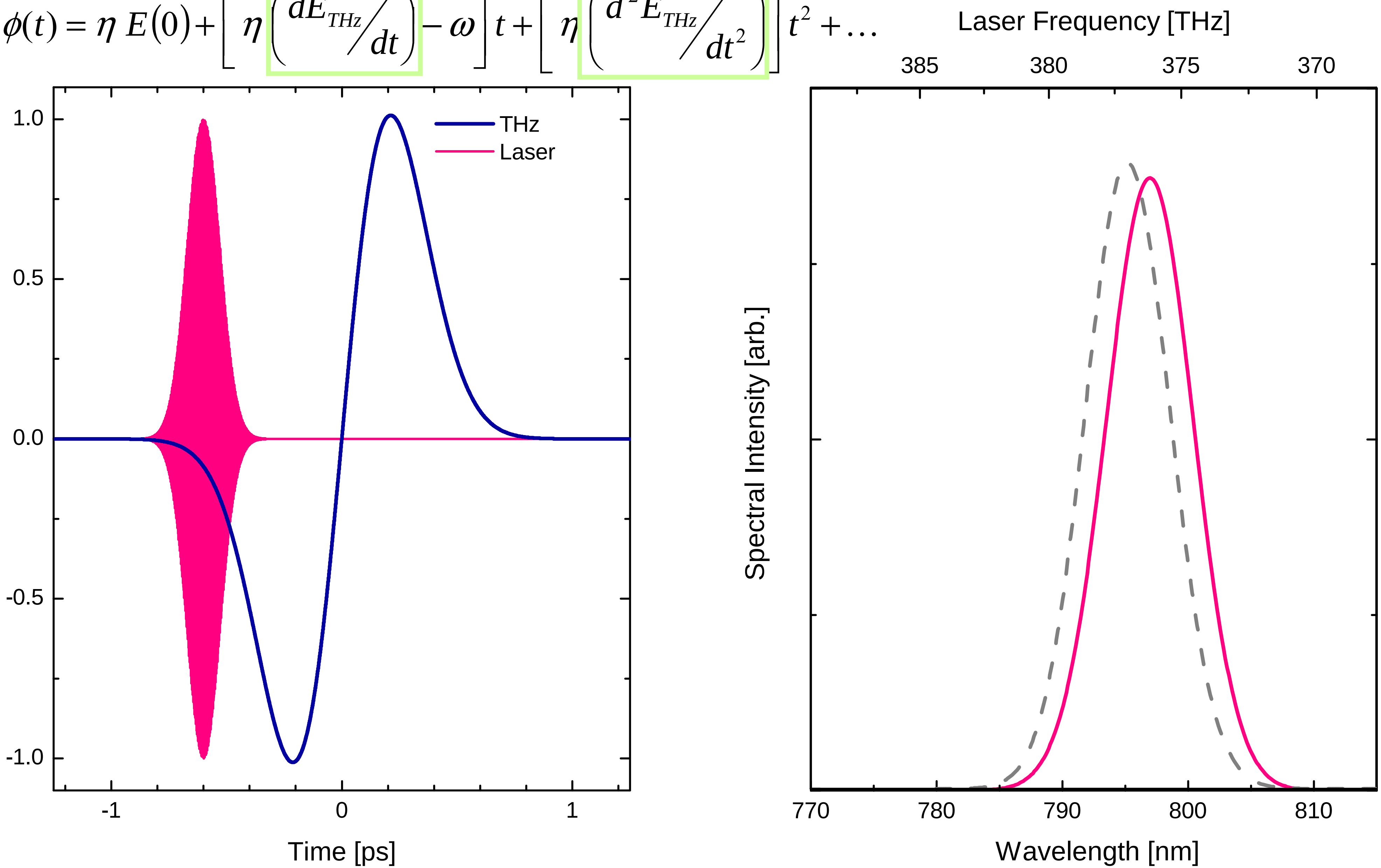




THz Phase Modulation of Sampling Laser

$$\phi(t) = \eta\, E(0) + \left[\eta \left({dE_{THz}}/{dt} \right) - \omega \right] t + \left[\eta \left({d^2 E_{THz}}/{dt^2} \right) \right] t^2 + \ldots$$



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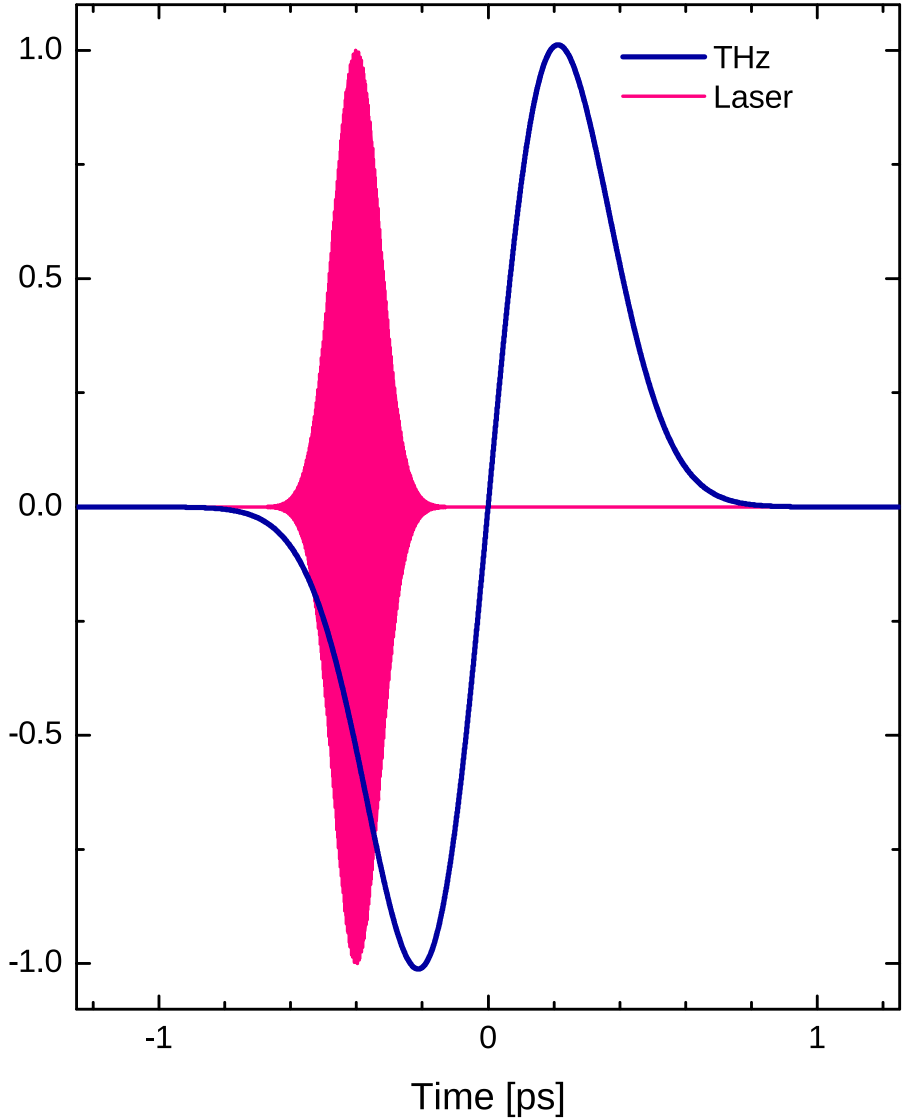

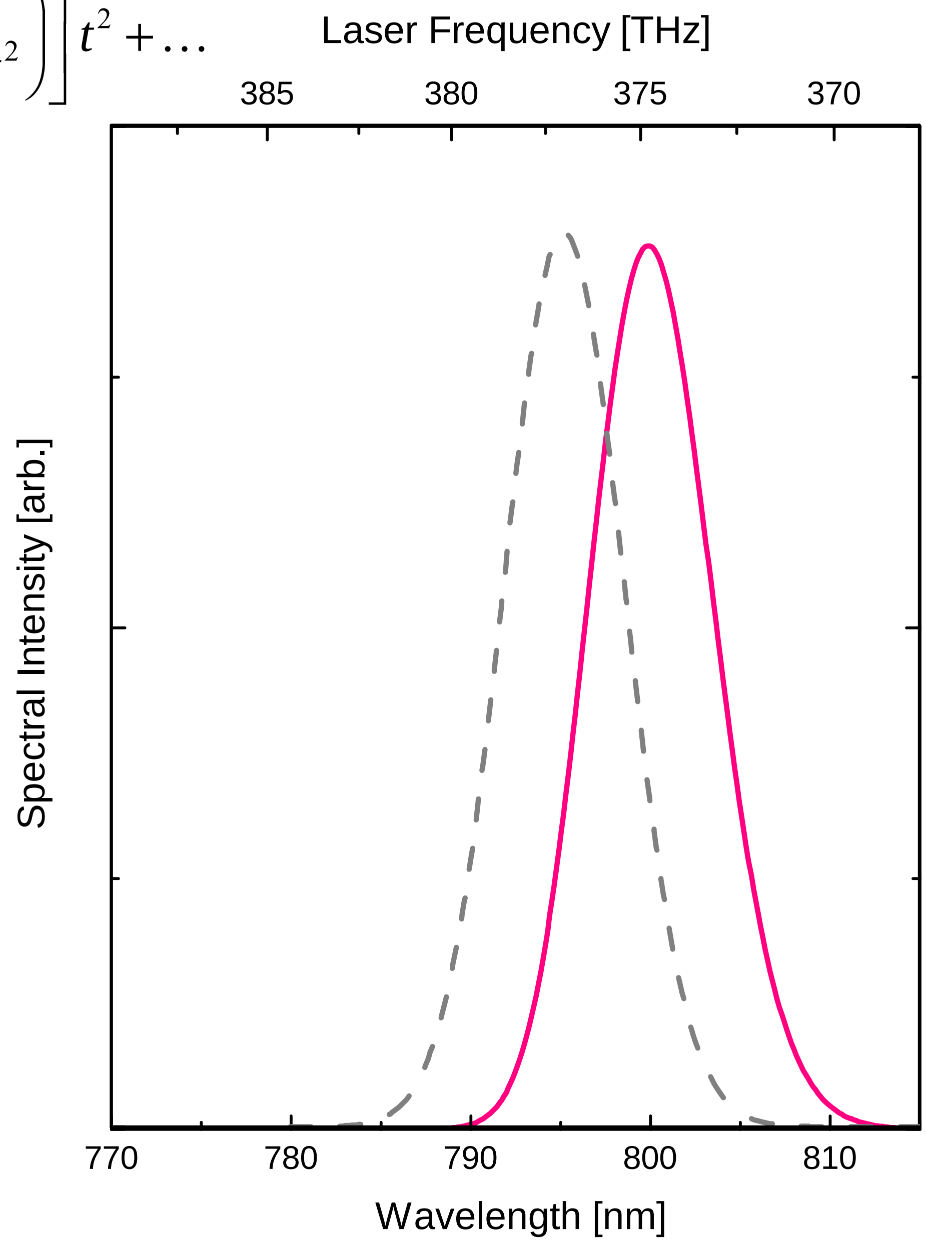

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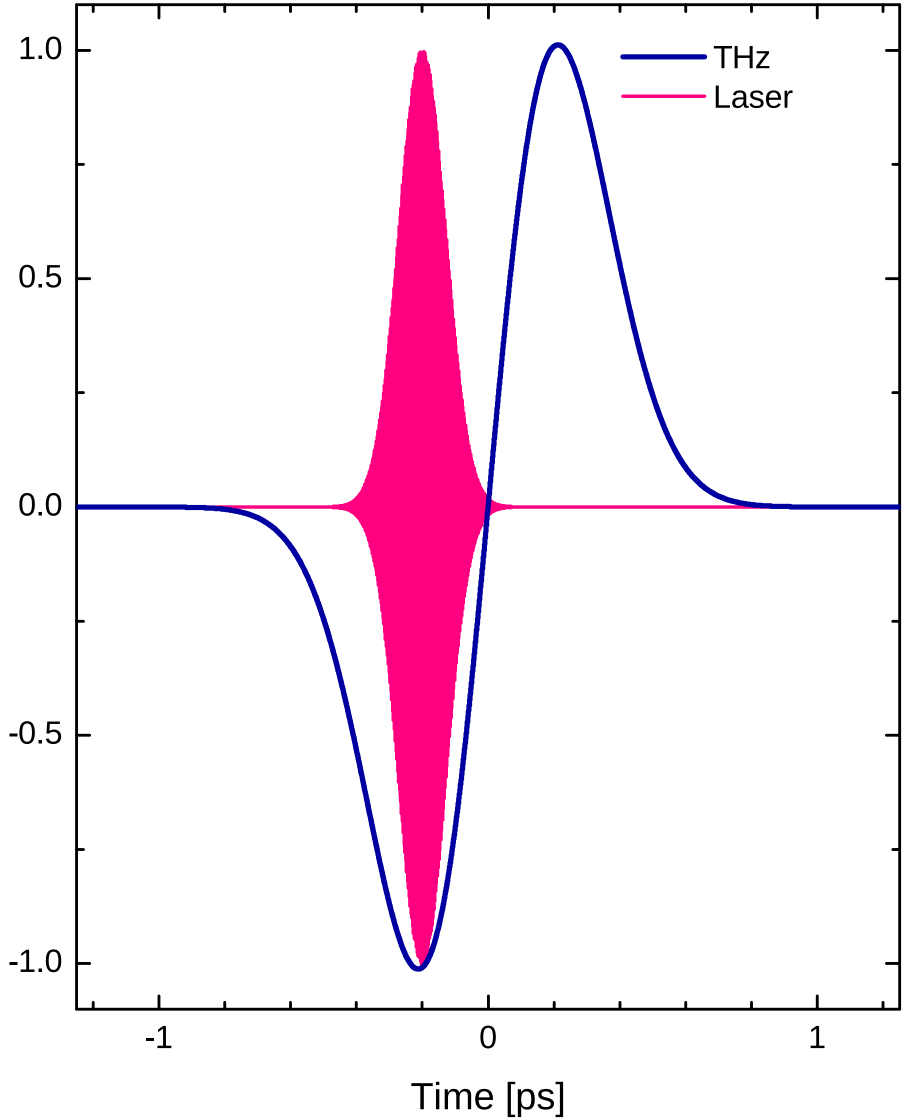

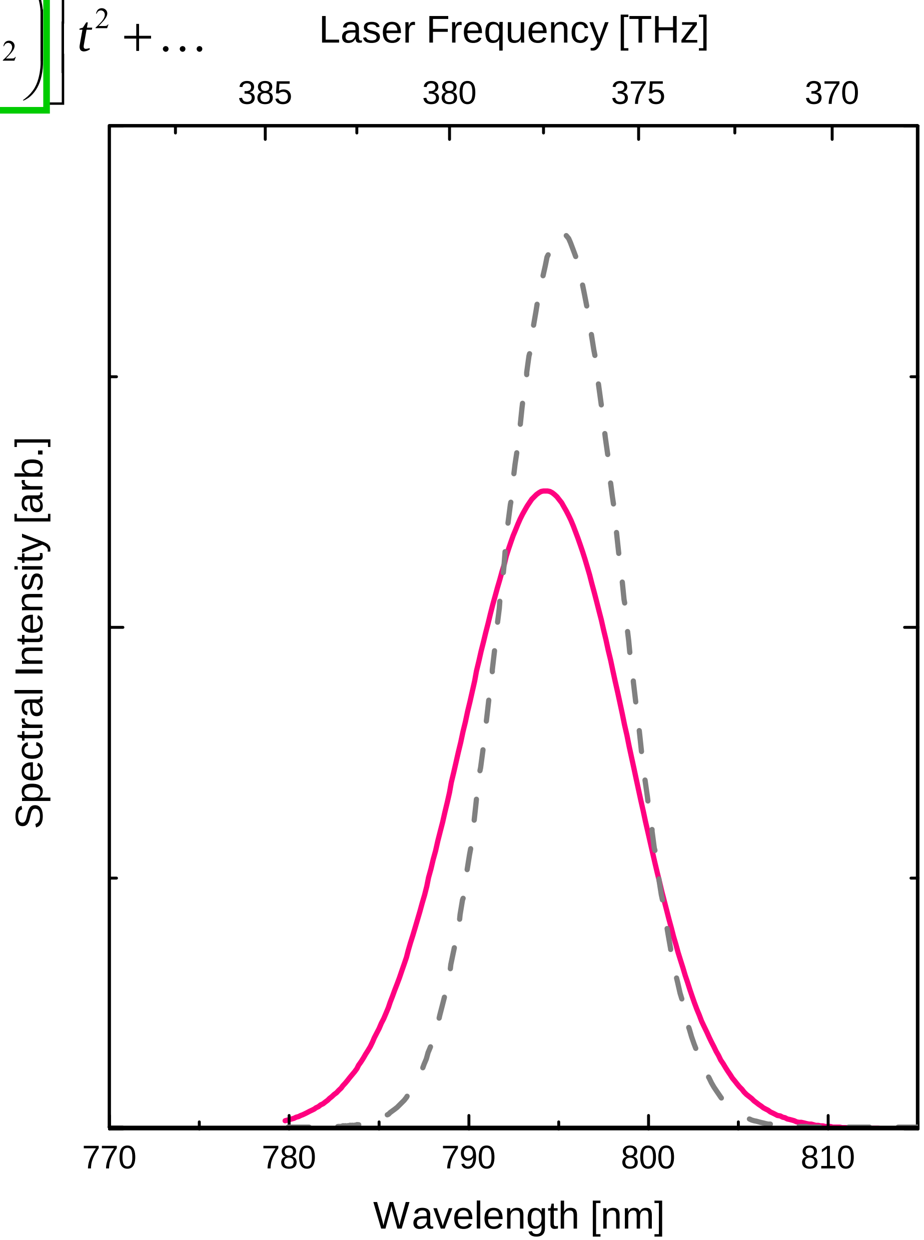

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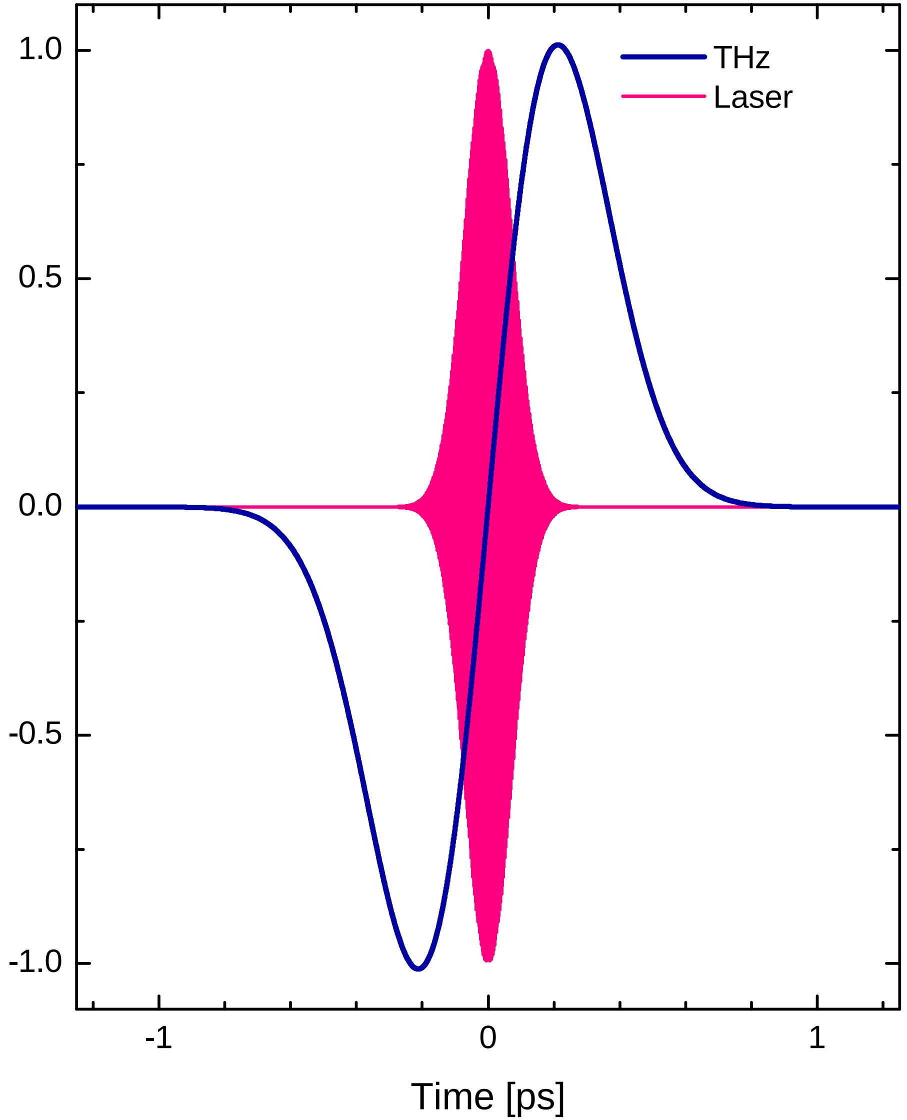
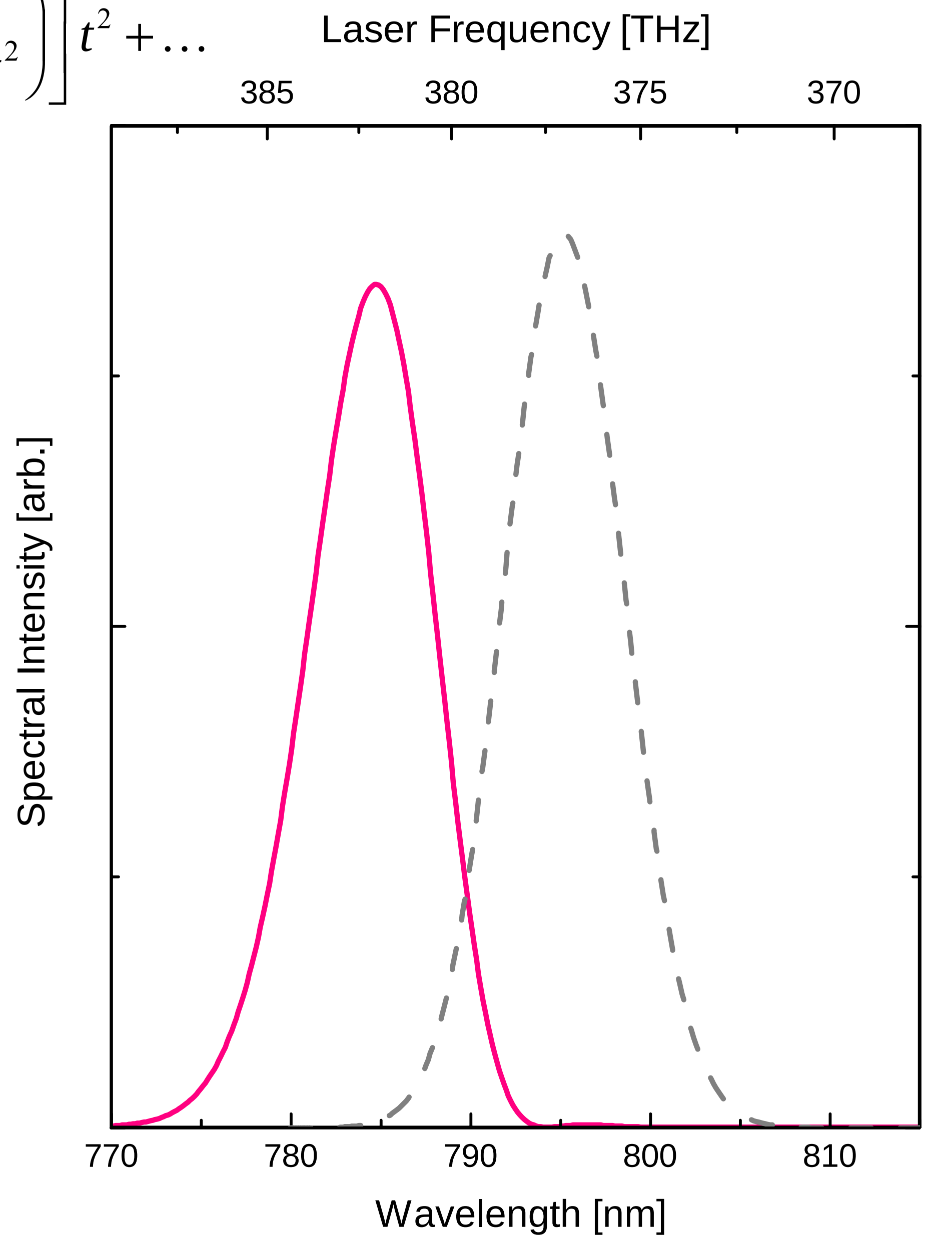
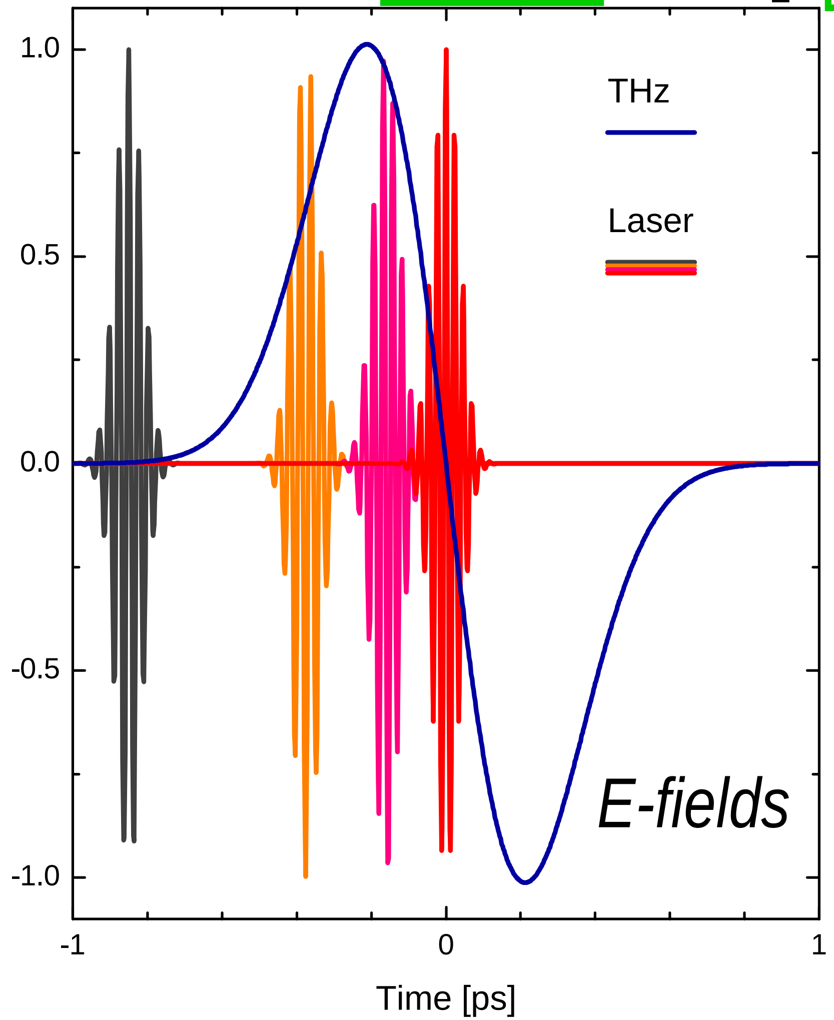




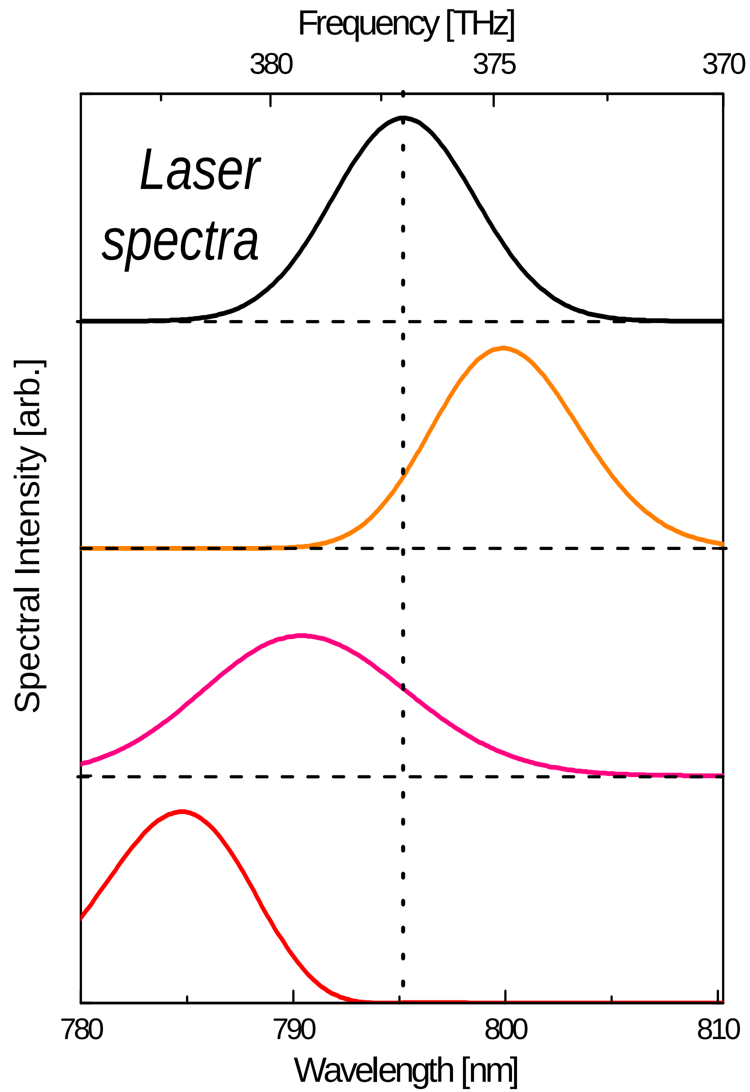
Calculated Phase Modulation Effects

$$\phi(t) = \eta\, E(0) + \left[\eta \left(\frac{dE_{THz}}{dt}\right) - \omega\right] t + \left[\eta \left(\frac{d^2 E_{THz}}{dt^2}\right)\right] t^2 + \ldots$$



500 kV/cm field

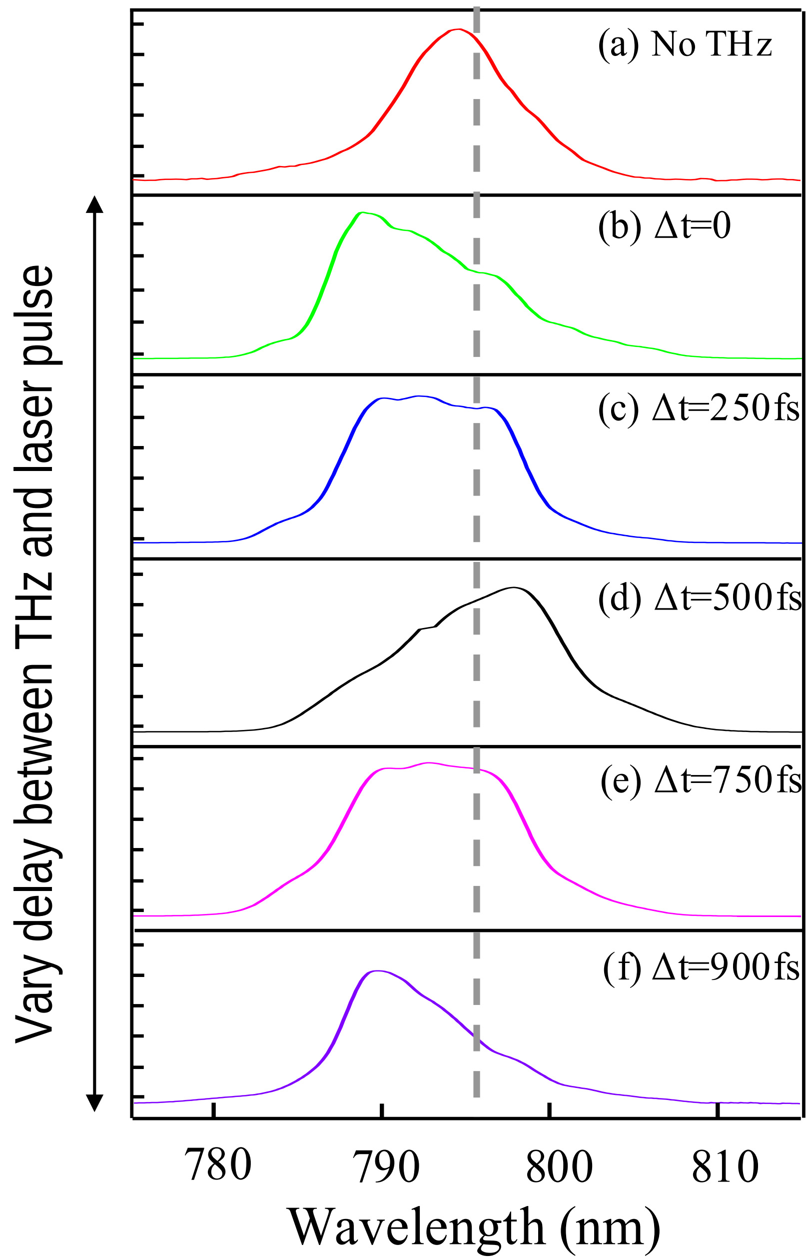
0.5mm thick ZnTe



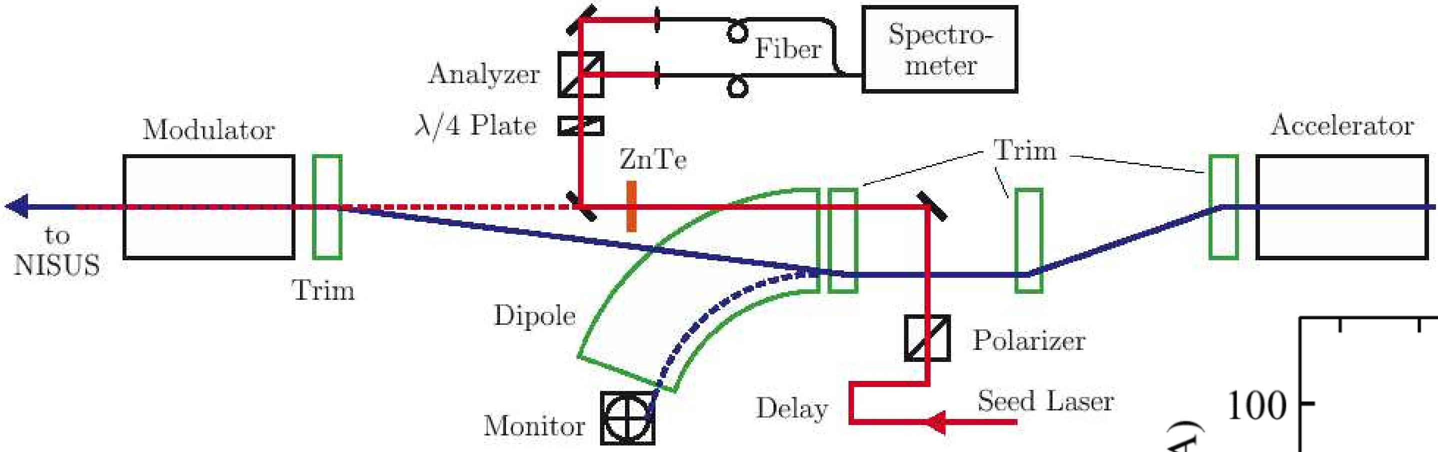
Other details: Lensing from spatial variation of $n(t)$ *(time-dependent gradient index lens)*

Measured Phase Modulation with SDL Linac Coherent THz

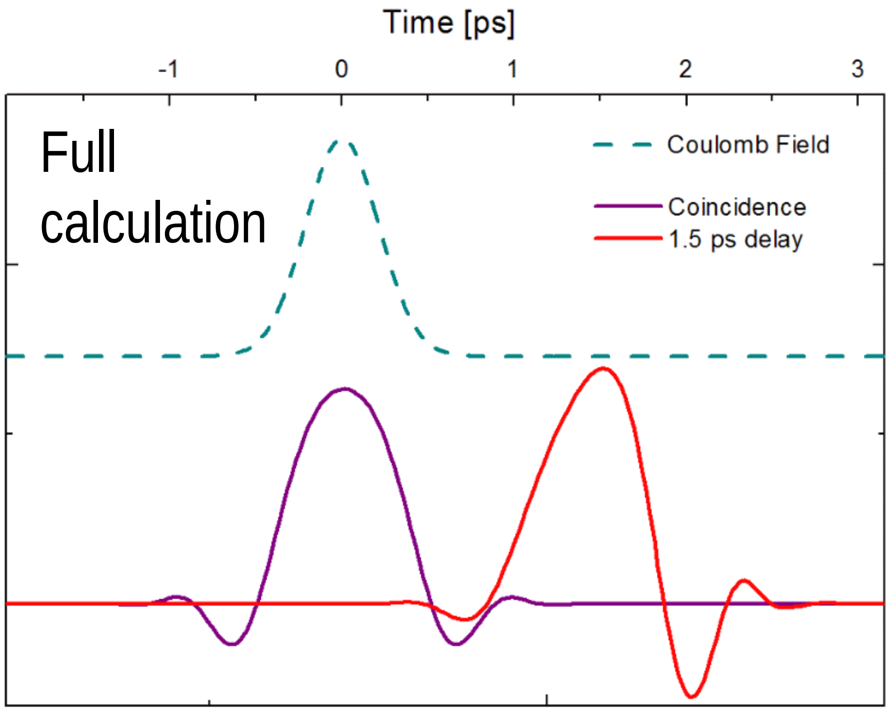
- Electro-optic measurements of SDL THz pulses.
  - 35 μJ pulses, 2mm focus, 0.5mm ZnTe.
- ~ 130 fs (FWHM) unchirped laser sampling pulse, no polarization analysis.
- Probably still a mixture of effects
  - optical alignment and waveform distortion
  - walk-off (velocity mis-match)
  - phase modulation (2nd and 3rd order NLO)
  - dynamic lensing that affects coupling into spectrometer's optical fiber.

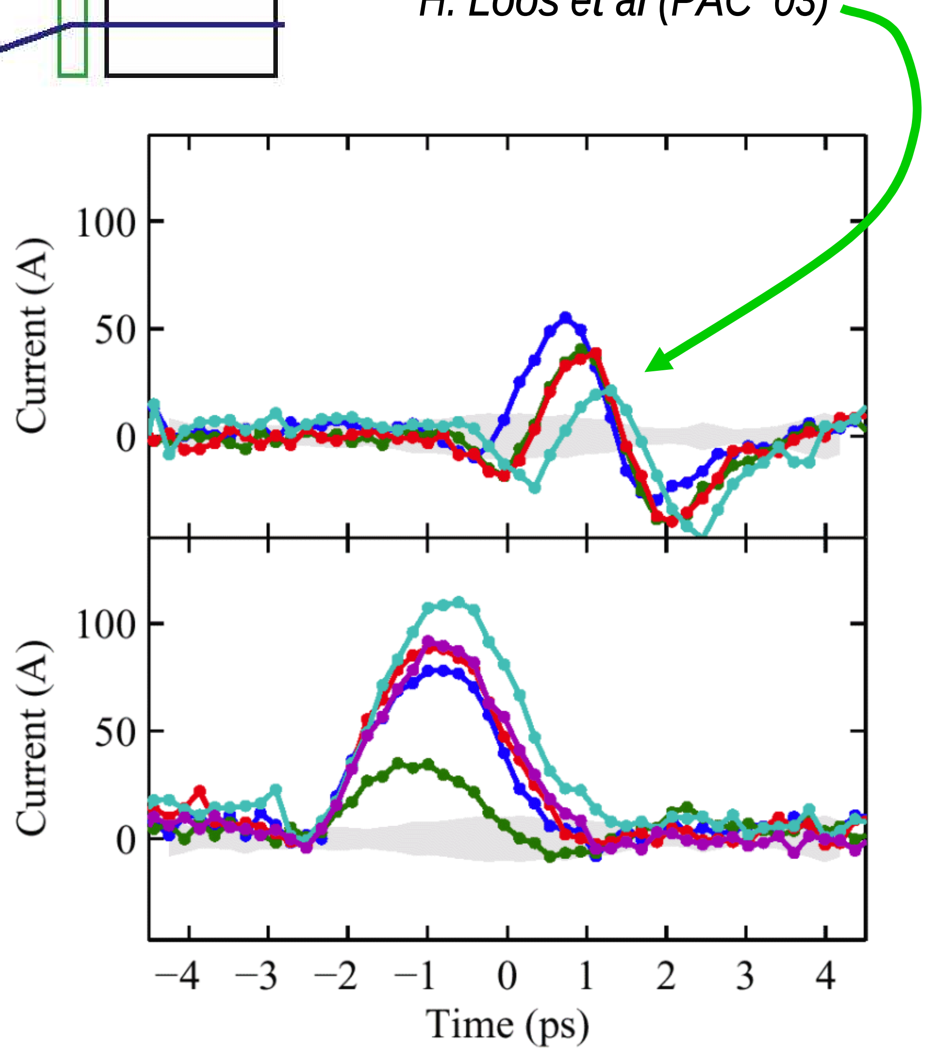


EO Detection of Bunch Coulomb Field (inside linac)



X. Yan et al (PRL '00)
I. Wilke et al (PRL '02)
H. Loos et al (PAC '03)





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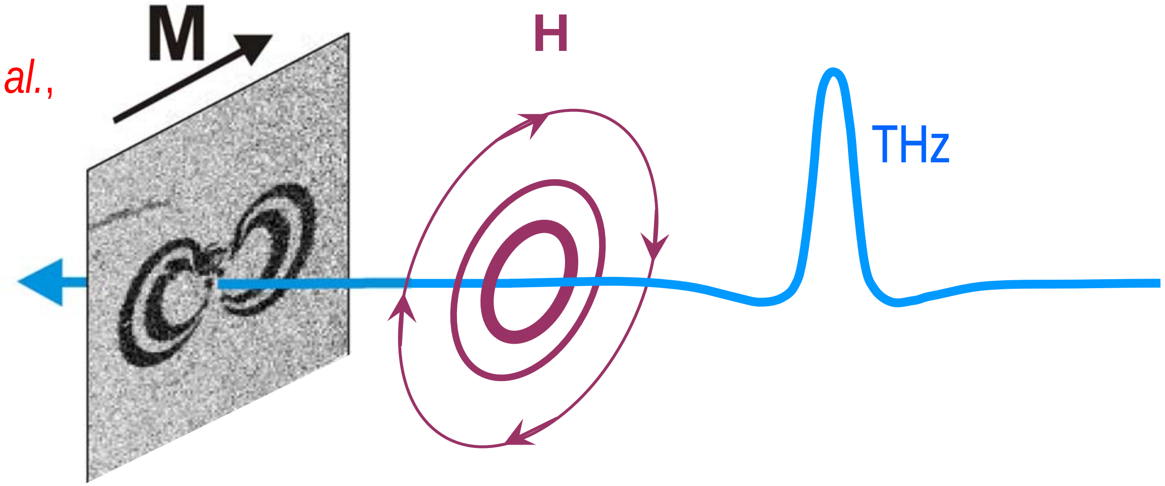
- Potential application:
  - switching behavior in ferroelectrics, ferromagnets, superconductors.

Potential Application: Studies of Magnetization Dynamics

Figure from C. H. Back, *et al.*, *Science* 285, 864 (1999)



- Idea:
  Use strong THz field to affect magnetization state of a thin film on < 10^{-12} s time scale.

- *Ex situ* approach
  Use propagating THz wave external to accelerator. Contrast study at SLAC/SPPS (Stöhr *et al*, *Nature*) where specimen was placed inside linac and directly exposed to electron beam.

- Method:
  pre-saturate film, expose to THz field pulse, then perform post image analysis (SEMPA)

- Similar approach could be used for the study of ferroelectric switching.

Potential Application: Non-equilibrium Superconductivity

Superconducting state described by complex order parameter (amplitude and phase).

Most time-resolved studies have explored pair breaking and recombination (amplitude out of equilibrium) using $\omega > \omega_g$ photons.

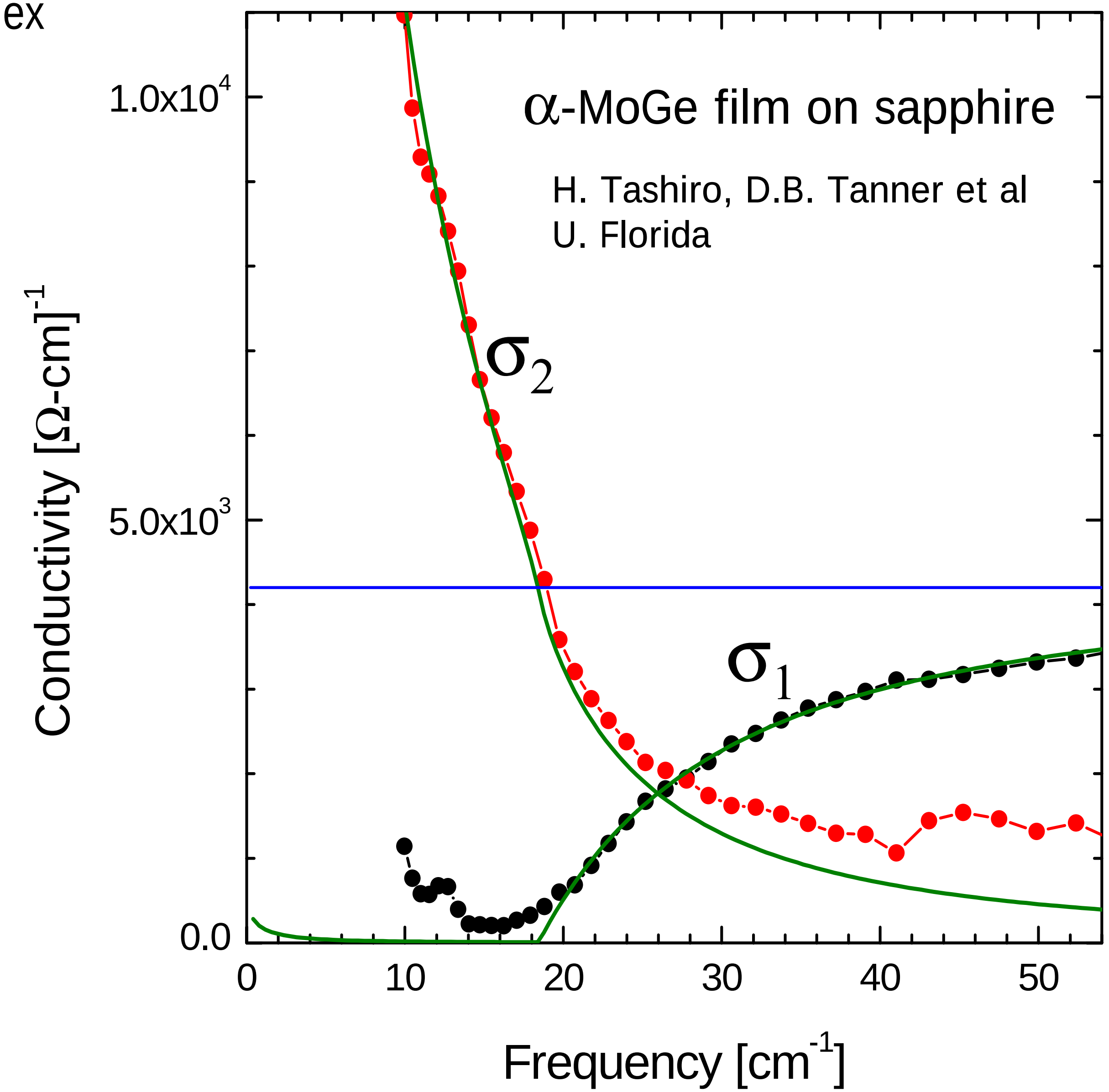
How does supercurrent (phase) react to a 1 MV/cm, ~ 1ps E-field transient?

Low frequency response is dominated by imaginary part of conductivity.

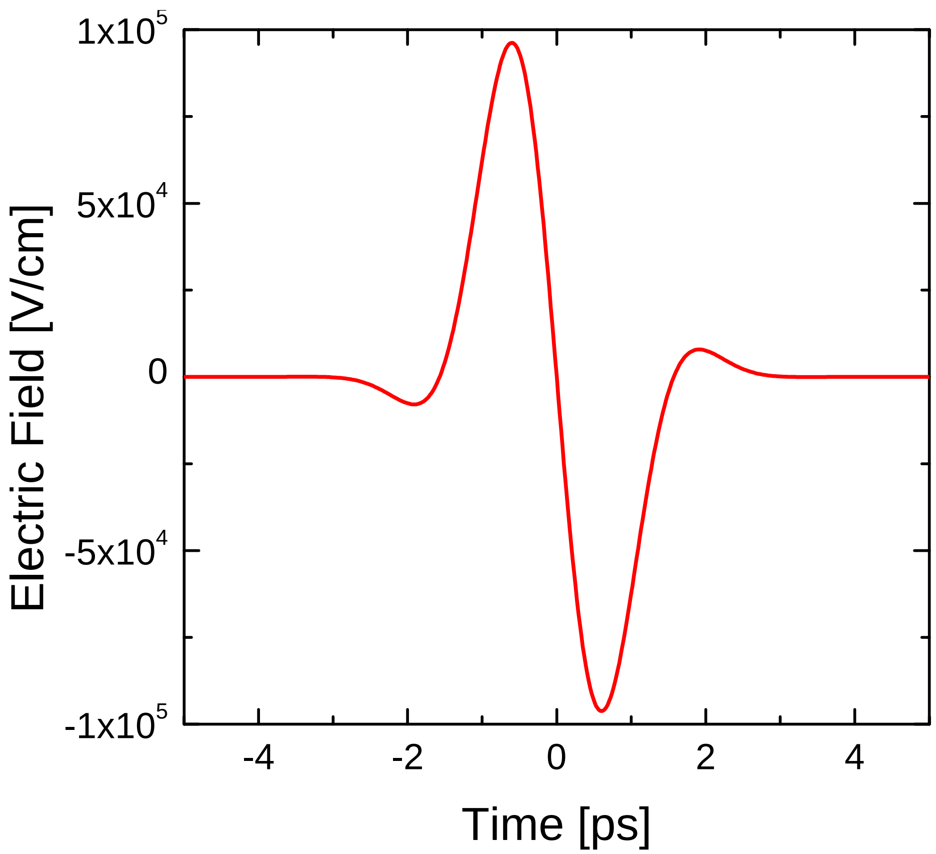
$$\sigma[\omega < \omega_g] \sim {}^{i}\!/_{\omega} \quad \text{(pure inductor)}$$

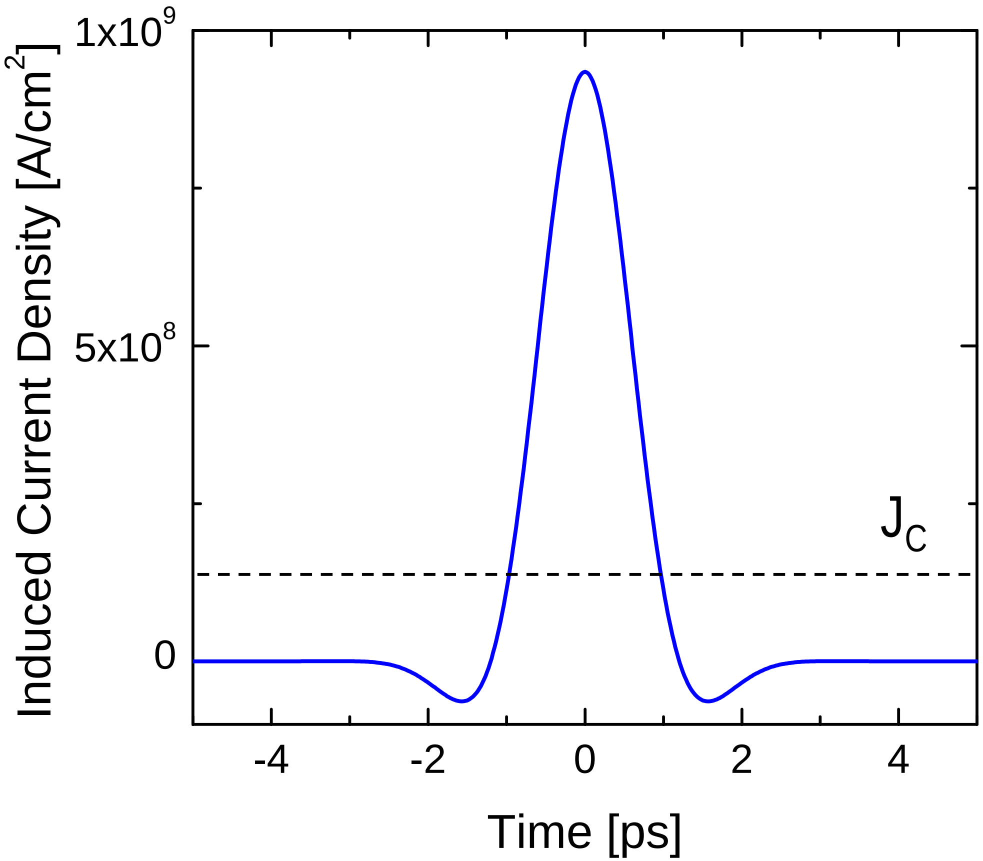
$$L\frac{dI}{dt} = V \qquad I(t) = \frac{1}{L}\int_{-\infty}^{t} V(t')\,dt'$$

$$J \cong \sigma_n \omega_g \int_{-\infty}^{t} E(t')\,dt'$$



Time-dependent Supercurrent in a Thin Film Superconductor





Note: a typical superconductor has critical current $J_C \sim 10^8$ A/cm^2

=> "over twist" the local superconducting phase, spin off vortices?

How quickly can a vortex be created? How does dissipation initially appear?

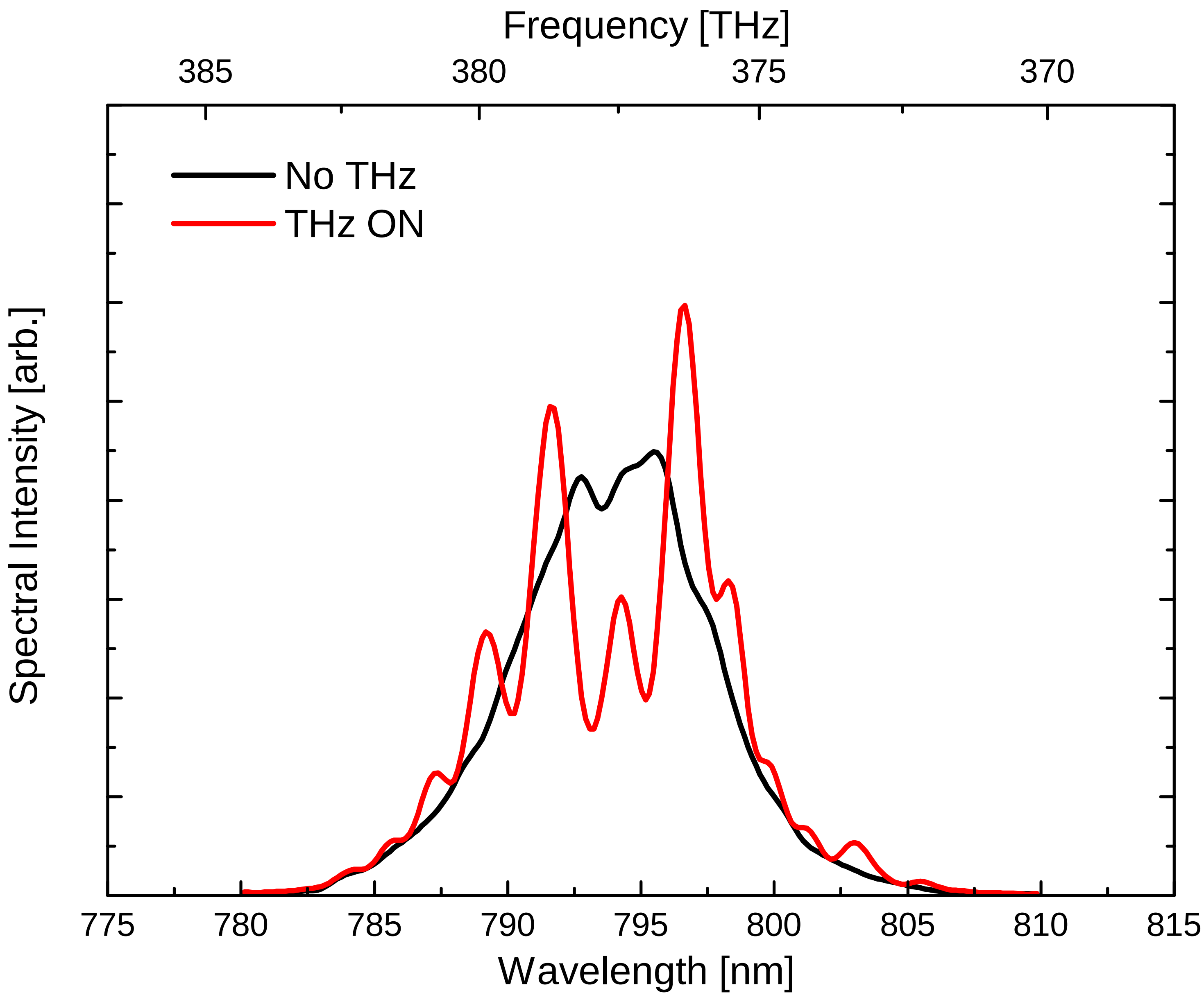
Summary

- Coherent SR bursts from NSLS VUV/IR ring
- Intense CTR pulses from photo-injected linac
  - single-cycle pulses
  - large electro-optic effects: time-dependence leads to laser phase modulation
    - spectral shifting & chirping
    - could be used to *control* ultrafast laser pulses.
    - affects in situ EO sampling of thee-beam Coulomb field.
- Large pulse energy –> strong electric (& magnetic) fields.
  - opportunity for studying field-induced ultra-fast switching.
  - initially: "photographic" samples
  - or waveform distortion in transmitted THz pulse.
  - ultimately: THz, other probe (x-rays, electrons)

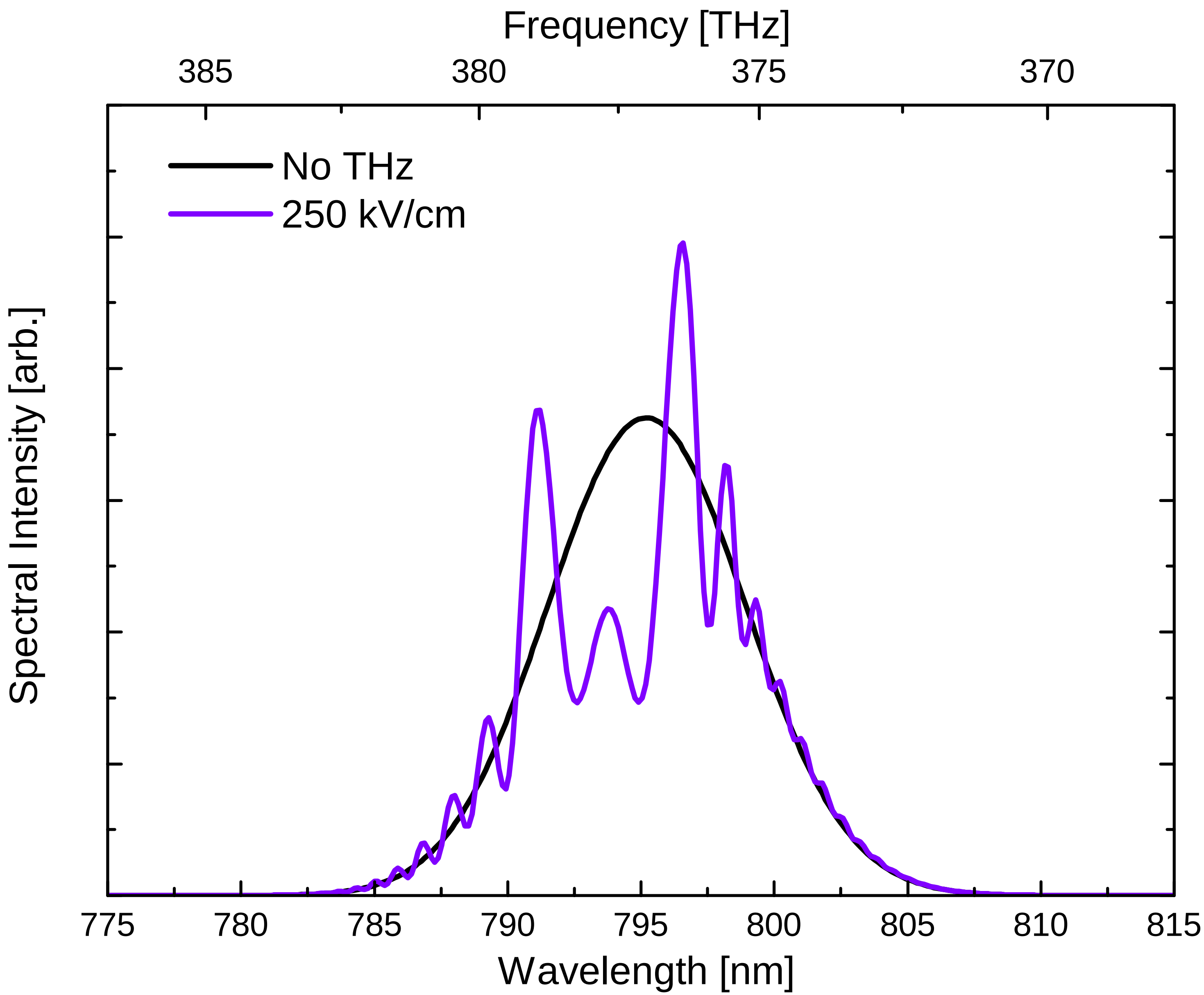
Acknowledgements: J. Misewich, G. Nintzel, R. Smith, B. Singh (Brookhaven), T.F. Heinz (Columbia), Dave Reitze (Florida)

end of slide show
please applaud now

Single-Shot EO Sampling of SDL THz Pulse: Higher intensity

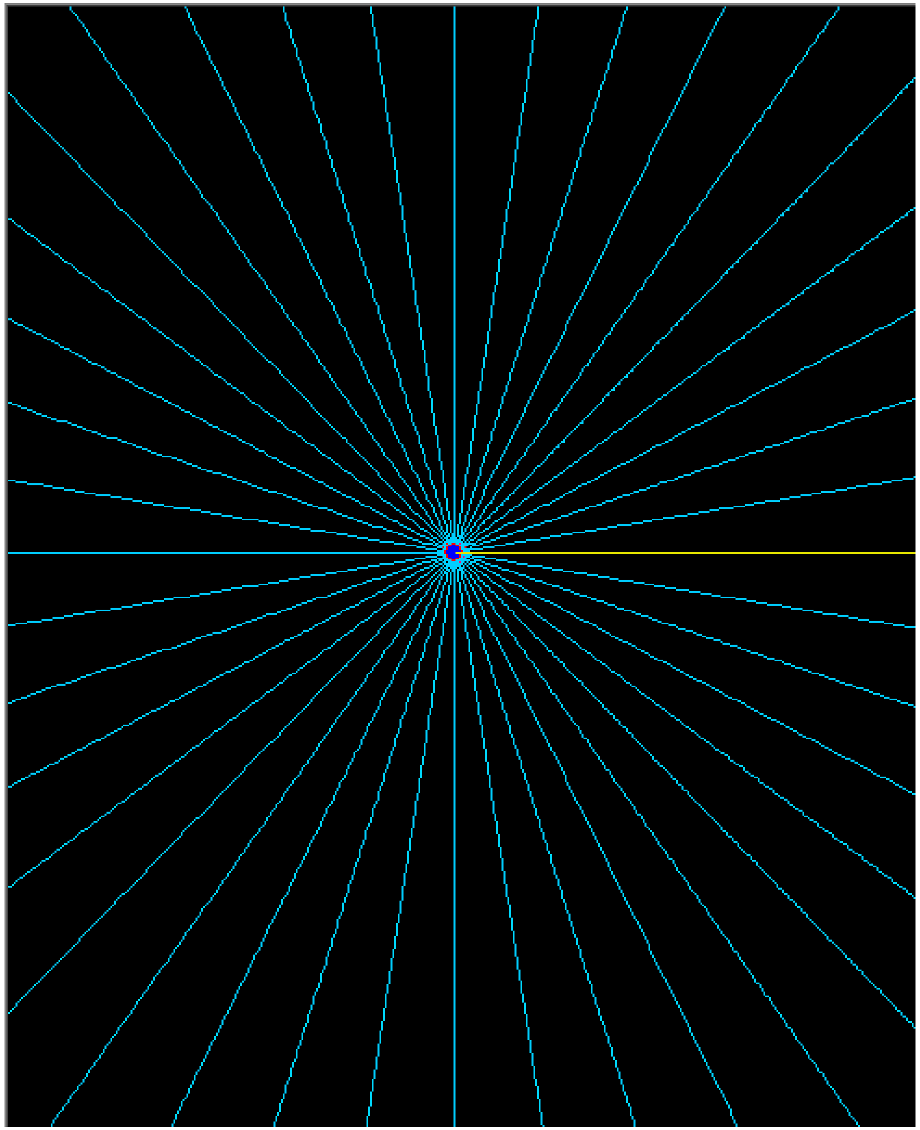


Full Electro-Optic Calculation

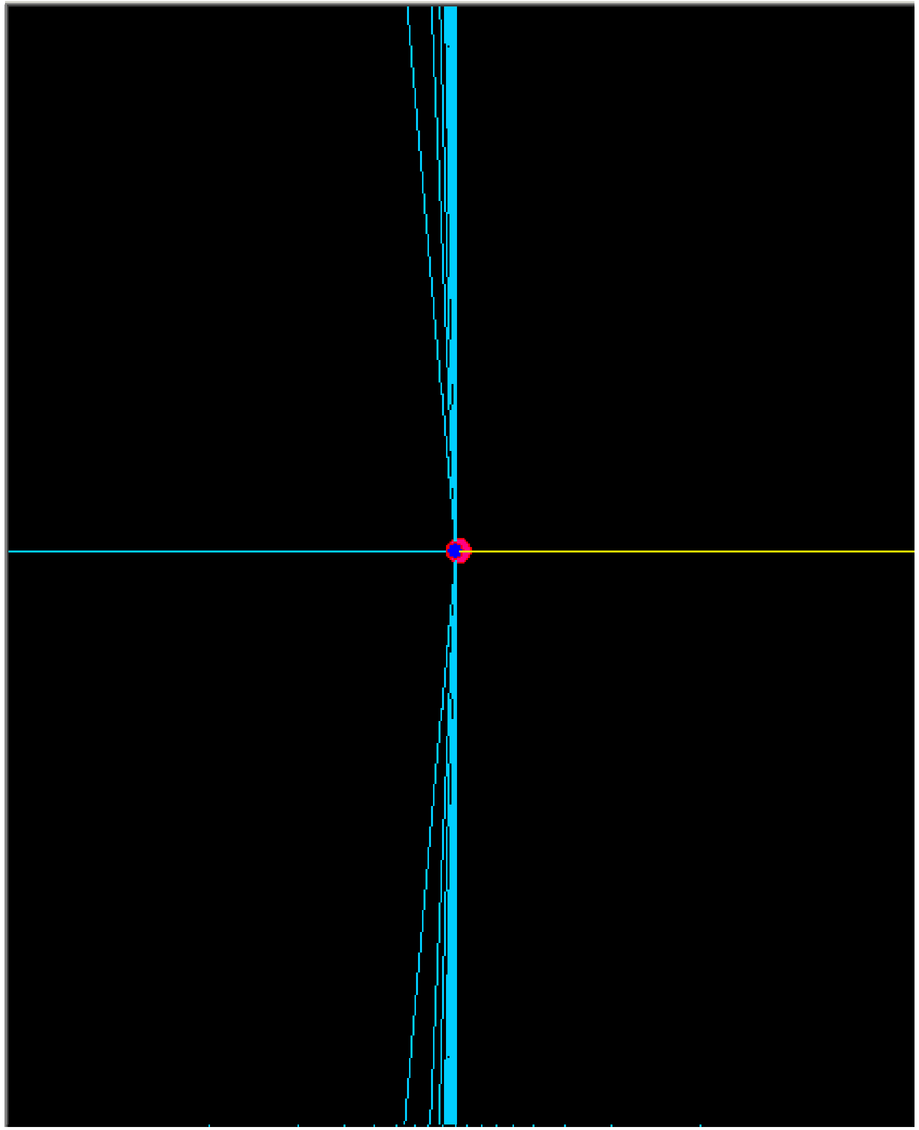


Fields for Relativistic Electron

Non-relativistic Coulomb Field



Relativistic (1 GeV) Coulomb Field



Radiation from Electron on Circular Orbit

Relativistic parameters

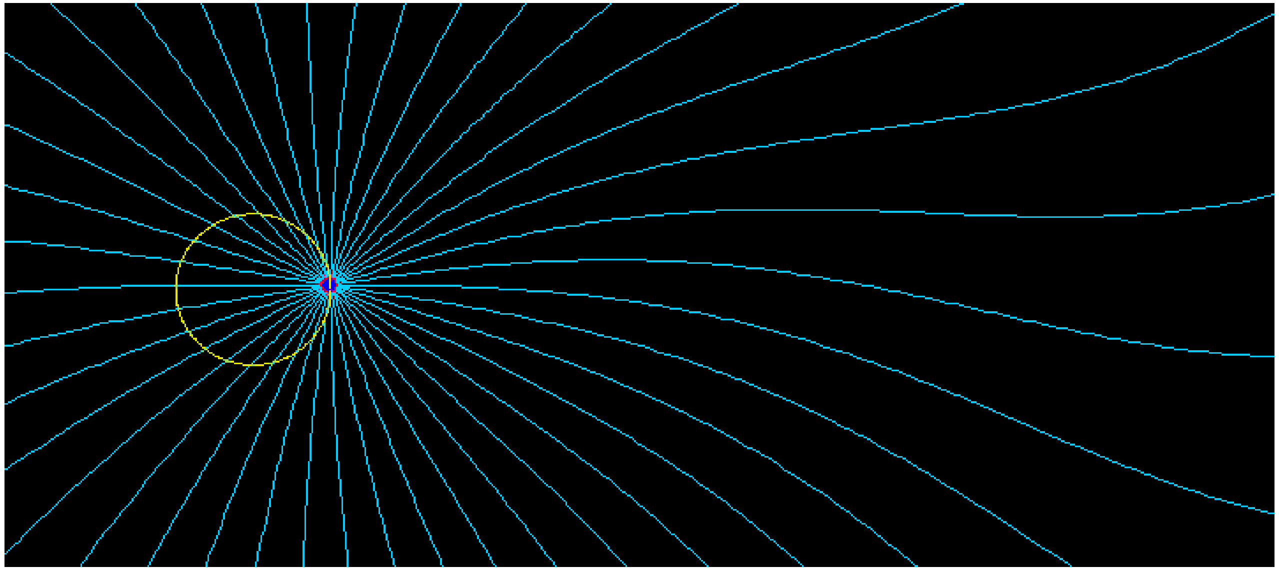
$$\beta = v/c \qquad \gamma = \frac{1}{\sqrt{1-\beta^2}}$$

$$m = m_0\gamma$$

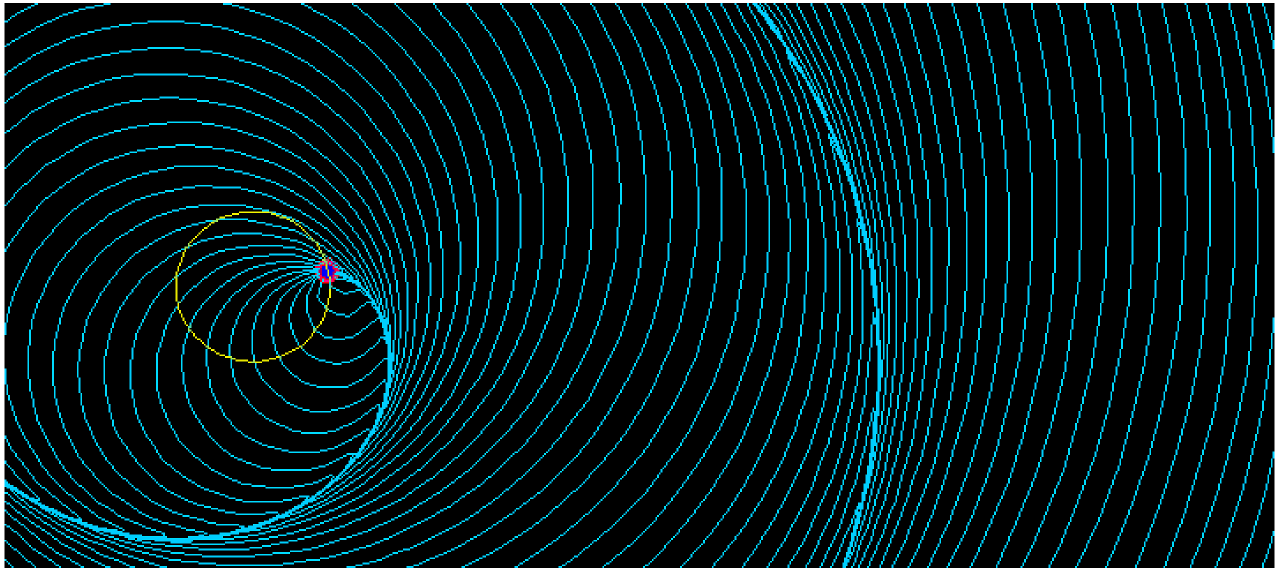
Modern accelerators:

$\beta \sim 0.99999999$

$\gamma \sim 6000$



$\beta \sim 0.95$

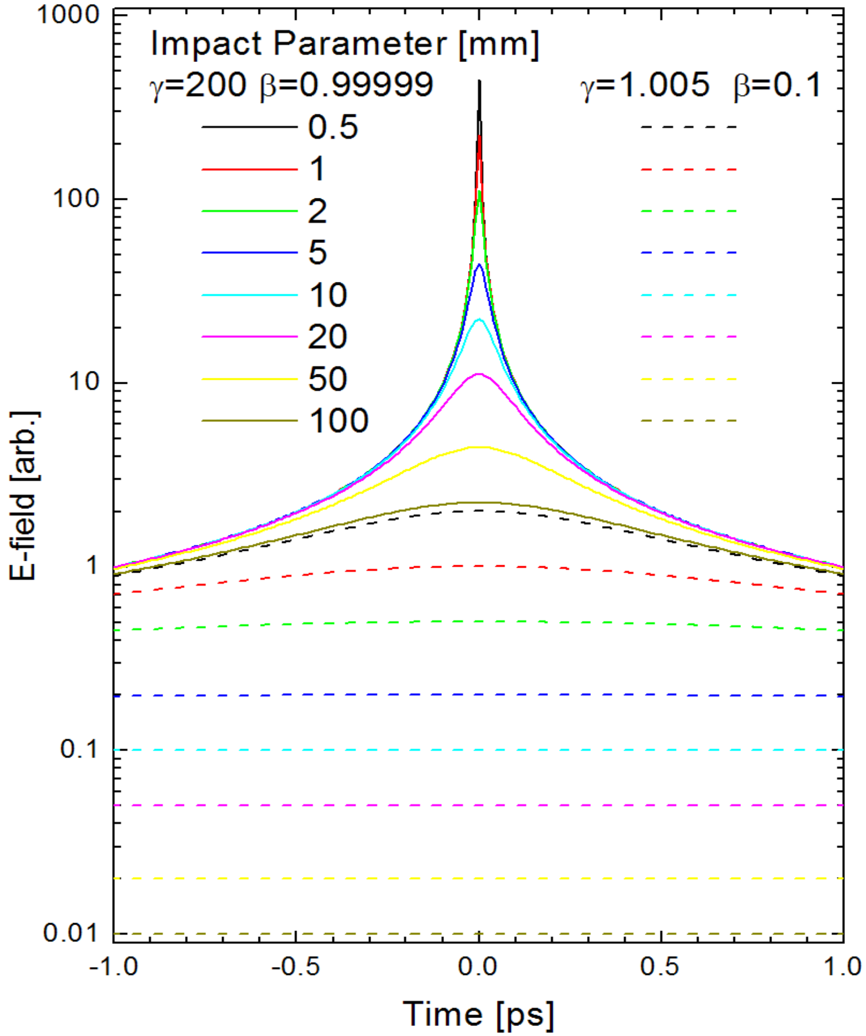


Calculated using
Radiation2D code
Tsumoru Shintake
RIKEN / Spring-8

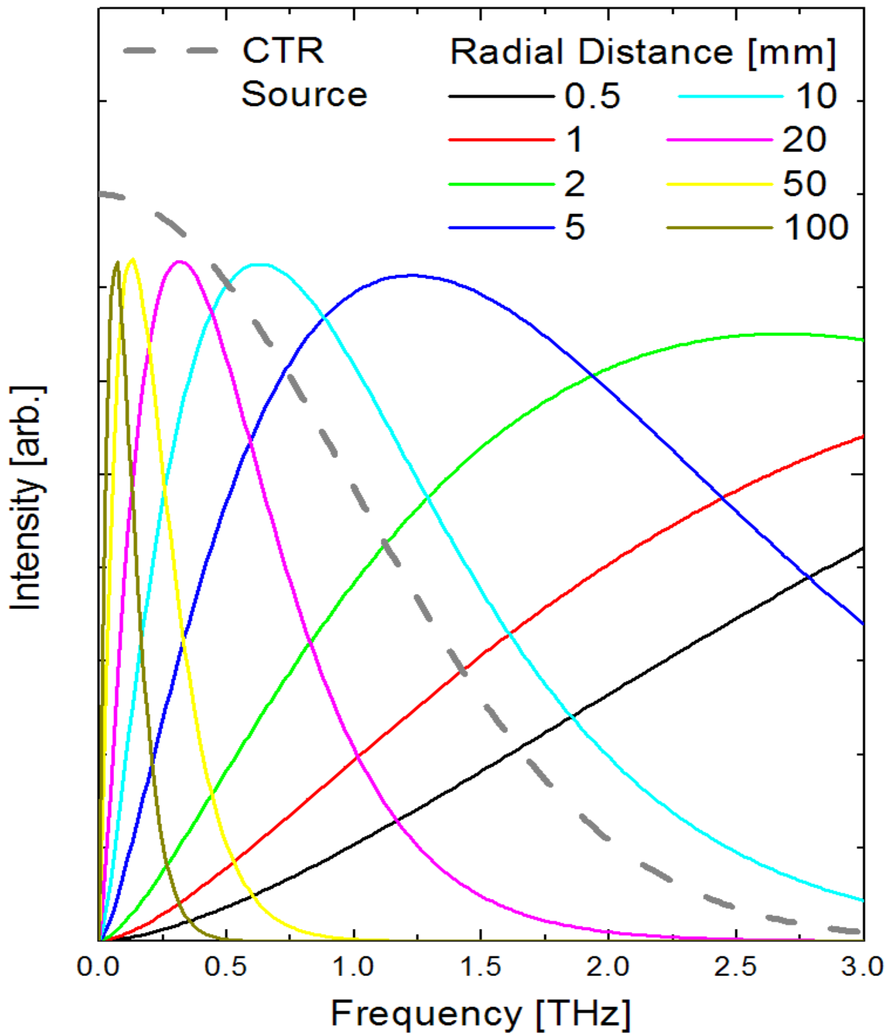
Transition Radiation: Coulomb Field & Spectral Content

Radial Source Size ("waist"): $W \sim \lambda\gamma/2\pi$

Time-dependent Coulomb field



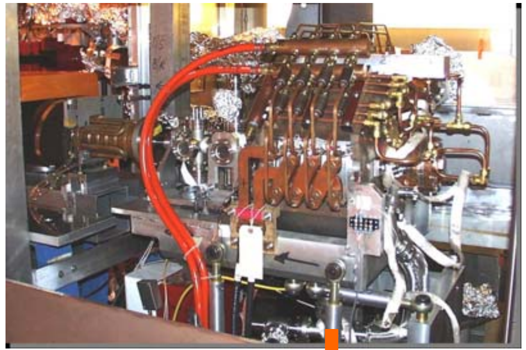
Spectral Content (not to scale)

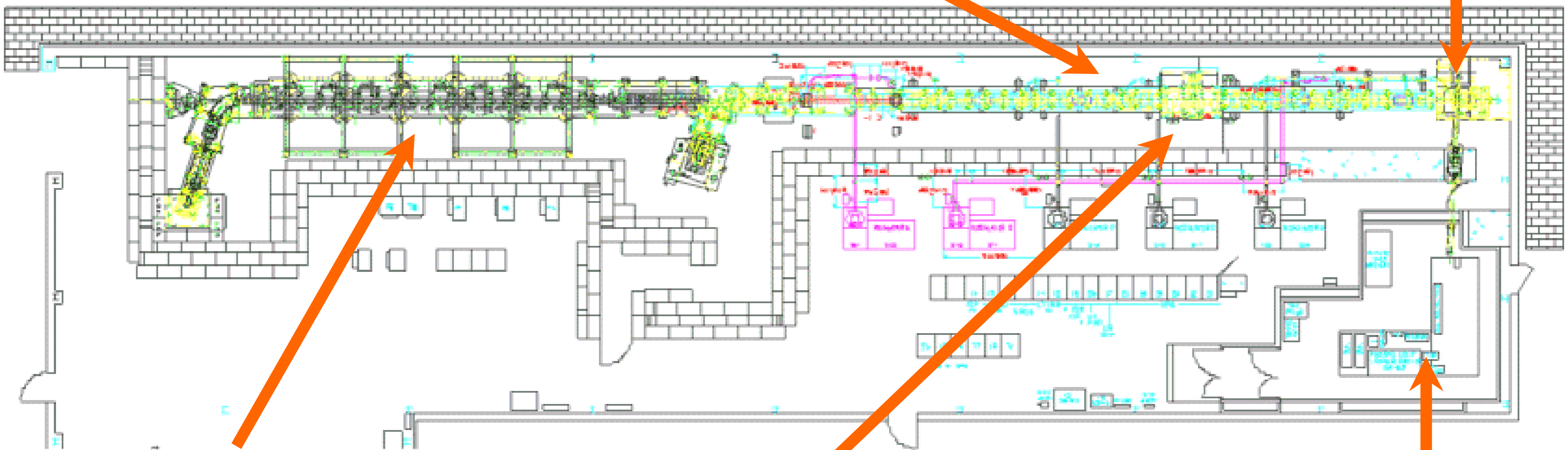


Short Bunch Source: The NSLS Source Development Lab Photo-injected Linac

300 MeV S-Band Linac (DARPA)

BNL Photo-injector IV

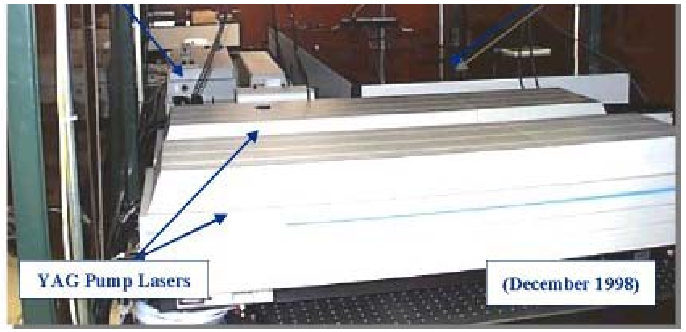




10 m NISUS Wiggler (SDI)

Chicane Bunch Compressor

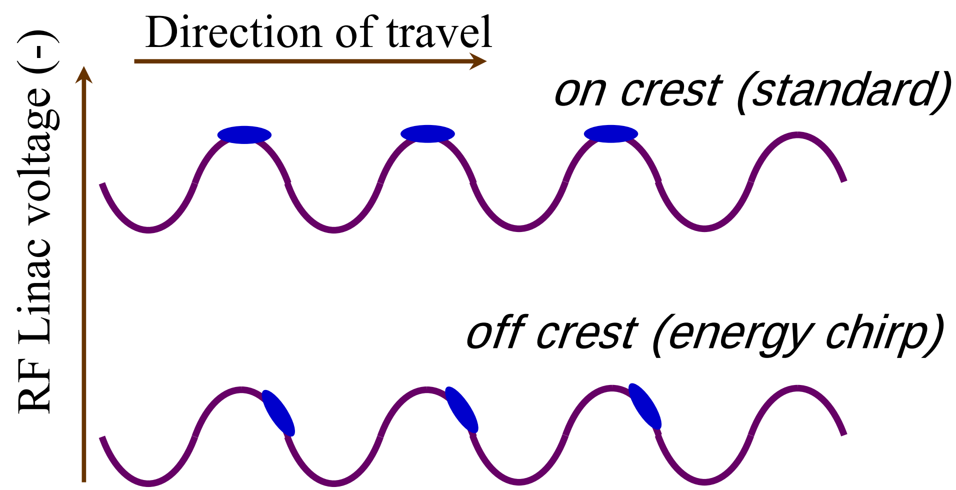
Ti:Sapphire Laser

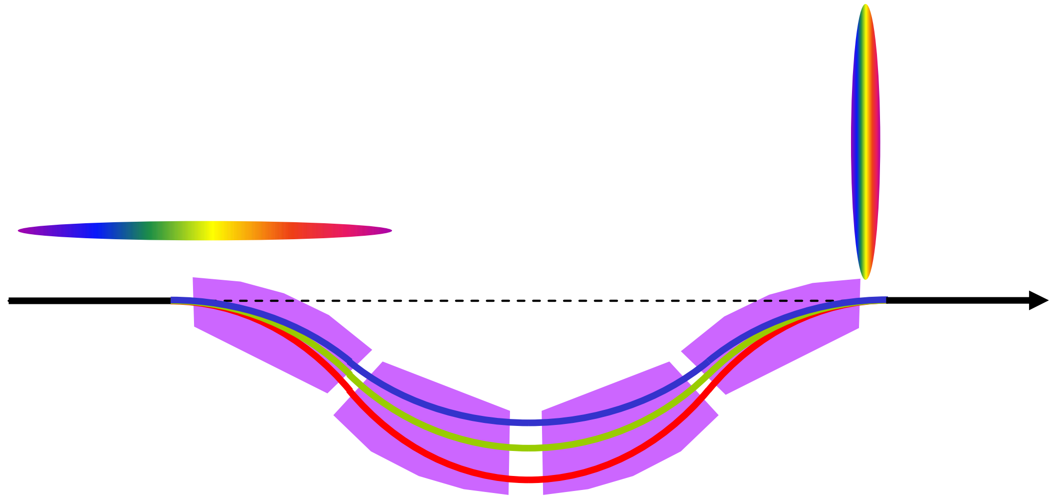


Making Short Bunches

- Problem: Electron charge ➔ Coulomb repulsion
  - Coulomb interaction causes spread in the energy distribution of a bunch.
  - For a non-relativistic electron, energy spread => velocity spread => distance spread.
  - BUT: For highly relativistic electrons, velocity spread remains small (*mass* varies). => Start with long bunch, accelerate to high energy, <u>then</u> compress.

Compression method analogous to light, magnets serve as dispersive optics for electrons.

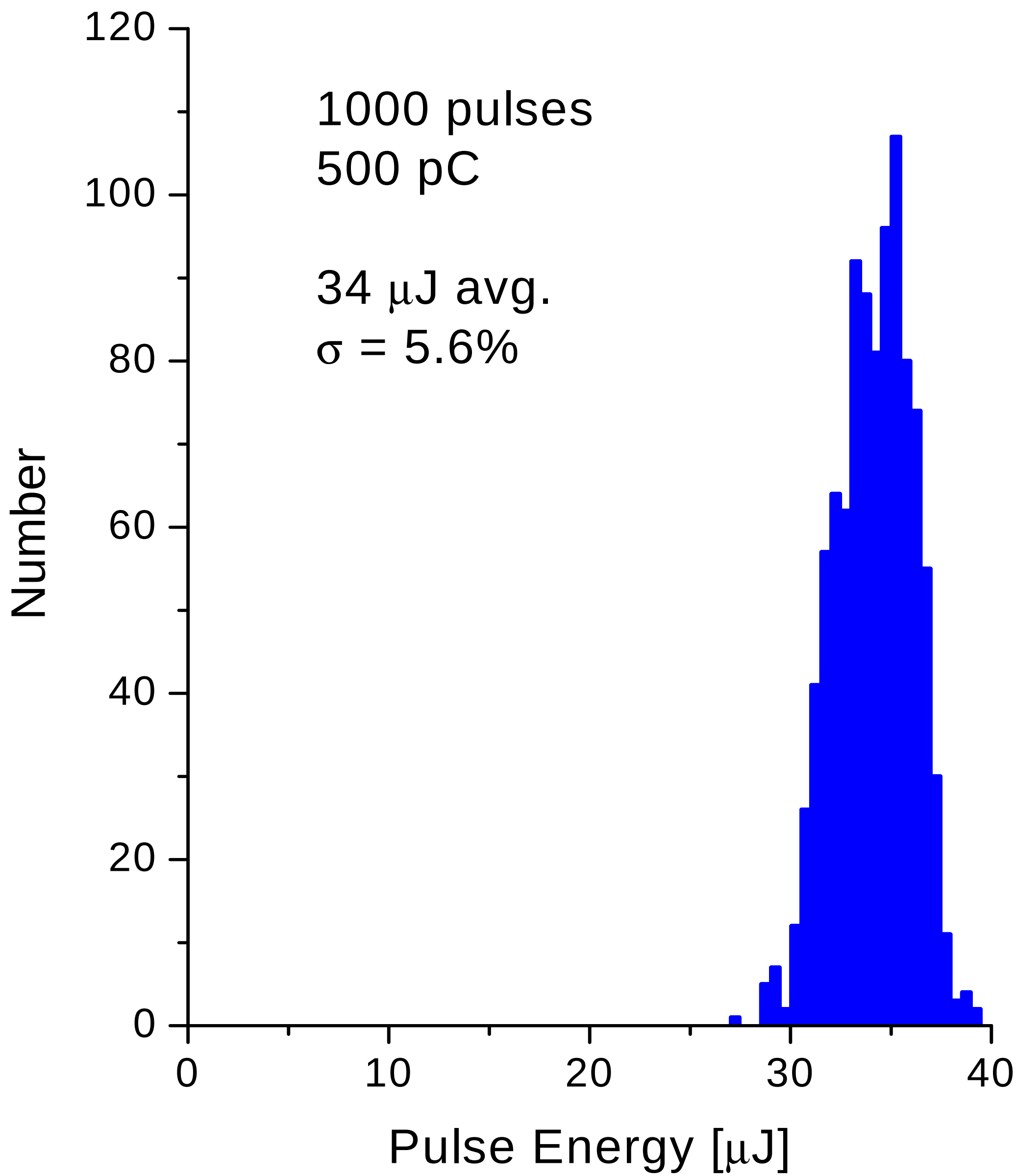




Dipole chicane to compress chirped bunch

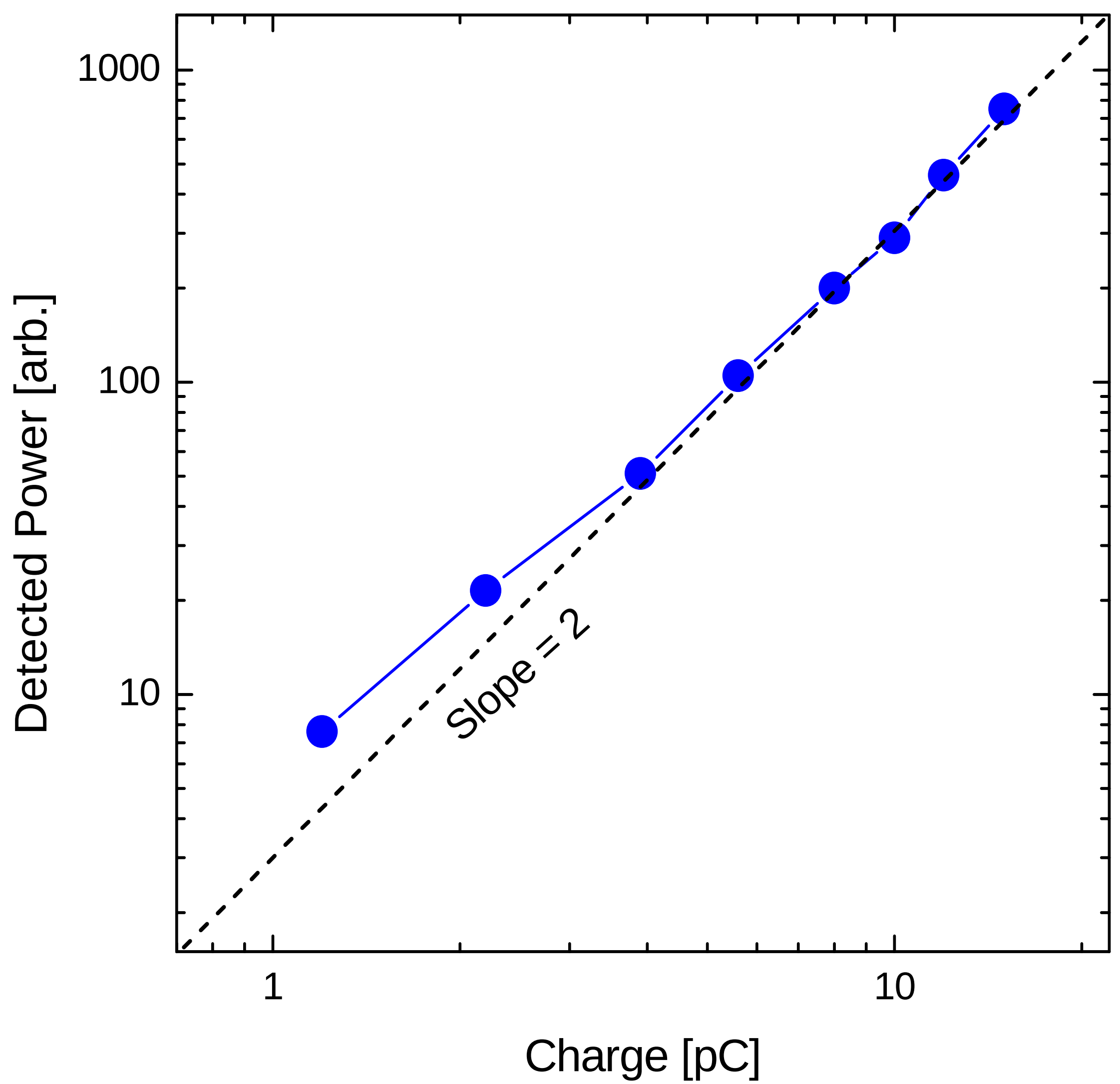
Statistics

- Shot-to-shot fluctuations affect usefulness of pulses for some applications.
  - Interferometry
  - Pump-probe spectroscopy
- Typical fluctuations 4 to 6% RMS.
  - due mostly to variations in charge (particle number) from laser fluctuations.
- High rep. rate (average) or single-shot capability needed.



N^2 dependence

- Intensity ~ Q^2 ($\propto N^2$) is a signature of coherent emission.

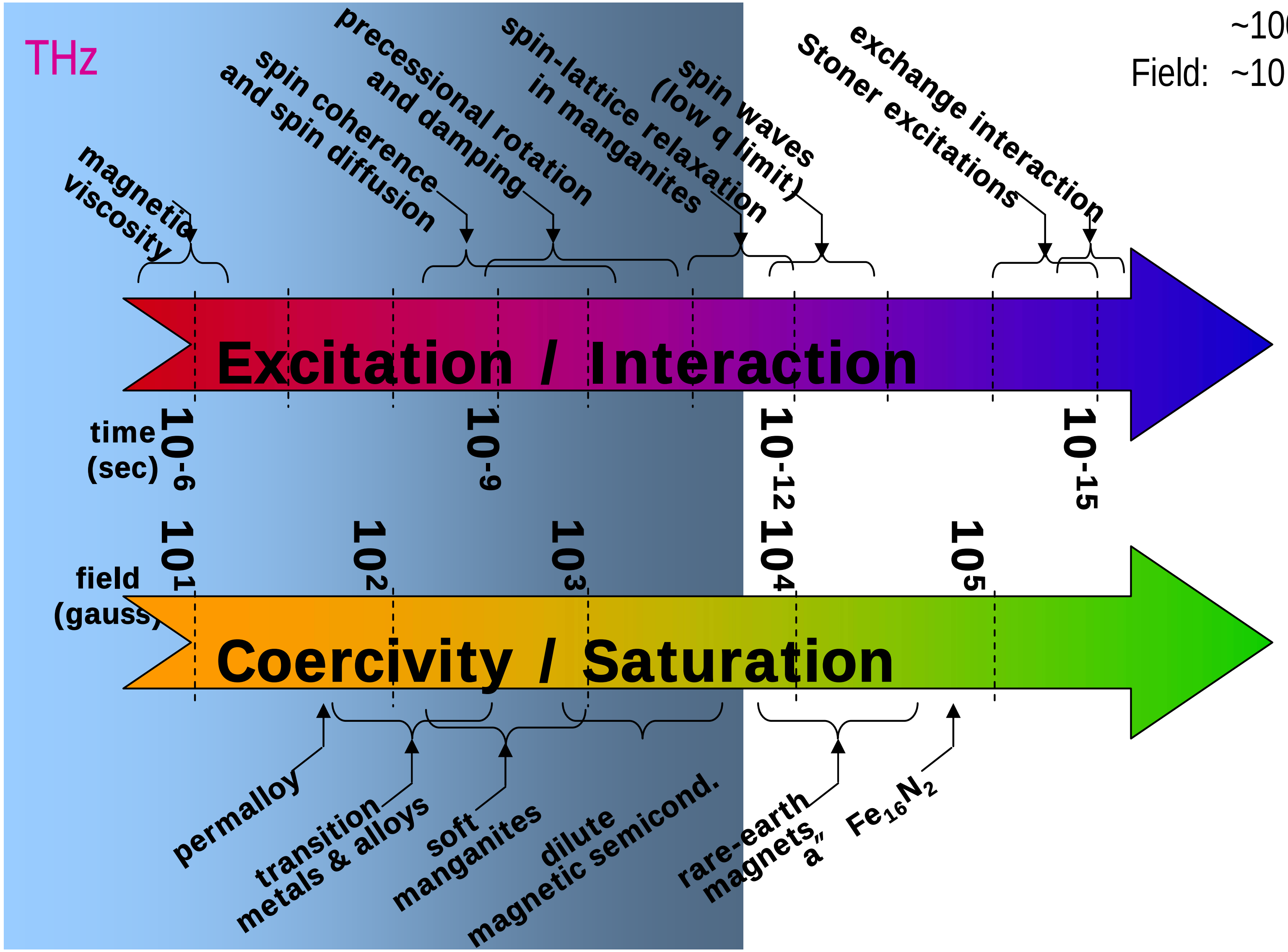


Opportunities in Magnetism with THz Pulses

Ultra-Short Pulses and/or High Fields -- D. Arena / NSLS

Current state of the art for "ultra-fast" dynamics experiments:

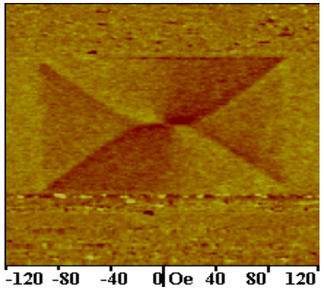
Time: ~100 fs (lasers)
~100 ps (synchrotron)
Field: ~10 – 100 gauss (stripline)



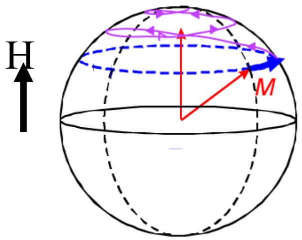
THz Driven Magnetic Dynamics

Time (s)

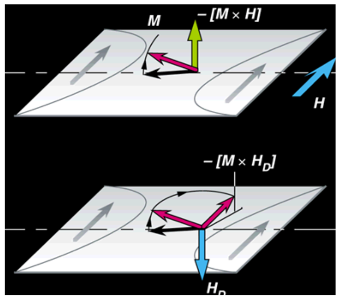
10^{-6} — **Domain Propagation**



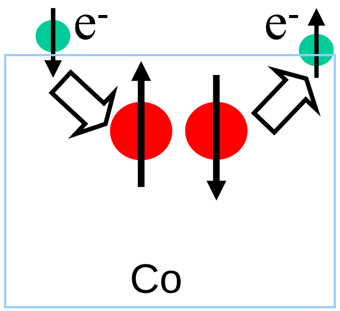
10^{-9} — **Spin-Lattice Relaxation**



10^{-12} — **Spin Precession**



10^{-15} — **Spin-Orbital Exchange**



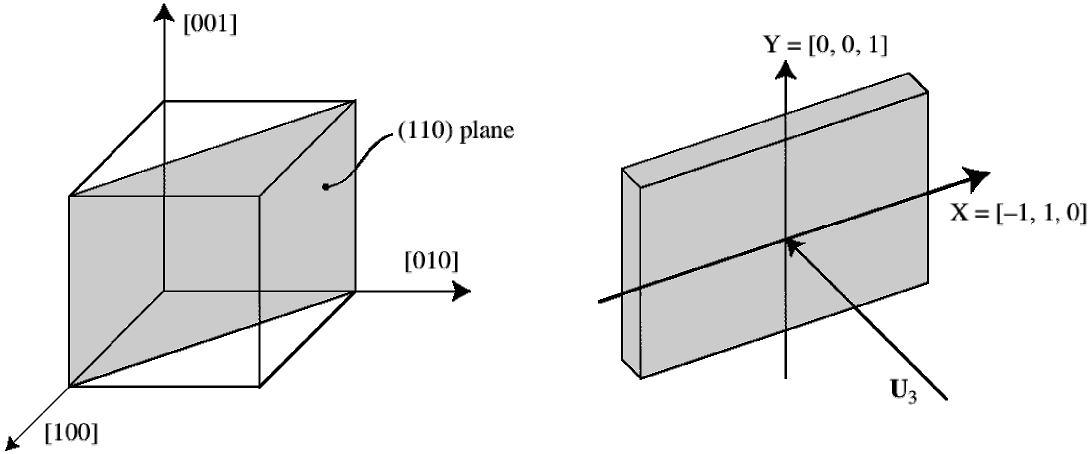
Use ultra-short magnetic field pulses to induce spin excitations (D. Arena / NSLS)

Excitation / Interaction	Timescale (sec)
Exchange interaction	10^{-15}
Stoner excitations	10^{-15} - 10^{-14}
Spin waves	10^{-12} (low q limit)
Spin – lattice relaxation	10^{-12} - 10^{-11} (in manganites)
Precessional motion	10^{-10} - 10^{-9}
Spin injection	TBD
Spin diffusion	TBD
Spin coherence	TBD

Electro-Optic Details for ZnTe

S. Casalbuoni, H. Schlarb, B. Schmidt, P. Schmüser, B. Steffen, A. Winter *DESY & Universität Hamburg*

“Numerical Studies on the Electro-Optic Sampling of Relativistic Electron Bunches” (TESLA Report 2005-01)



$$\cos 2\psi = \frac{\sin\alpha}{\sqrt{1+3\cos^2\alpha}}$$

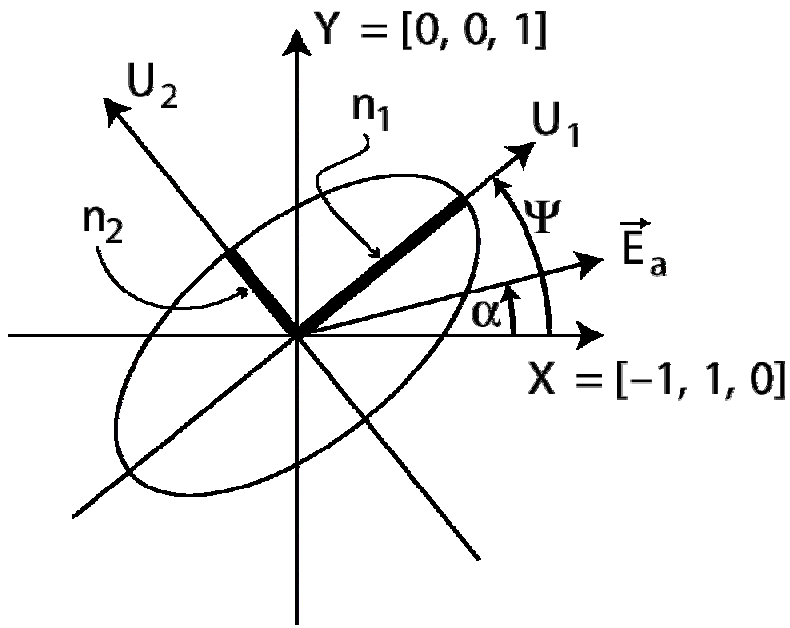
α = 0 –> ψ = π/4 (45°)

$$n_1 = n_0 + \frac{n_0^3 r_{41} E_a}{4}\left(\sin\alpha + \sqrt{1+3\cos^2\alpha}\right)$$

$$n_2 = n_0 + \frac{n_0^3 r_{41} E_a}{4}\left(\sin\alpha - \sqrt{1+3\cos^2\alpha}\right)$$

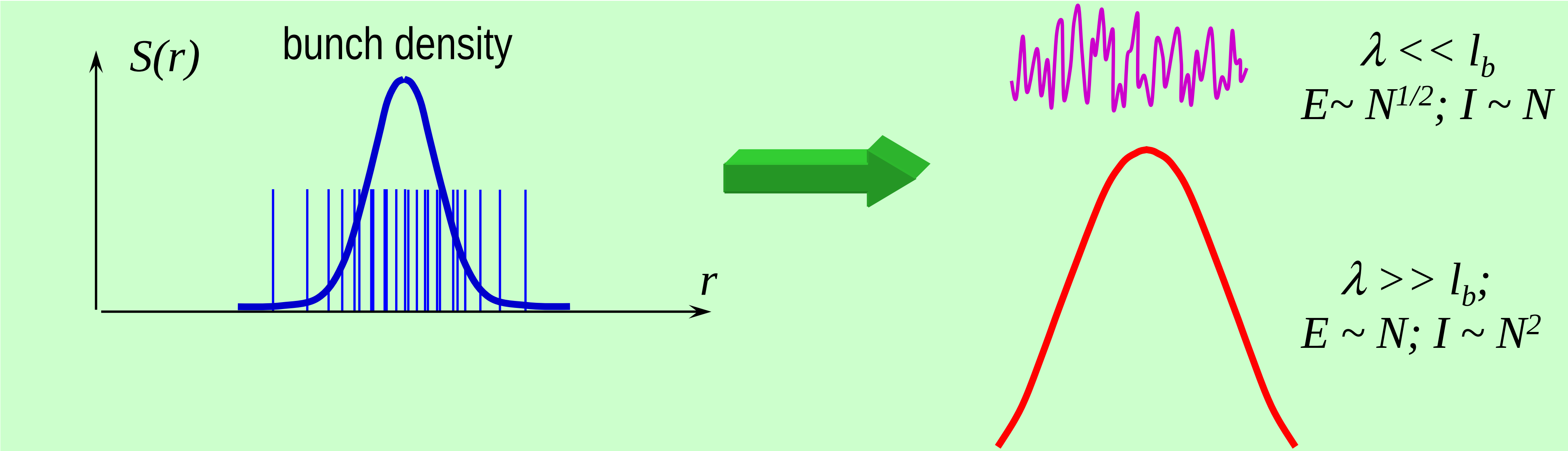
$$n_3 = n_0 - \frac{n_0^3 r_{41} E_a}{2}\sin\alpha \; .$$

$$\Delta\phi(E) = \frac{2\pi\, L}{\lambda_0}(n_1 - n_2) = \frac{2\pi\, L}{\lambda_0}\Delta n(E)$$



Multi-particle Coherent Synchrotron Radiation (CSR)

Accelerators typically have many electrons traveling in a "bunch". Can emission be coherent?
Yes -- if bunch (or some portion of it) has length that is short compared to wavelength.



$$\left.\frac{dI(\omega)}{d\omega}\right|_{multiparticle} = [N + N(N-1)f(\omega)]\frac{dI(\omega)}{d\omega} \sim N^2$$

$$\text{where } f(\omega) = \left| \int_{-\infty}^{\infty} e^{i\omega \hat{n}\cdot\vec{r}/c} S(r)\,dr \right|^2 \quad \textit{(Nodvick \& Saxon)}$$

In some accelerators, bunch lengths are 100s of fs (=>THz), and N can be large e.g. ~ 10^{10}

Threshold dependence on f_{s0}

Keil-Schnell

(coasting / unbunched beam)

$$eI_{ave} \frac{Z_n}{n} \leq 2\pi\alpha E\sigma_E^2$$

$$\Rightarrow \quad I_{th} \propto \alpha \sim f_{s0}^2$$

Boussard

replace I_{ave} with I_{peak}

$$\Rightarrow \quad I_{th} \propto \alpha^{3/2} \sim f_{s0}^3$$