Exploring Ultrafast Excitations in Solids with Pulsed e-Beams

S. J. Gamble, M. H. Burkhardt
SLAC, Stanford University Department of Applied Physics

Stanford Linear Accelerator Center

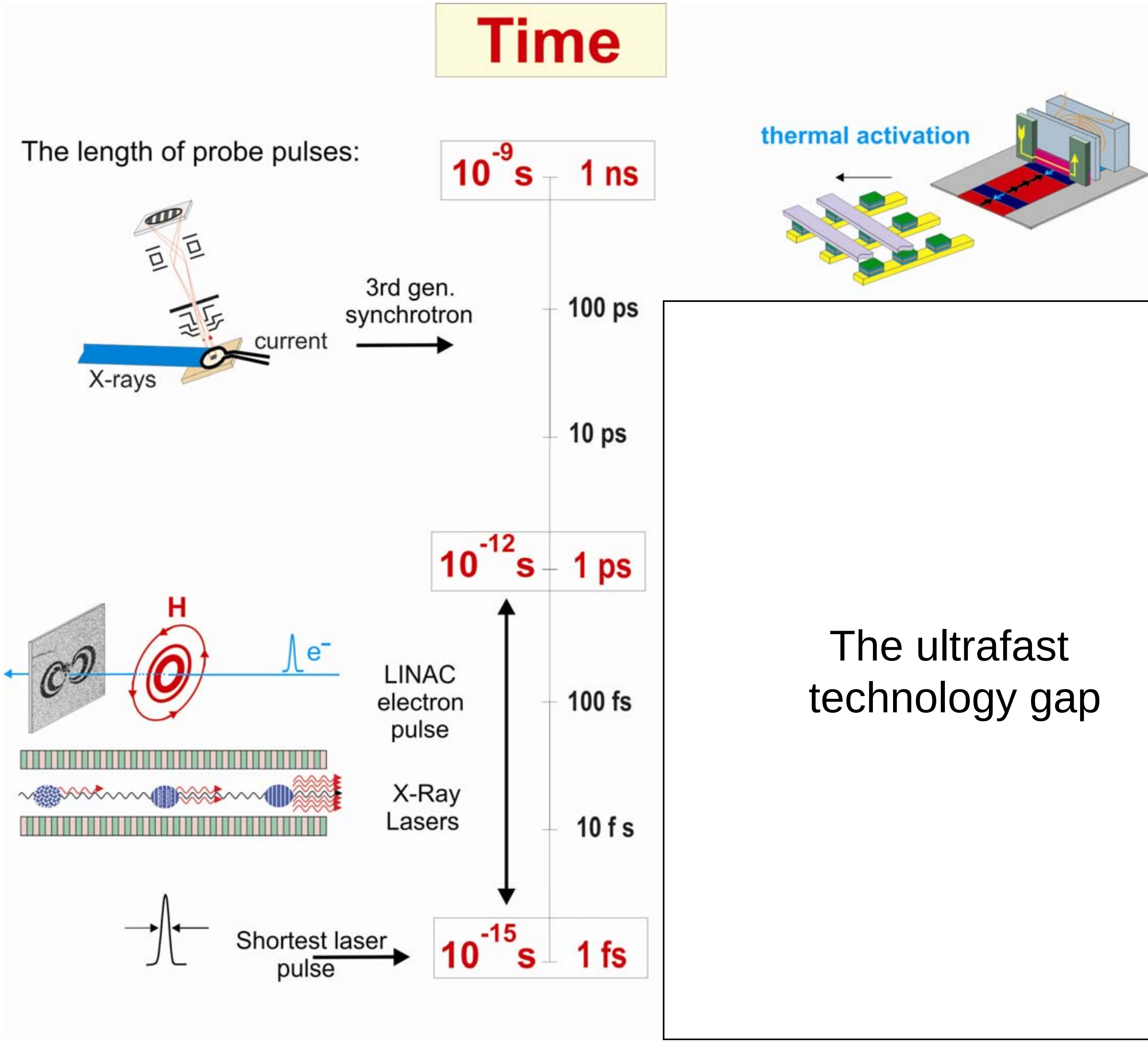
H. C. Siegmann, J. Stöhr
SLAC

SSRL

A. Kashuba
Bogolyubov Institute for Theoretical Physics, Kiev, Ukraine

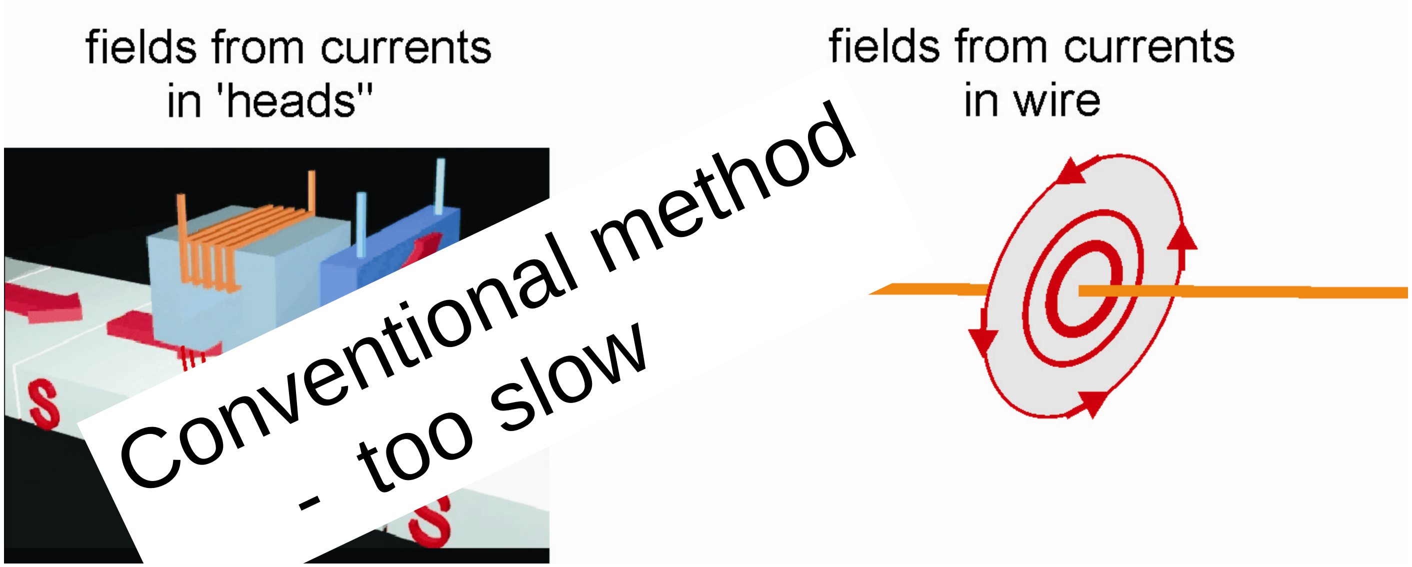
R. Allenspach
IBM Research Division, Zürich Research Laboratory

S. S. P. Parkin
IBM Almaden Research Center

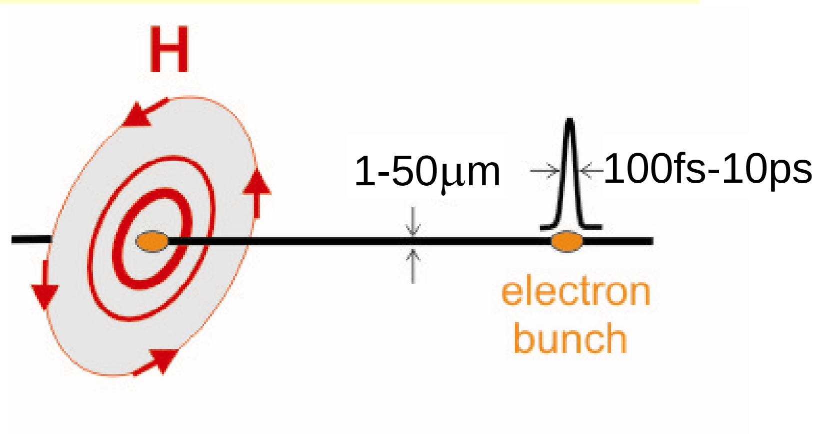


The ultrafast technology gap

Creation of large, ultrafast magnetic fields

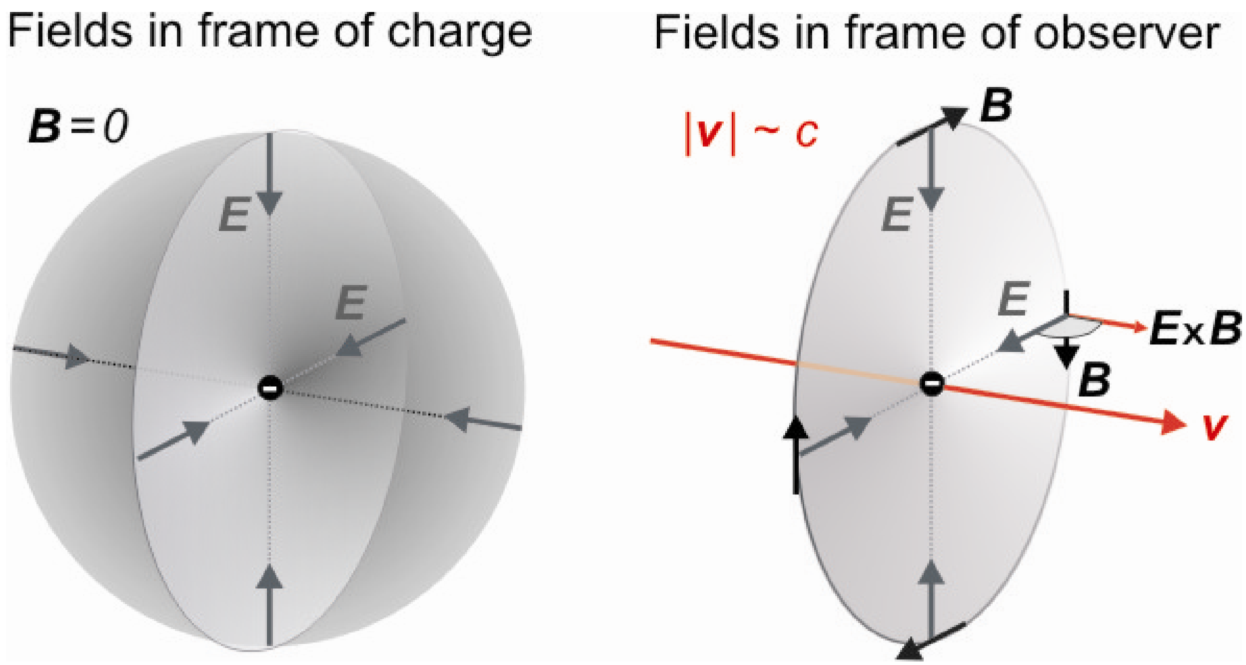


Ultrafast pulse – use electron accelerator

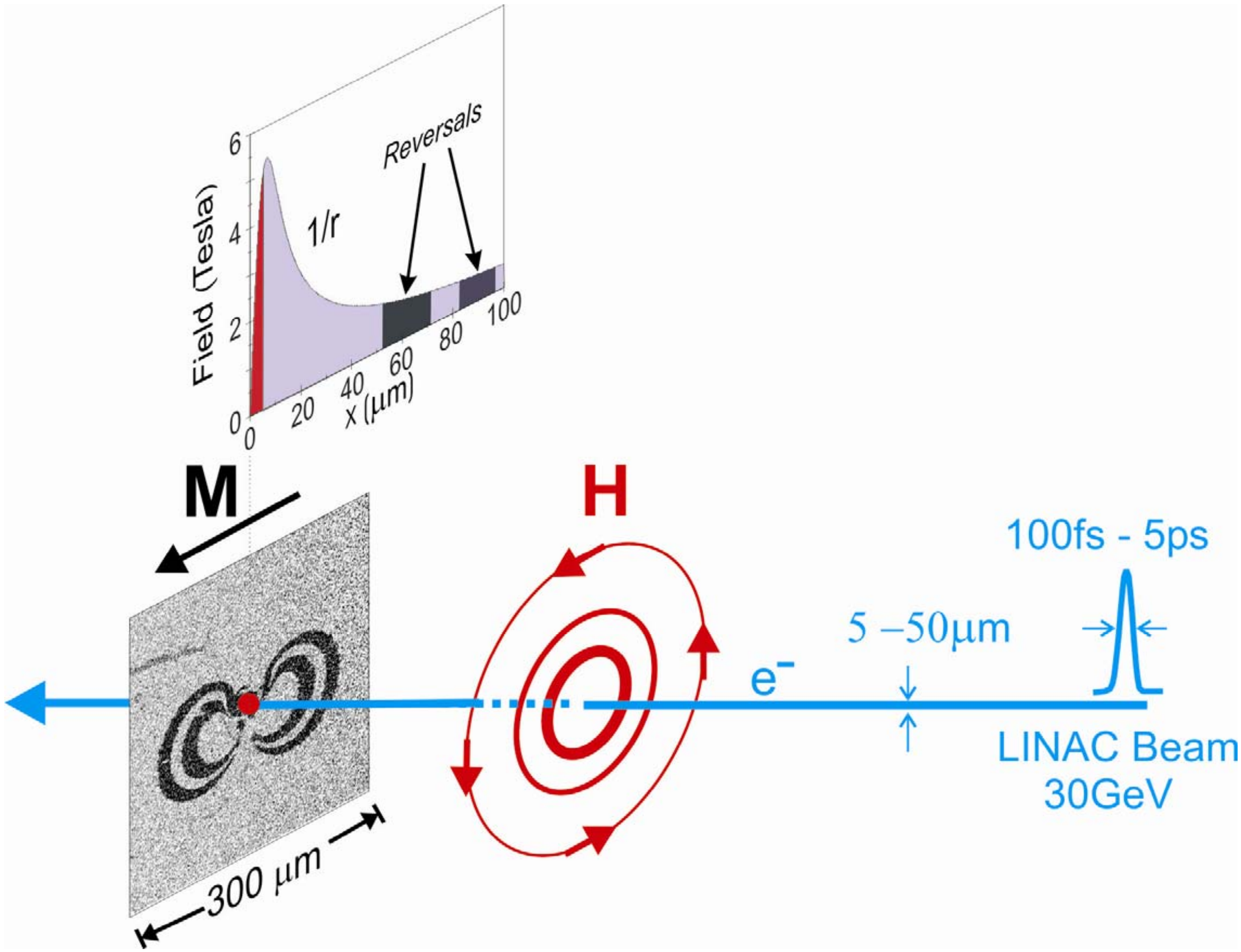


C. H. Back et al., *Science* **285**, 864 (1999)

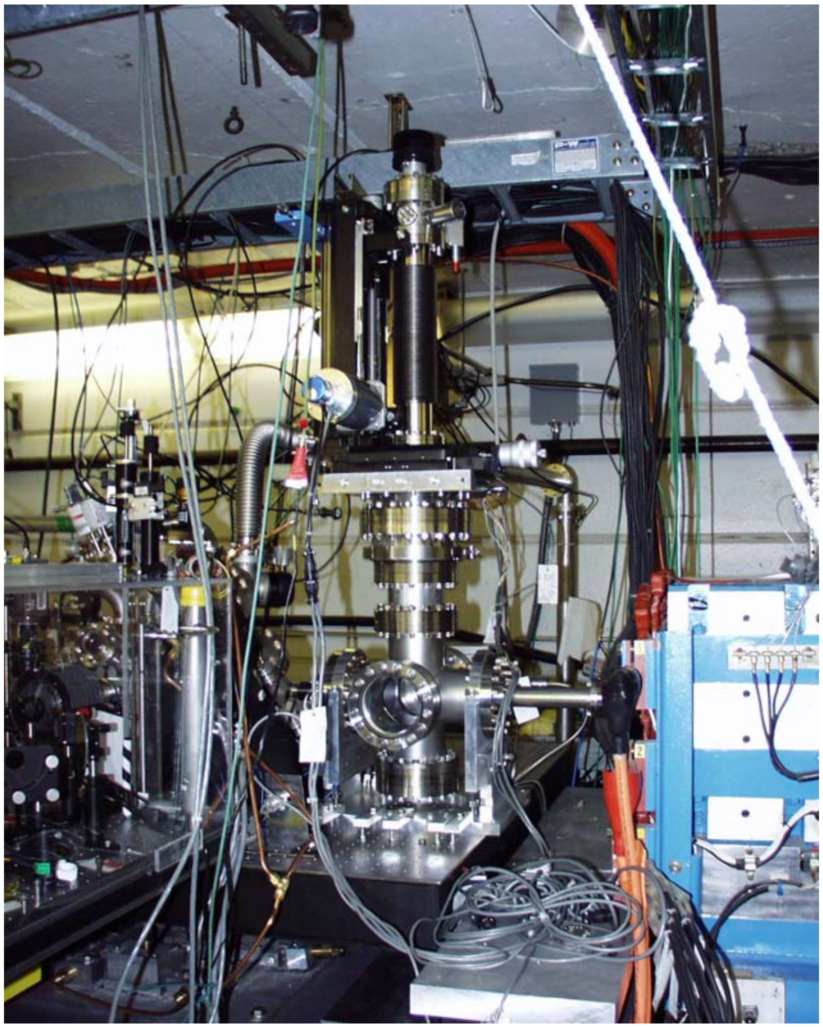
Fields of SLAC e-beam

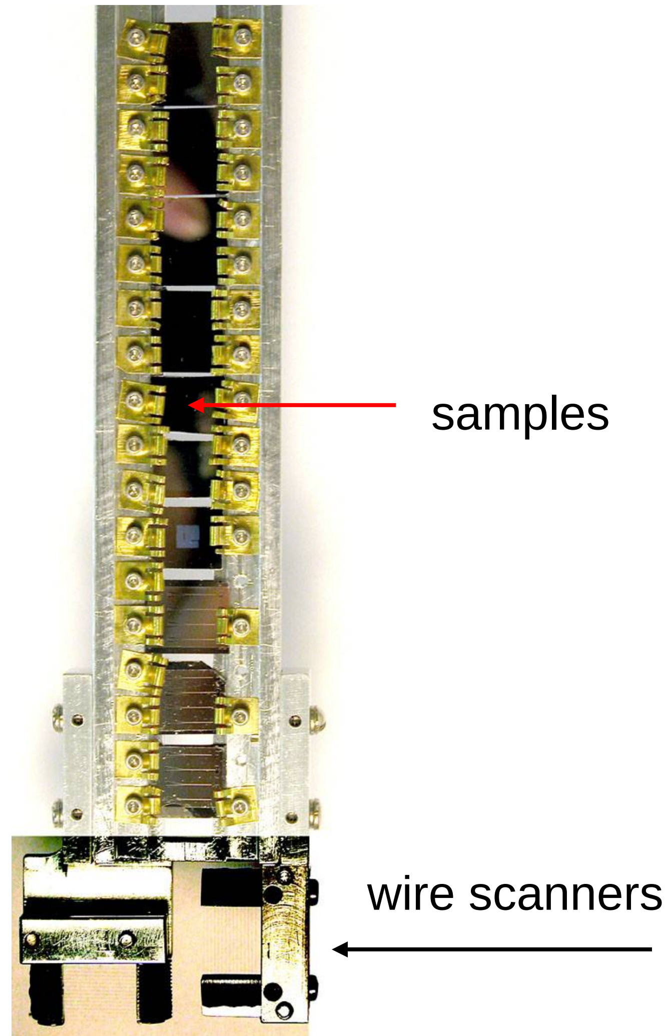


Experimental Geometry and Magnetic Field



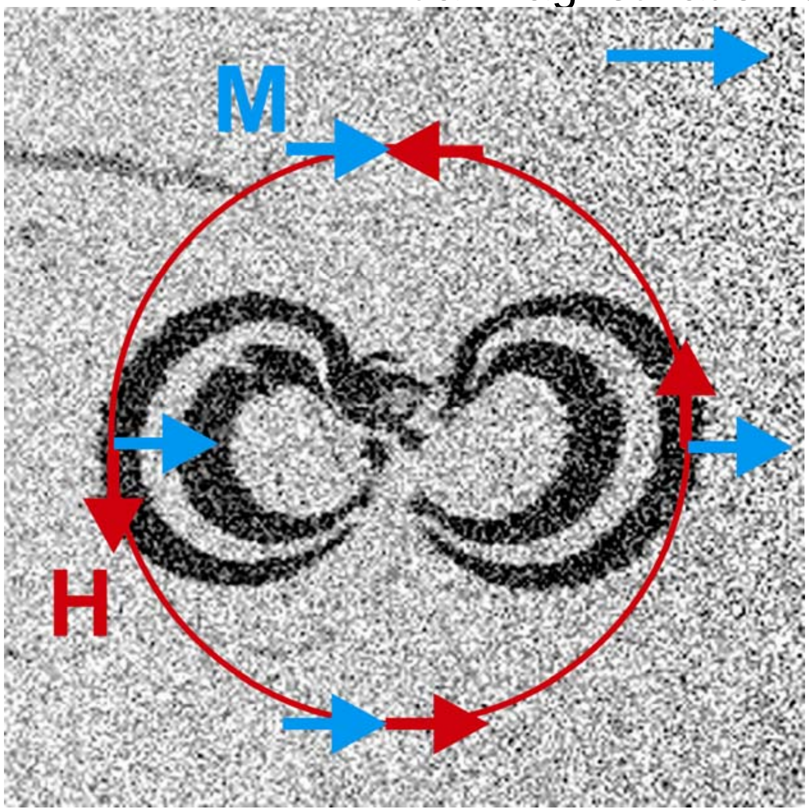
Experimental Setup in FFTB





Torques on in-plane magnetization by beam field

Initial magnetization of sample

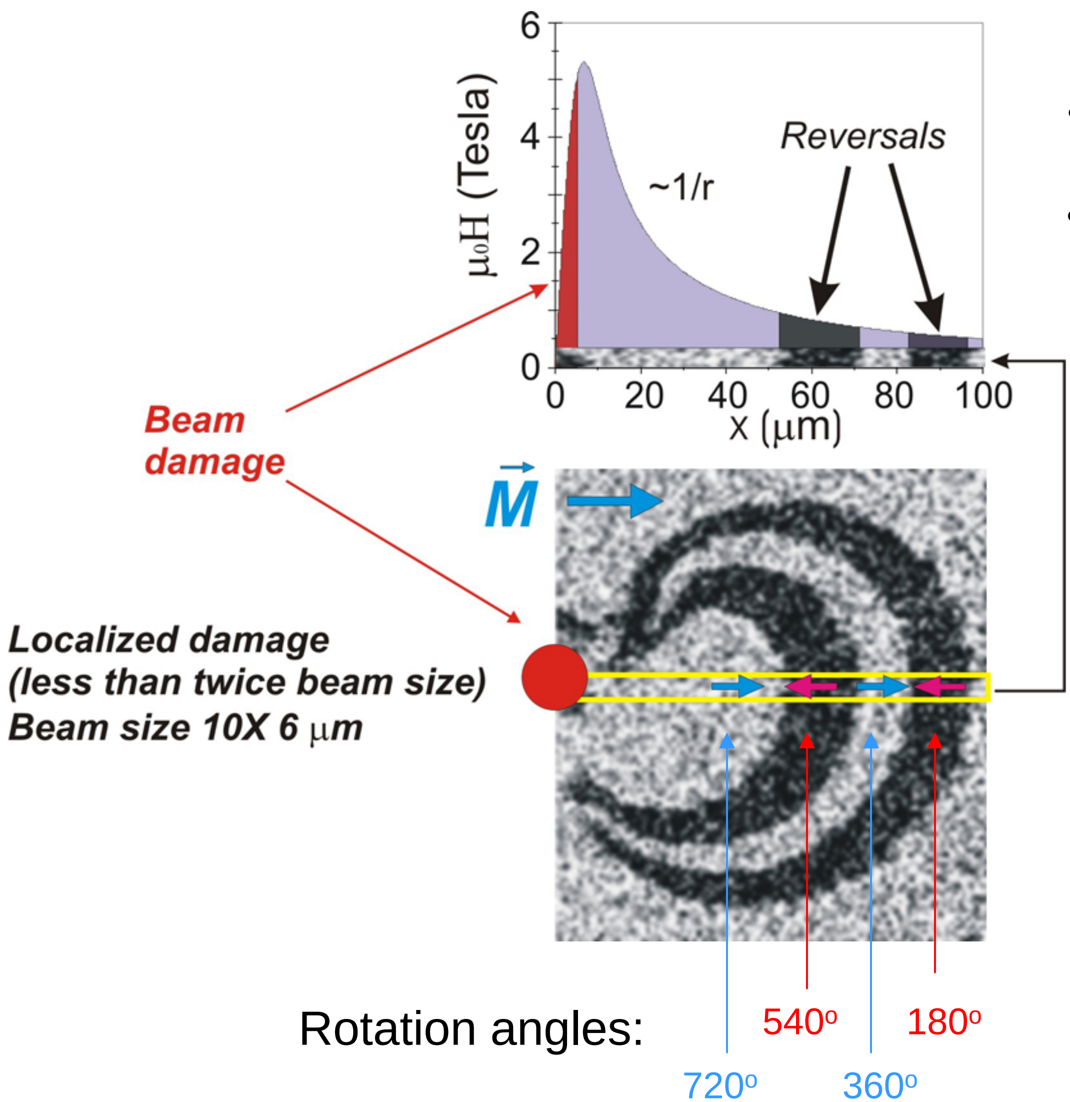


Max. torque

Min. torque

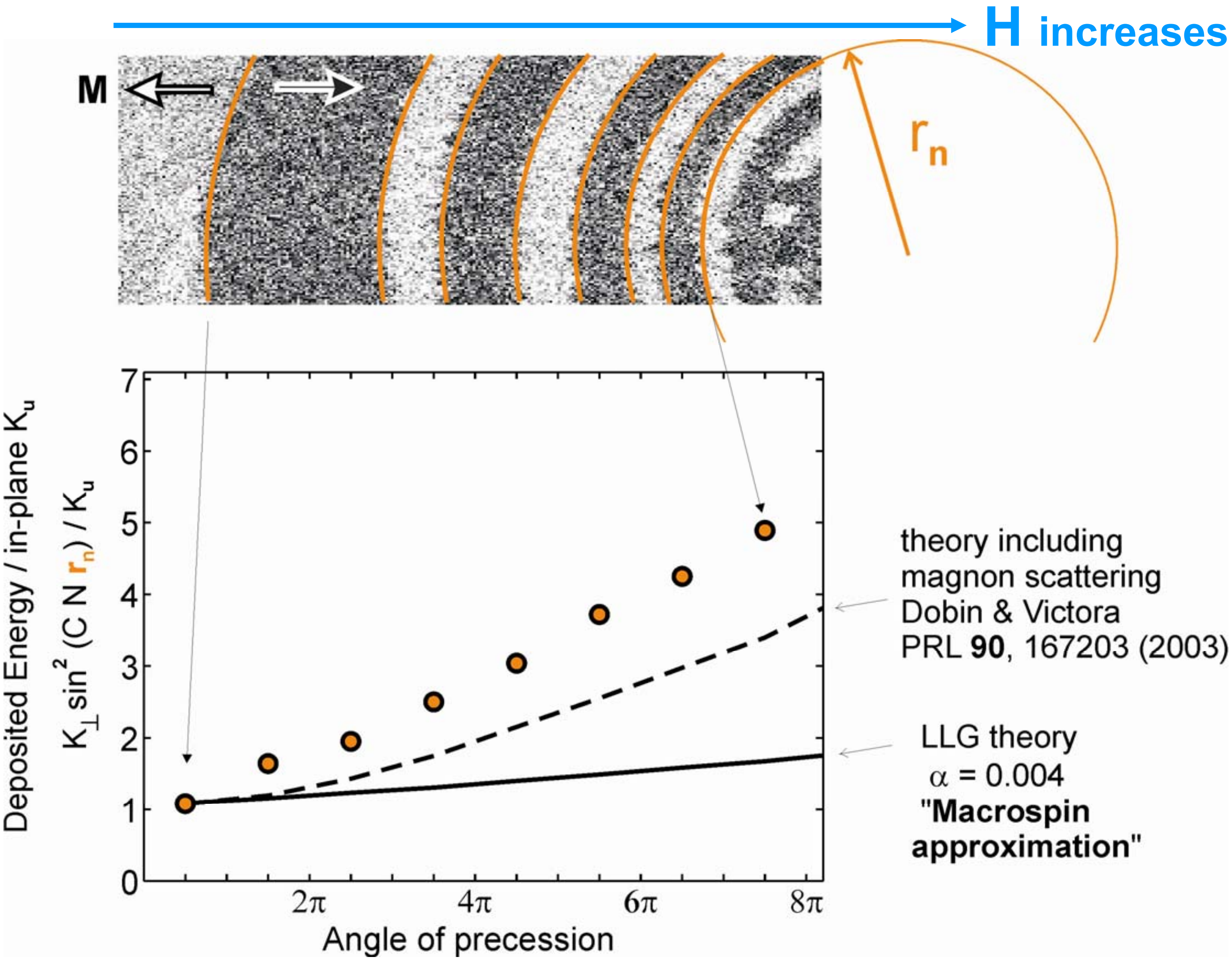
Fast switching occurs when **H** ⊥ **M**

In-Plane Magnetization: Pattern development



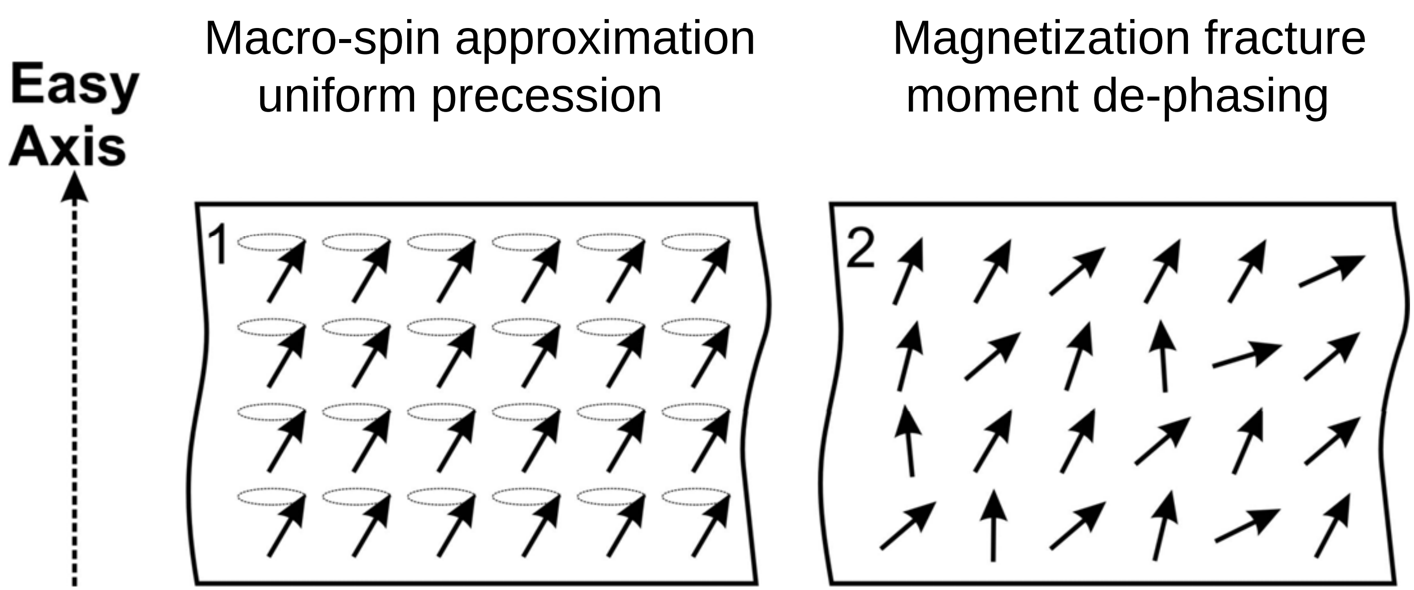
- Magnetic field intensity is large
- Precisely known field size

Breakdown of the Macrospin Approximation



With increasing field, deposited energy far exceeds macrospin approximation
this energy is due to increased dissipation or spin wave excitation

Magnetization fractures under ultrafast field pulse excitation



Breakdown of the macro-spin approximation

Tudosa ***et al.***, Nature **428**, 831 (2004)

C. Stamm ***et al.*** Phys. Rev. Lett. **94**, 197603 (2005)

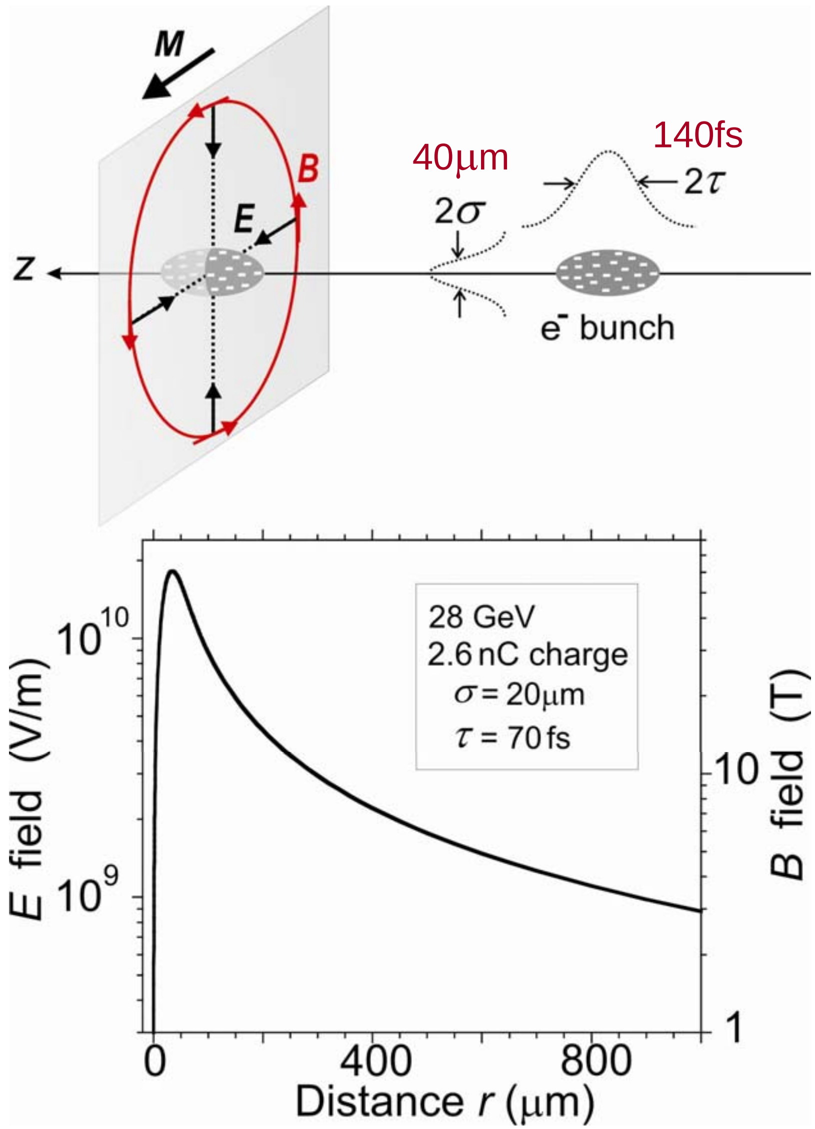
Experiments with Femtosecond Bunches

- reduce bunch length from ~5 ps to ~140 fs
- keep beam energy and charge fixed
- fields increased by factor of 35
- fields have unprecedented strength in materials science:

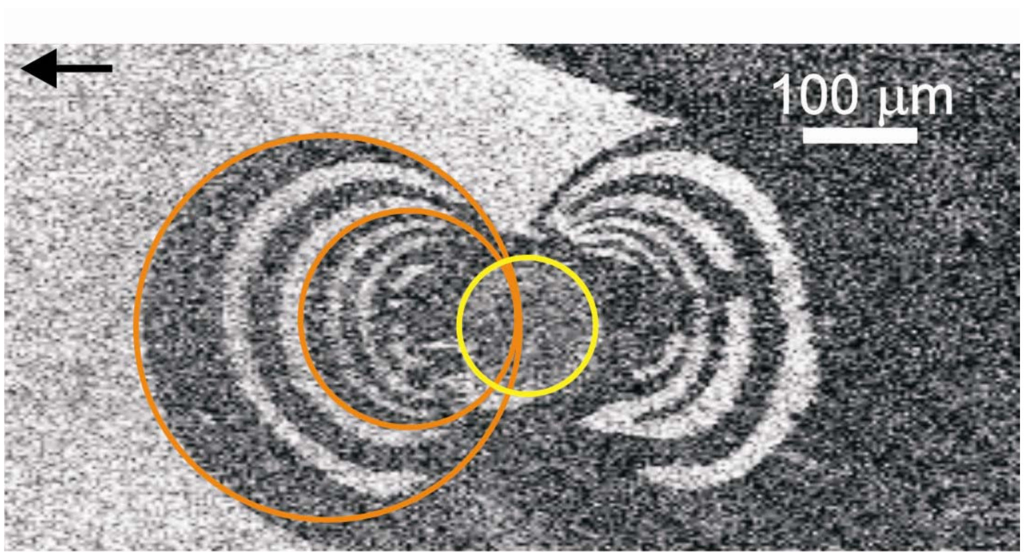
B-field: 60 Tesla

E-field: 20 GV/m

Experiments with femtosecond bunches

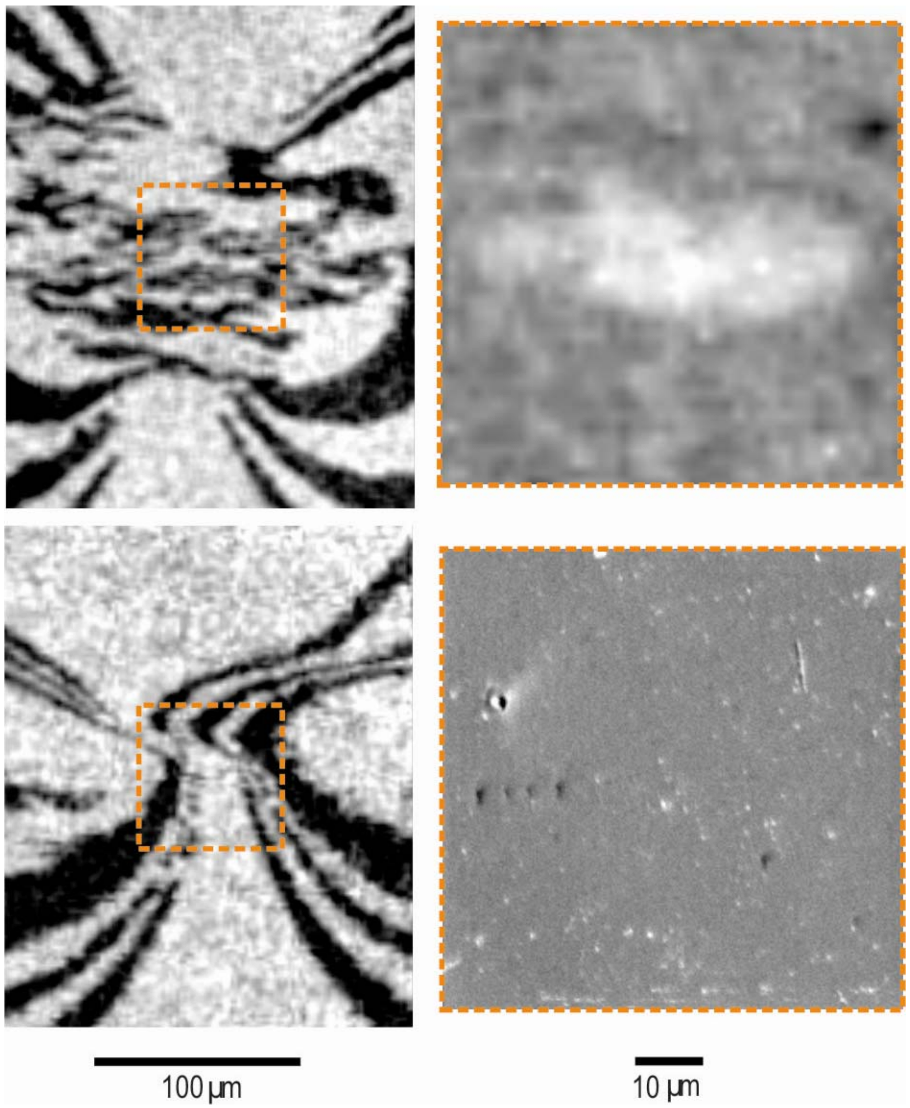


Observe two key new effects



5 ps

Ultra-short, ultra-strong field pulse shows no heating and damage



Pulse length: 4 ps

Pulse length: 140 fs

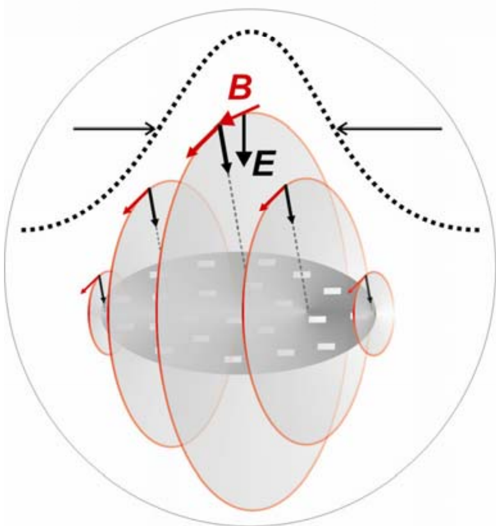
Peak field 35 times stronger

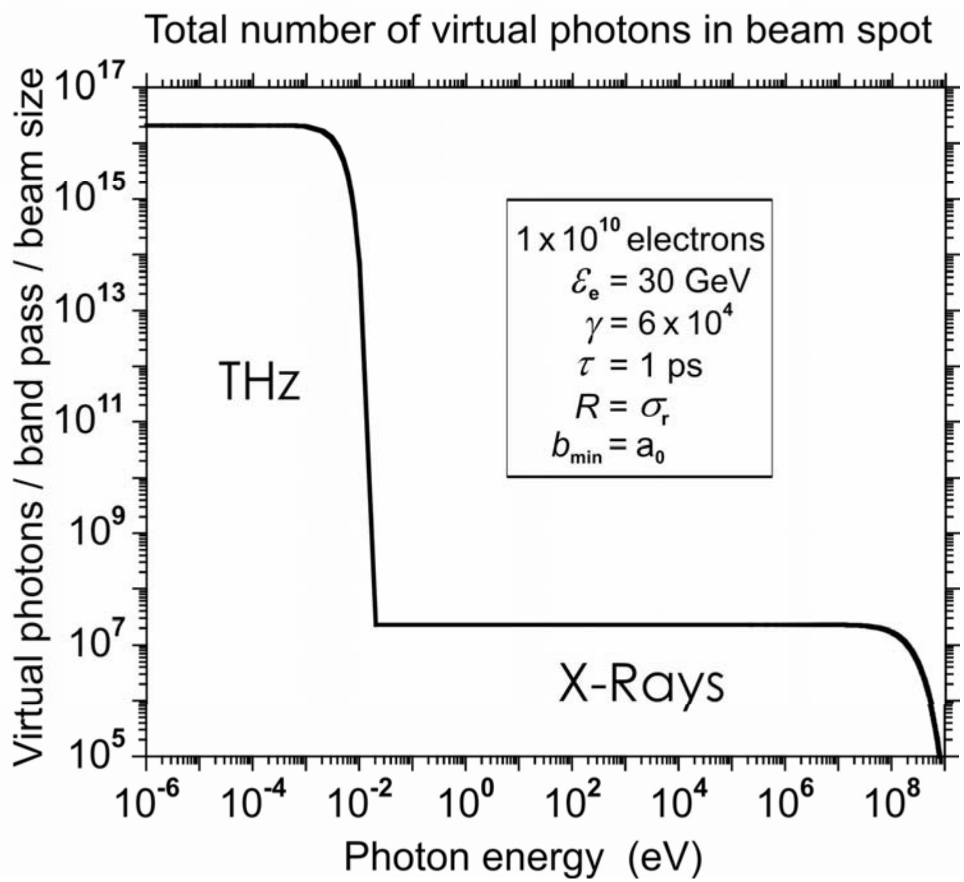
Surprising results:

- Magnetic pattern is severely distorted
- No apparent damage or heating by beam

Materials behave unexpected under extreme conditions !

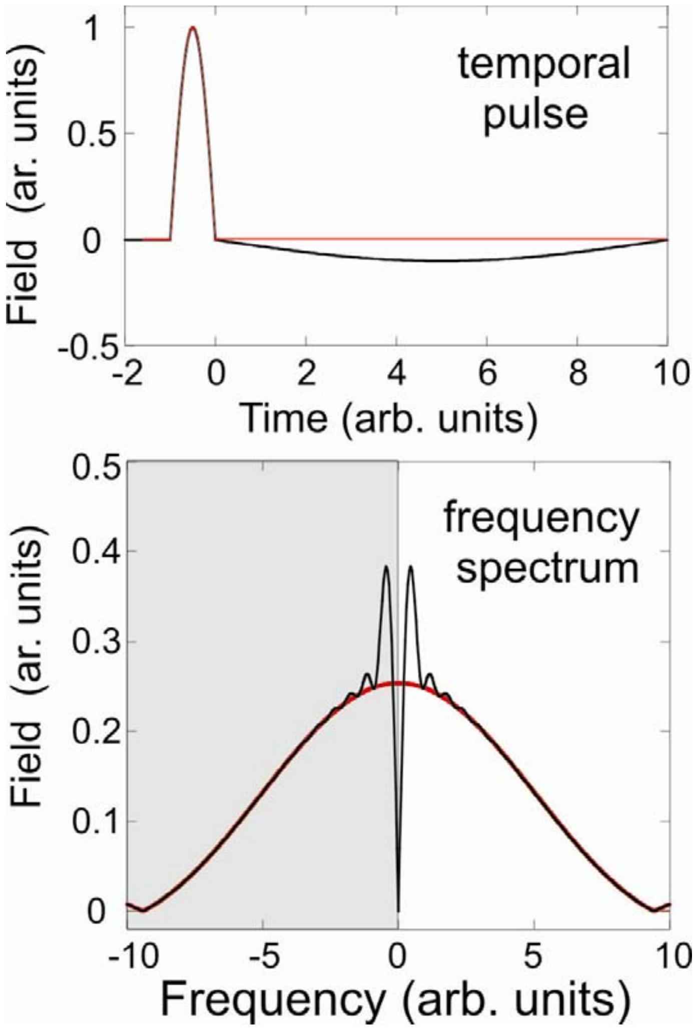
The Weizsäcker-Williams Method of Virtual Photons





Electron beam is equivalent to ultra-strong half-cycle THz pulse

SLAC e-beam pulse versus THZ half-cycle pulse

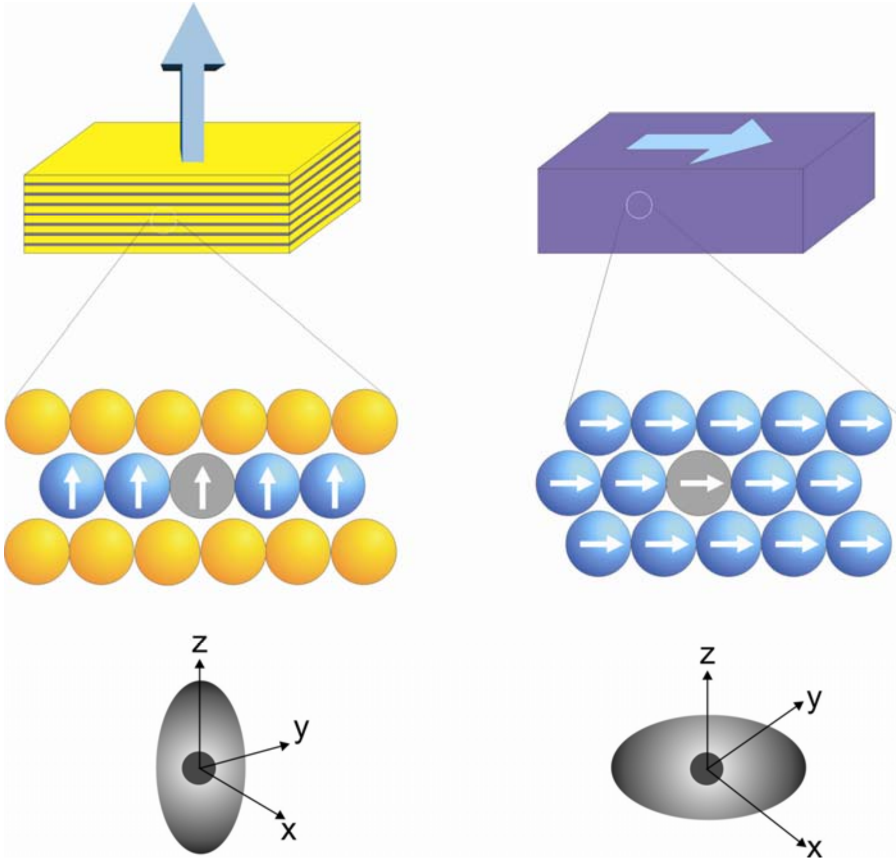


red: SLAC pulse

black: THz half cycle pulse

SLAC THz pulses > 100 times stronger than previously produced pulses

Electronic distortion known to lead to magnetocrystalline anisotropy

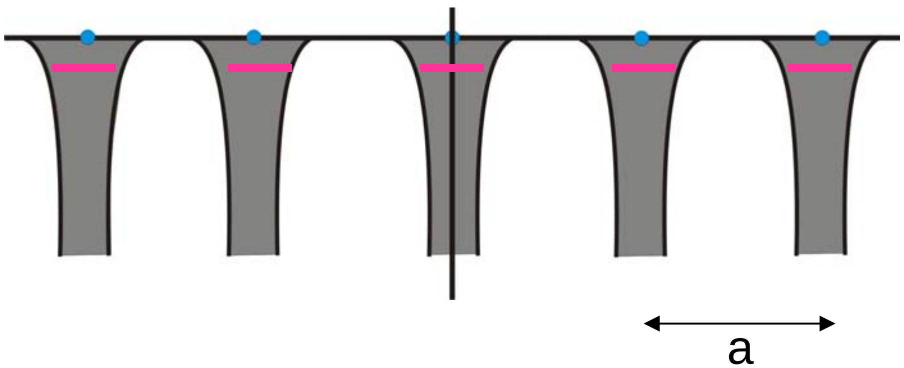


Bonding fields are a few eV / atom

E ~ 10^{10} V / m = 1 V / Å rivals bonding fields

Electric Fields and Electronic Structure

Potential of a regular linear lattice



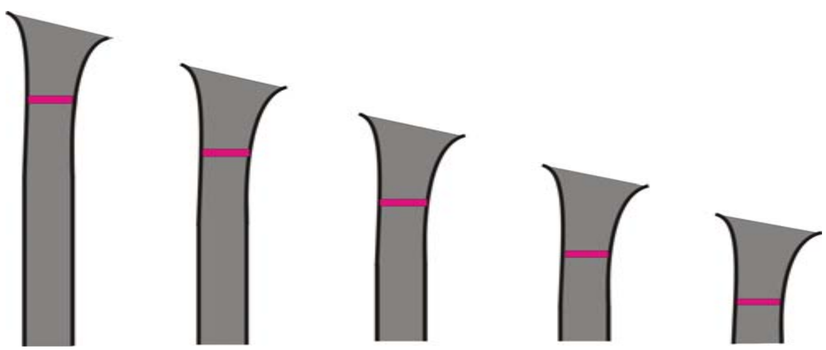
Co bandwidth ~ 3eV

$E \sim 10^{10}$ V/m

$a = 0.25$ nm

$\Delta V = e\,E\,a \sim 2.5$ eV

Potential along E field direction



potential gradient leads to breakup of conduction path
no current flow due to field – not heating

Summary

- The breakdown of the macrospin approximation for fast field pulses limits the reliability of magnetic switching

- At ultrafast speeds (< 1 ps) new ill-understood phenomena exist one approaches timescales of fundamental interactions between electrons, lattice and spin

- Future experiments will explore the details using both **H** and **E** fields

- In the future, e-beam "pump"/ laser "probe" experiments are of interest, as well

For more, see: http://www-ssrl.slac.stanford.edu/stohr

and

J. Stöhr and H. C. Siegmann

Magnetism: From Fundamentals to Nanoscale Dynamics

800+ page textbook (Springer, 2006)