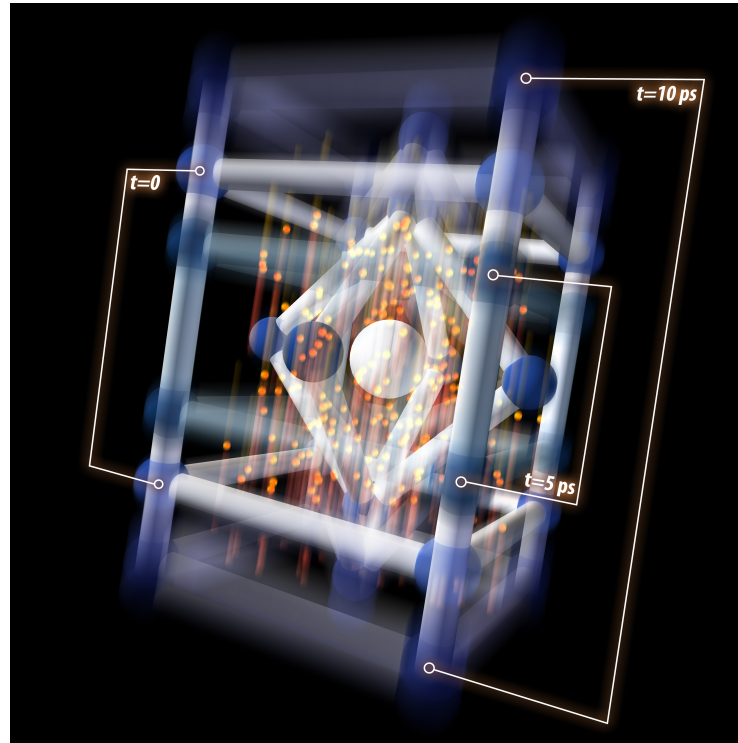


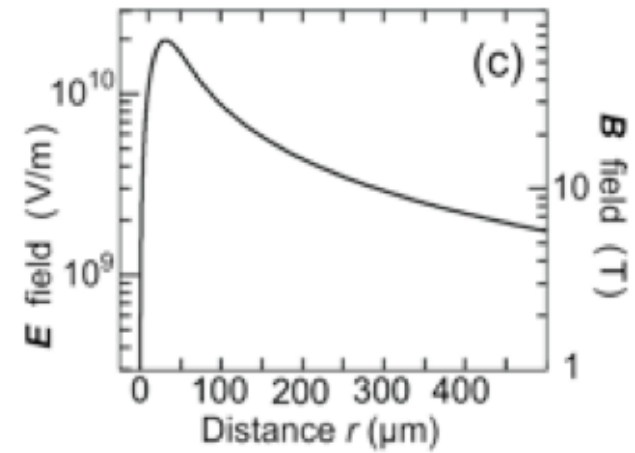
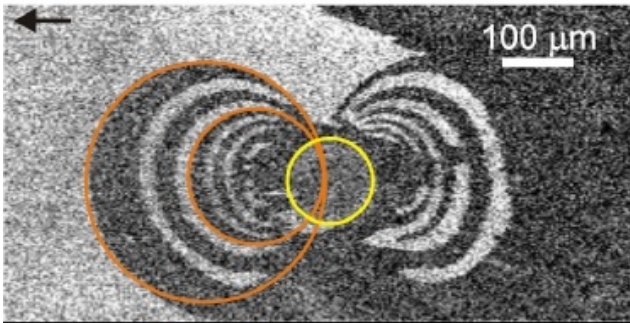
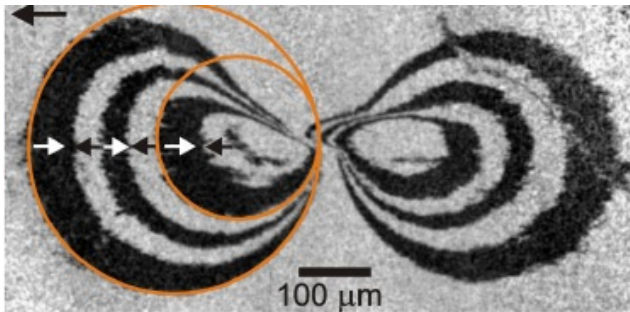
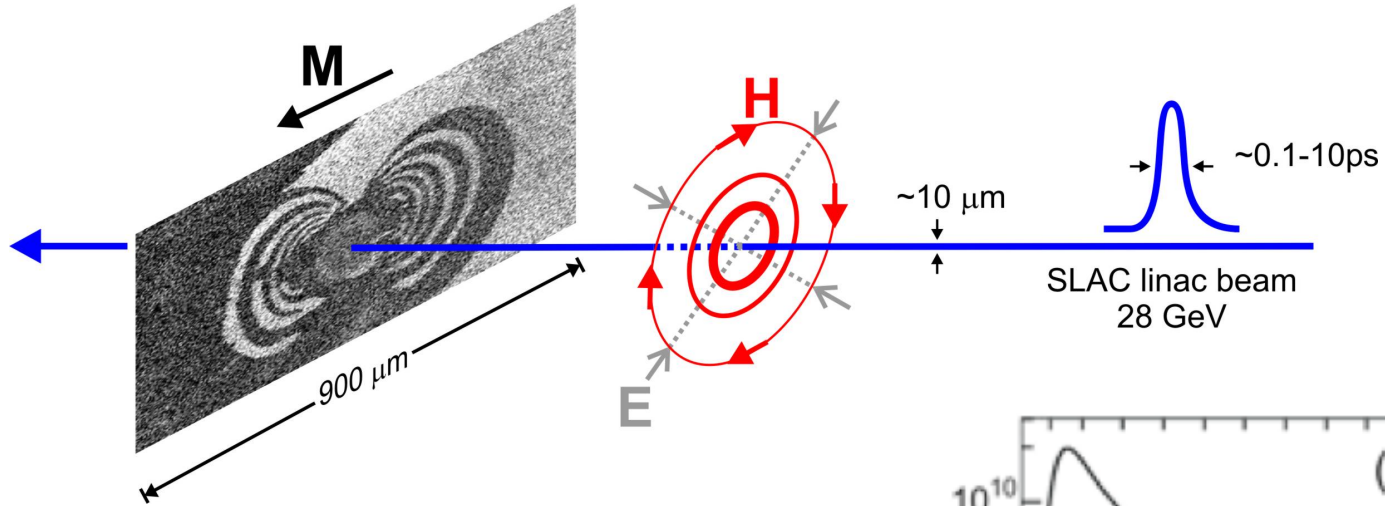
High field THz science with linac-based sources

Aaron M. Lindenberg
Dept. of Materials Science and Engineering, Stanford University
SLAC National Accelerator Laboratory



Workshop on Terahertz Sources for Time Resolved Studies of Matter
Argonne, IL
July 30, 2012

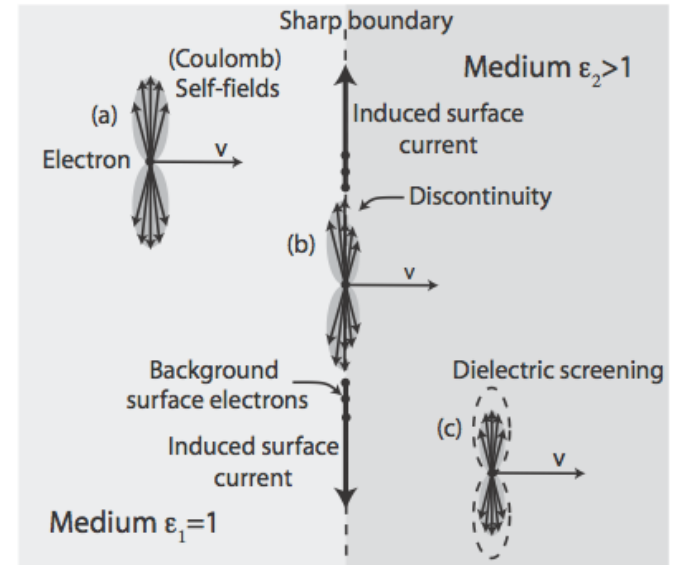
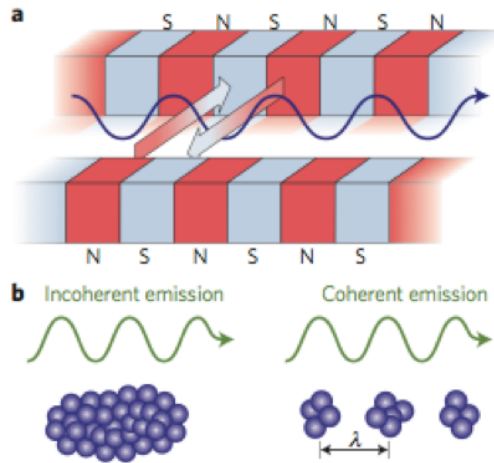
Electron-beam-driven switching



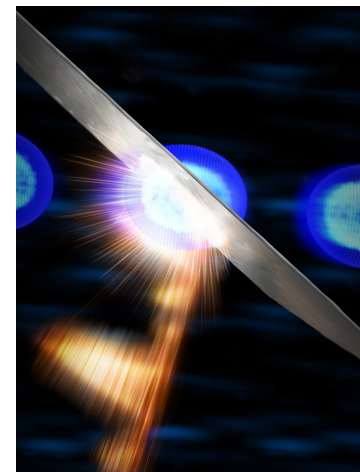
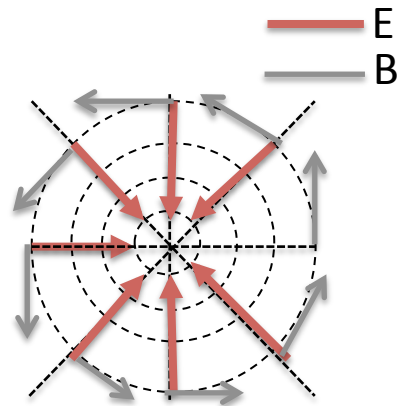
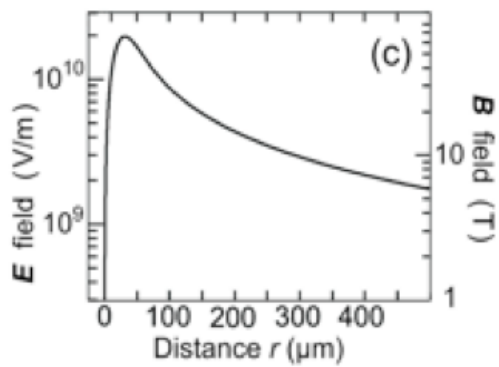
$$\vec{E}(\vec{r}, t) = \frac{Q}{(2\pi)^{3/2} \epsilon_0 c r \tau} \left(1 - \exp\left[-\frac{r^2}{2\sigma_r^2}\right] \right) \exp\left[-\frac{t^2}{2\tau^2}\right] \frac{\vec{r}}{r}$$

Gamble et al. PRL (2009)
Tudosa et al. Nature (2004)

THz Coherent Transition Radiation from the LCLS



N^2 scaling for wavelengths $>$ electron bunch length



Short pulse THz sources based on coherent synchrotron radiation

High-power terahertz radiation from relativistic electrons

Nature **420**, 153 (2002)

G. L. Carr[†], Michael C. Martin[†], Wayne R. McKinney[†], K. Jordan[‡],
George R. Nell[‡] & G. P. Williams[‡]

Coherent single-cycle pulses with MV/cm field strengths from a relativistic transition radiation light source

Opt. Lett. (2011)

Matthias C. Hoffmann^{1,*}, Sebastian Schulz², Stephan Wesch², Steffen Wunderlich², Andrea Cavalleri^{1,3} and Bernhard Schmidt²

PRL **96**, 014801 (2006)

PHYSICAL REVIEW LETTERS

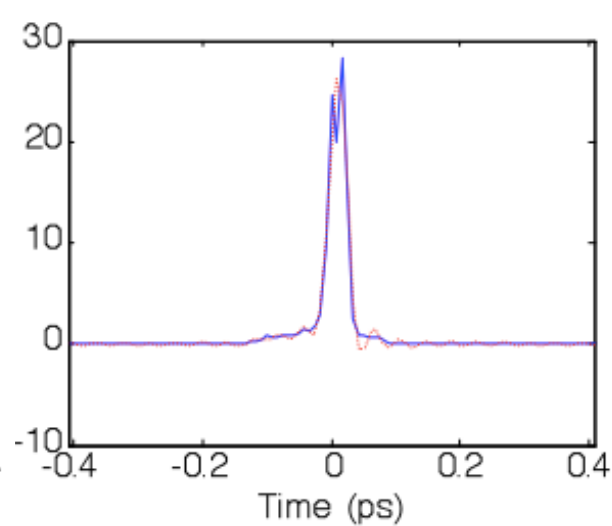
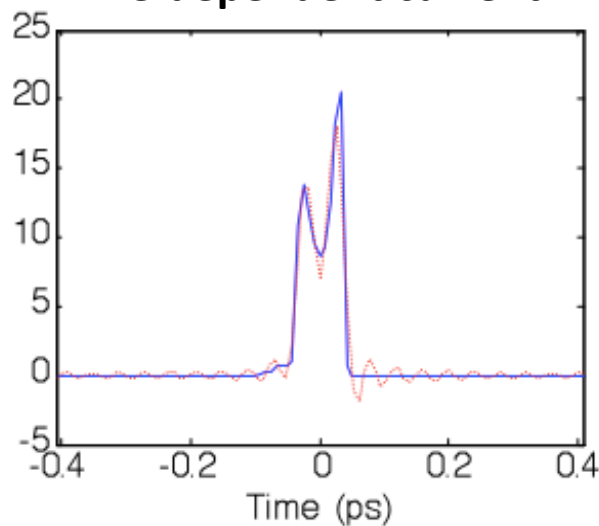
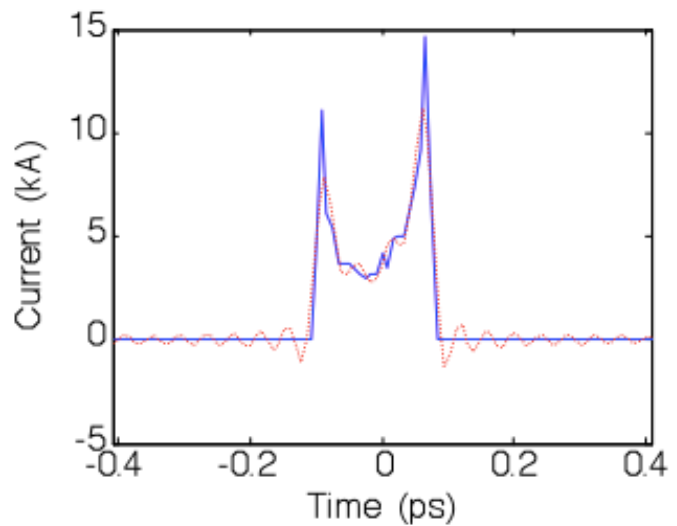
week ending
13 JANUARY 2006

Temporal Characterization of Femtosecond Laser-Plasma-Accelerated Electron Bunches Using Terahertz Radiation

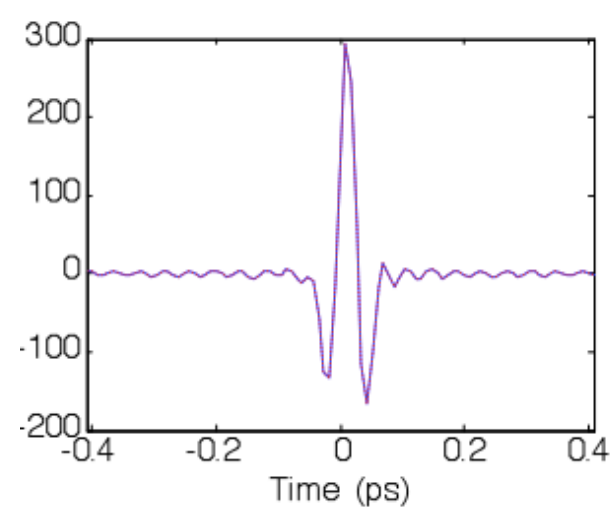
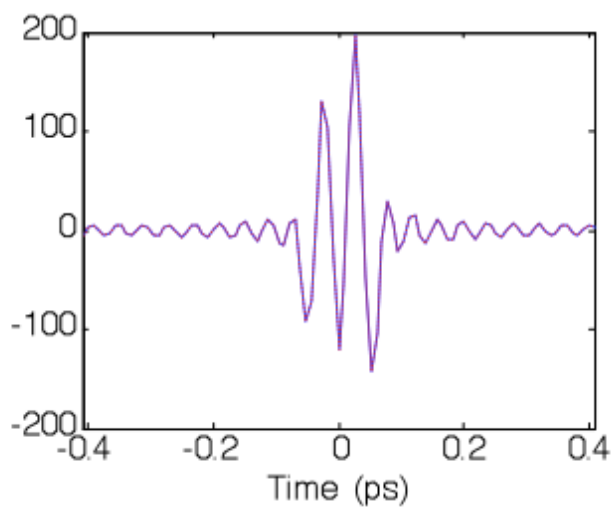
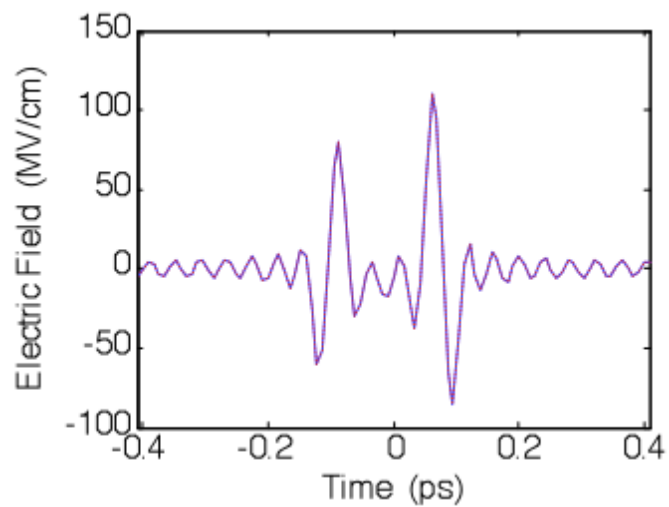
J. van Tilborg,^{1,*} C. B. Schroeder,¹ C. V. Filip,² Cs. Tóth,¹ C. G. R. Geddes,¹ G. Fubiani,^{1,†} R. Huber,¹ R. A. Kaindl,¹
E. Esarey,^{1,2} and W. P. Leemans^{1,2}

Simulations

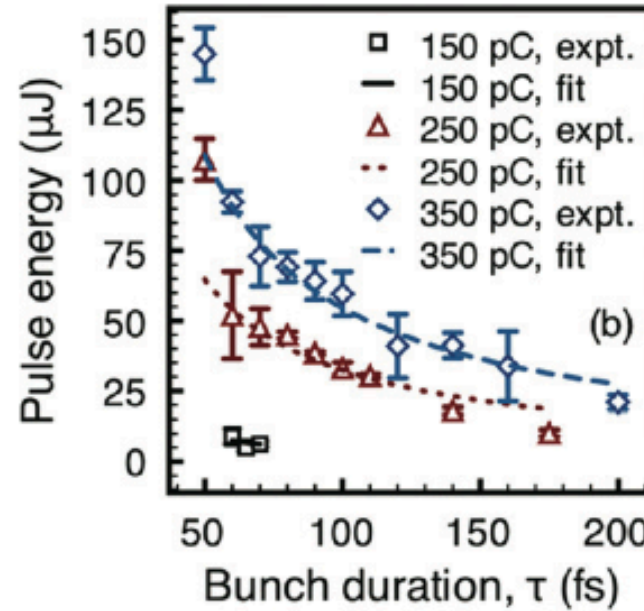
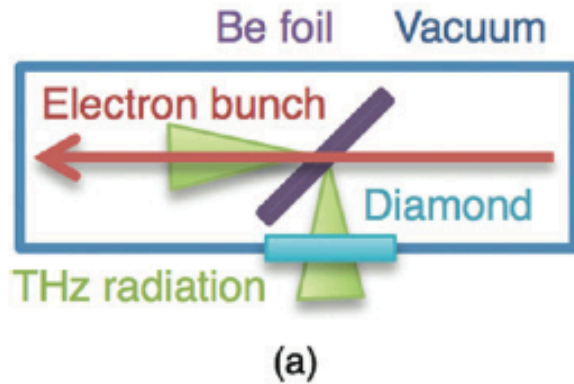
Time-dependent current



THz electric field

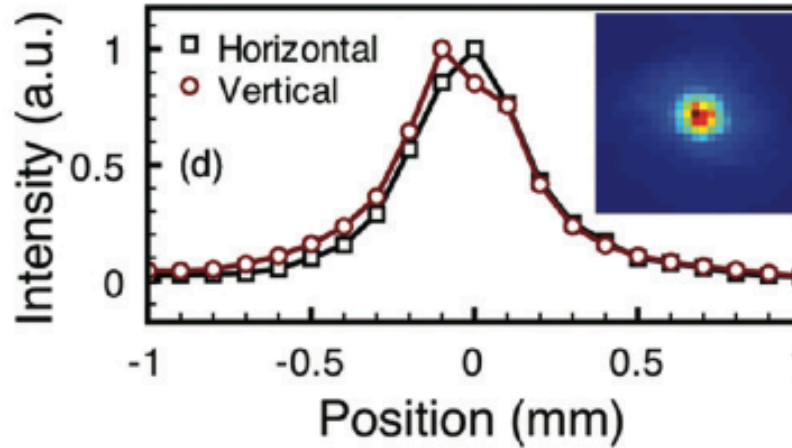
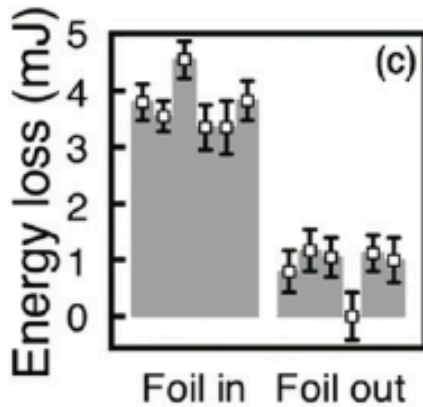


Generation of ultrashort, ultraintense single-cycle fields



$$U \sim \frac{Q^2}{\tau}$$

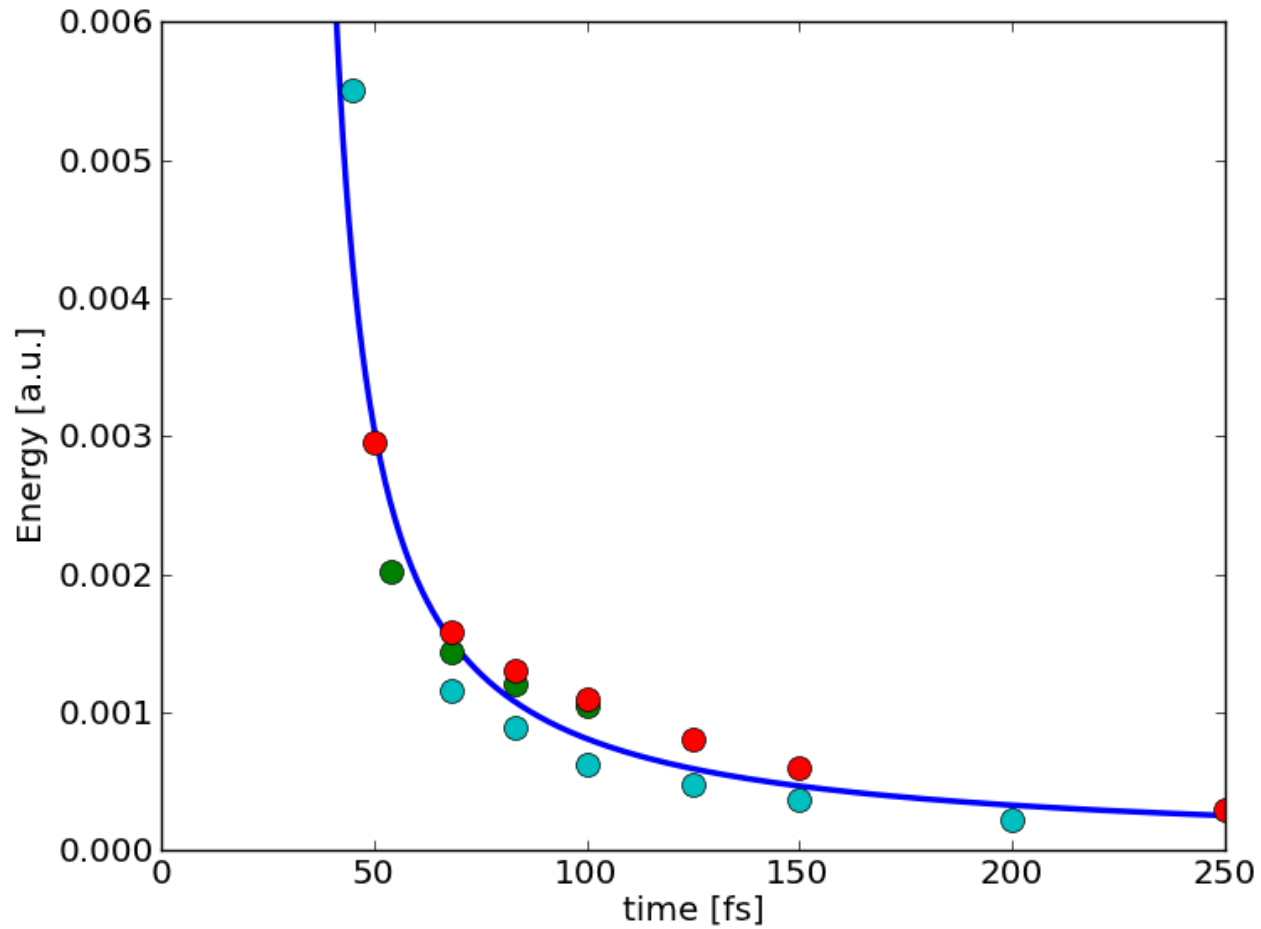
Electron beam energy loss due to THz radiation



$E \sim 20 \text{ MV/cm}$; $B \sim 7 \text{ T}$

Daranciang et al.,
Appl. Phys. Lett. (2011)

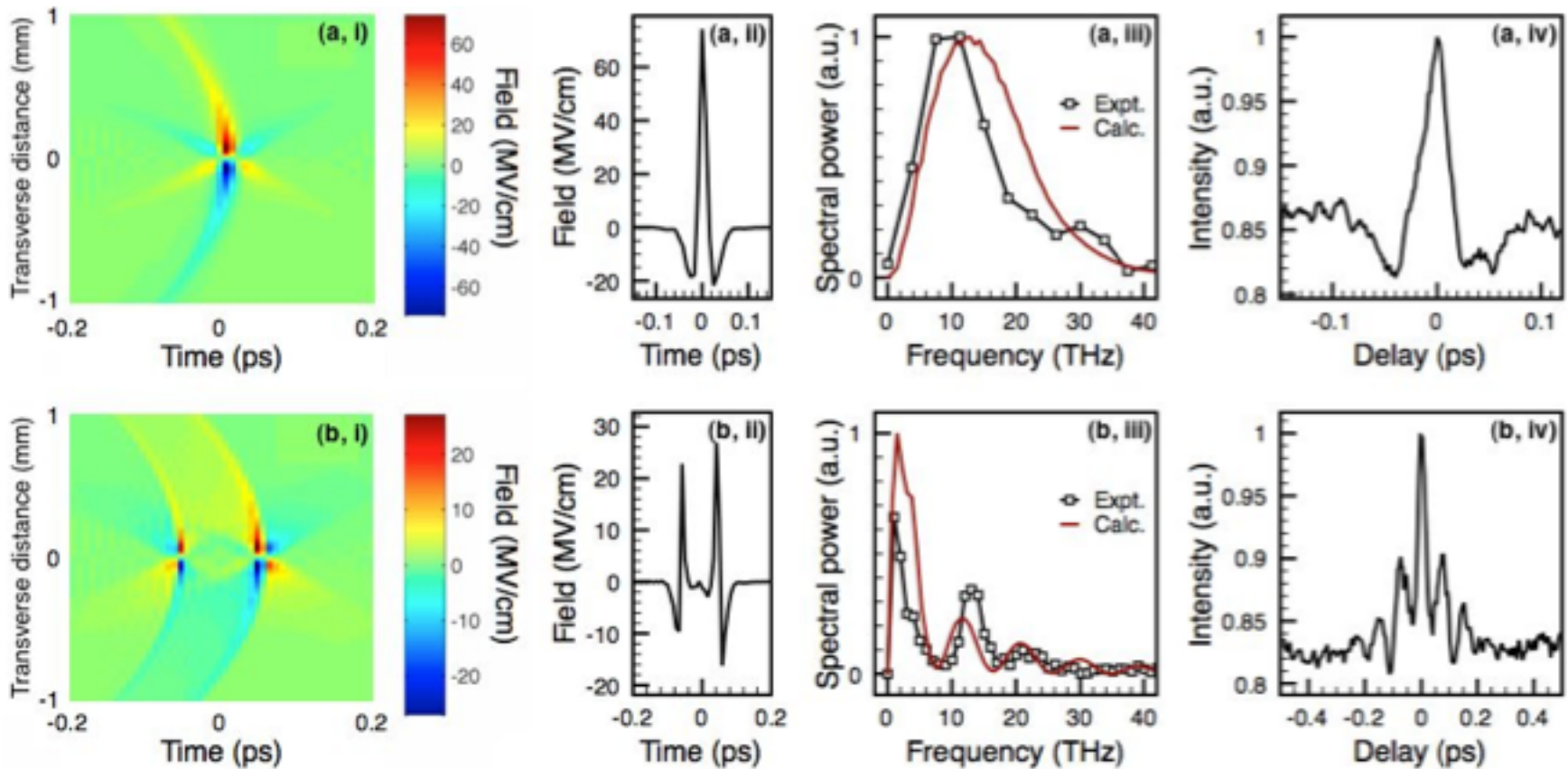
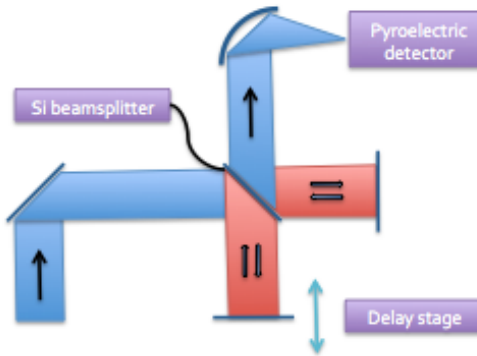
Scaling with charge and pulse duration



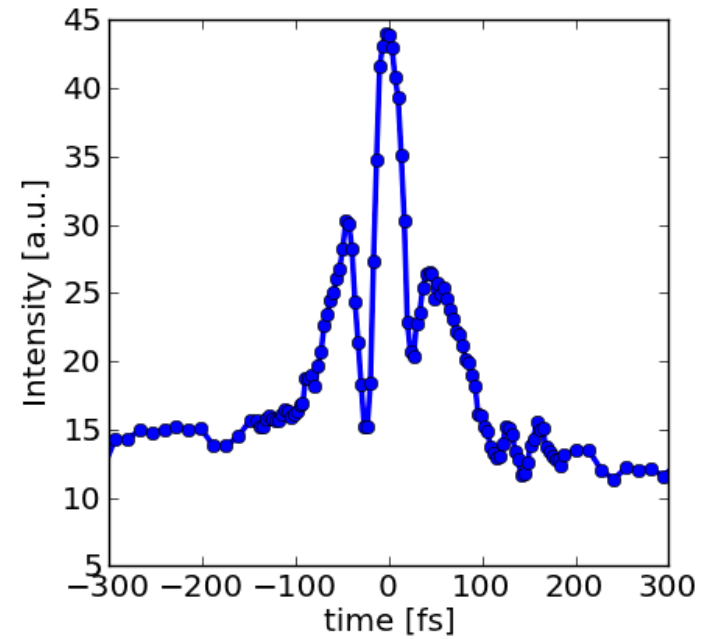
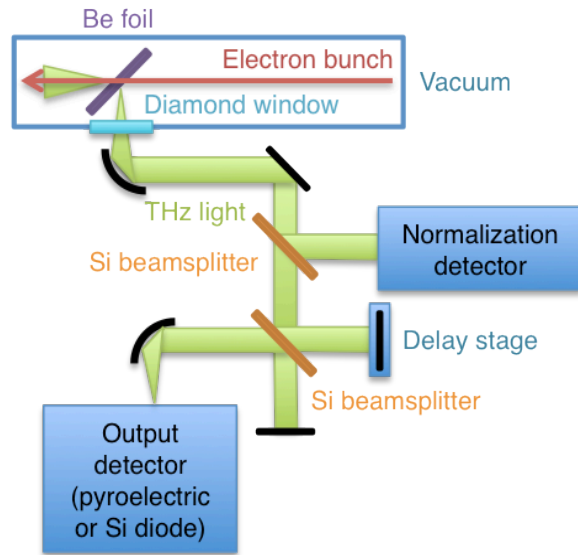
Peak energies of ~ 0.3 mJ

E-fields ~ 0.2 volt/angstrom; B fields ~ 10 T

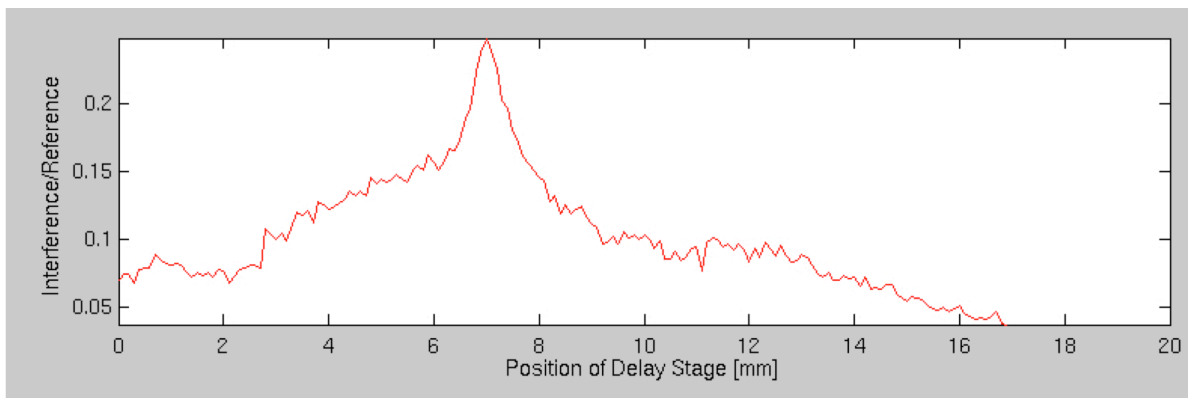
Field autocorrelations - Spectrum



THz nonlinear response and nonlinear autocorrelations

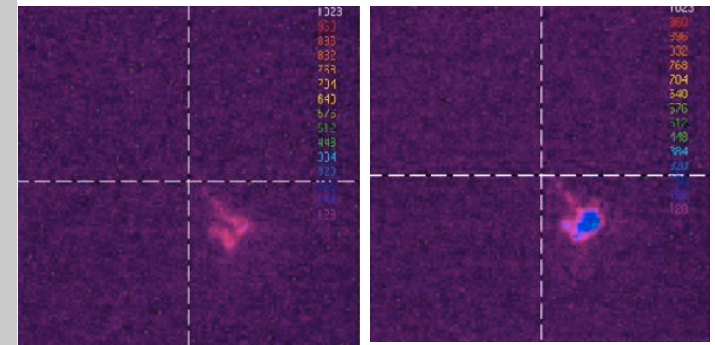


Z-scan

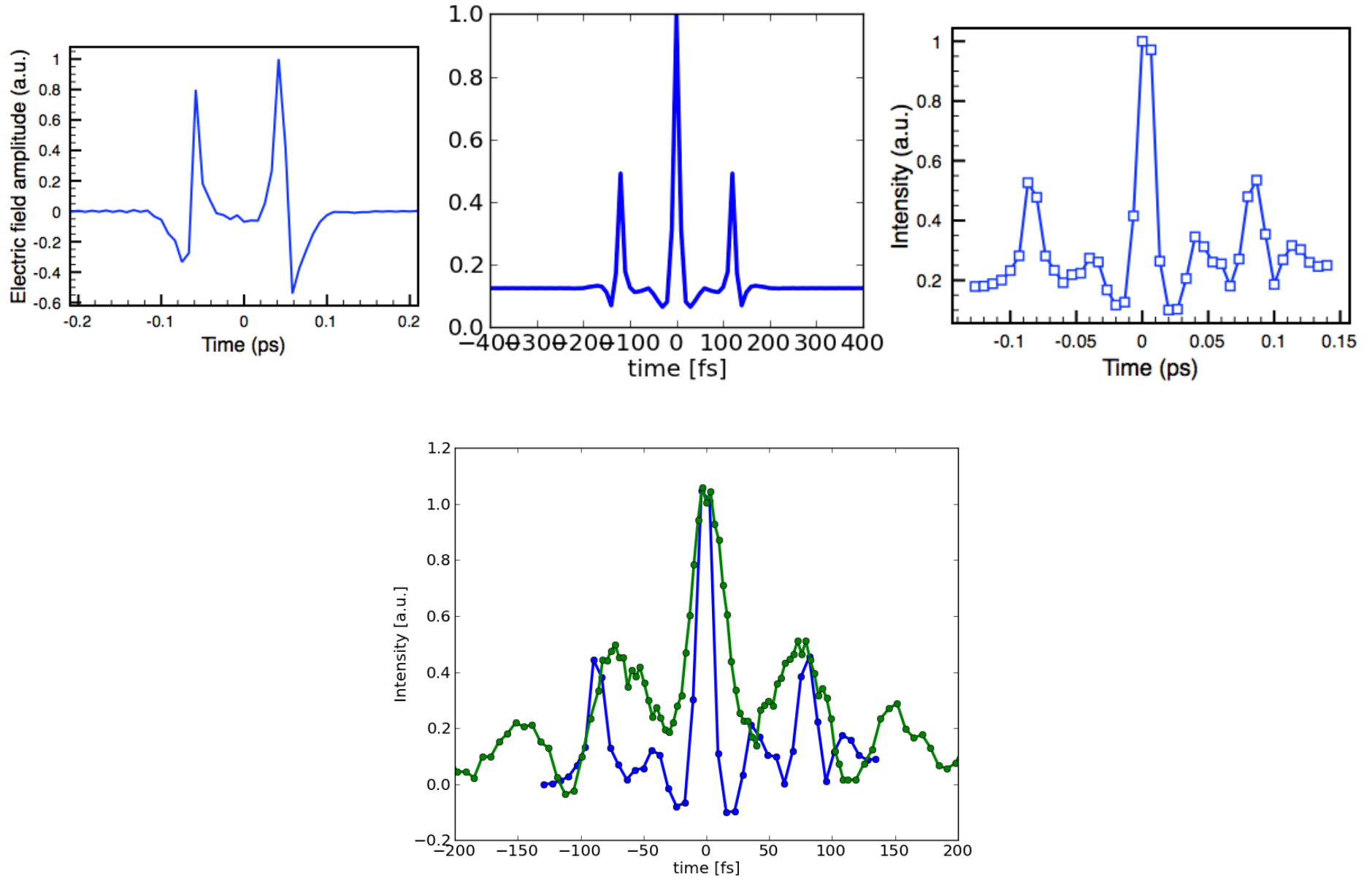


On focus

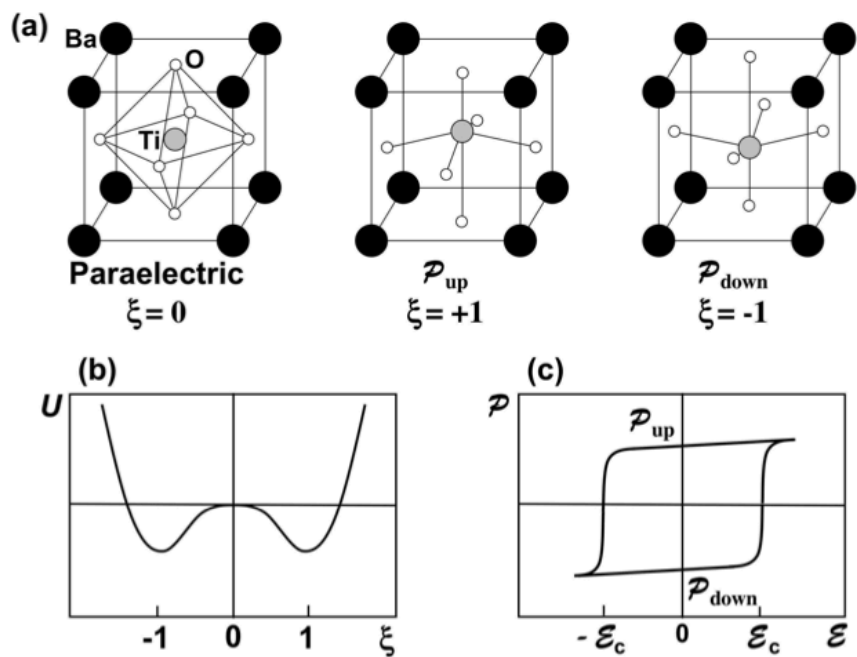
Off focus



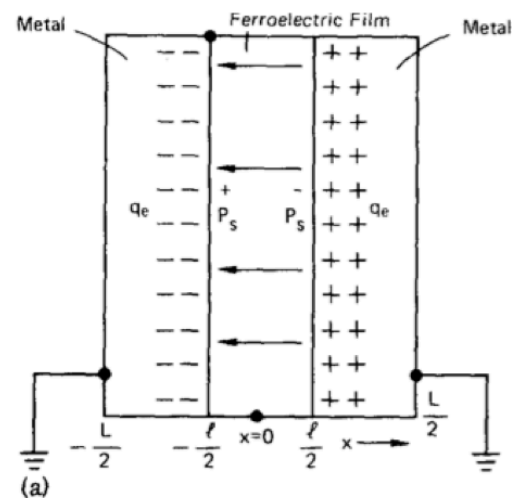
THz nonlinear autocorrelations



Ferroelectric perovskite oxides

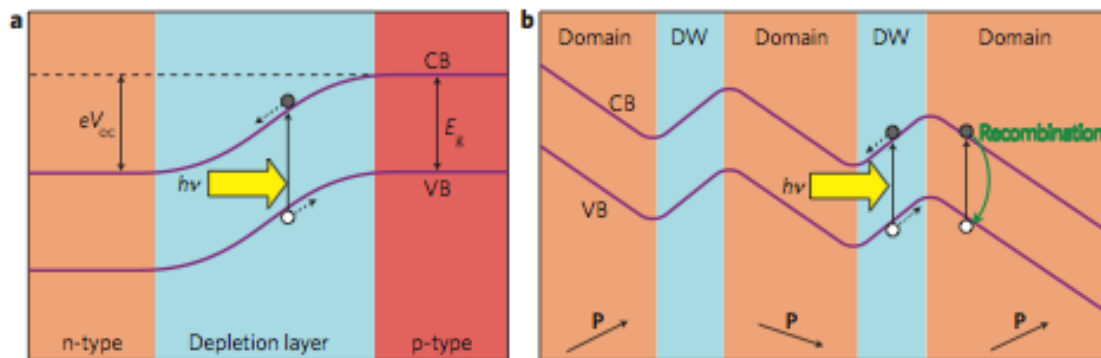


Ghosez, Junquera et al.



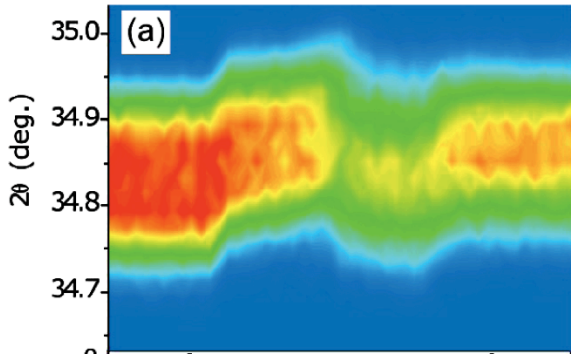
Mehta et al. (1973)

Photovoltaic response

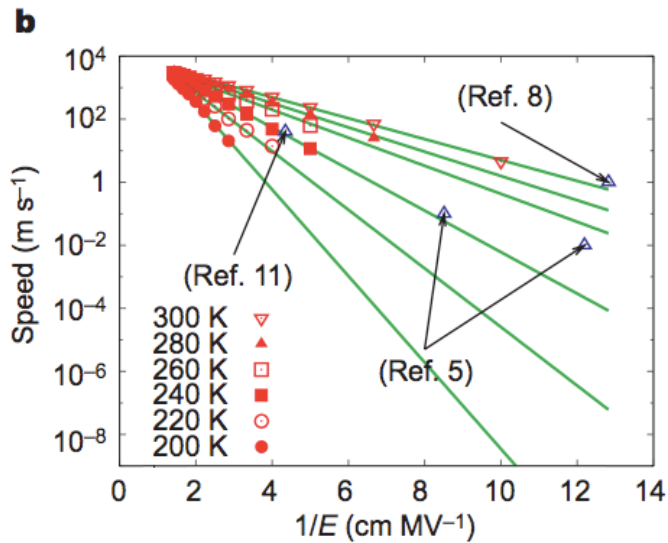


Yang et al. Nature Nano (2010)

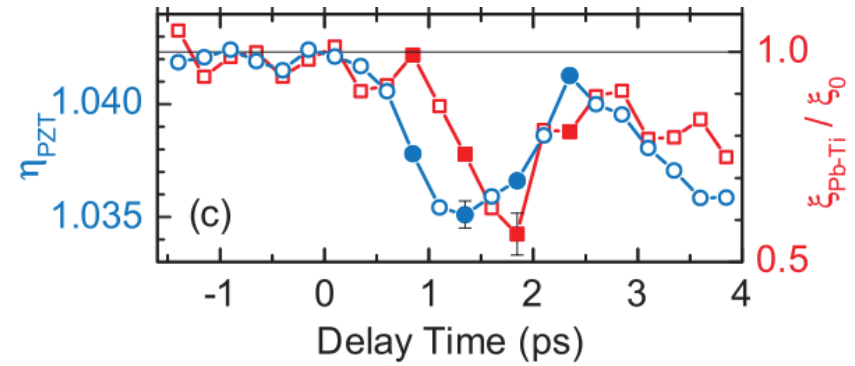
Dynamics



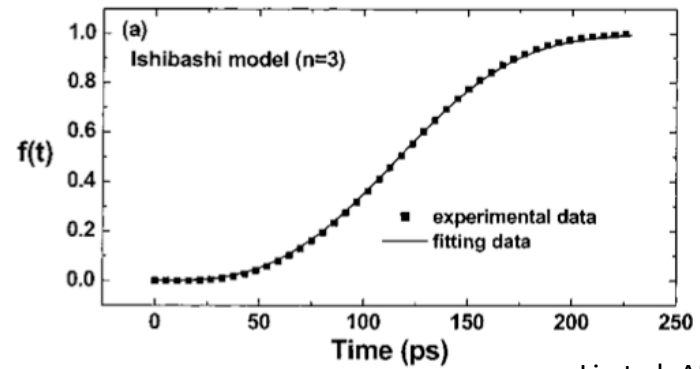
A. Grigoriev et al., PRL (2006)



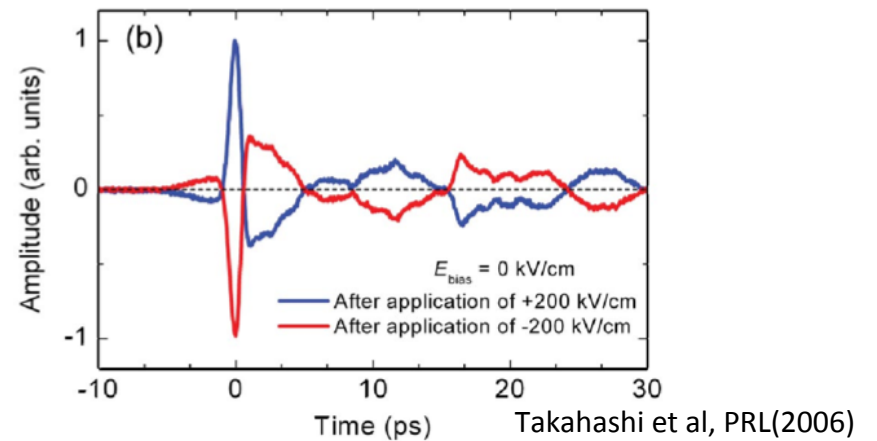
Rappe et al. Nature (2007)



Korff-Schmising et al. PRL (2007)



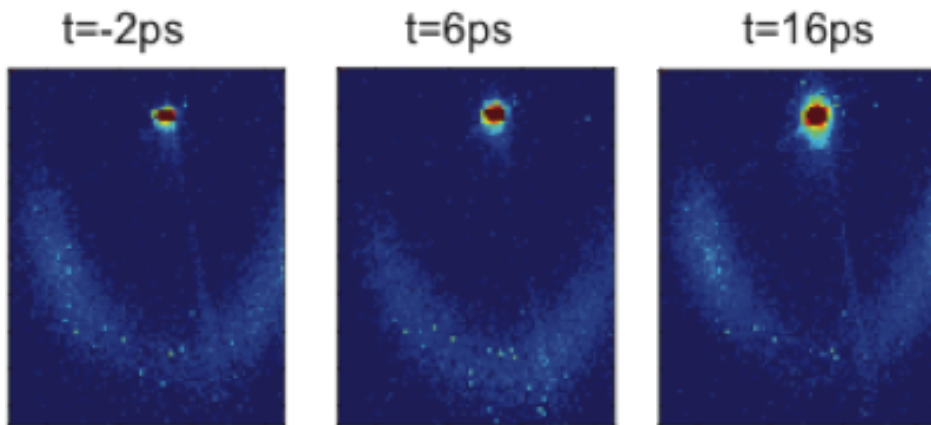
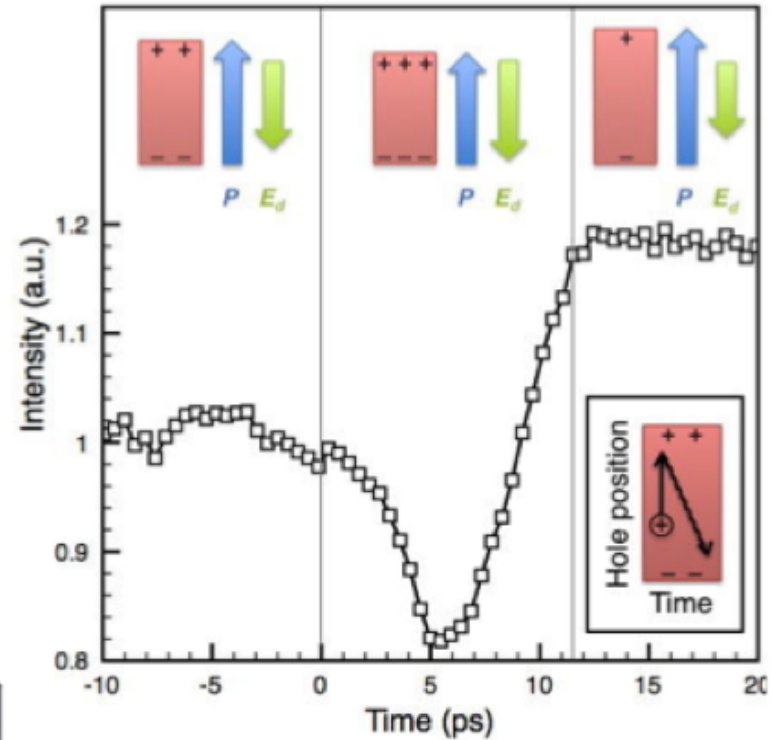
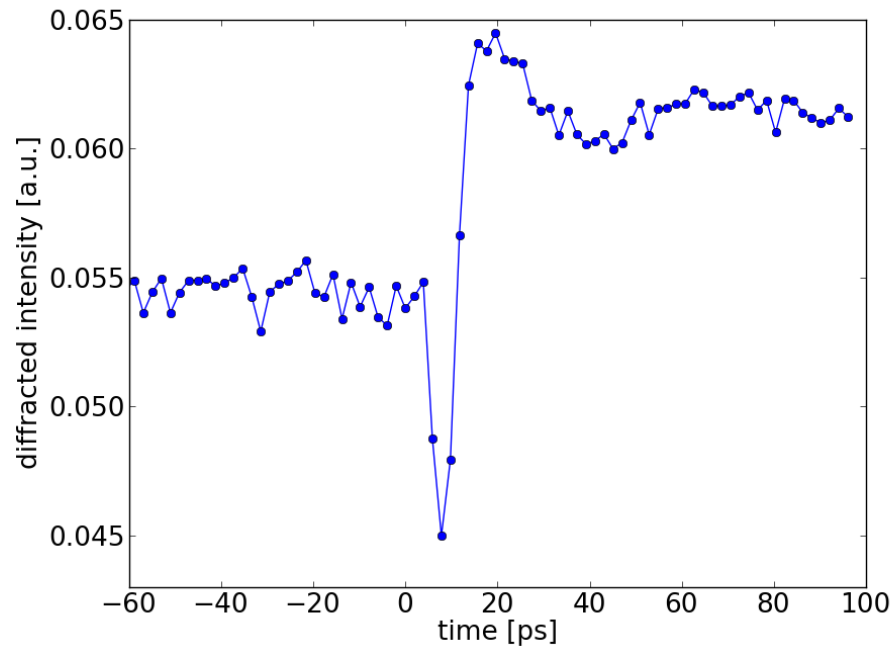
Li et al, APL (2004)



Takahashi et al, PRL(2006)

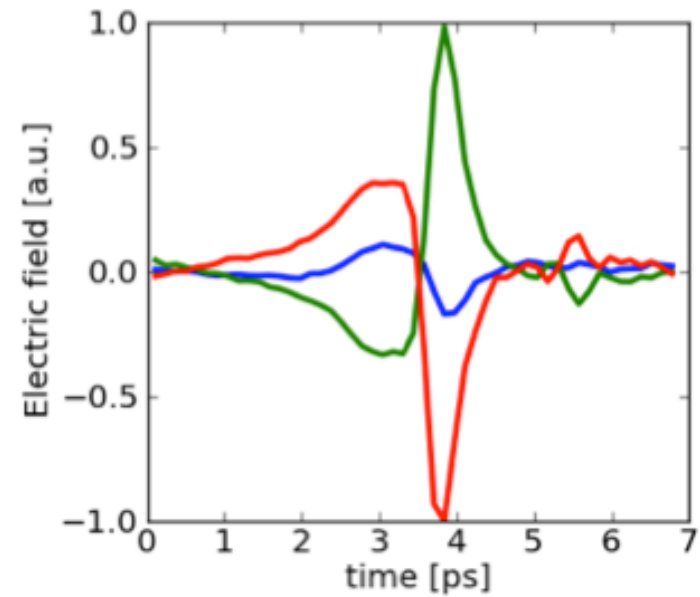
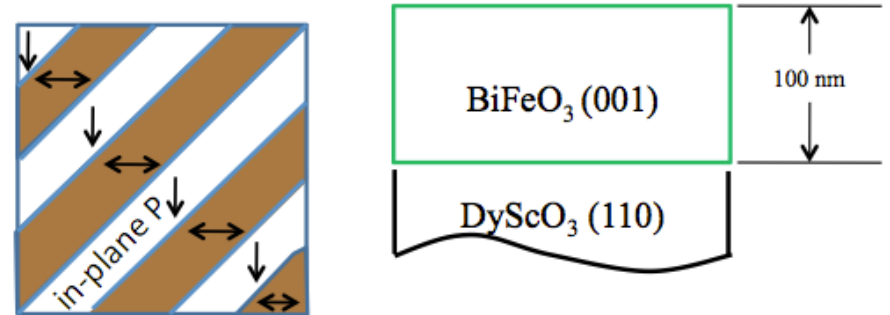
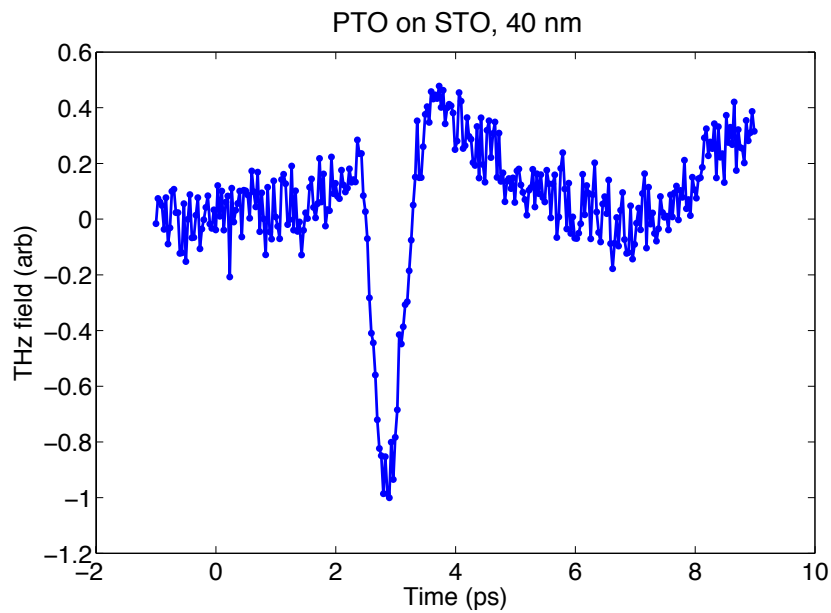
Ultrafast photovoltaic response in PbTiO_3 thin films

Time-dependent structural changes driven by photo-induced currents and fields

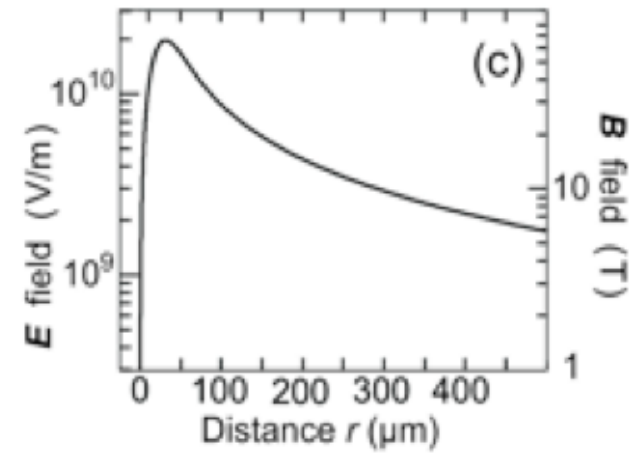
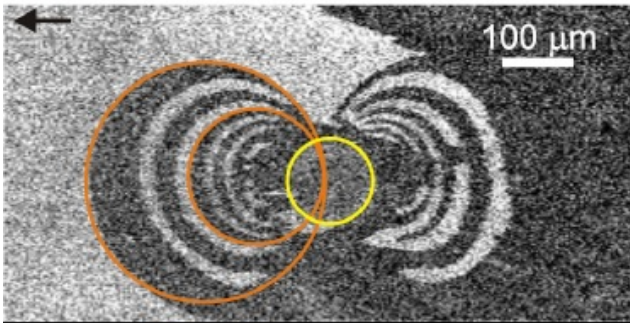
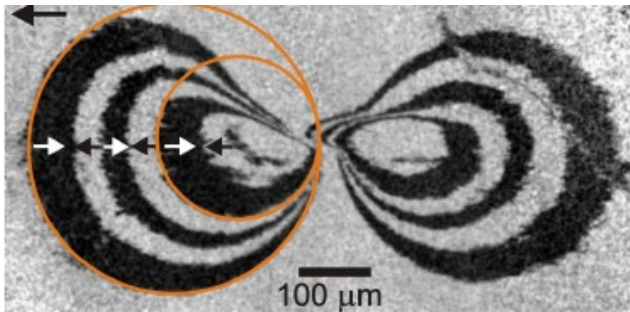
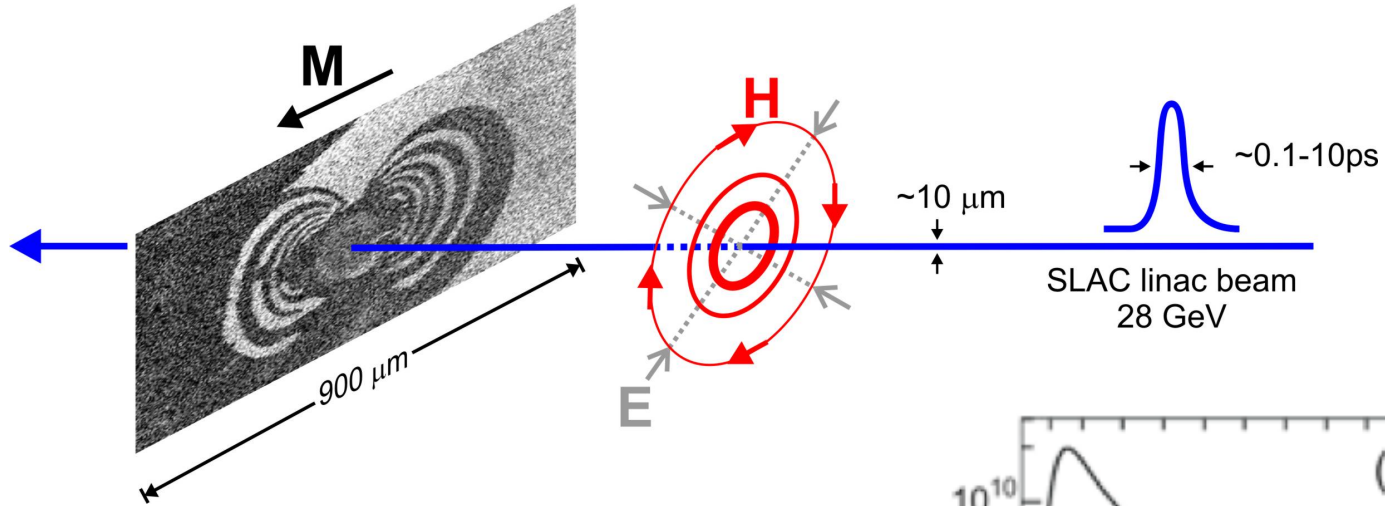


THz emission spectroscopy of photo-induced currents

$$E_{THz} \propto \int_0^{\infty} \left(\frac{\partial \vec{J}}{\partial t} + \frac{\partial^2 \vec{P}}{\partial t^2} \right) dz$$



Electron-beam-driven switching

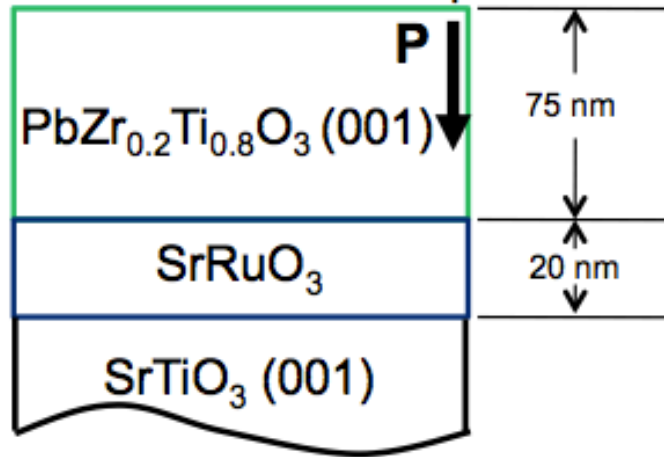


$$\vec{E}(\vec{r}, t) = \frac{Q}{(2\pi)^{3/2} \epsilon_0 c r \tau} \left(1 - \exp\left[-\frac{r^2}{2\sigma_r^2}\right] \right) \exp\left[-\frac{t^2}{2\tau^2}\right] \frac{\vec{r}}{r}$$

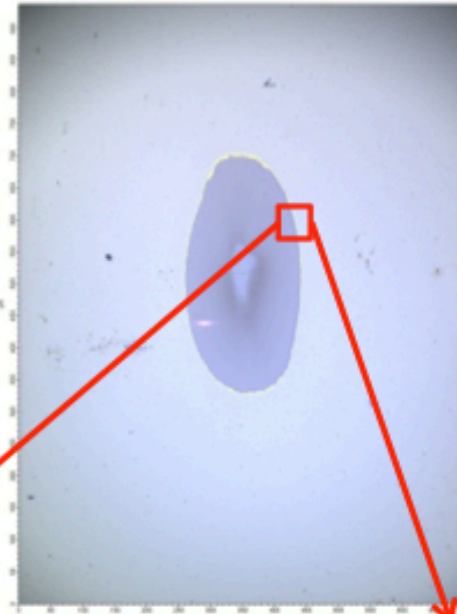
Gamble et al. PRL (2009)
Tudosa et al. Nature (2004)

FACET experiments: 75 nm PZT/SRO electrode/STO

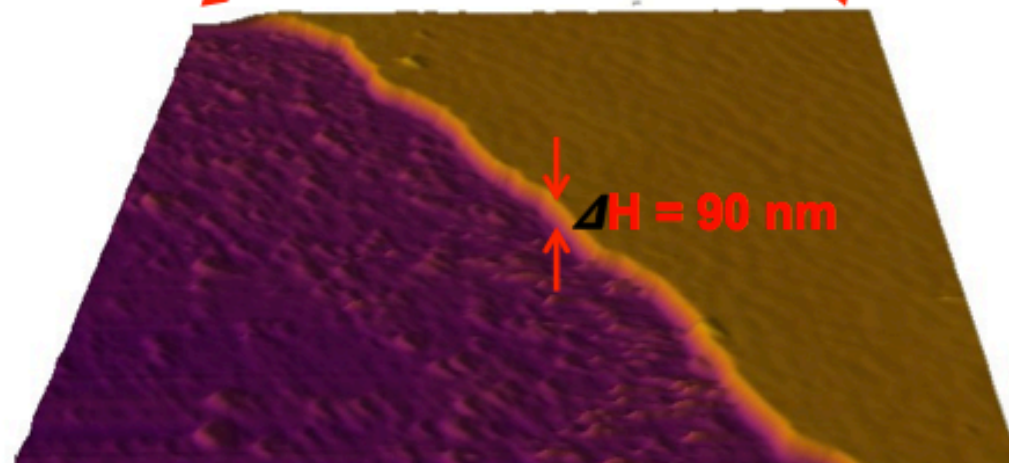
Overview of the sample



Optical micrograph: Short bunch shot location



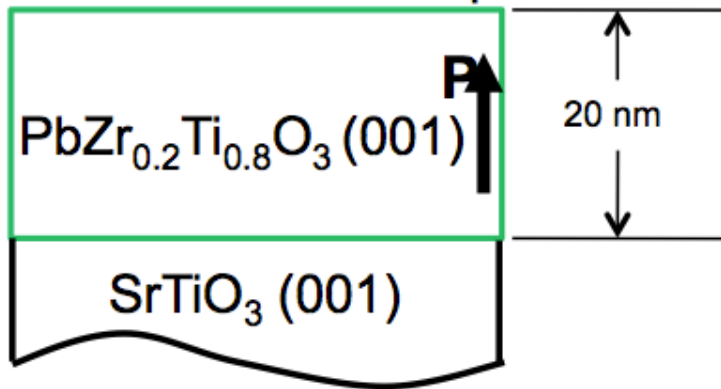
Step height, $\Delta H \sim 90$ nm
→ no film in this region



AFM Topography

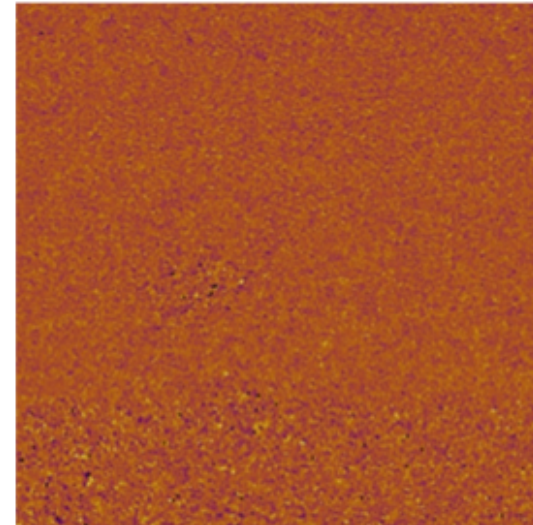
PZT/STO (no electrode)

Overview of the sample

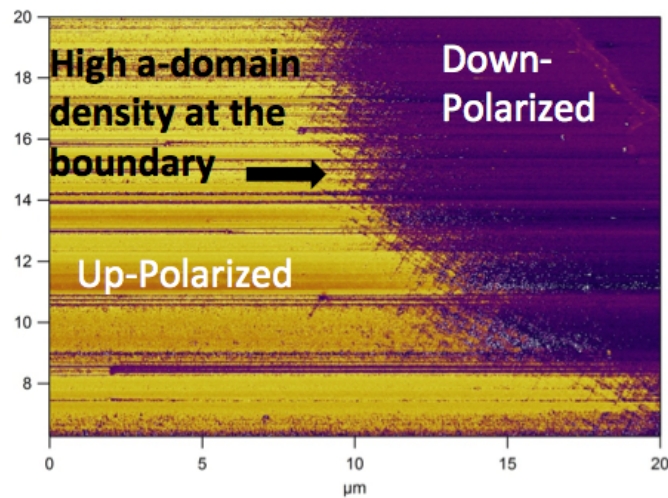


PFM

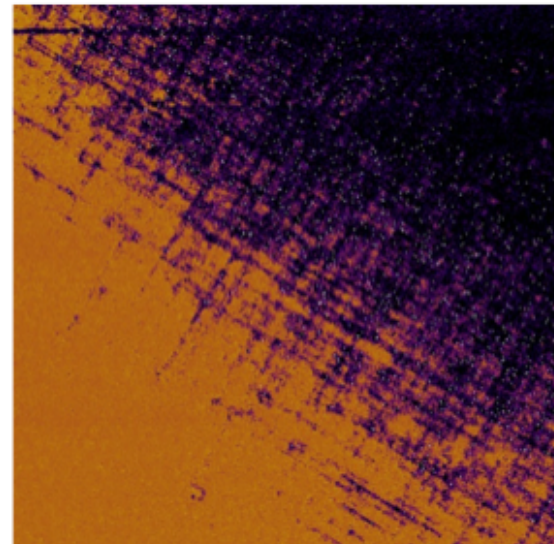
before

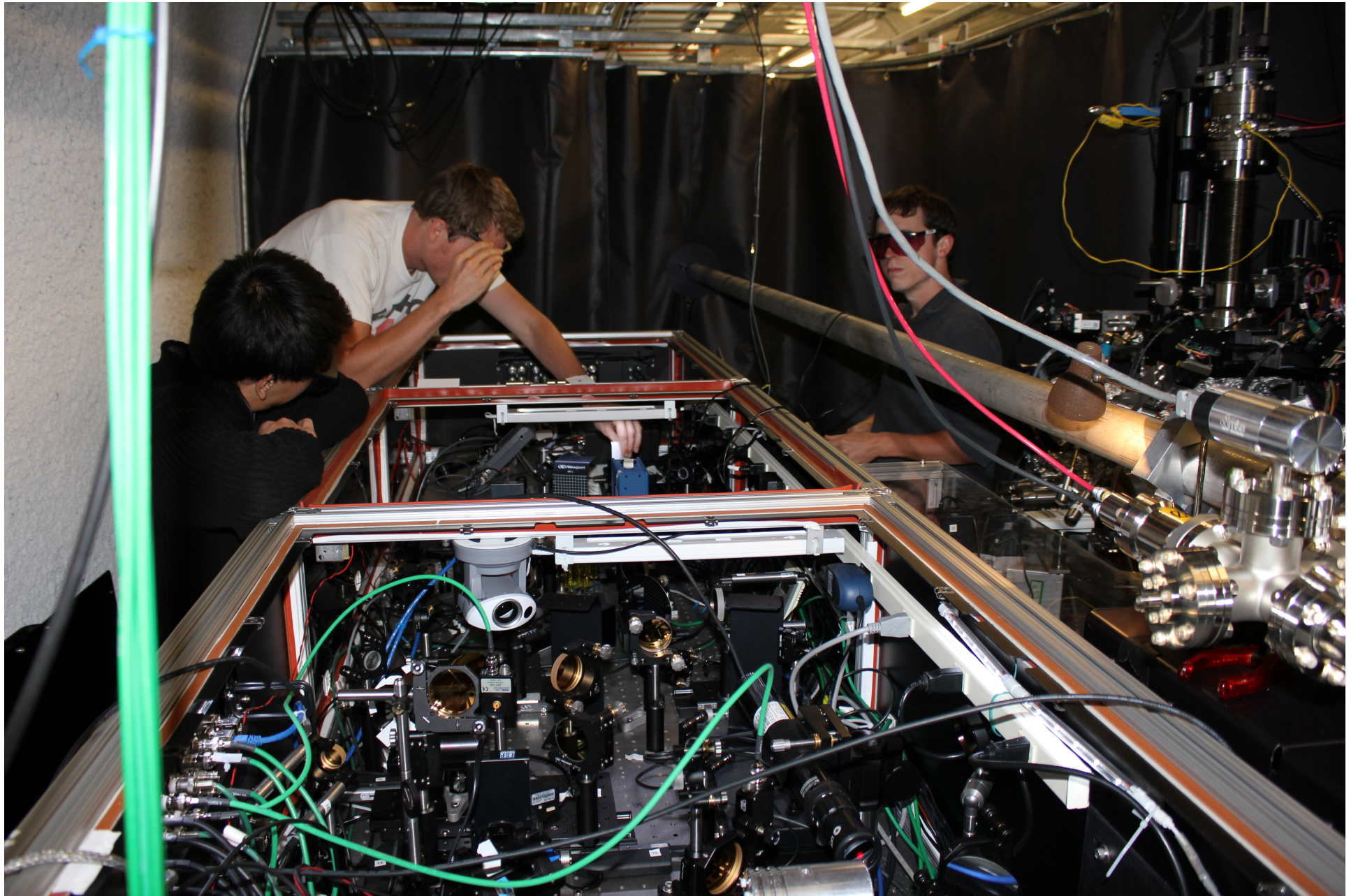


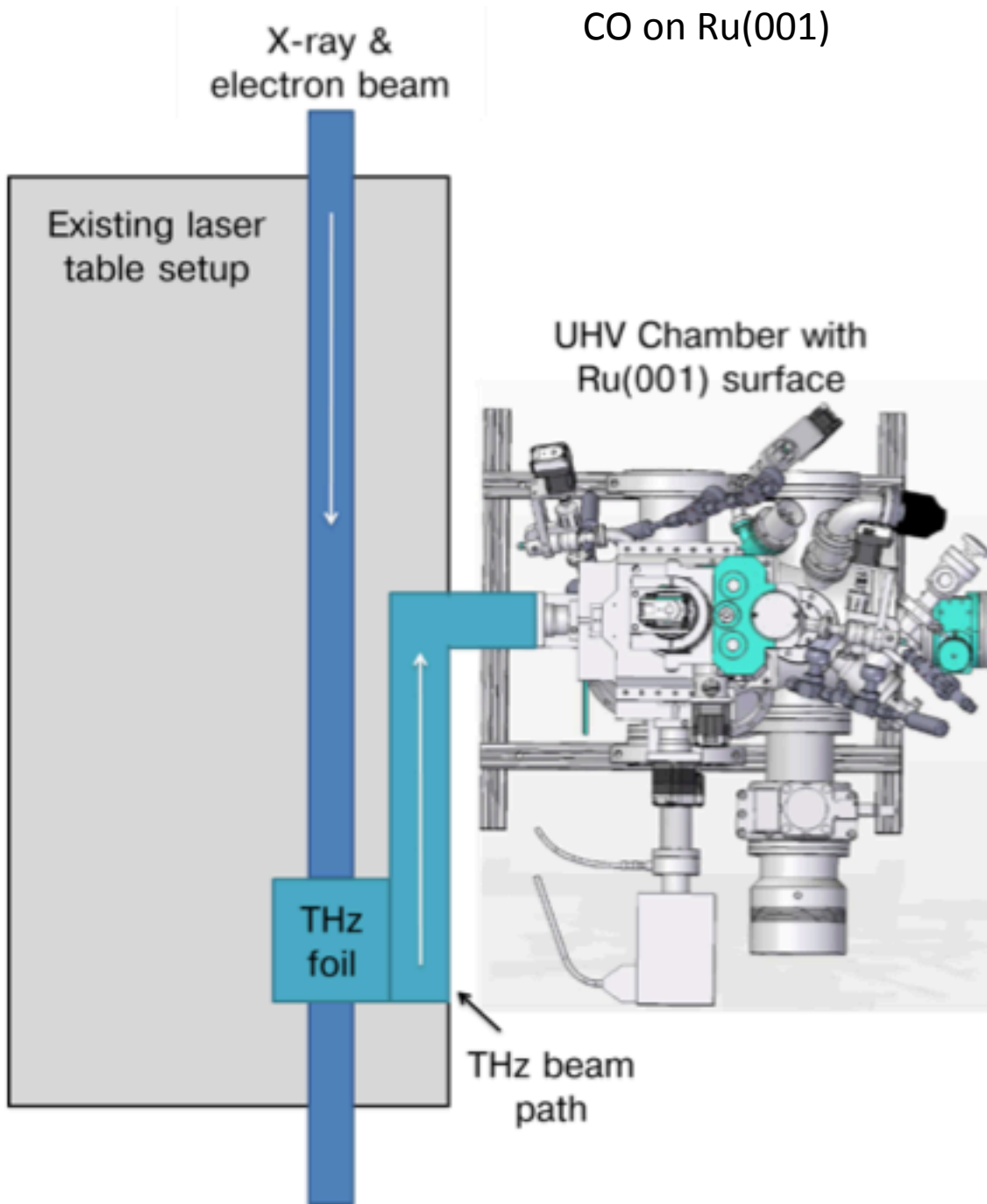
AFM



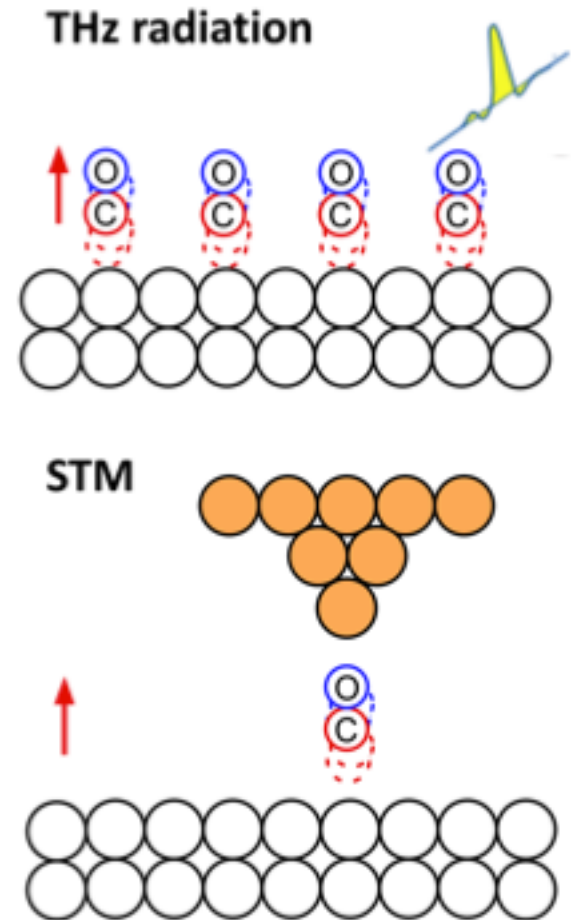
after





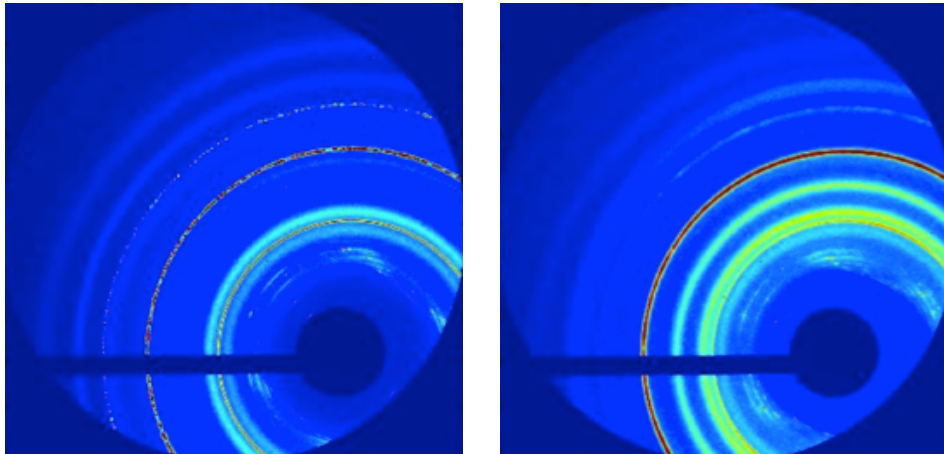
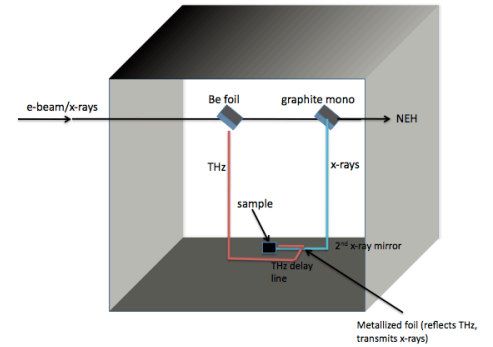


CO on Ru(001)



Conclusions, Future Directions, and Acknowledgements

1. Many novel opportunities for accelerator-based sources of single-cycle THz radiation (1-10 THz range)
2. Opportunities for coupling to existing x-ray sources
3. Novel triggers, new directions in control of materials: $E > \text{breakdown fields}$, piezoelectric, electrostrictive \rightarrow large amplitude acoustic responses; $P \sim 1 \text{ GPa}$.



Acknowledgements

Stanford University

D. Daranciang, J. Goodfellow

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M. Highland, H. Wen, P. Fuoss, B. Stephenson

LCLS

D. Fritz, M. Cammarata, H. Lemke, D. Zhu

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Steve Young, T. Qi, I. Grinberg, A. Rappe

UIUC

A. Damodaran, L. Martin

MIT

H. Hwang, N. Brandt, K. Nelson



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