The Development of Femtosecond Relativistic Electron Diffraction: Using Particle Accelerators to Watch Atoms Move in Real Time.

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7/11/2011

Outline

- FRED: Femtosecond Relativistic Electron Diffraction
- Generation of bright ultrashort MeV electron beams
- Single shot high quality diffraction patterns using MeV e-beams
- An example of time resolved relativistic electron diffraction: ultrafast heating and melting of single crystal gold samples.
- RF streak camera based truly single-shot electron diffraction

- Future of FRED @ UCLA
  - Pushing high brightness beam physics frontier.

Electron diffraction

- Electrons are waves of wavelength $\lambda = h / p$
- Discovered by accident. Davisson & Germer Phys. Rev. 30, 705 (1927)

1906 Nobel prize in Physics

J. J. Thomson

"in recognition of the great merits of his theoretical and experimental investigations on the conduction of electricity by gases"

father and son

1937 Nobel prize in Physics

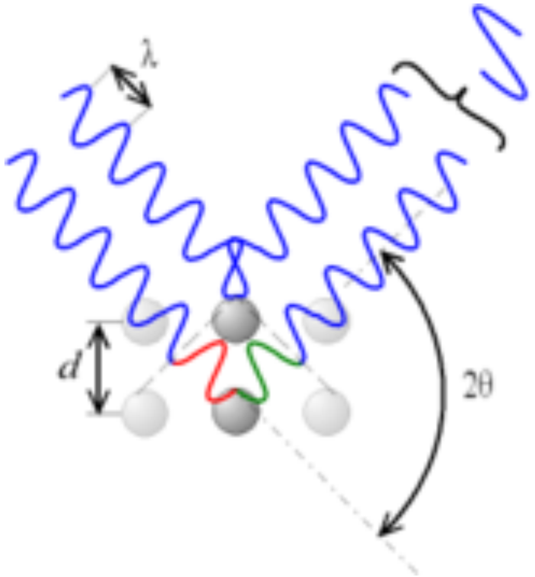
C. J. Davisson and
G. P Thomson

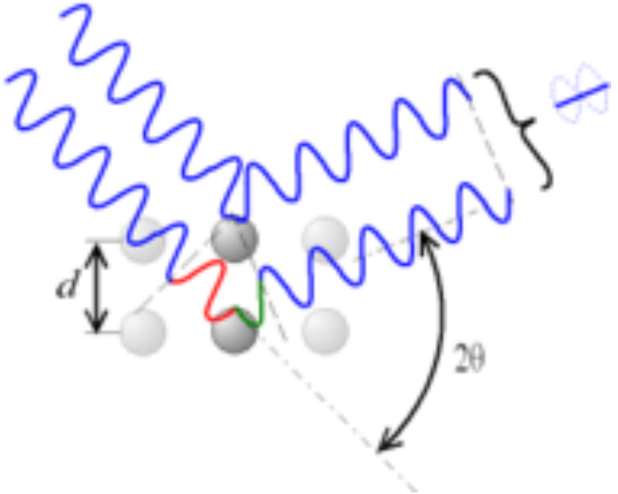
"for their experimental discovery of the diffraction of electrons by crystals"

Bragg scattering

- Short wavelength yields atomic scale resolution
  - For 30 KeV λ = 6 pm
  - For 5 MeV λ = 0.25 pm
- Interference effects when scattering over a lattice. Peak intensity at Bragg angles

$$\sin(\theta) = \frac{\lambda}{2d}$$





Electron vs. x-ray diffraction

- Rutherford vs Thompson cross section

$$\sigma_e = \frac{4m_e^2 e^4}{\hbar^4 \left|s^4\right|} = 10^{-20}\, cm^2 \quad f\ or \quad s = 20\ \bar{A}^{1}$$

$$\sigma_x = \frac{8\pi}{3} r_0^2 = 6.6 \cdot 10^{-25}\, cm^2$$

- Looking at the atomic position directly

$$L_e = \sum_{\alpha} Z_\alpha e^{i\mathbf{s}\cdot\mathbf{r}_\alpha} - \sum_{i} e^{i\mathbf{s}\cdot\mathbf{r}_i}$$

$$L_X = \sum_{i} e^{i\mathbf{s}\bullet\mathbf{r}_i}$$

- Probing with electrons is preferred choice for surfaces, thin films, gas phase
- Small size of typical set-ups (compared to 3rd-4th generation light sources).
- Damage in biological samples 400-1000 times less
  - Elastic/inelastic scattering ratio 3 times higher for X-ray
  - Energy deposited per inelastic scattering event:
    20 eV for 500 KeV electron vs. 8 KeV for 1.2 Å x-ray

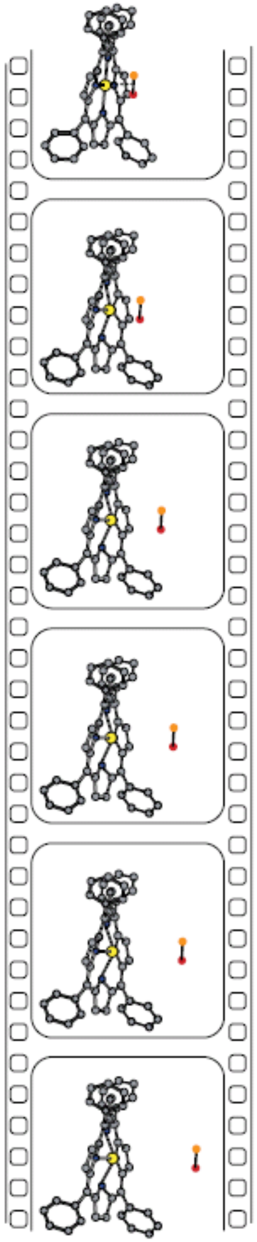
Ultrafast Science: time resolved structural dynamics

- What is the time scale required to look at atomic motion?

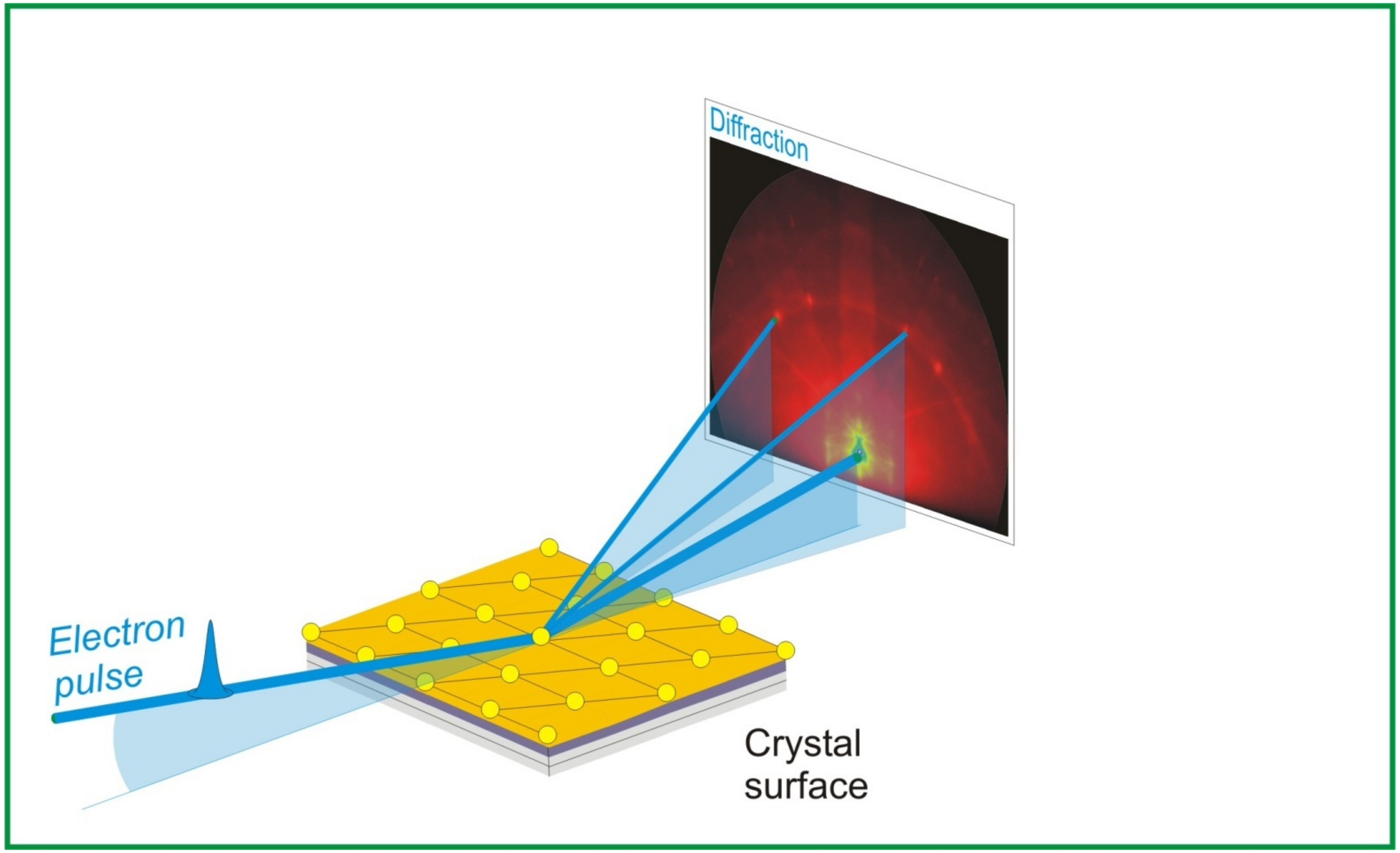
- Typical atomic distances few Angstroms
- 100 fs is the time it takes for an atom to move by a fraction of the lattice spacing.

- Ultrafast lasers give temporal resolution

- But X-ray or electron diffraction (sub-Angstrom wavelength) can give spatial resolution.

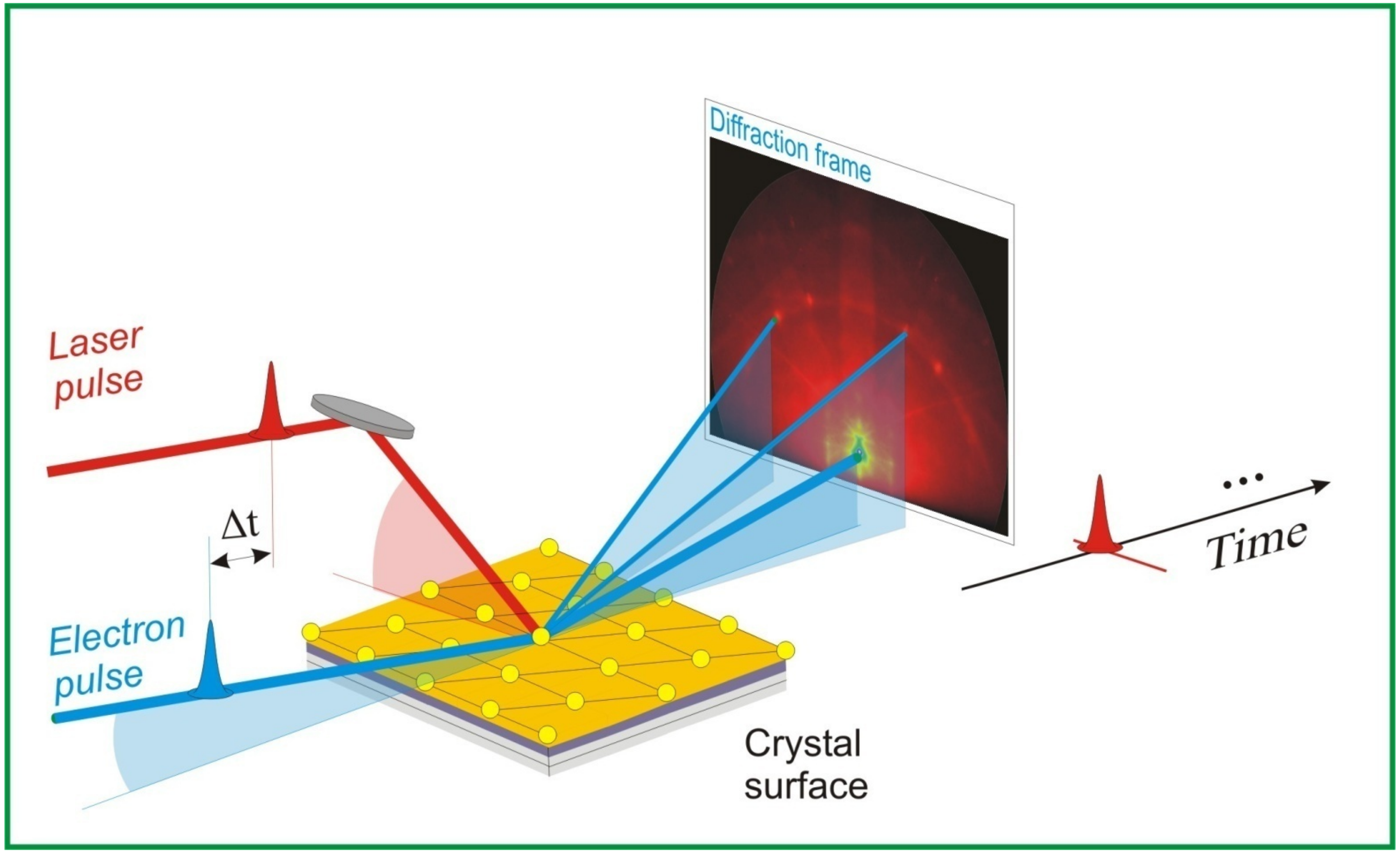


UED Methodology: Pump-probe



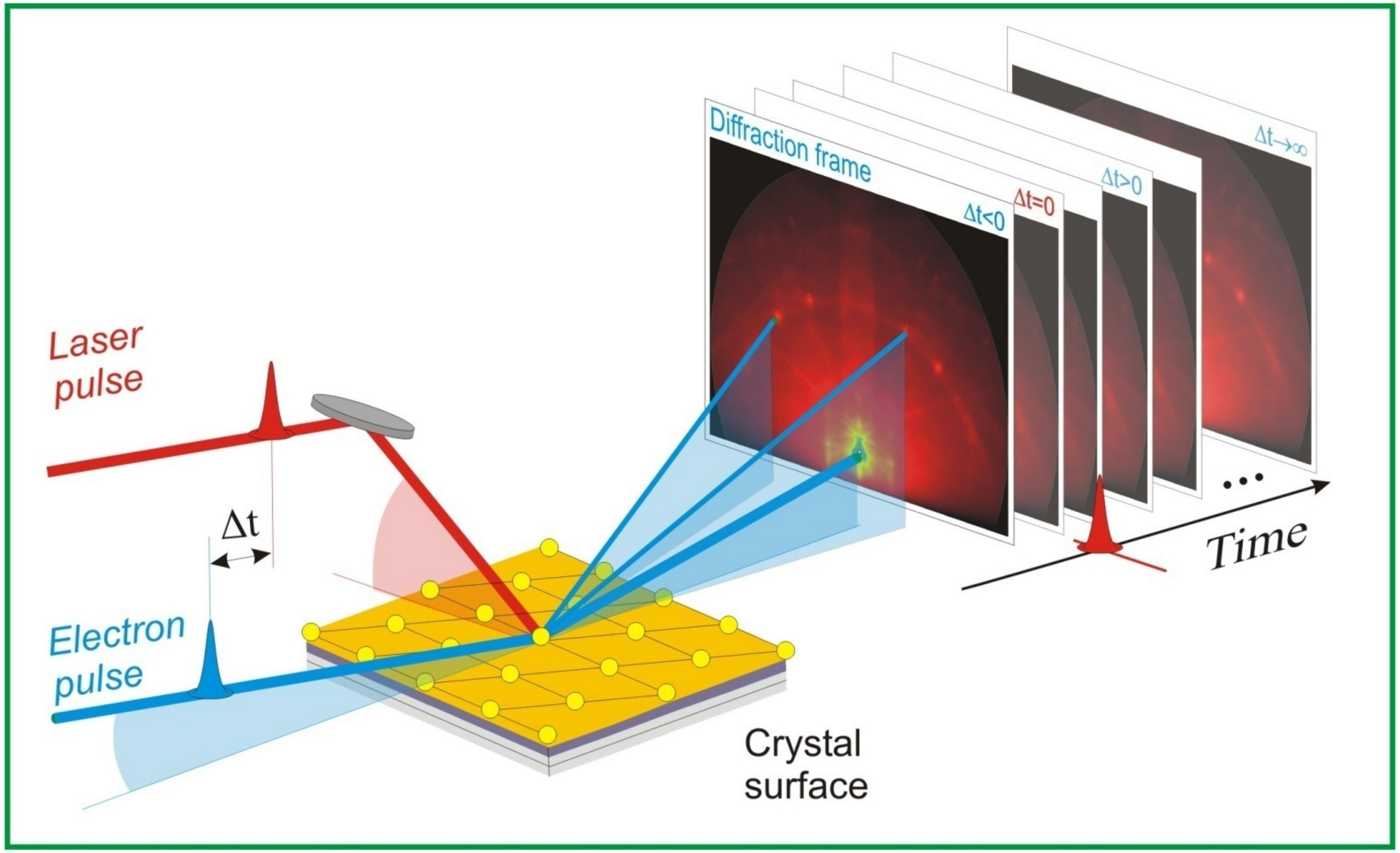
- Electron pulse as probe pulse
  - Diffraction pattern shows transient structure

UED Methodology: Pump-probe



- Laser pulse as pump pulse
  - Initiate the dynamics
  - Serve as a reference point in time

UED Methodology: Pump-probe



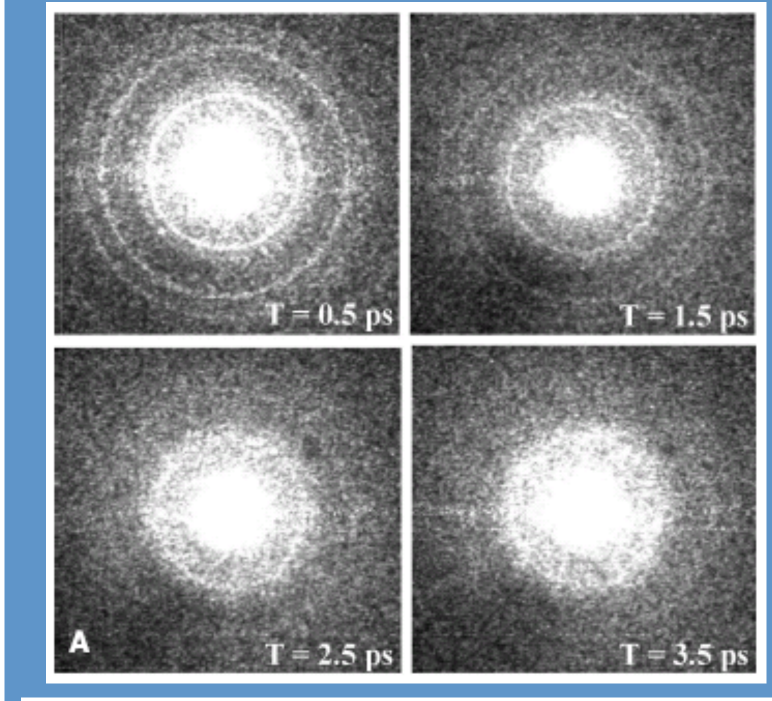
- Movies of dynamics
  - Delays between the pump (laser) — probe (electron) pulses
  - Time series of diffraction patterns

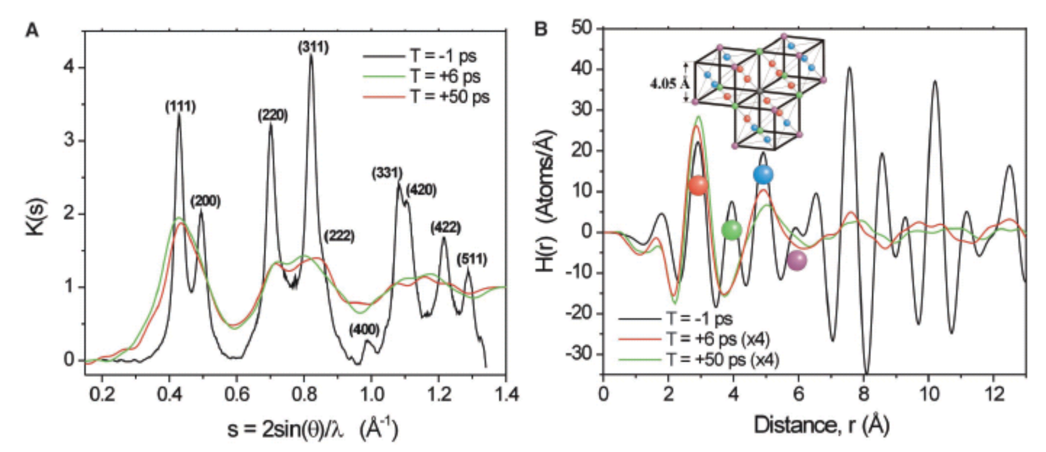
Courtesy of Nuh Gedik

Scientific highlights using UED

Ultrafast melting of Aluminum

B. J. Siwick, *et al. Science* **302, 1382 (2003)**



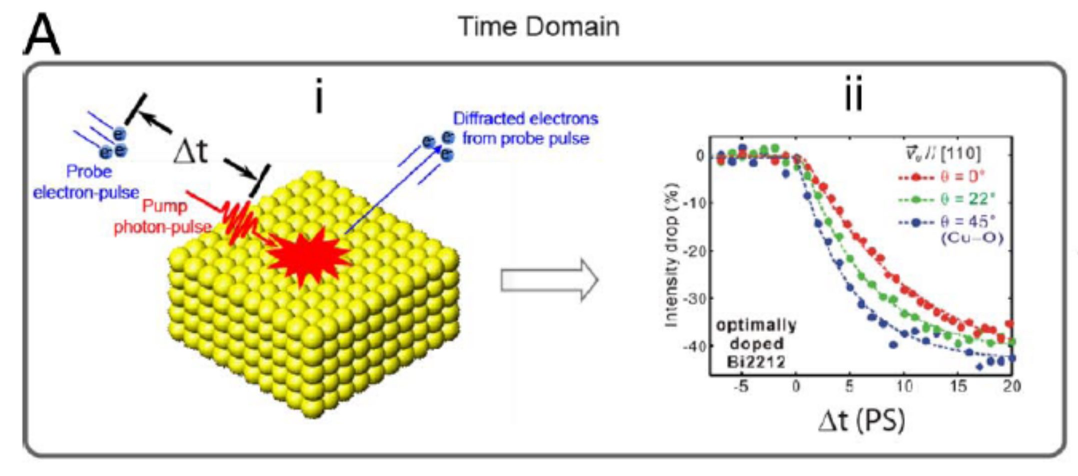


A step closer to visualizing the electron–phonon interplay in real time

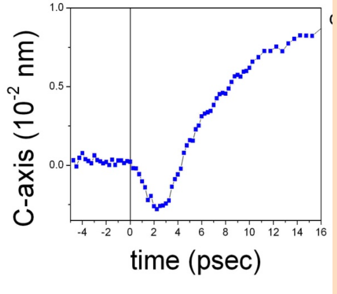
PNAS, 106, 963, 2009

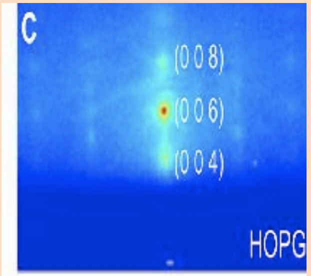
Y. L. Chen, W. S. Lee, and Z. X. Shen[1]

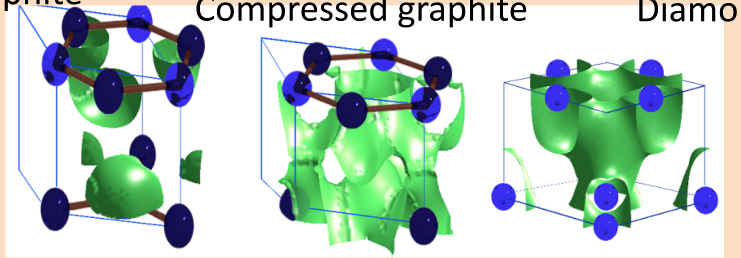
Departments of Applied Physics and Physics, and SLAC Photon Science, Stanford University, Stanford, CA 94305



Carbone et al. PRL, 100, 035501 (2008)

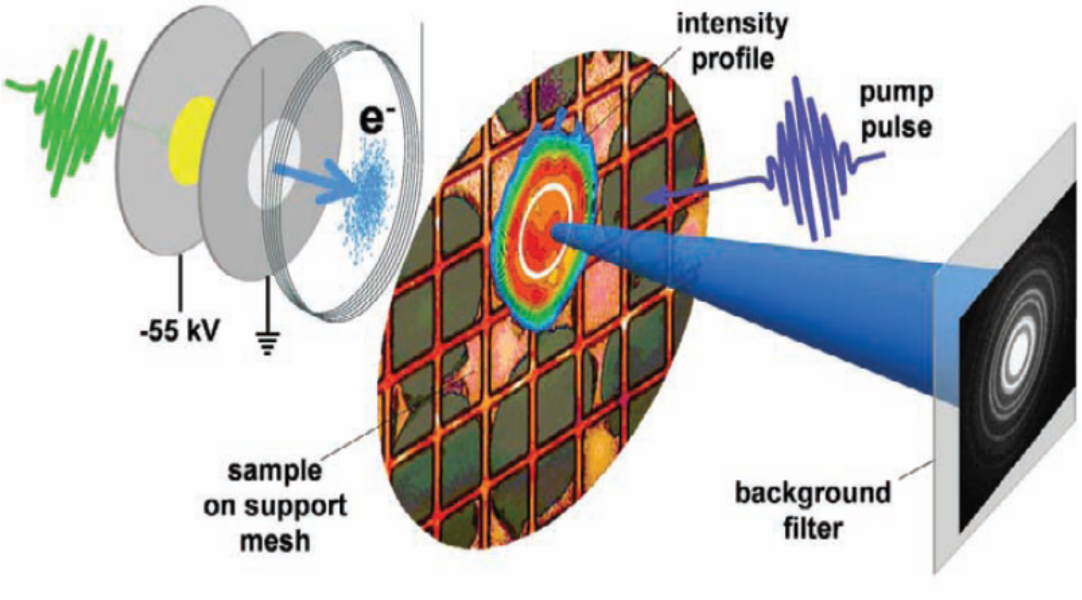






State-of-the-art ultrafast diffraction

- ☐ Currently the limit in time-resolution for conventional UED systems is determined by how short an electron pulse can be made. These systems use beam energies in the range of tens of KeV
- ☐ At low e-beam energies, space charge effects broaden the pulse during propagation.
- ☐ Researchers have been able to reduce the time resolution to sub-ps level only by dramatically reducing the number of electrons per pulse with the compromise of integrating over multiple pulses to collect a single diffraction image.



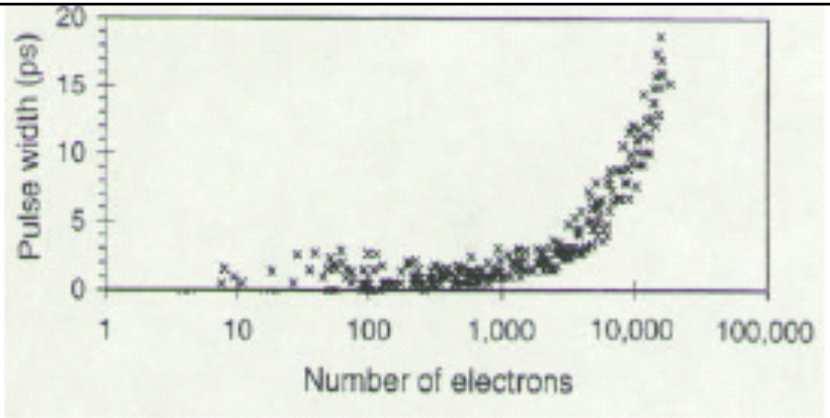
from R. Ernstorfer et al. Science (2009)

Science results include:

- ❖ Physics of melting (metals and semiconductors)
- ❖ Formation of WDM
- ❖ Ultrafast dynamics in Graphite
- ❖ High Tc superconductors

and many others…

Limitation:
Number of electrons per pulse



- Forefr

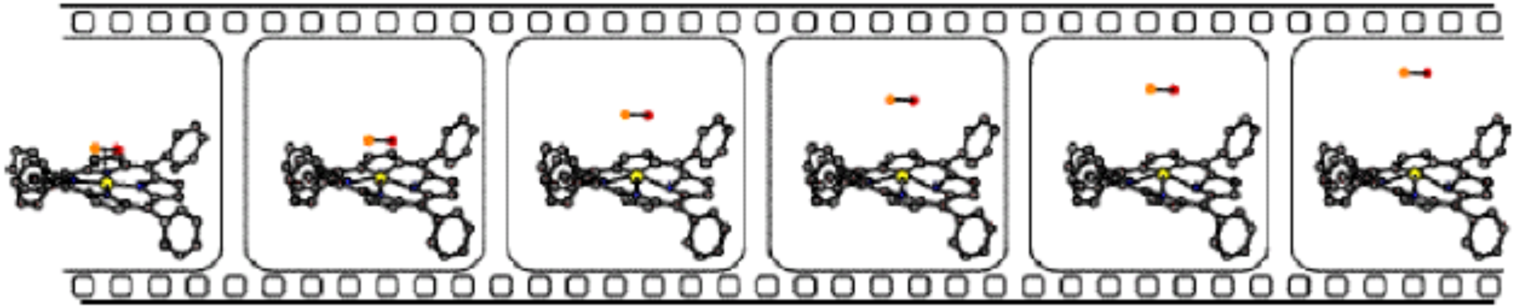
So far th

- Chemi

Lasers p

- Electron Diffraction limited to ps range

Chemistry is about Motion



$H_2O \rightarrow OH + H$

about 10 fs

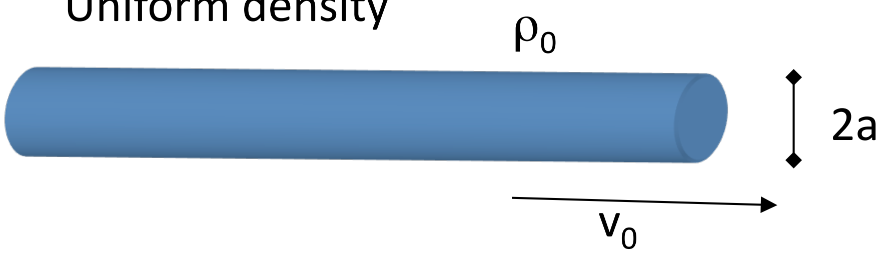
time depends on mass →

$CH_2I_2 \rightarrow CH_2I + I$

about 100 fs

Use relativistic electrons !!!

Uniform density



Beam current

$$I = e\rho_0 v_0 \pi a^2$$

Transverse self-fields

Gauss theorem

$$E_r = \frac{e\rho_0}{2\varepsilon_0} r = \frac{I}{2\pi\varepsilon_0 v_0 a^2} r$$

Biot-Savart

$$B_\phi = \frac{\mu_0}{2\pi}\frac{Ir}{a^2} = \frac{v_0}{c^2} E_r$$

Transverse Lorentz force

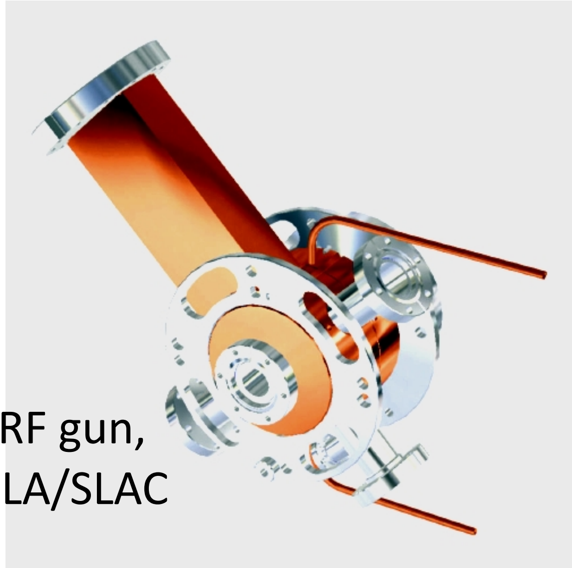
$$\frac{dp_r}{dt} = \boxed{m\gamma}\frac{dv_r}{dt} = -e\left(E_r - vB_\phi\right) = -\frac{eE_r}{\boxed{\gamma^2}}$$

Longitudinal Lorentz force

$$\frac{dp_z}{dt} = \frac{md\left(v_z\gamma\right)}{dt} = \boxed{m\gamma^3}\frac{dv_z}{dt} = -eE_z$$

The RF photoinjector

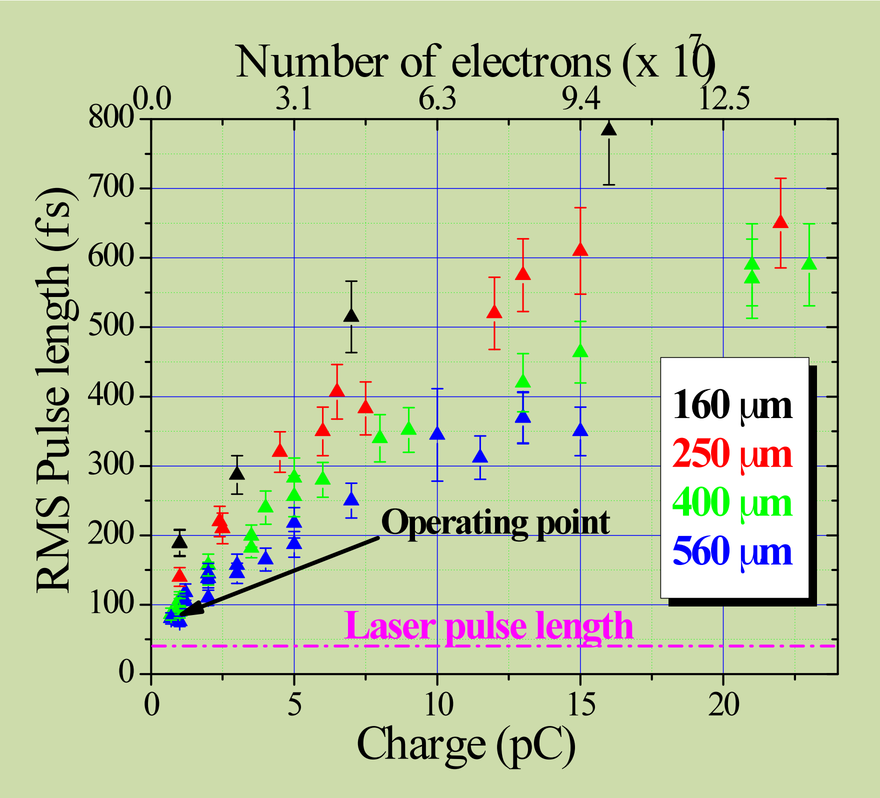
- Photo-emission inside ultrahigh field RF cavity
  - Sub-ps beams possible (response time from metal cathodes is <50 fsec)
  - High charge (1 pC – 1 nC)
  - Low emittance



1.6 cell RF gun, BNL/UCLA/SLAC design

- High brightness electron beam source
  - Developed for advanced accelerators & FELs
  - Apply to UED
- 3-5 MeV energy
- High peak rf power (6-8 MW)
  - Peak field E_0>100 MV/m
- Three orders of magnitude more charge + sub-ps bunch lengths !!!
  - Higher field at the cathode ~ 100 MV/m
  - Higher final energy. Suppression of space-charge forces.

Data from Pegasus laboratory. 2008



Ultrafast electron diffraction going relativistic !

- Solution/mitigation of existing problems in electron diffraction.
  - Higher beam energy
  - Higher gradients at cathode to accelerate particles as fast as possible.

	Conventional UED	*Relativistic ED*
Energy	20-300 KeV	3-5 MeV
Accelerating gradient at the cathode	10 MV/m	80-100 MV/m
Number of particles per bunch	10^4	$10^7 – 10^8$
Pulse length	~ 1 ps	< 100 fs
Typical Bragg angle (d = 2 Å)	10 mrad	0.5 mrad
Elastic mean free path in Al	20 nm	200 nm
Normalized emittance	50 nm	< 1 μm
Energy spread	<0.01 %	< 0.2 %

Ultrafast electron diffraction going relativistic !

- Solution/mitigation of existing problems in conventional electron diffraction.
  - ✓ Higher beam energy (3-5 MeV)
  - ✓ Higher gradients at cathode (80-100 MV/m) to accelerate particles as quickly as possible.

Pros

Single shot diffraction patterns with sub 100 fs resolution possible

Probe particles go deeper. Analyze thicker foils.
EMFP of 5 MeV e- in Al ~ 200 nm

Only known solution for gas-phases.
Velocity mismatch of non relativistic e- and laser in few mm long interaction

RF recompression and manipulation of bunch length.

Cons

Shorter e- wavelength λ, longer diffraction camera length

Quality of the diffraction patterns.
But intrinsic beam angular divergence goes as $1/\gamma$ same as λ.

Knock-on damage? Extensive HVEM literature.
But dose is few pC/mm^2 or 10^{-7} e/Å^2....

Need a relativistic electron source (small particle accelerator).

RF photoinjector based ultrafast relativistic electron diffraction

Initial experiments
Static diffraction from metal foils.

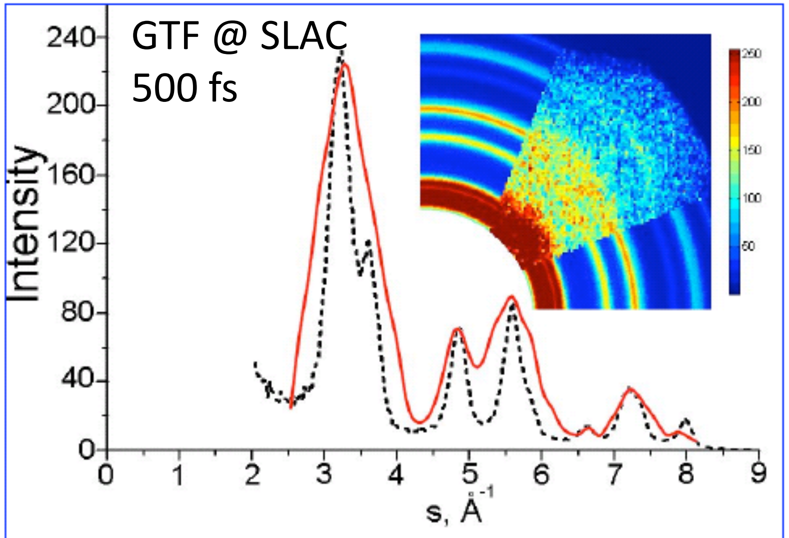
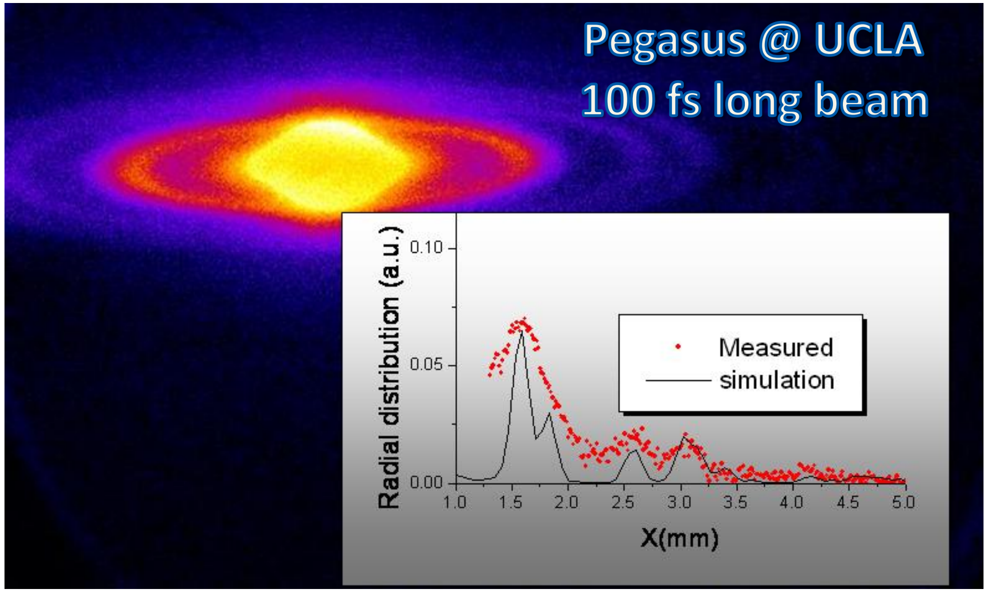

GTF @ SLAC
500 fs

Figure 10: Diffraction pattern of 160 nm aluminum foil; inset - center pie slice: experimentally measured pattern, using a single 500 fs electron pulse; outer pie slices: theoretically simulated pattern. Line traces: Experimental (red line) and theoretical (dashed line) patterns.

J. Hastings et al. ,
Applied Physics Letters, **89**, 184109 (2006)

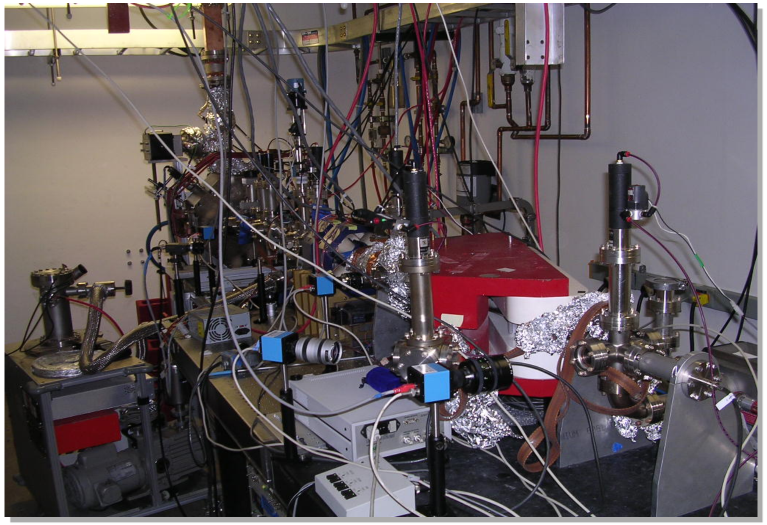

Pegasus @ UCLA
100 fs long beam

P. Musumeci et al. ,
Ultramicroscopy, **108**, 1450 (2008)

Growing field:
Efforts in BNL, China, Japan, Korea,UK, Netherlands, Germany, etc….

UCLA Pegasus Laboratory

- Laser, RF, control room, radiation shielded bunker
- Sub-basement of UCLA Physics Department.
- Home of the first UCLA SASE FEL experiments (Pellegrini & Rosenzweig)
- Advanced photoinjector system
  - 3 mJ 1 KHz Ti:Sapphire ultrafast drive laser
- Not exactly a table-top material characterization instrument.
  - More like particle accelerators setup.

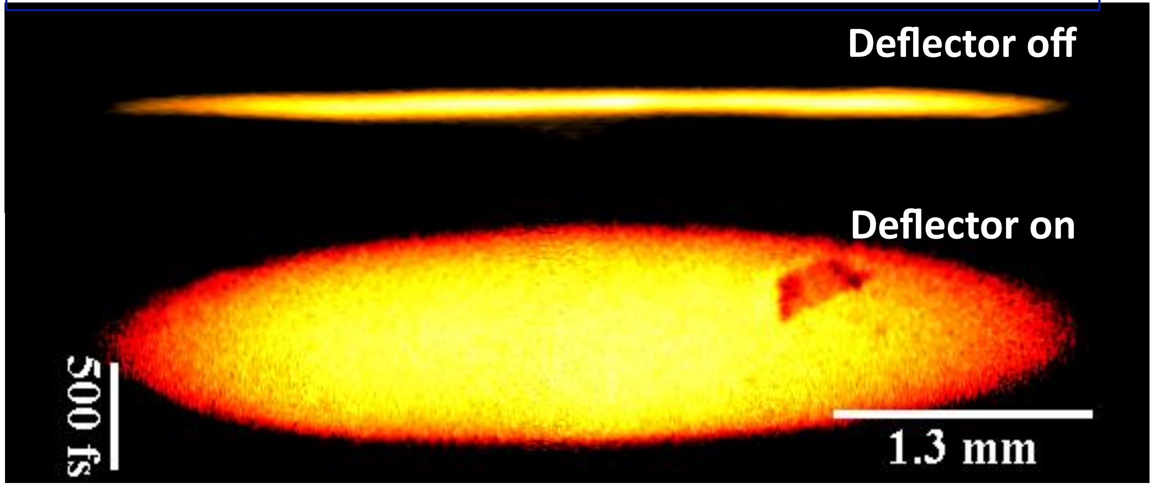


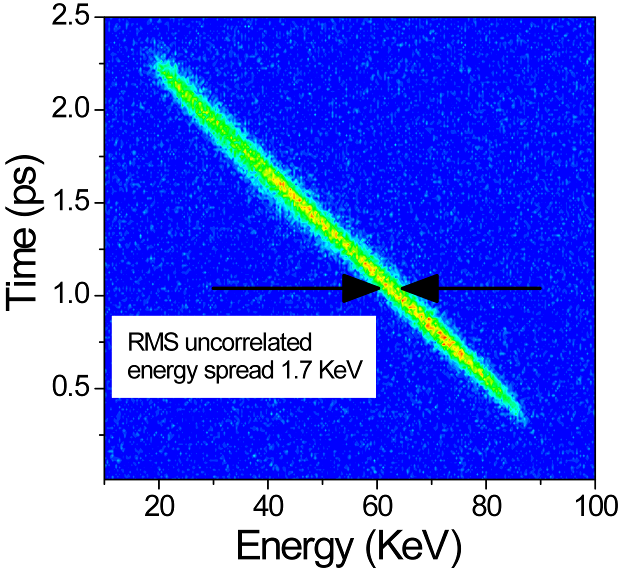
Launch an ultrashort beam at the cathode

- High charge: Blow-out regime of operation of RF photogun
  - Strong space-charge expansion
  - Generation of uniformly filled ellipsoidal beam distributions
  - Linear phase spaces & High beam brightness !
- Low Charge: Ultrashort e-beam generation for FRED

Parameter	Value
Laser pulse length	35 fs (rms)
Laser spot size on cathode	400 um (rms)
Peak field on the cathode	80 MV/m
Beam energy	3.5 MeV
Beam energy spread (rms)	0.5 %
Beam charge	20 pC (blow-out) 1.6 pC (FRED)
Injection phase	25 degrees
Beam emittance	0.7 mm-mrad
Bunch length	100 fs rms (FRED)

P. Musumeci et al. , *Phys. Rev. Lett.* **100**, 244801 (2008)





Surprising consequences of ultrashort laser pulse cathode illumination.

- “Violating” Einstein photoelectric effect…
  - For a given metal and frequency of incident radiation, the rate at which photoelectrons are ejected is directly proportional to the intensity of the incident light.
  - For a given metal, there exists a certain minimum frequency of incident radiation below which no photoelectrons can be emitted. This frequency is called the threshold frequency
- …..and few years of RF photoinjector common practice spent on “getting ready the UV on the cathode”
- Two or more small photons can do the job of a big one.
- Generalized Fowler-Dubridge theory: photoelectric current can be written as sum of different terms.

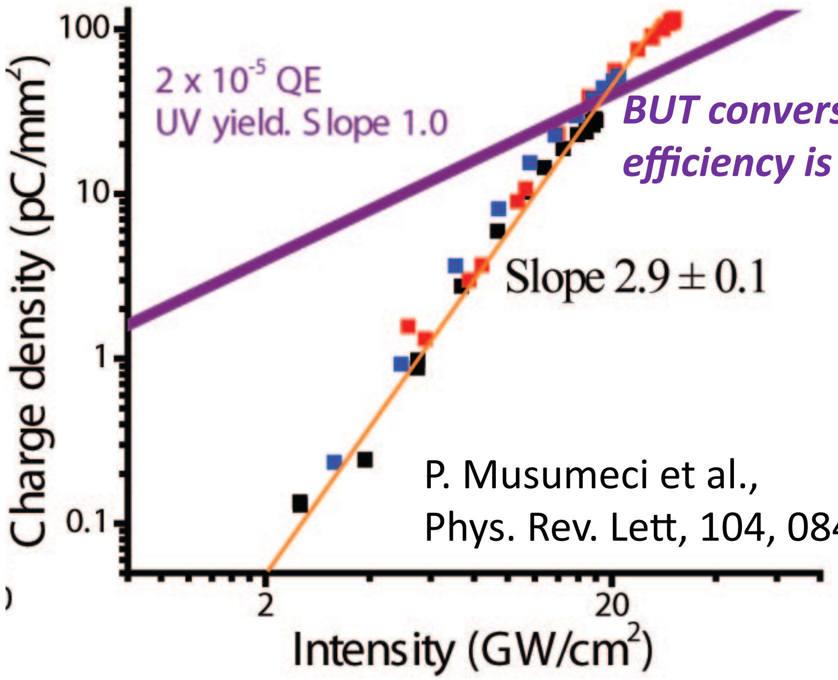
Fowler function selects the dominant n -order of the process

$$J = \sum_n J_n$$

where

$$J_n = \boxed{\alpha_n} A \left(\frac{e}{h\nu} \right)^n (1 - R)^n \boxed{I^n} T_e^2 F\left(\frac{nh\nu - e\Phi_0}{kT_e} \right)$$

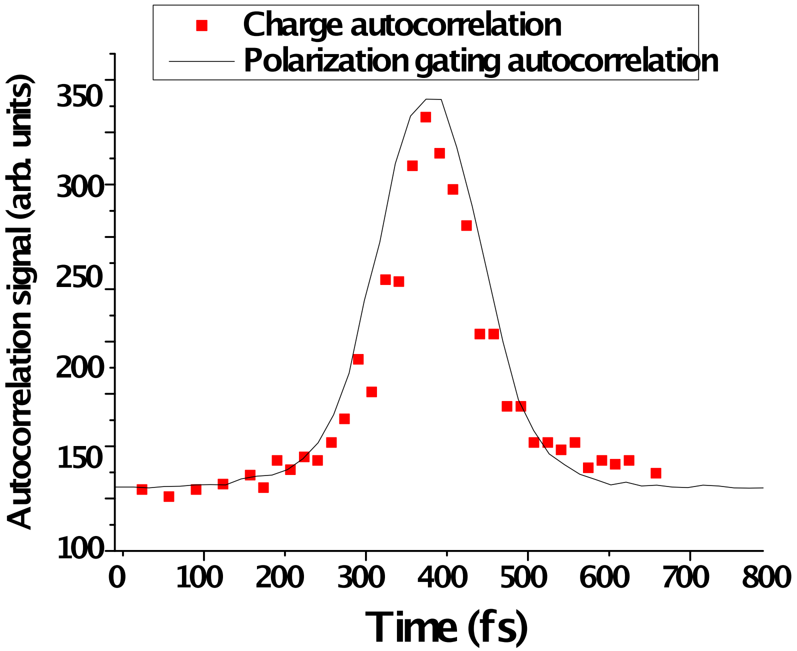
Save laser energy. Use IR photons on the cathode



BUT conversion efficiency is ~10%

P. Musumeci et al.,
Phys. Rev. Lett, 104, 084801 (2010)

Measure yield for different spot sizes.



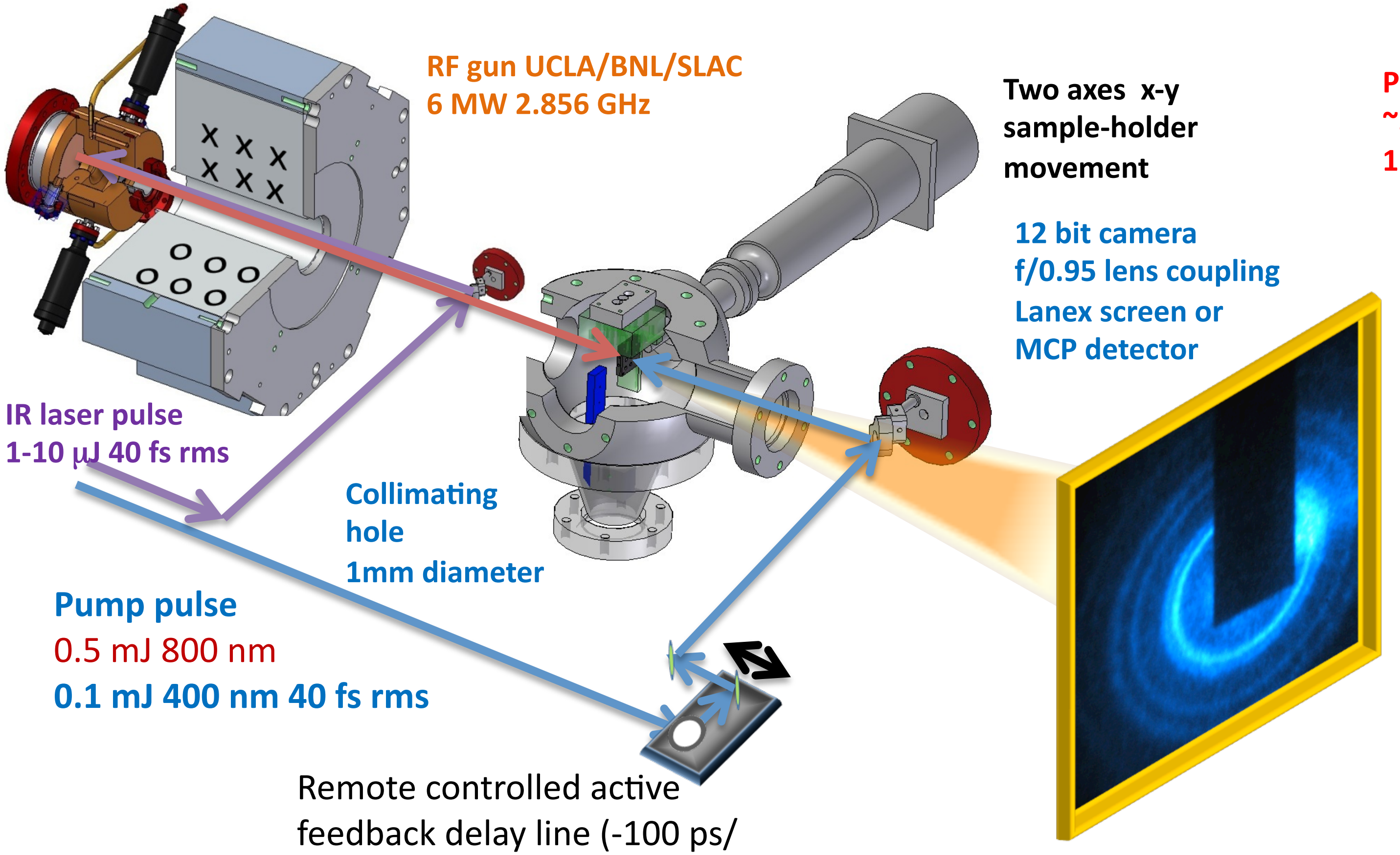
Autocorrelation of two IR pulses on the cathode shows promptness of emission.

Question: Why hasn't this been done before?

- Recent interest in pancake regime. Ultrashort beam at cathode => uniformly filled ellipsoidal beam.
- Very high extraction field in RF photoinjector: away from space-charge induced emission cutoff. (Early experiments using low gradient setups.)
- Damage threshold few 100 GW/cm^2 at sub-100 fs pulse lengths.
- AR coating on the cathode improves charge yield. (**at Pegasus 2 μJ of 800 nm -> 50 pC**)

Pegasus pump and probe setup

- High quality single shot static diffraction patterns from Ti, Al, Au. (RSI, **81**:013306, 2010)
- Extensive particle tracking simulations and optimization of setup.
- Hole collimation to minimize intrinsic beam divergence at sample (need to keep < $2\theta_{bragg}$)
  - 1 mm diameter to guarantee enough particles for single shot diffraction pattern capability
  - Gives complete control of probed area.
  - Suppression of dark current back ground.



RF gun UCLA/BNL/SLAC
6 MW 2.856 GHz

Two axes x-y
sample-holder
movement

Probing electron beam
~200 fs rms long
1 pC 3.5 MeV

12 bit camera
f/0.95 lens coupling
Lanex screen or
MCP detector

Illuminating fluence
< 10 mJ/cm^2

IR laser pulse
1-10 μJ 40 fs rms

Collimating
hole
1mm diameter

Pump pulse
0.5 mJ 800 nm
0.1 mJ 400 nm 40 fs rms

Data acquisition
For each point of the
sample and delay
line position:
1 shot with no laser +
1 shot with laser +
1 shot post-mortem.

Remote controlled active
feedback delay line (-100 ps/
+500 ps).

Temporal resolution

For a typical pump and probe experiment the temporal resolution is given by

$$(\Delta t)^2 = (\Delta t_{laser})^2 + (\Delta t_e)^2 + (\Delta t_{VM})^2 + (\Delta t_{jit})^2$$

Pump pulse length
≈ 10s fs

Duration of probe
relativistic electrons , X-ray photons ≈ 100 fs
Conventional, non relativistic electrons ≈ 500 fs

Velocity mismatch
Depends on the geometry of interaction.
Spot sizes and angles of pump and probe beams.
For 5^0 and 50 μm spot size $\Delta t_{vm} \approx$ 10 fs

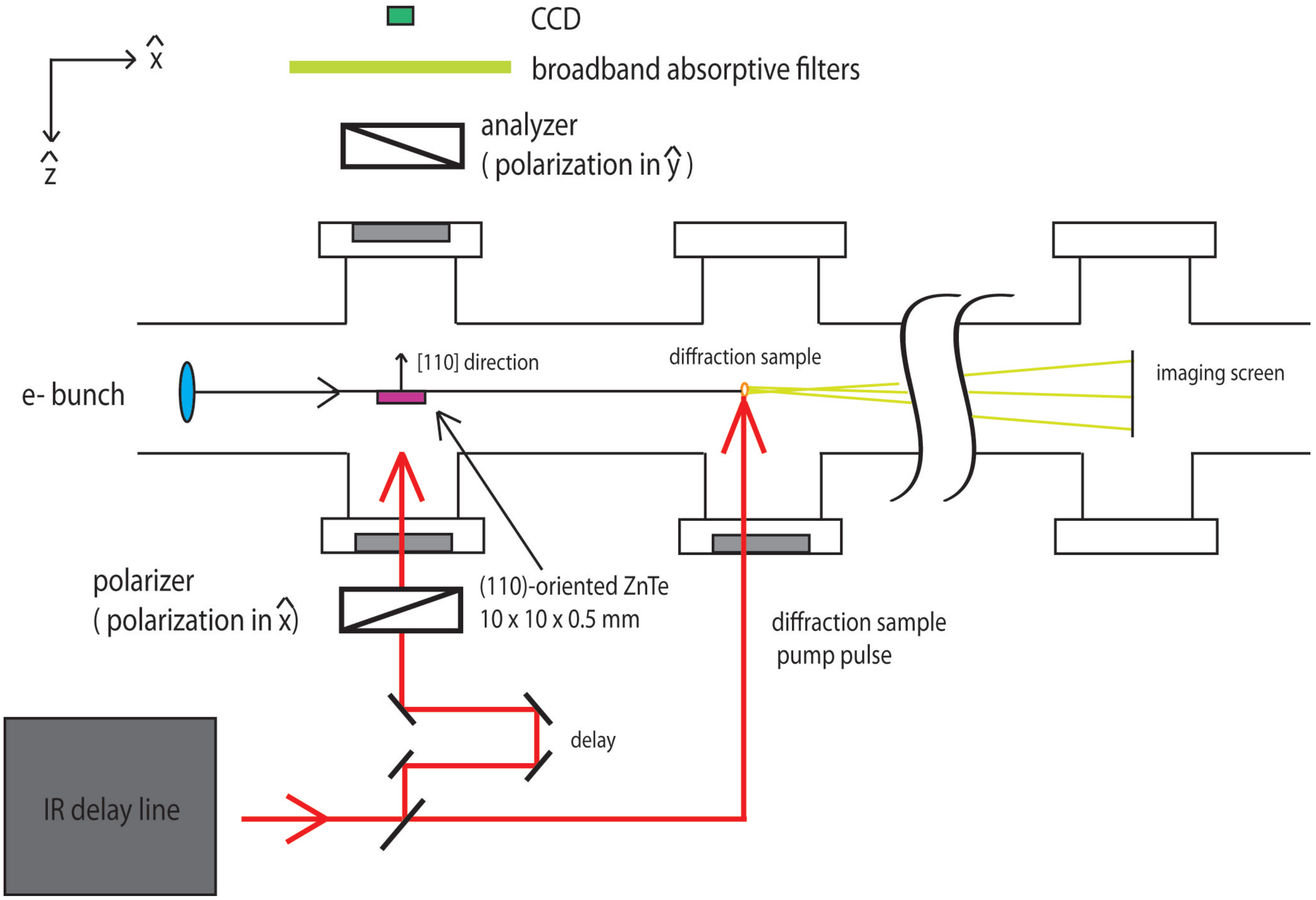
Timing jitter
Synchronization and time of arrival fluctuations

Right now the probe length is the limiting factor.
But will we able to take really advantage of shorter probes?

Timing jitter solution: Electro-Optic Sampling based time-stamping

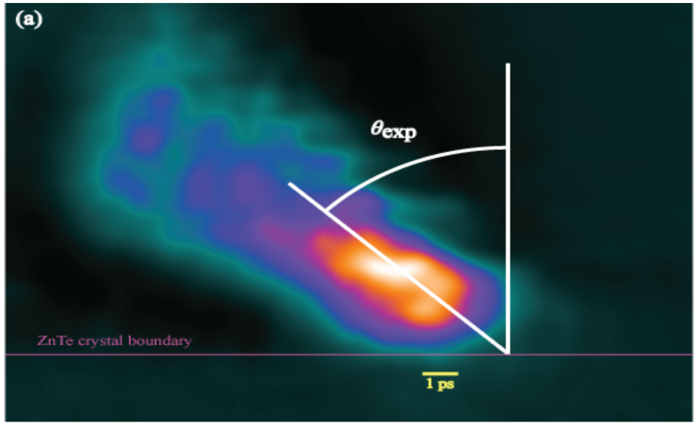
For synchronization tolerances < 10s fs there is no real alternative to time-stamping.

Pioneered at SPPS@SLAC. Cavalieri et al. Clocking fs X-rays. PRL, 94, 114801 (2005)

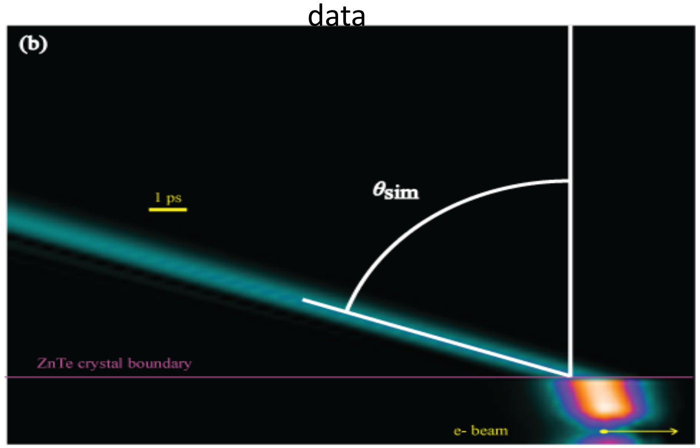


Electro-Optic Sampling.
Non destructive single-shot synchronization

C. M. Scoby, P. Musumeci et al.,
PRSTAB **13**, 022801 (2010)

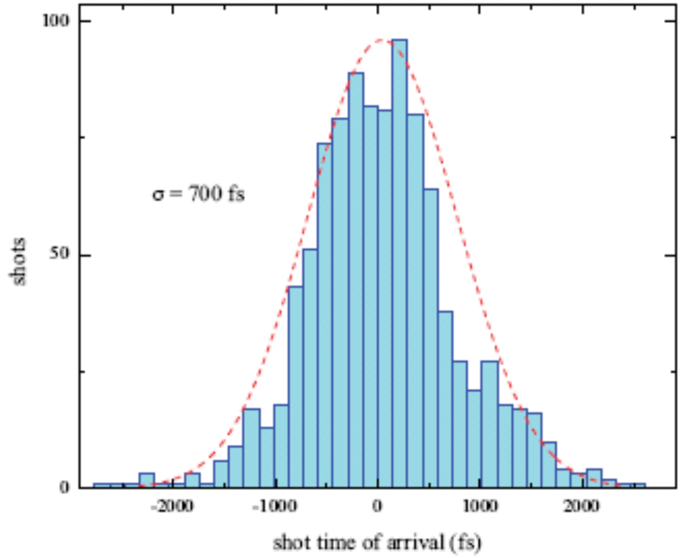


data



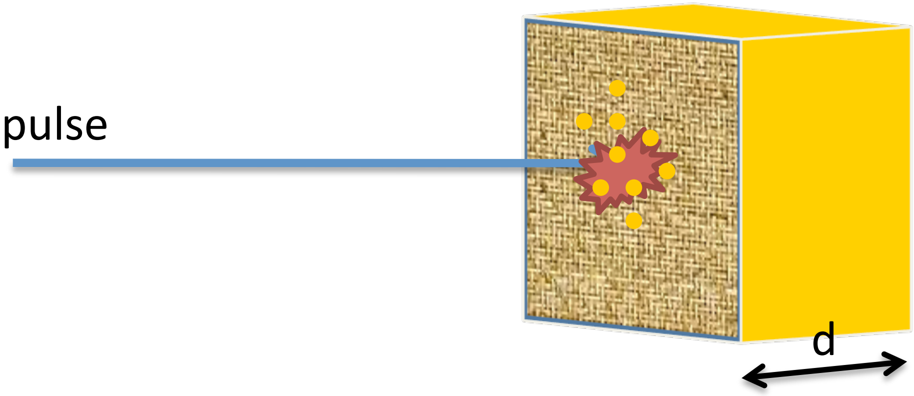
OOPIC Simulation

Jitter measurement



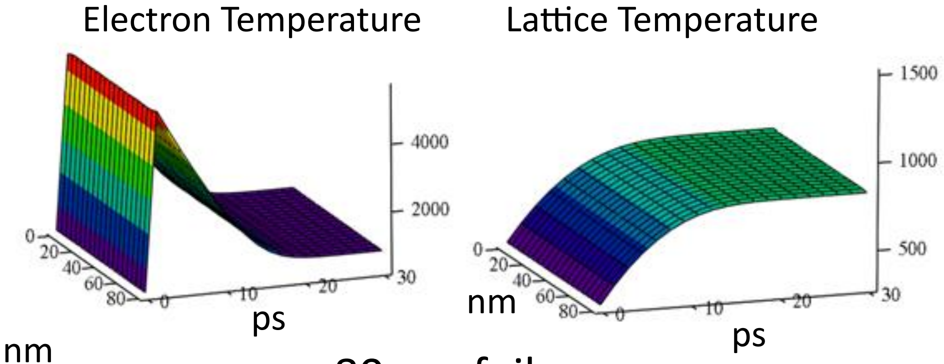
Time-stamping will remove completely the jitter contribution to the temporal resolution of the technique.

Test ultrafast process to benchmark FRED: Heating and melting of gold.

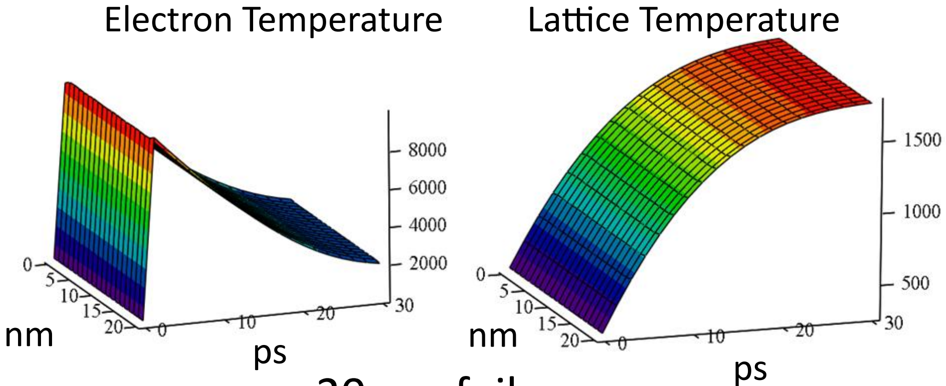


The process is well described by the two temperature model (TTM)

Two Temperature Model simulations. Au sample. 400 nm 40 mJ/cm^2



80 nm foil



20 nm foil

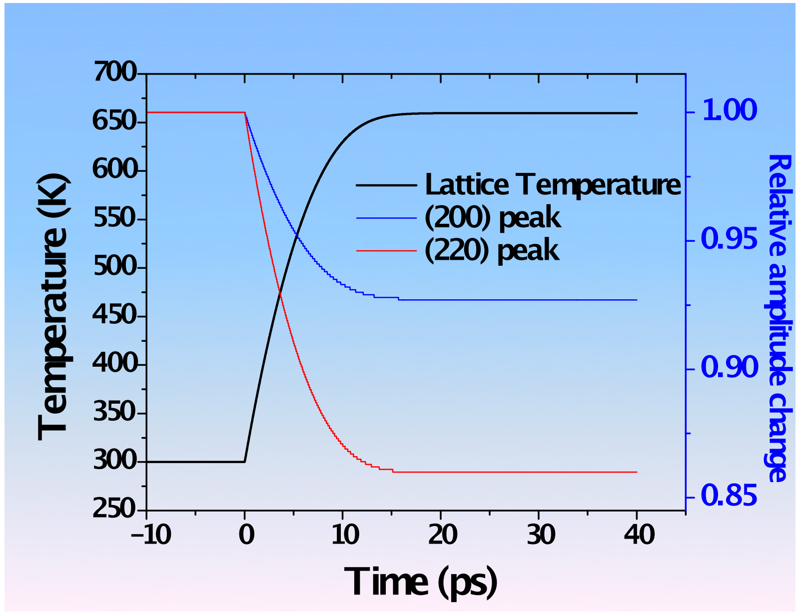
Electron phonon coupling constant g = 3 $\cdot 10^{16}$ W/m^{3}K or equivalently $\lambda\langle\omega^2\rangle$ = 26 meV^2

P. B. Allen, PRL, 59, 1460 (1987); S. D. Brorson et al. PRL, 64, 2172 (1990)

Heating and melting using ultrafast relativistic electron diffraction

Lattice temperature is detected in ED by Debye-Waller effect on Bragg peaks amplitudes.

$$\frac{I(s(hkl),t)}{I(s(hkl),t=-\infty)} = \frac{\exp[-2M(T_l(t),s(hkl))]}{\exp[-2M(300\,K,s(hkl))]}$$



☐ Previous conventional UED studies used ultrathin gold foils

☐ Foil thickness is important.

- Range of ballistic electrons is >100 nm.
- Matching of pumped and probed volumes.
- Different melting threshold.

☐ How fast heat is transported through a foil?

  ○ Complex problem, not just textbook heat diffusion.

  ○ Microscale heat transfer. Fourier model vs. Cattaneo model

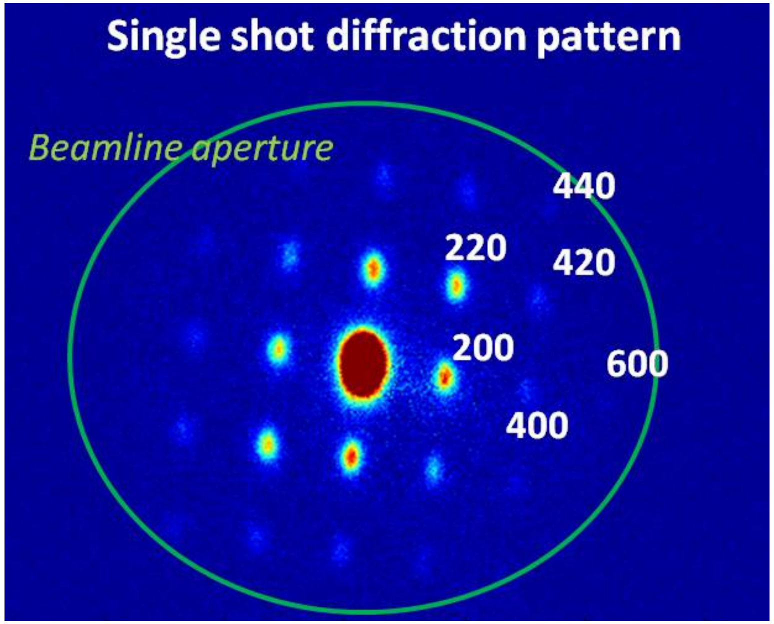
☐ When thickness is same size of typical grains in polycrystalline materials. Is the solid-liquid phase transition kinetics the same?

Single crystal Gold melting studies

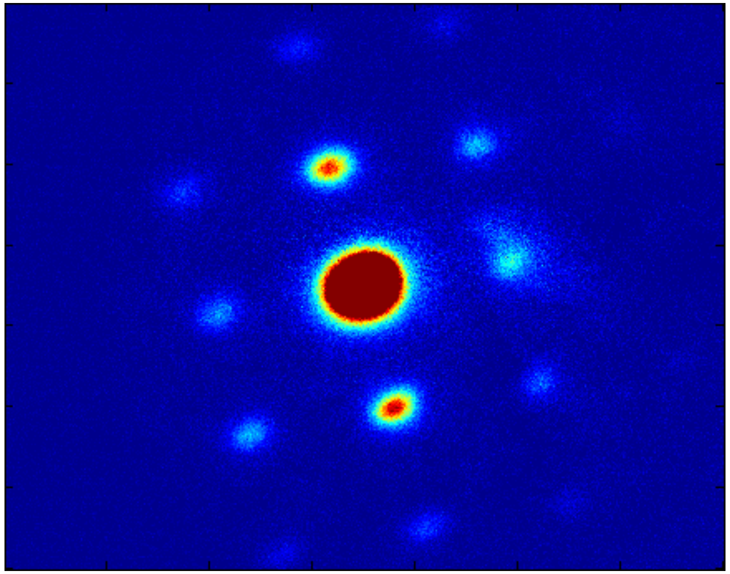
- ☐ First attempts with thick 100 nm polycrystalline foil only partially successful
  - Not really a replica of previous experiments.
  - Observed a delay-dependent change in diffraction pattern, but…
  - Small pumped/probed area ratio ! Need a more powerful laser.

- ☐ 20 nm thick single crystal samples.
  - Thin samples (enough laser energy to induce a phase transition)
  - Good signal-to-noise
  - Mo re than 20 Bragg peaks identified and indexed for each shot

Static

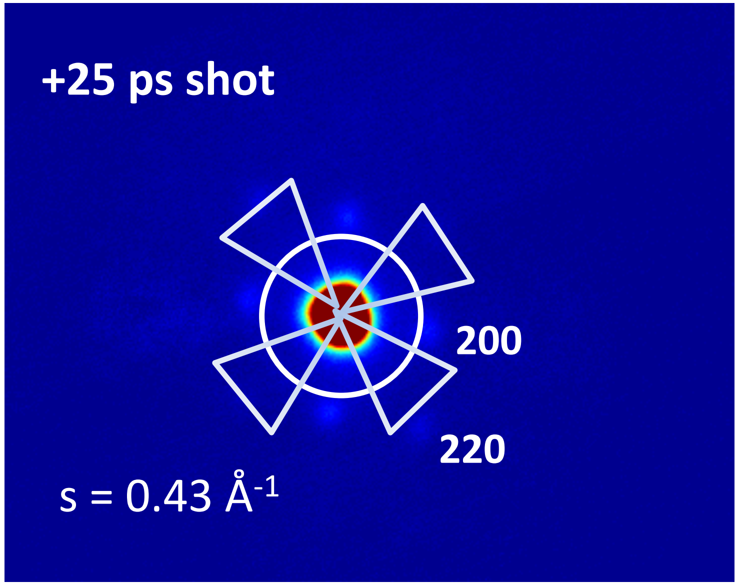


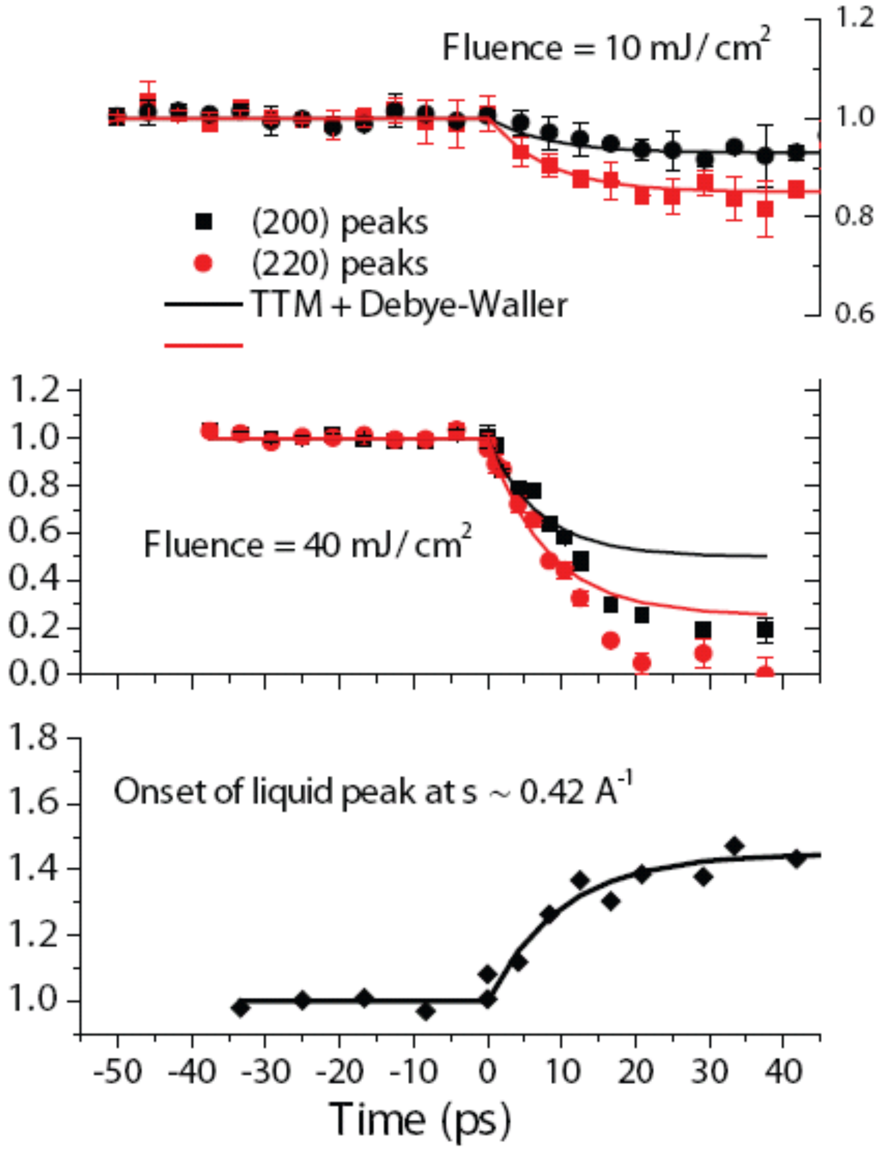
Turning the laser on



First demonstration of time resolved ultrafast relativistic electron diffraction

- Analysis for each Bragg peak: Amplitude, position, width
- Each data point is a single shot
- Vertical error is rms deviation from average of 4 peaks with same diffraction order
- For $s = 0.43$ Å^{-1} in regions not shadowed by Bragg peaks, liquid correlation function peak is observed.

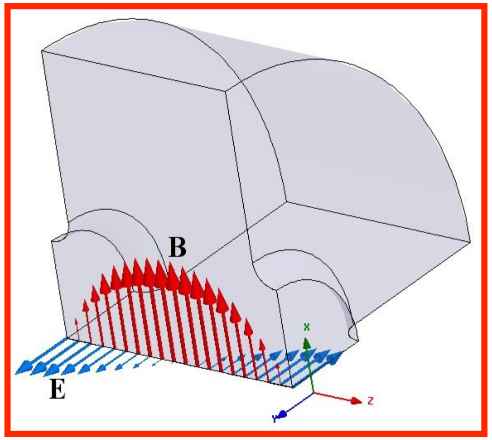




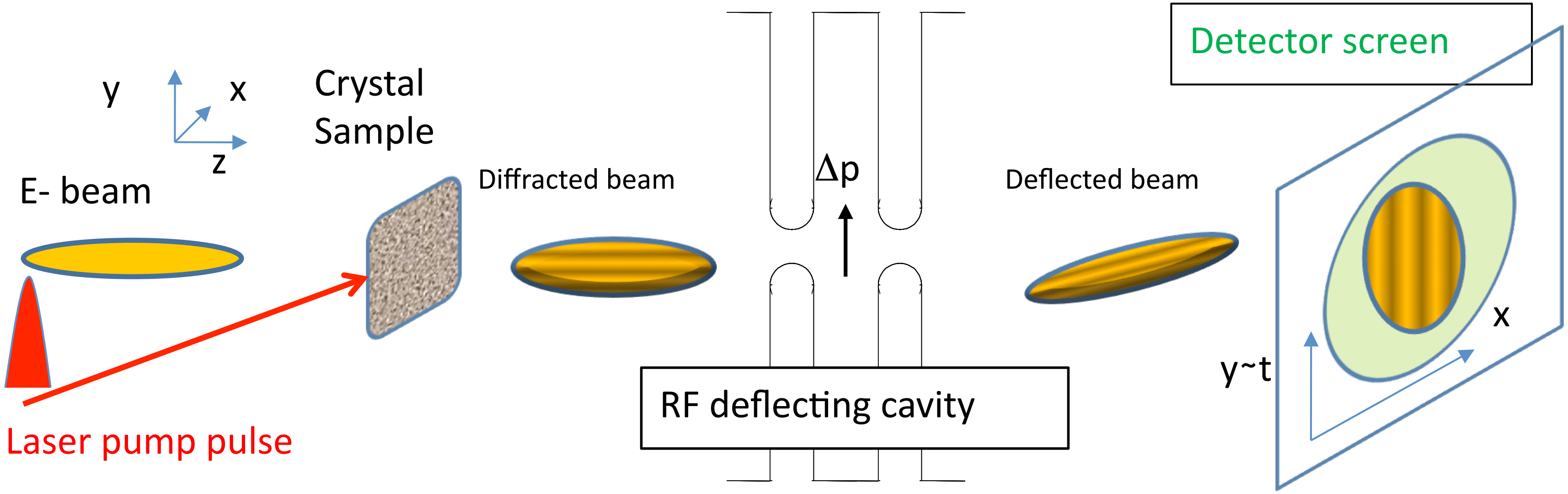
P. Musumeci et al. Applied Physics Letters, 063502 (2010)

How about truly single shot UED?

- The *new* concept: Rf streak camera based electron diffraction.
- Idea in Mourou-Williamson original paper on UED.
- Use RF deflecting cavity as a streak camera to time-resolve a relatively long (10s of ps) electron beam after its interaction with the diffraction sample.



RF deflector
field distribution



y
x
z

Crystal
Sample

E- beam

Diffracted beam

Δp

Deflected beam

Detector screen

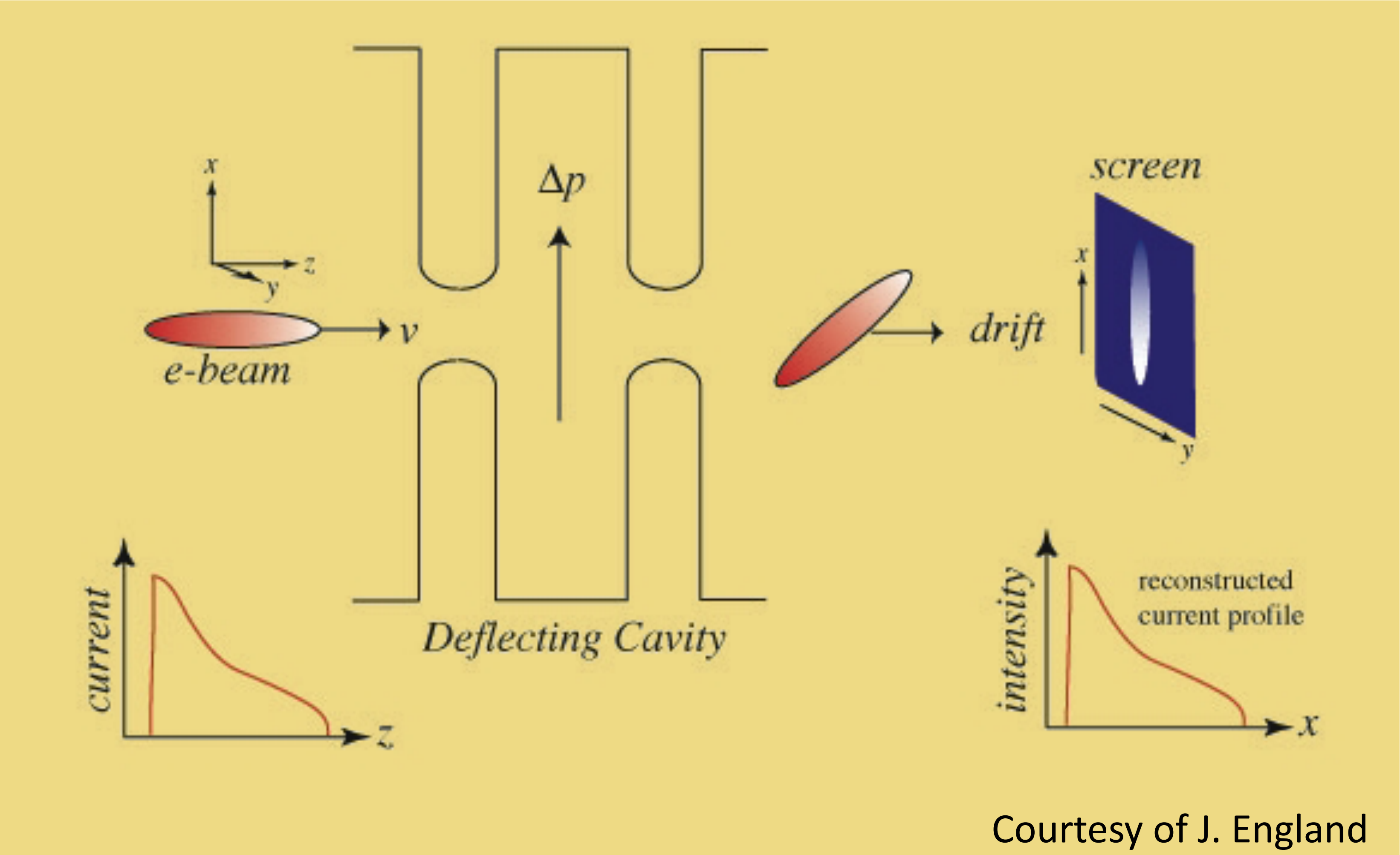
x

y~t

RF deflecting cavity

Laser pump pulse

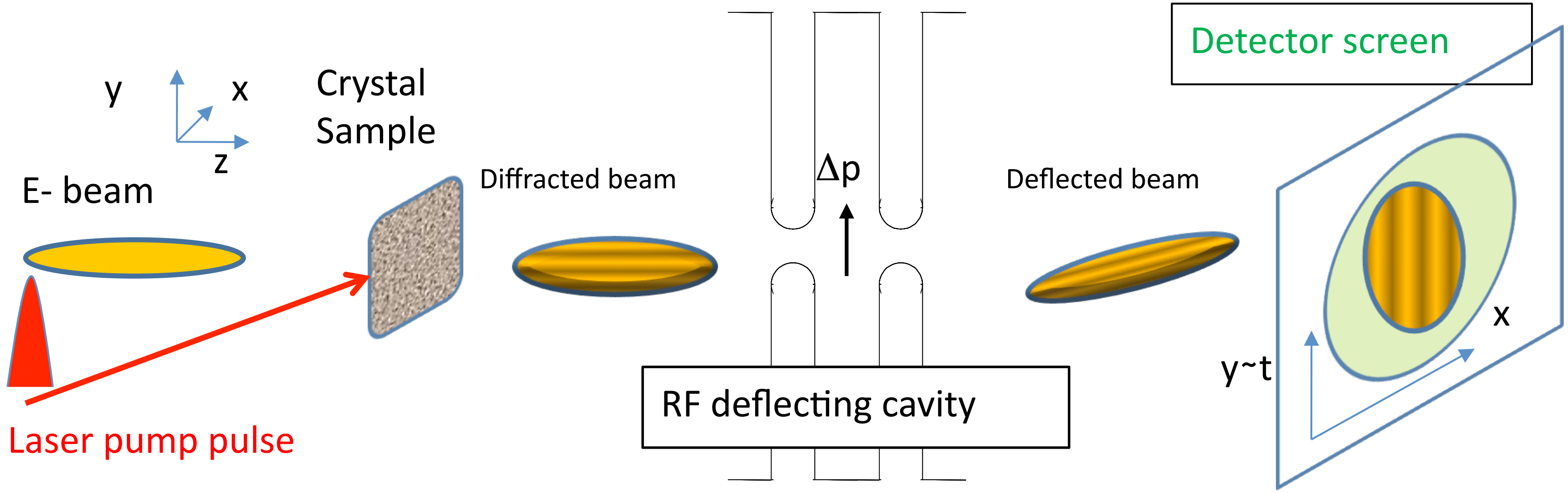
RF deflecting cavity concept



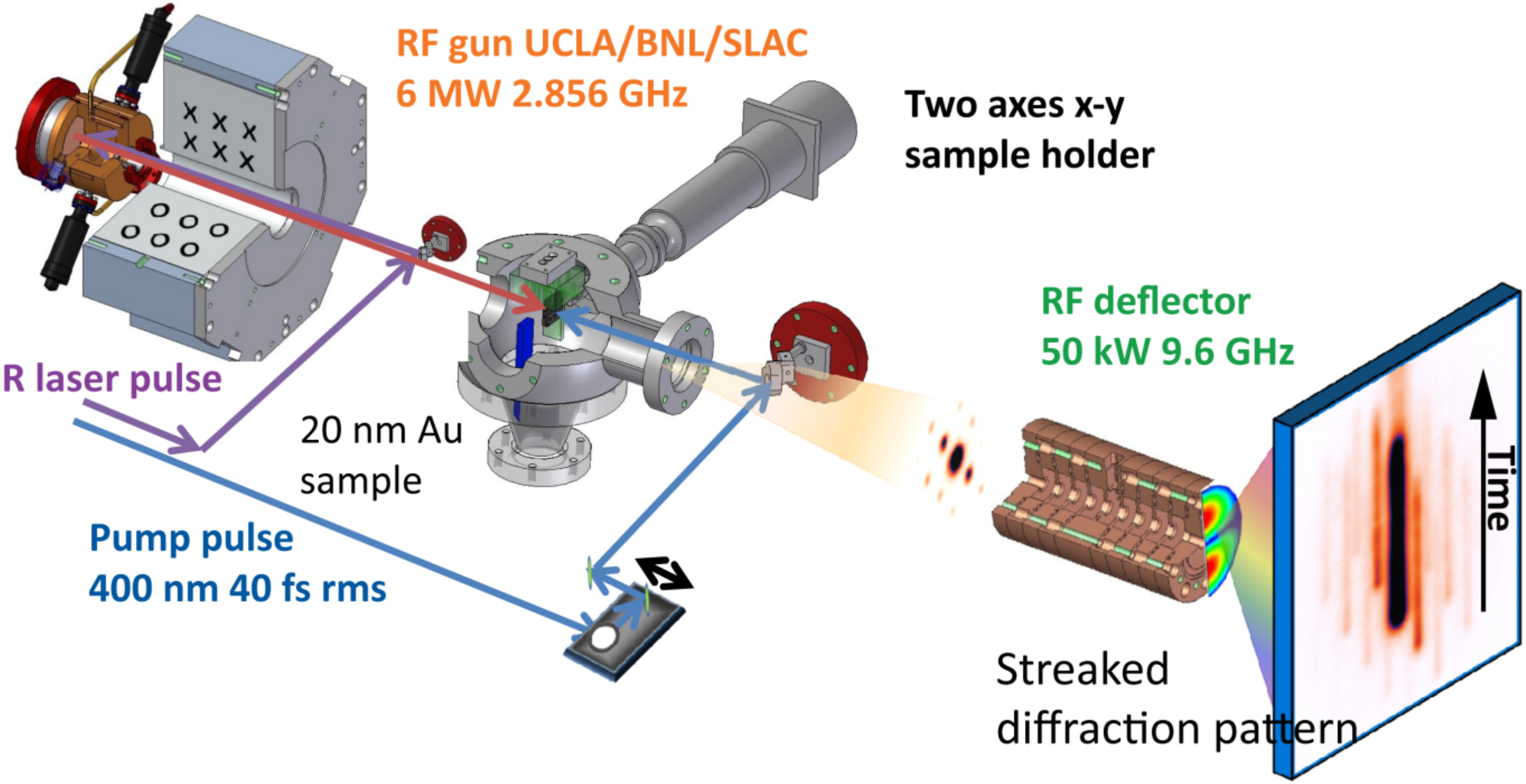
Courtesy of J. England

How about truly single shot UED?

- The *new* concept: Rf streak camera based electron diffraction.
- Idea in Mourou-Williamson original paper on UED.
- Use RF deflecting cavity as a streak camera to time-resolve a relatively long (10s of ps) electron beam after its interaction with the diffraction sample.
- Three significant advantages
  - Free UED by the limitation due to the length of the electron beam.
  - Improve significantly the temporal resolution of the technique.
  - Yield true single-shot structural change studies revolutionizing the approach of the conventional pump-probe experimental procedure.



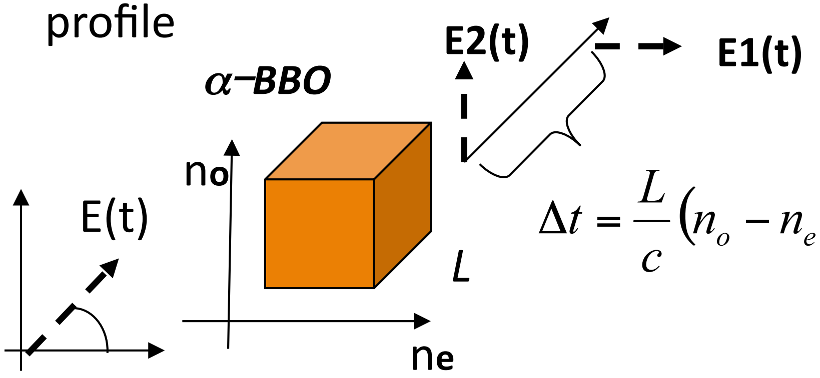
RF streak camera based ultrafast relativistic electron diffraction



- Single shot ultrafast structural dynamics (for example determination of electron-phonon coupling constant).
- RF streak camera based UED can potentially offer sub-10 fs resolution.

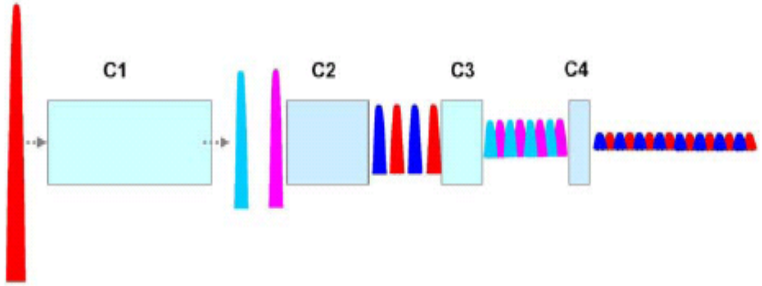
In order to probe in a single shot the Au solid-liquid phase transition a relatively long electron bunch is needed

- Use birefringent alpha-BBO crystals to manipulate longitudinal laser profile

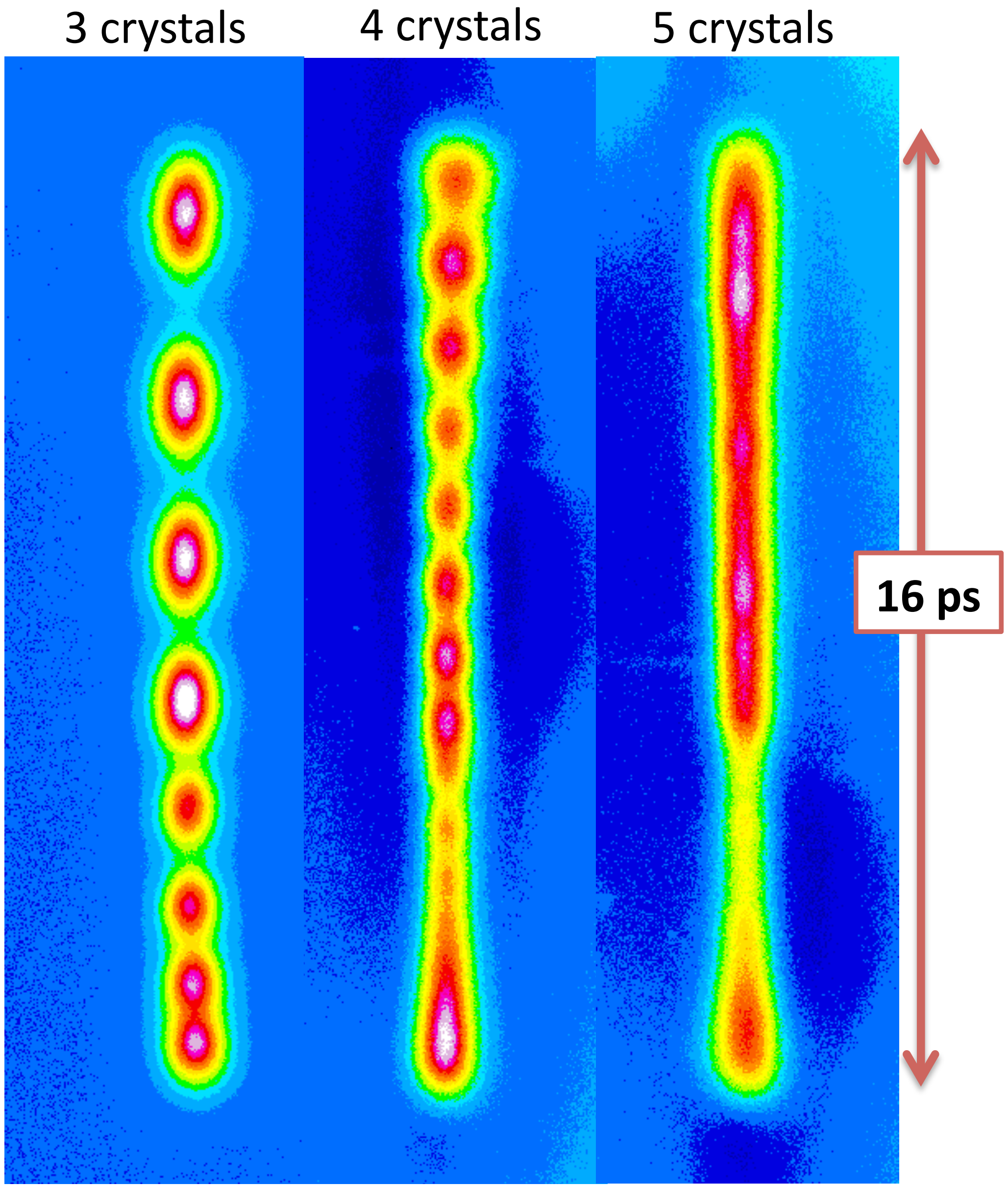


$$\Delta t = \frac{L}{c}(n_o - n_e)$$

- 2^n pulses
- 1 mm smallest thickness -> 0.5 ps spacing
- n = 5 crystals of increasing thickness

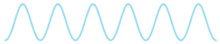


For small spacing, the space charge removes current modulation and one has a quasi flat-top beam.



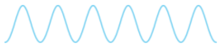
Non linear longitudinal space charge oscillations in relativistic electron beams

- Start with e-beam modulated at the cathode.

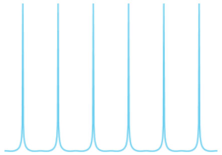


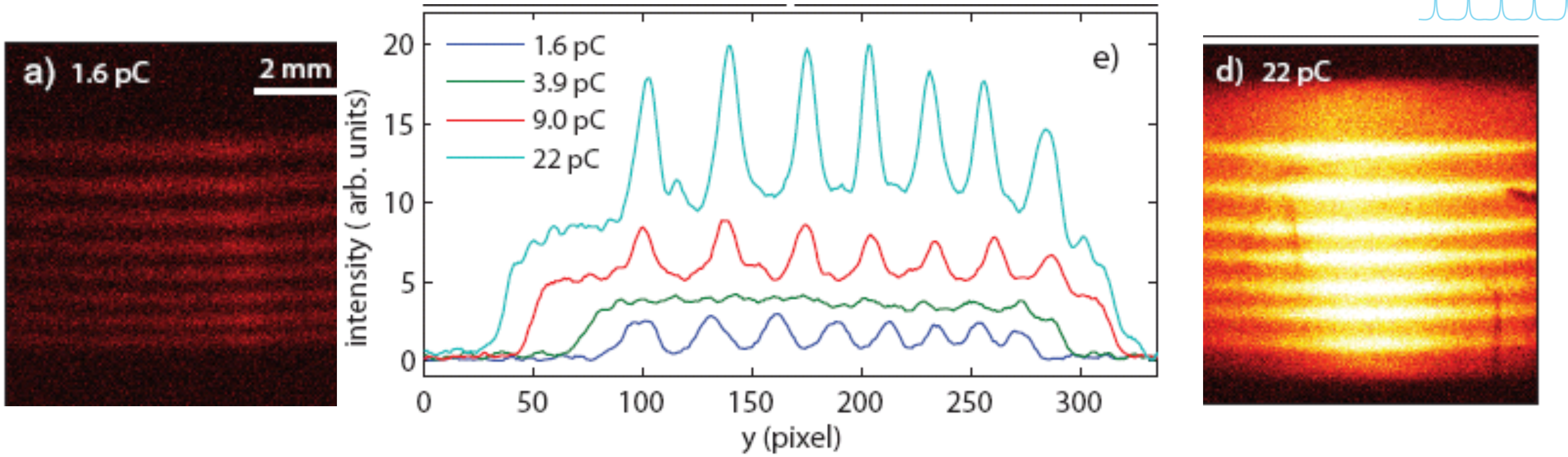
- By increasing charge, modulation washes out.

- After a ¼ plasma period, beam distribution is completely flat (shot noise suppression techniques).
- After ½ plasma oscillation, linear theory predicts modulation to come back.



- Nonlinear theory is even better… Modulation comes back with increased harmonic content and enhanced peak current !!!

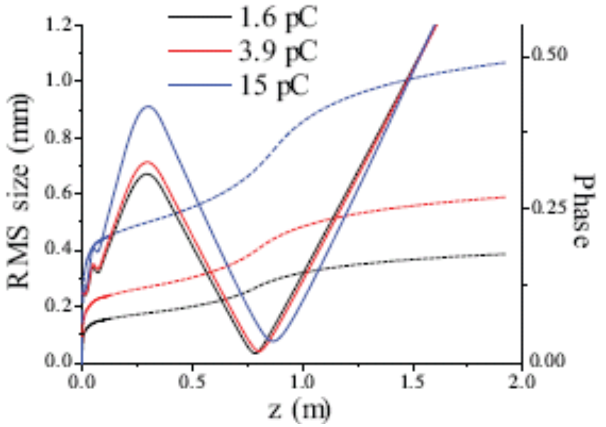


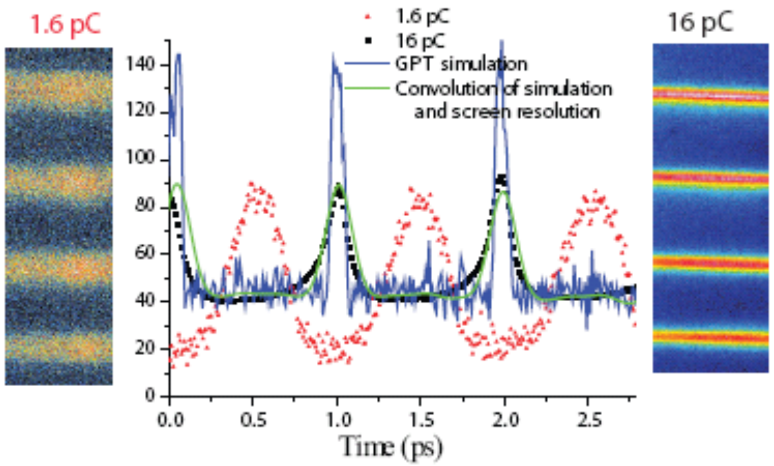


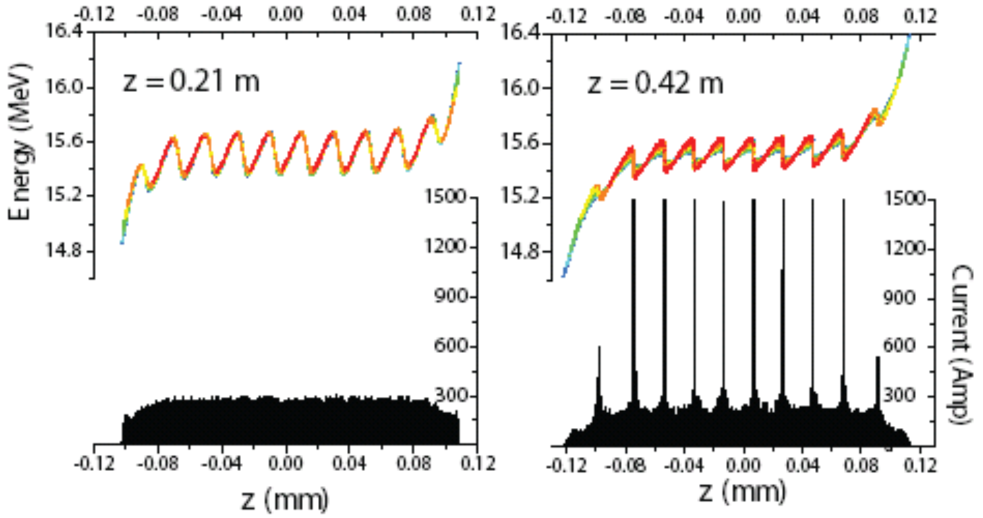
P. Musumeci, R. K. Li and A. Marinelli, Phys. Rev. Lett. 106:184801 (2011)

Non linear longitudinal space charge oscillations in relativistic electron beams

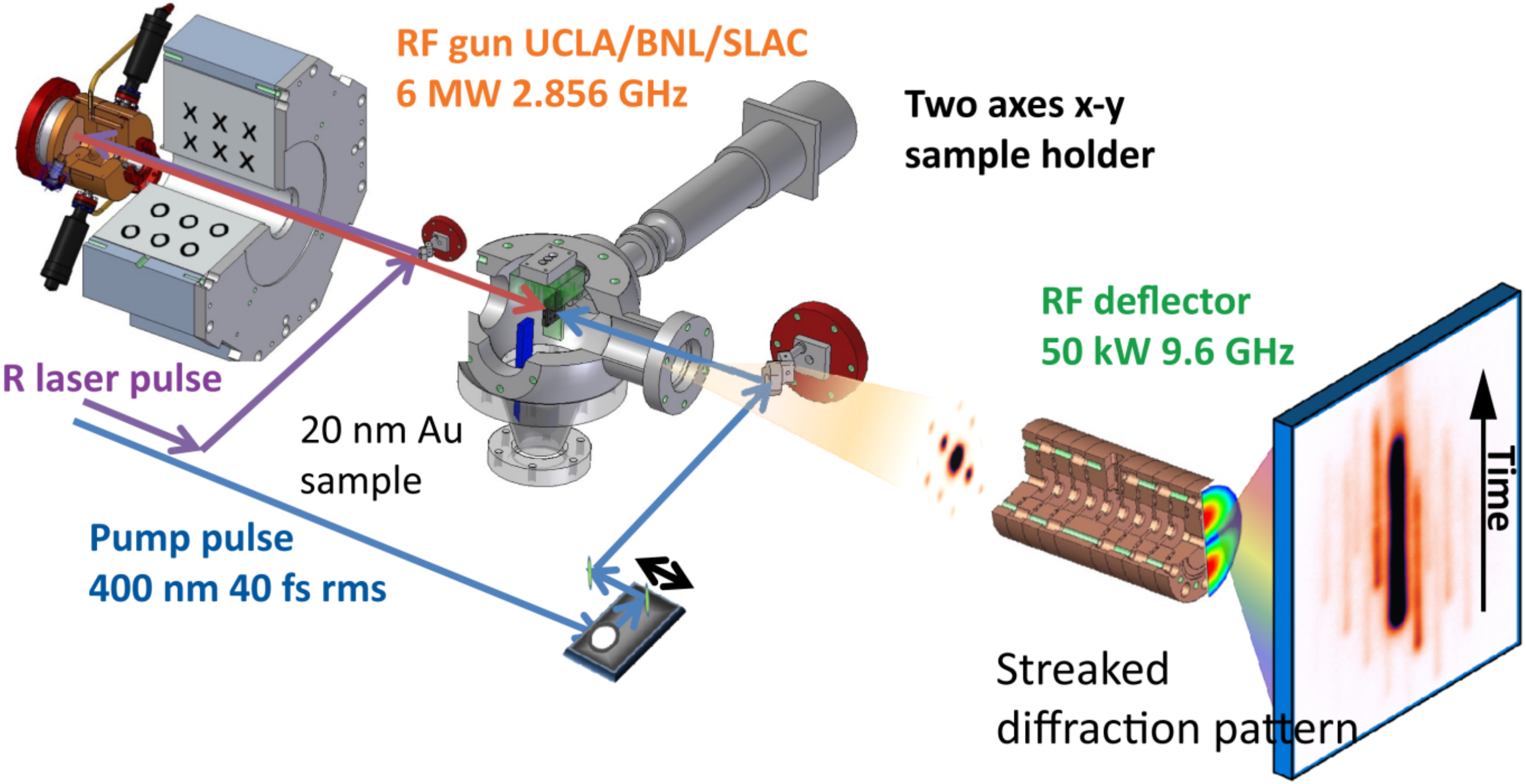
- By changing charge and keeping solenoid constant, it is possible to control the plasma phase advance.
- Measurement is resolution limited. (convolution of screen resolution).
- Coasting beam simulations show significant peak current and harmonic content enhancement.







RF streak camera based ultrafast relativistic electron diffraction



RF gun UCLA/BNL/SLAC
6 MW 2.856 GHz

Two axes x-y
sample holder

IR laser pulse

20 nm Au
sample

Pump pulse
400 nm 40 fs rms

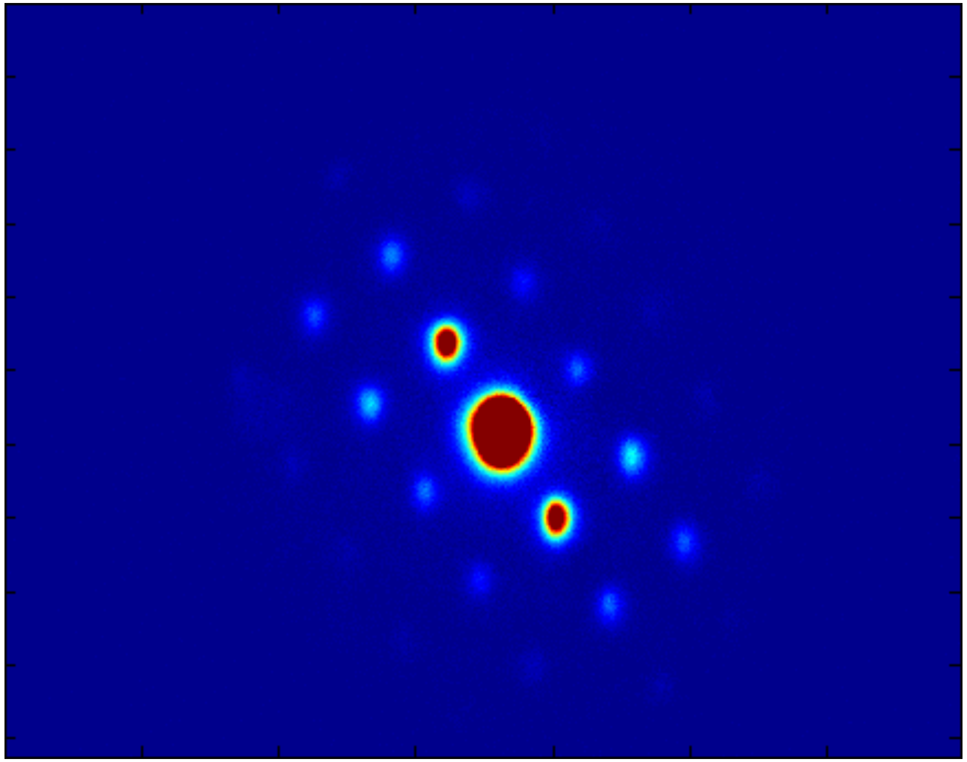
RF deflector
50 kW 9.6 GHz

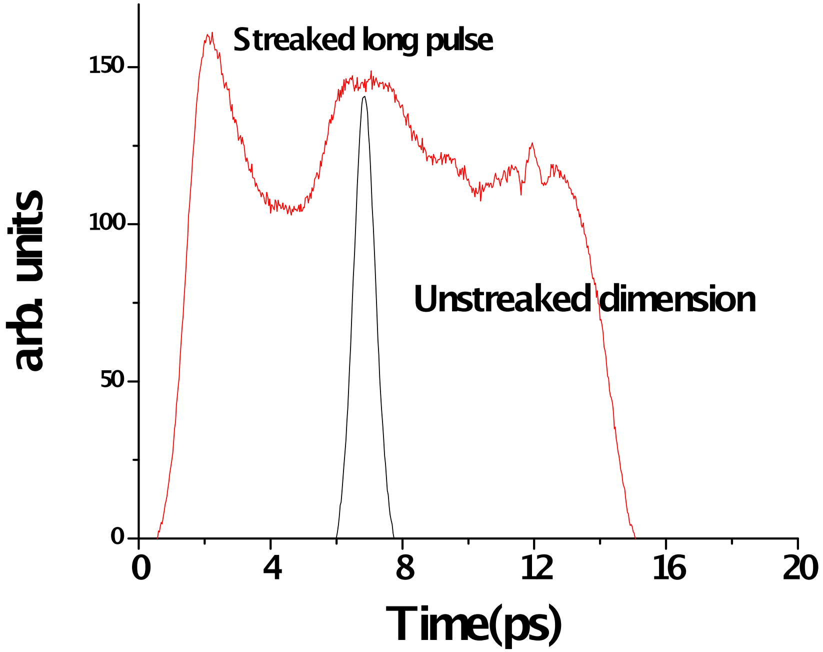
Streaked
diffraction pattern

- Single shot ultrafast structural dynamics (for example determination of electron-phonon coupling constant).
- RF streak camera based UED can potentially offer sub-10 fs resolution.

Streaking an electron diffraction pattern

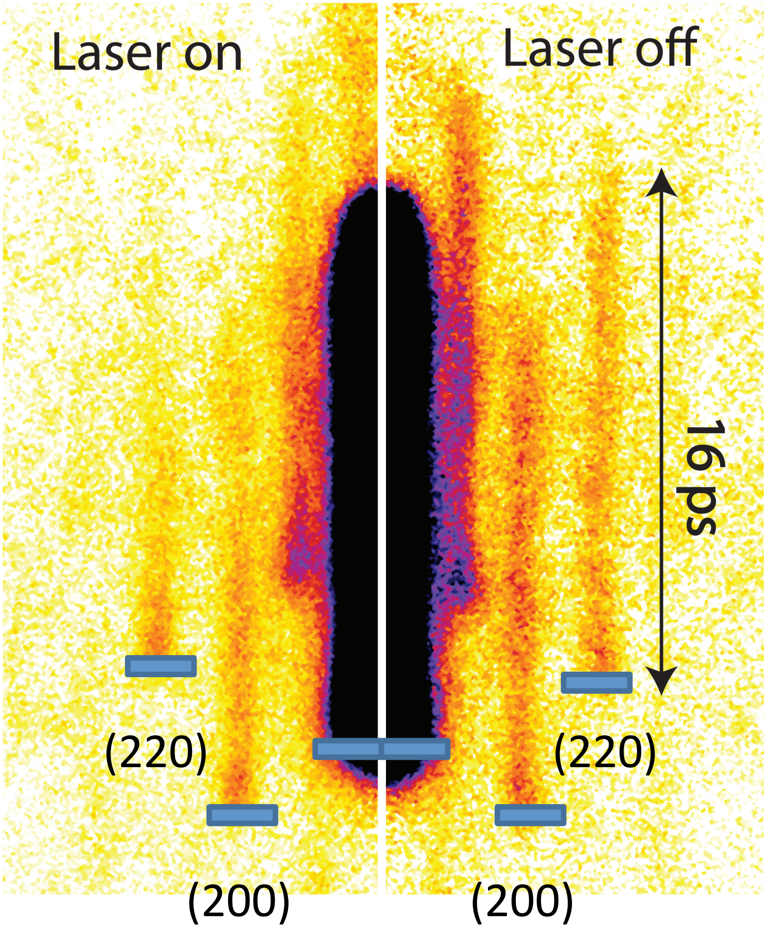
- Use alpha-BBO crystals to make a long (16 ps) beam on the cathode
- Get single crystal diffraction pattern.
- Turn on deflecting RF voltage
- Resolution is linked to ratio of beam sizes between streaked and un-streaked direction.
- At this time limited to 400 fs, but just from screen dimensions.

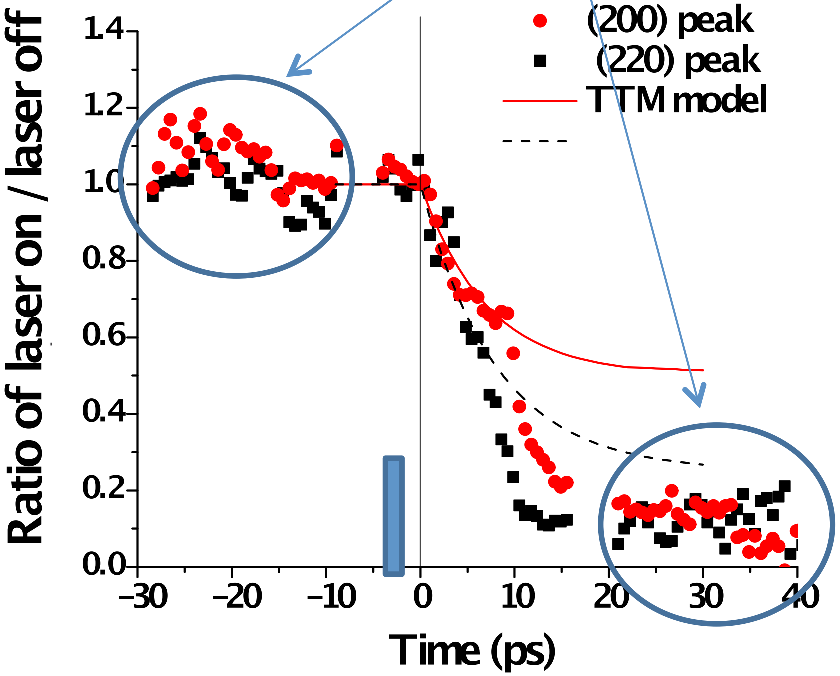




Analyze images by slicing up in 400 fs segments

These are obtained by moving the mechanical delay line



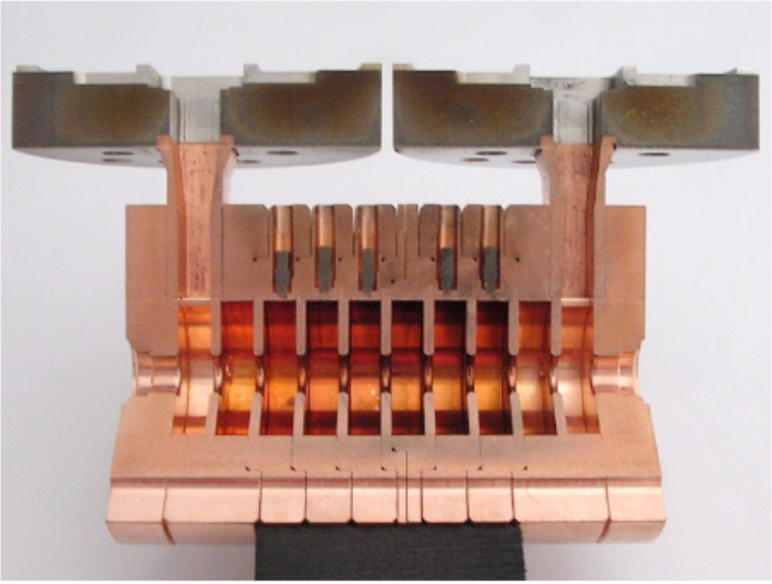


Capturing ultrafast structural evolutions with a single pulse of MeV electrons: RF streak camera based electron diffraction.

P. Musumeci et al. Journal of Applied Physics, **108**, 114513 (2010)

RF deflector based UED promising direction

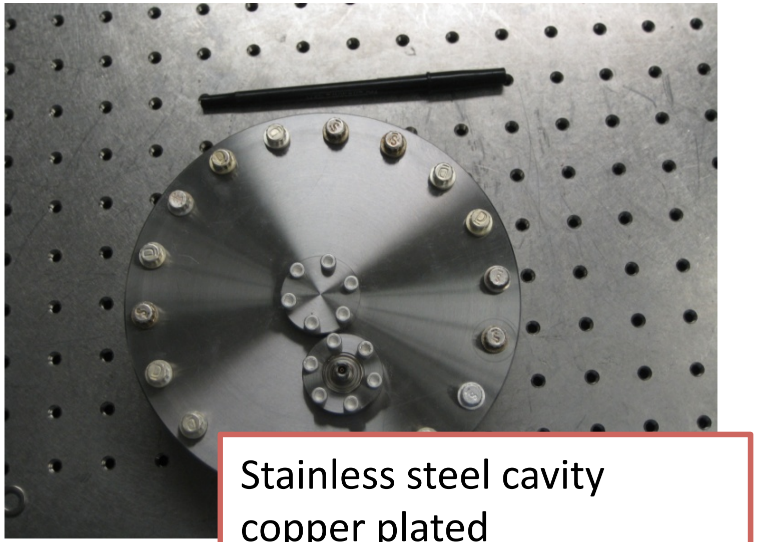
- Temporal and spatial resolution to be understood and improved
- Using an X-band deflector (and 5 MW X-band klystron) potentially could get <5 fs resolution !!!



Cross section of X-band deflecting cavity prototype (Radiabeam)

Good also for conventional setups:

- Could use long beams from semiconductor cathode (spin polarized electrons)
- RF deflector for keV electrons. Driven by KW amp.
- DC photogun (30 keV) beamline for EPFL under test @ UCLA.

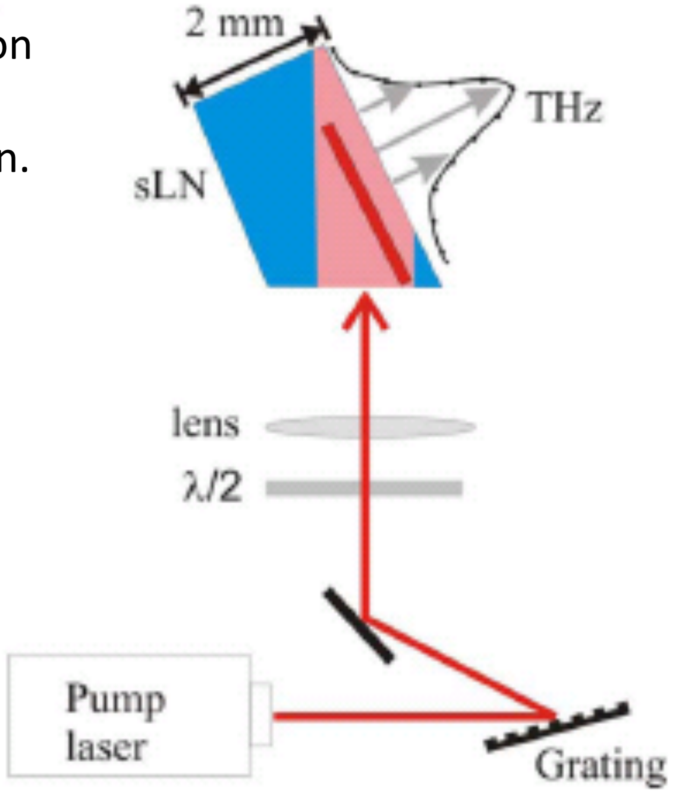


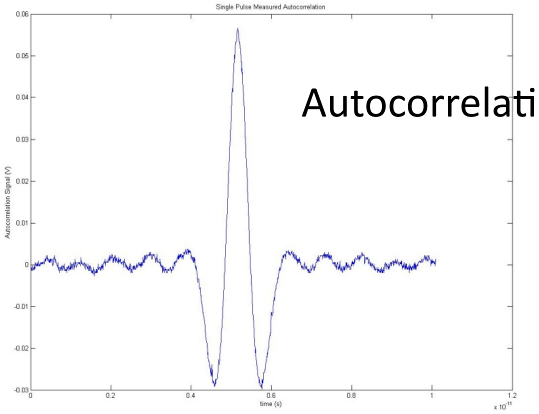
Stainless steel cavity
copper plated
Temperature tuned
Vacuum tested to 10^{-7} torr

Pegasus electron diffraction next goal: THz pump - electron probe

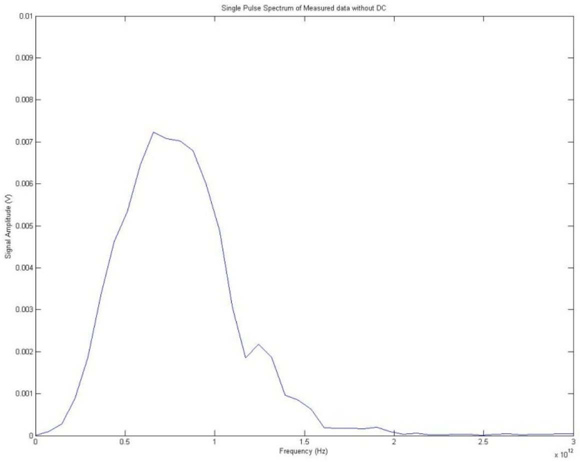
- Why is this attractive?
    - Visible laser is not the best way to make the atoms move….
    - THz wave couples directly with atomic motion.
- Difference Frequency Generation between different components of the IR spectrum.
- Due to different index of refraction emission from LN is Cherenkov-like. Pulse front tilt scheme to maximize conversion efficiency.
- Liquid N cooled crystal holder to minimize phonon absorption.

Janos Hebling, Ka-Lo Yeh, Matthias C. Hoffmann, and Keith A. Nelson.
IEEE JOURNAL OF SELECTED TOPICS IN QUANTUM ELECTRONICS, 14: 345 2008



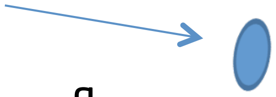


Autocorrelation

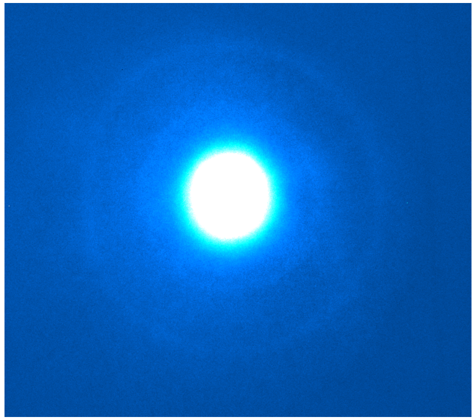


❖ 3 μJ / 1 ps *3 MW of peak power* (@ 1 KHz !!! 3 mW average power) with 0.3 % conversion efficiency.

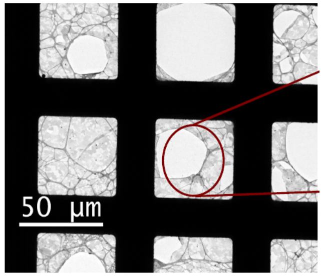
New directions: Extreme samples



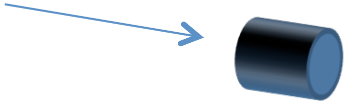
- Very thin.
- Take advantage of large flux
- Diffraction pattern from graphene foil
- Still polycrystalline sample. Need smaller (< 5 um) probe area.



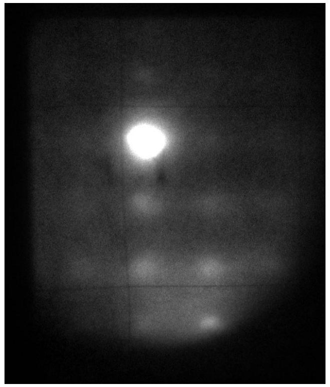
With compressed beams, we can access the visualization of hard in-plane phonons



TEM image of sample

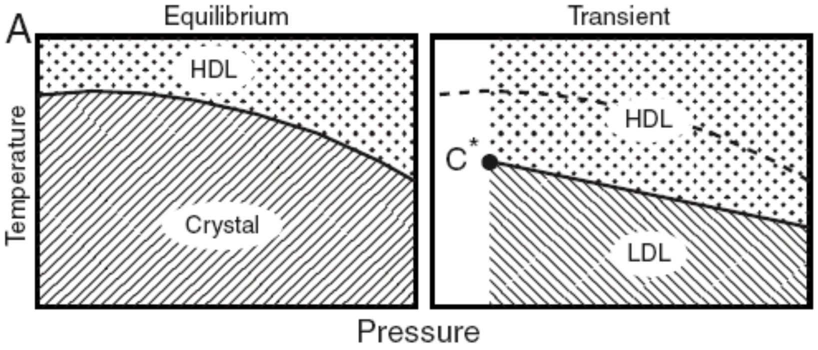


- Very thick
- Take advantage of penetrating power
- Diffraction pattern from 1 um thick Si sample
- Low density liquid phase?
- Need powerful pump (upgrading Pegasus laser system)



Single shot diffractionpattern through 1 um thick Si foil

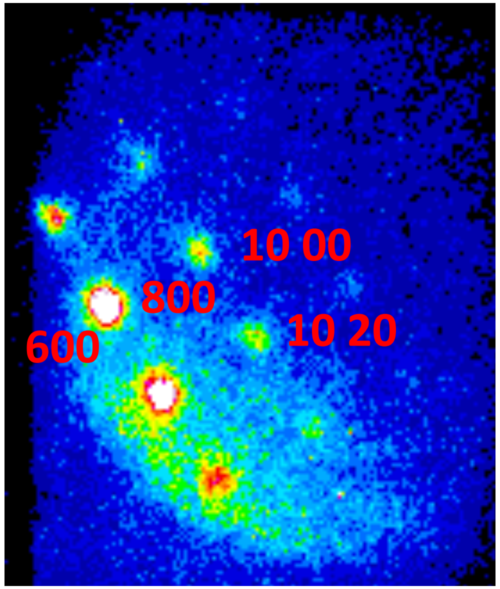
Phase diagram for Si



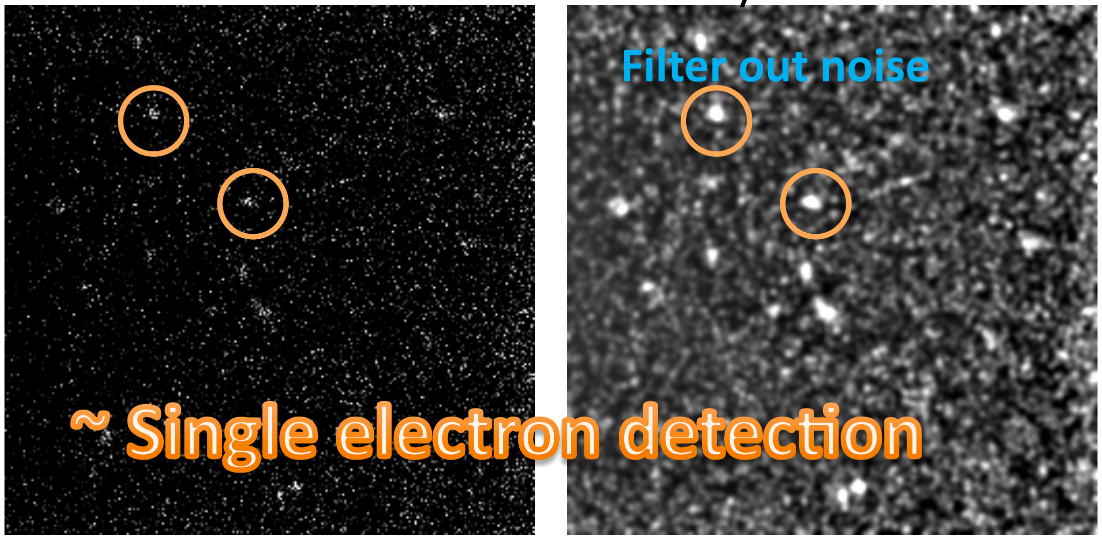
New directions: High efficiency Detector

- Need a high efficiency electron detector.
  - Existing in conventional non relativistic keV UED setup
- Tested different cameras (12 bit, 16 bit, EMCCD, ICCD)
- Different screens: YaG crystal, Lanex, different thickness of Phosphor screens.
- Active: Image intensifier/MicroChannel-Plate. (NSTec collaboration)
- Lens coupling. Using a f/0.95 lens to maximize light collection.
- Recent results: Use EMCCD + Lanex screen+ high collection optics. Improvement by a factor of 50+. *<u>Achieved Single electron detection capability !</u>*

At high gain even 12 00 is visible. (<70 electrons).
Dark current noise (not camera sensitivity) is the limit.



Dark current only

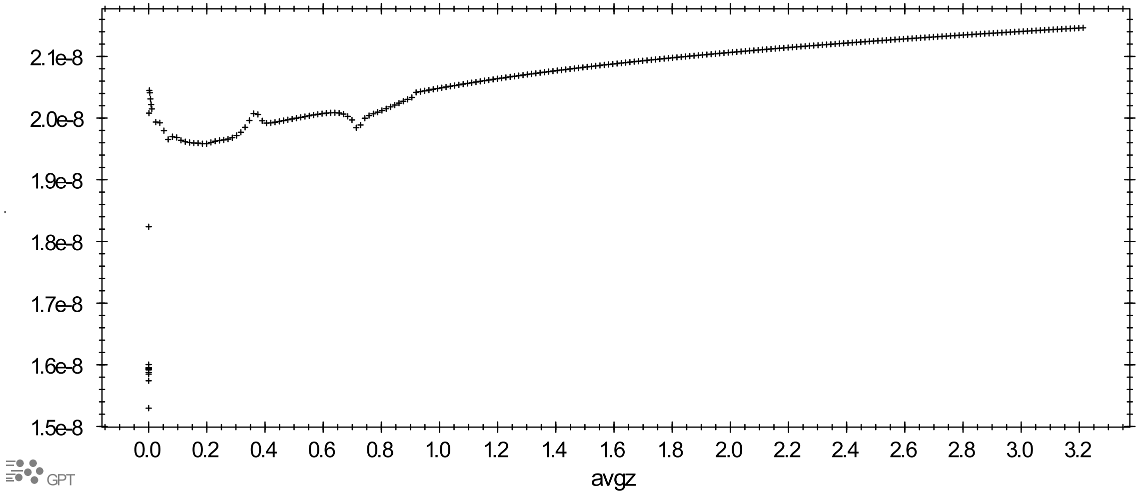


New direction: Cigar beams and nm-emittance measurements.

- How to deal with thermal emittance brightness limit?
- Focus the laser tight (< 20 um rms) on the cathode.
  - Surface charge density limit $\sigma < \varepsilon_0 E$
  - Damage threshold (Cu ~ 100 GW/cm^2)

Charge < 1 pC

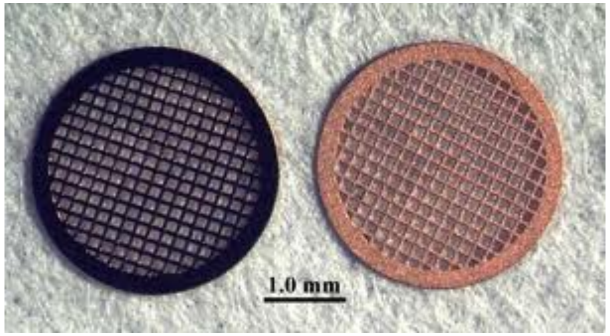
- Cigar beam 0.1 pC – 1 pC. Space charge expansion should preserve emittance (same as blow-out).
- First estimates using new darkfield pepper-pot technique give normalized emittance below 25 nm in agreement with GPT.



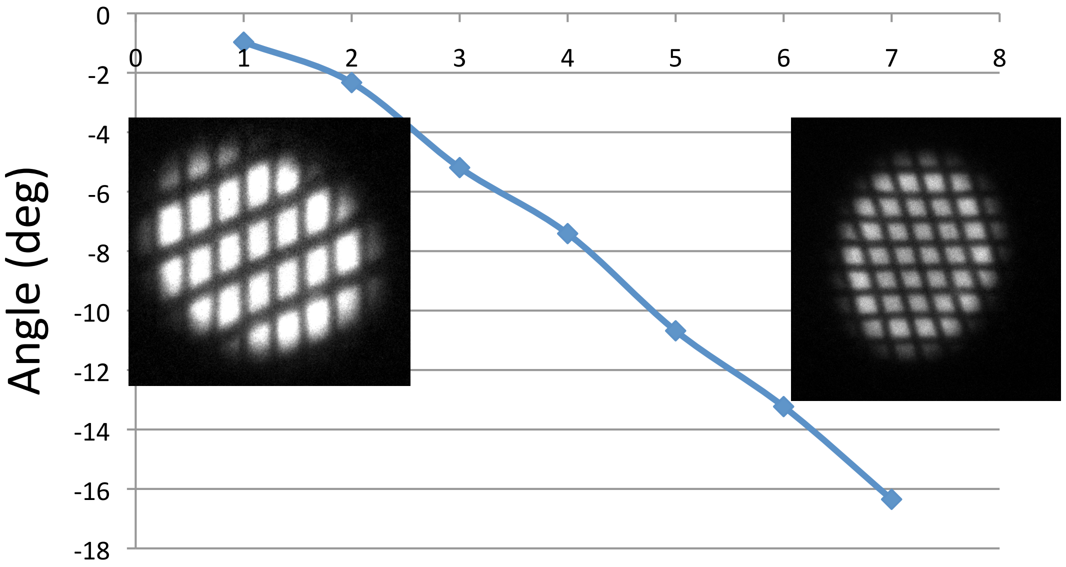
Dark-field pepper-pot emittance measurement

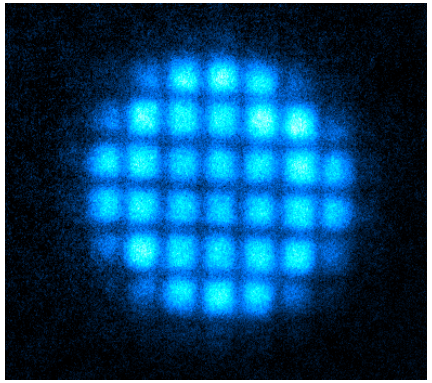
- The problem is to measure emittance of ultralow charge beams.
- Send the beam through a TEM grid.
- Size of the grid and pitch can be chosen depending on beam dimensions and emittance
  - We use 125 um pitch and 35 um bars.
- Same information as pepper-pot technique.
- Great diagnostics for 4D transverse phase space.

Use TEM grid as “pepper-pot”



Correction of skew quadrupole at the gun exit.

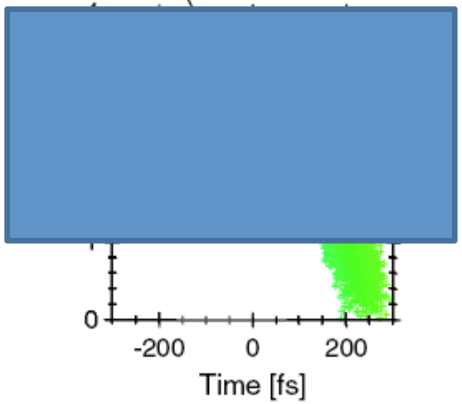


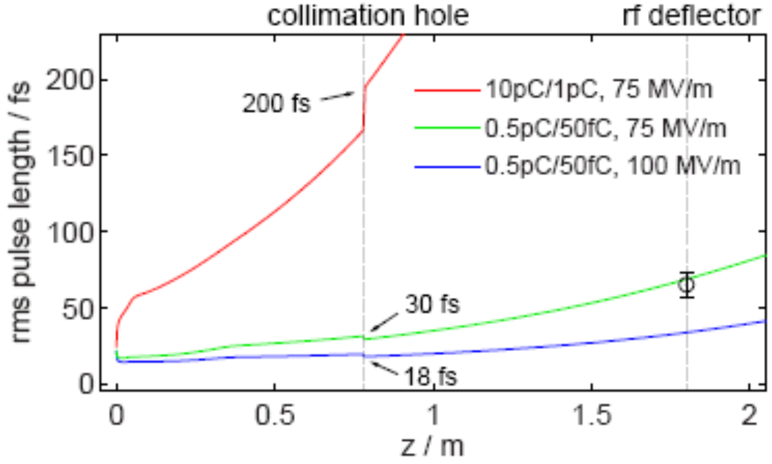


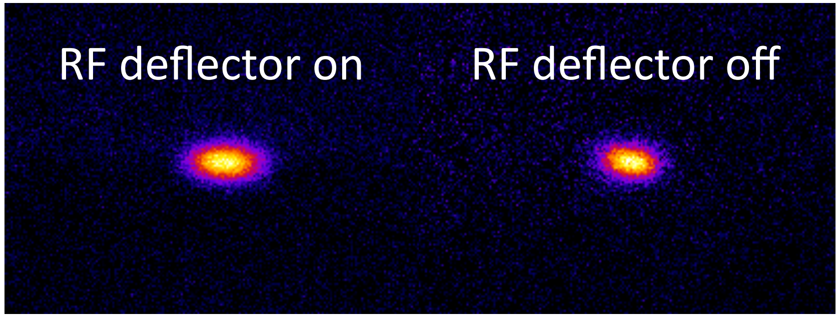
New directions: Shorter beams

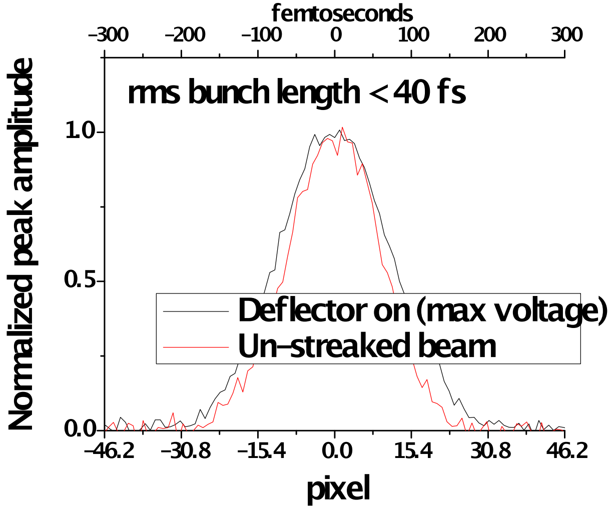
- The increase in detection efficiency allows a much lower charge beam.
- Measurements in agreement with simulations using 70 MV/m, 0.1 pC show < 45 fs rms bunch lengths
  - At the limit of RF deflector resolution
- At higher gradient and still lower charges (right now we are limited by arcing in the gun) < 20 fs is possible.
- Synchronization becomes the limiting factor.

De Loos et al. PRSTAB 9, 084201 (2006)



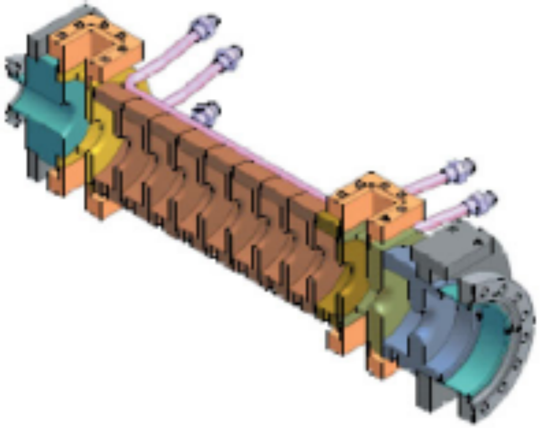


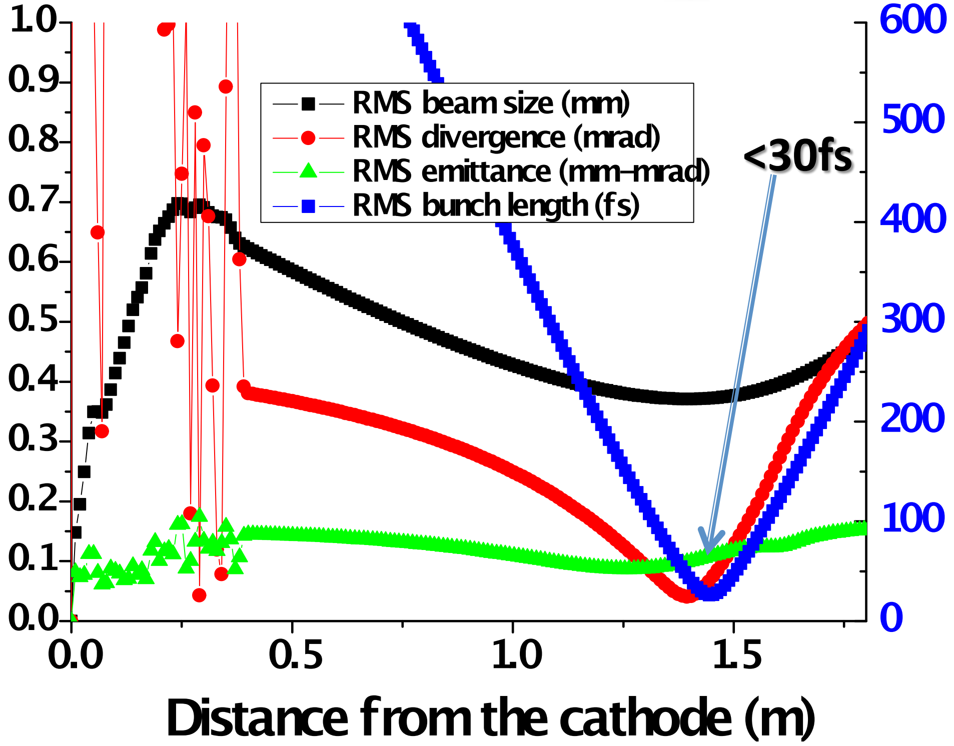




Is the 1.6 cell RF photogun the best approach to the problem?

- Standard 1.6 cell RF photoinjector *not* designed for UED
- Even at low charge beam slightly expands longitudinally due to space-charge, non-optimum RF design
  - Full cell “too long”, defocusing
- Longitudinal focusing necessary
- New rf structure development @ UCLA – INFN
  - *Hybrid gun*
  - ***New X-band hybrid project!!! (SLAC)***
- Many applications…
  - THz generation
  - Inverse Compton Scattering
  - Free-electron lasers

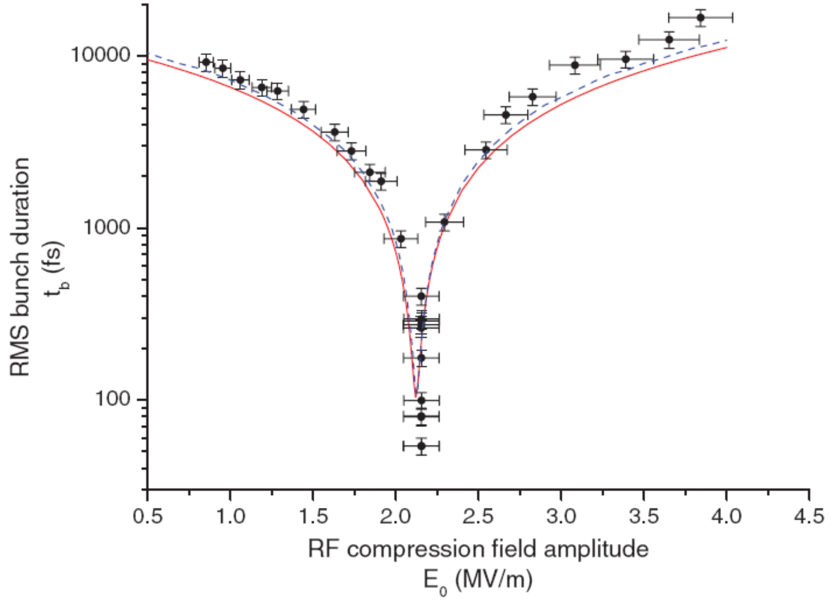




Compression of ellipsoidal bunches

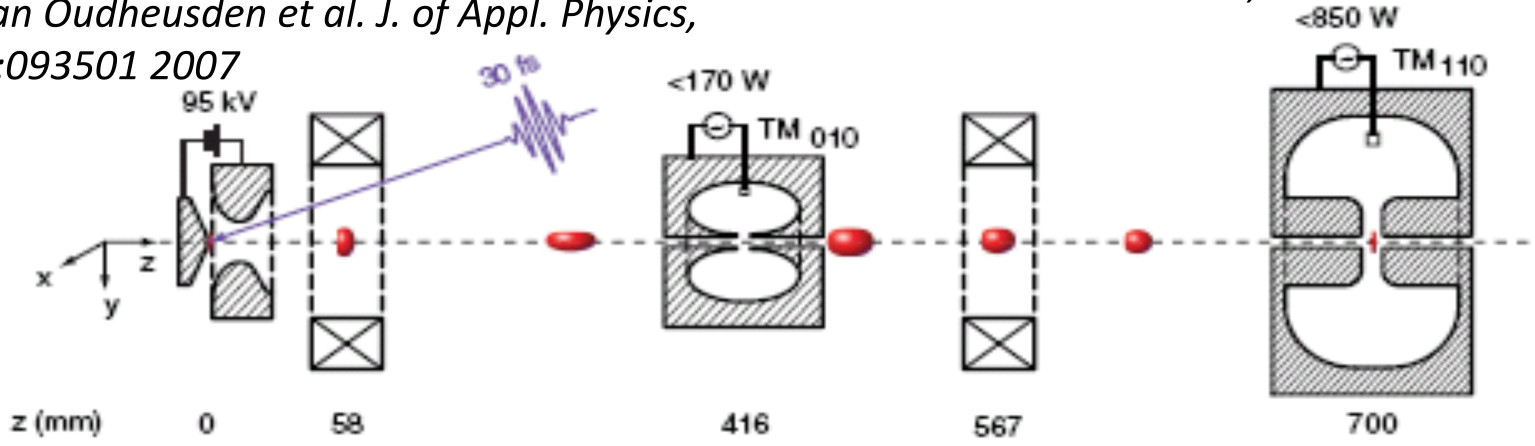
- Ellipsoidal bunches have very linear longitudinal phase spaces
- Van Oudheusden et al. proposed to compress 100 keV ellipsoidal bunches.
- Demonstrated sub-100 fs 0.1 pC beam by velocity bunching.

- **Advantages.**
  - Beam energy similar to conventional UED
  - Detector already existing.



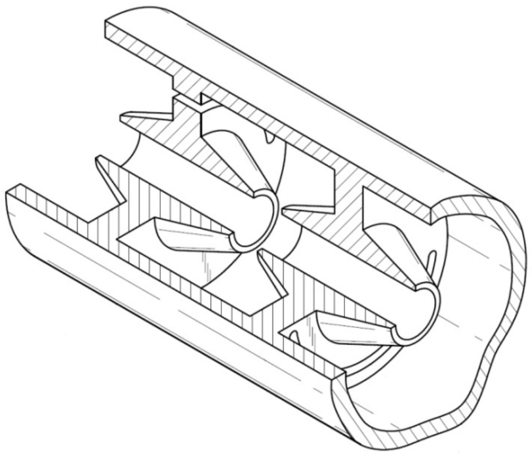
T. Van Oudheusden et al. Phys. Rev. Lett. 105:264801, 2010

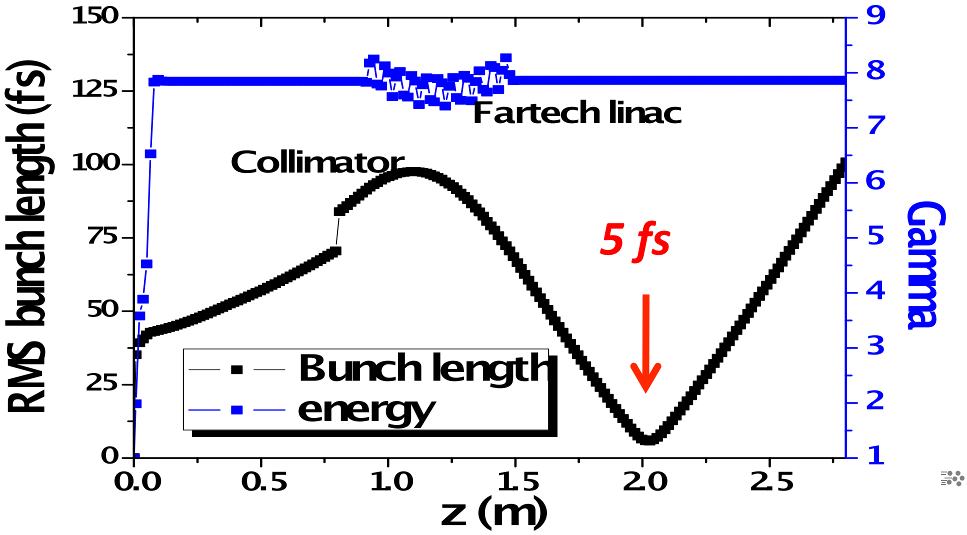
T. Van Oudheusden et al. J. of Appl. Physics, 102:093501 2007

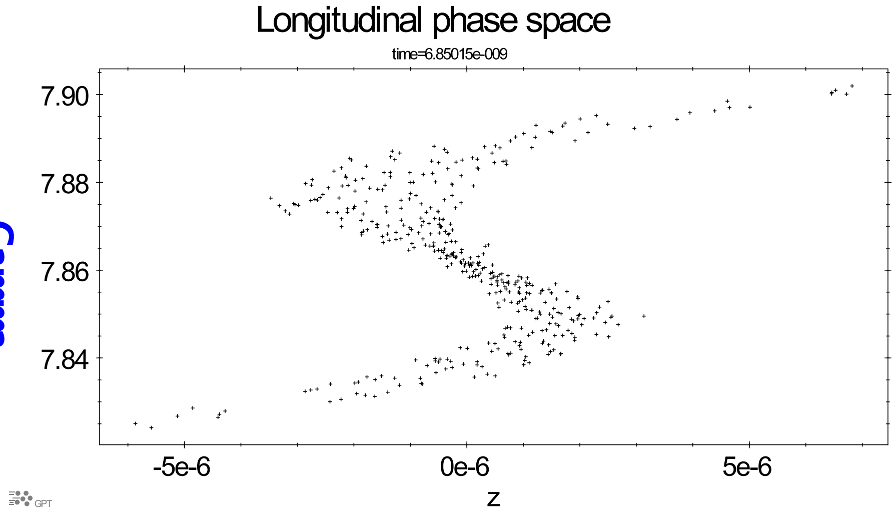


RF Compression at Pegasus

- At relativistic energy velocity compression also works.
  - Larger energy spread, but the sharpness of diffraction patterns is emittance-dominated.
- Space charge effects lower !
- Install in 2011 @ Pegasus: High shunt impedance slot resonant coupled linac developed by *Fartech*.
- Collimator removes path length different trajectories from cathode.
  - Large spot to lower surface charge density.
- Longitudinal focus sub 10 fs.







Conclusions

- RF photoinjector based FRED: “Poor man’s X-FEL”, a new technique for ultrafast structural dynamics.
  - Sub-100 fs temporal resolution. Single shot capability.
  - Irreversible ultrafast transformations
  - Different samples (thickness, gas phase, etc.)
- Lots of new science just behind the corner.
  - Metal sample melting phase transition vs. thickness.
  - THz pump – electron probe.
  - Visualizing phonon oscillations in graphite/graphene.
- Continuosly resolved MeV electron diffraction. Truly single shot technique !
- Towards sub-10 fs temporal resolution
  - Better detectors
  - Novel RF structures
  - RF-deflector based UED
- Great opportunity for cross-fertilization.

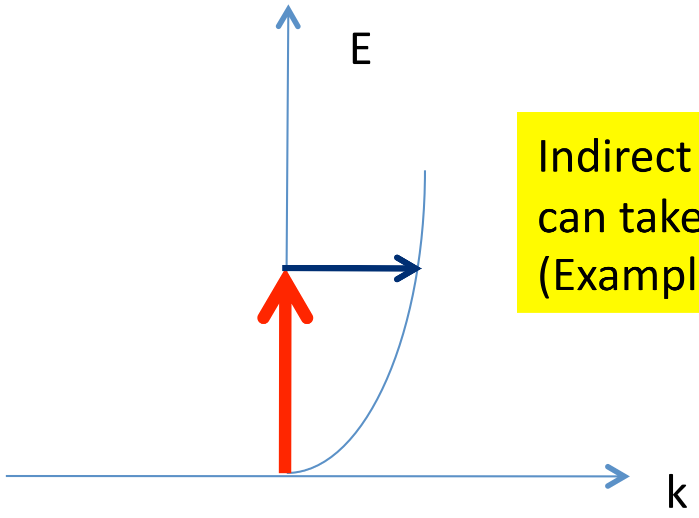
Where extreme time resolution can help?

Strong coupling between lattice and electronic structure: superconductors, Jahn-Teller, ferroelectric, metal-insulator transitions (Example: VO_2)

$$\frac{1}{\tau_{\mathrm{el-ph}}} \approx \frac{3\hbar\lambda\langle\omega^2\rangle}{\pi k_B T_e}$$

At high λ, characteristic time of coupling between lattice and electrons can be few fs

During light excitation, certain structural rearrangements can take place on a time-scale as fast as phonon`s single cicle, i.e. ~1 fs. Example : graphite coherent phonons



Indirect optical transitions, phonon assisted for example, can take few fs and live signatures in the structural dynamics (Example: Cuprates)

UED vs optics and photoemission

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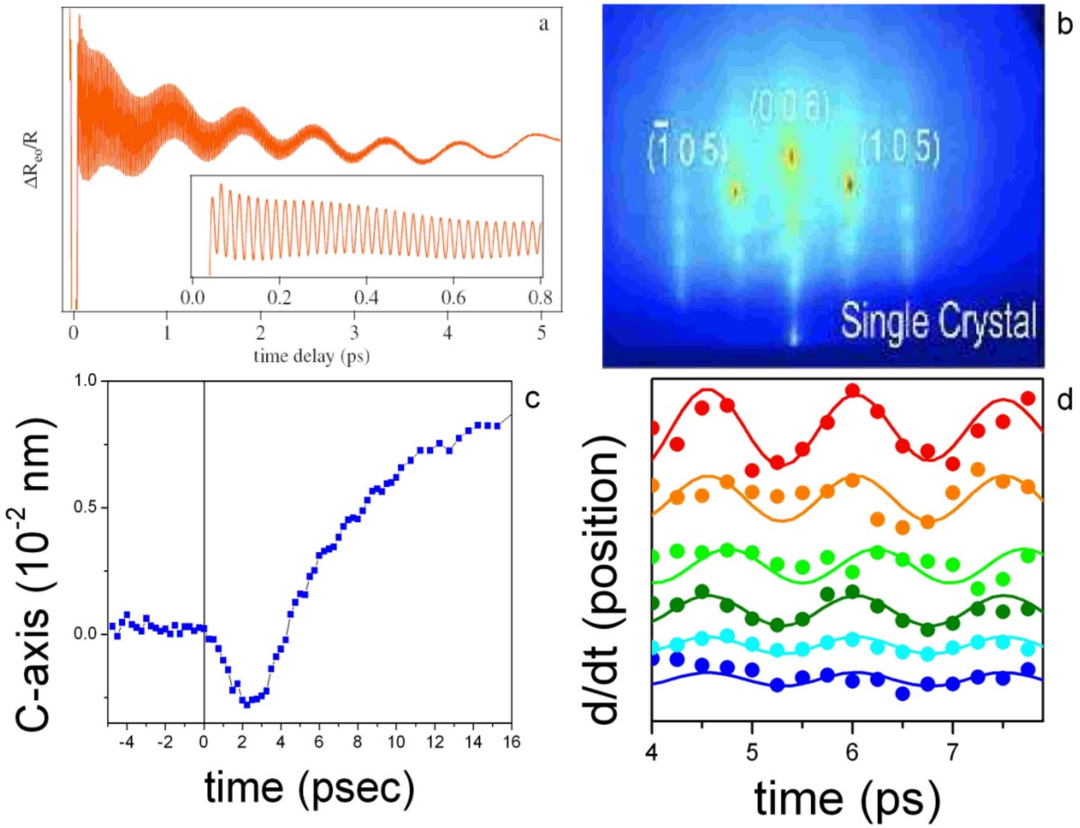
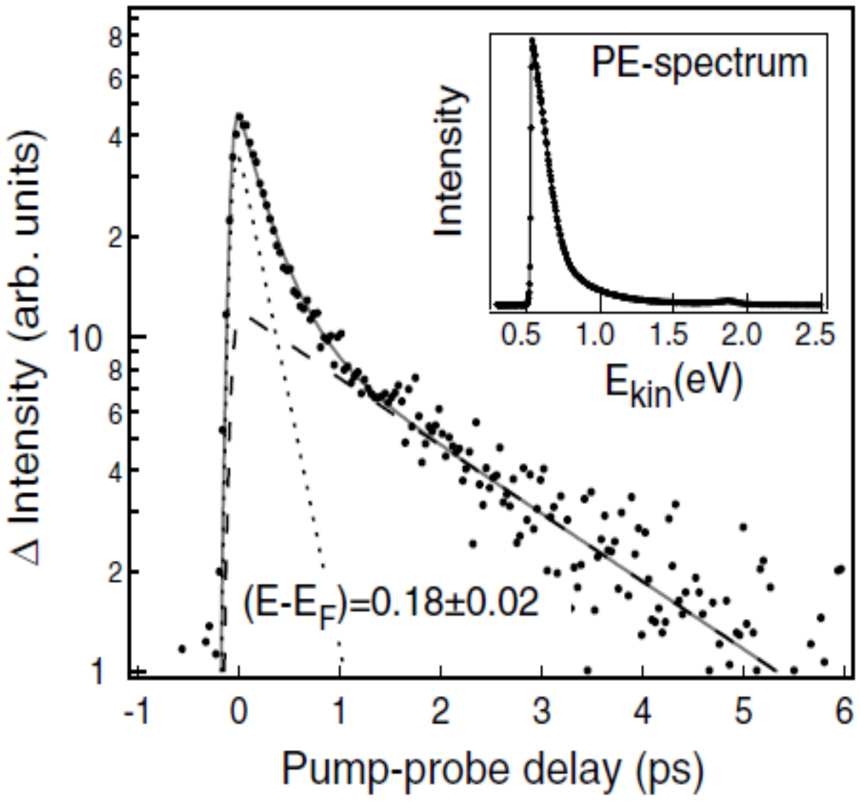
Ultrafast electron-phonon decoupling in graphite

Kunie Ishioka,* Muneaki Hase,† and Masahiro Kitajima





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Anisotropy of Quasiparticle Lifetimes and the Role of Disorder in Graphite from Ultrafast Time-Resolved Photoemission Spectroscopy

Gunnar Moos,[1] Cornelius Gahl,[2] Roman Fasel,[3] Martin Wolf,[2] and Tobias Hertel[1]