Progress in ultrafast x-ray streak cameras at Berkeley Lab

John Byrd (LBNL, Berkeley, California)

Abstract

Streak cameras remain one of the tools for study of ultrafast phenomena. We present progress on modeling of x-ray streak cameras with application to measurement of ultrafast phenomena. Our approach is based on treating the streak camera as a photocathode gun and applying modeling tools for beam optics and electromagnetic fields. We use these models to compare with experimental results from a streak camera developed at the Advanced Light Source. We also show how this model can be used to explore several ideas for achieving sub-100 fsec resolution.

Paper not received
(See slides of talk on following pages)

Progress in ultrafast x-ray streak cameras at Berkeley Lab

John Byrd
23 May 2007

Overview

- Introduction to x-ray streak cameras
- Applications of X-ray SC
- ALS SC R&D program
- Start-to-end SC model
- Future improvements

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People

H. Padmore, J. Feng, T. Young, A. Scholl , J. Nasiatka, A. Comin, A. Bartelt - ESG / ALS
W. Wan - Accelerator Physics Group / ALS
J. Byrd, J. Qiang, G. Huang – Center for Beam Physics / AFRD
R. Falcone (UCB/ALS)
K. Opachich (USD) / ESG, M. Greaves (UCB) / ESG

•Joint effort between beamline and accelerator scientists
•Combined expertise of accelerator tools and detectors
•Light source environment ideal for “mixing the gene pool”

Streaking: a brief history

The first recorded incident of streaking by a college student in the United States occurred in 1804 at then Washington College (now Washington and Lee University) when senior George William Crump was arrested for running nude through Lexington, Virginia, where the university is located. Crump was suspended for the academic session, and would later go on to become a U.S. Congressman and Ambassador to Chile.

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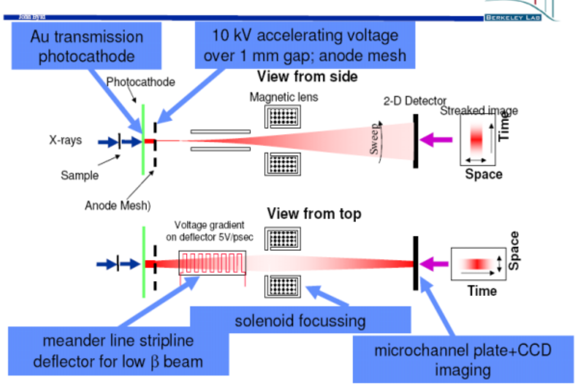
ALS X-ray streak camera



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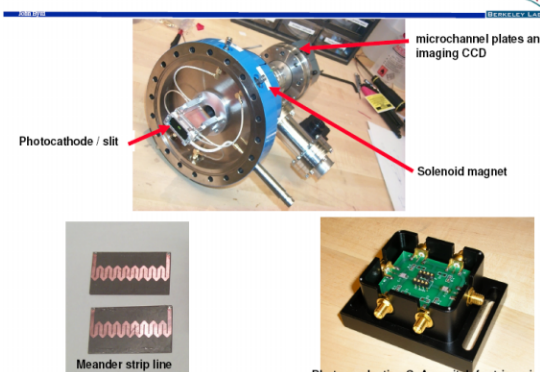
ALS x-ray streak camera



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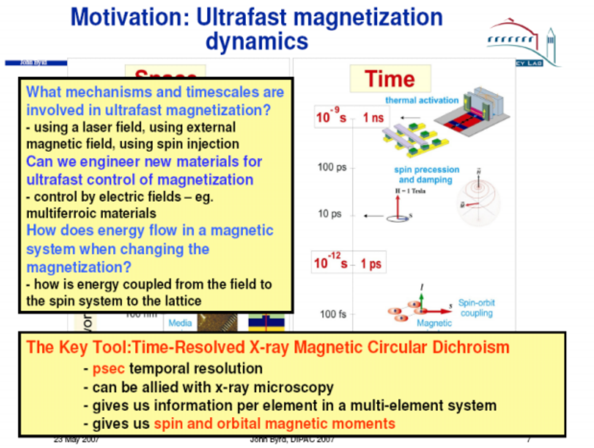
Motivation: Ultrafast magnetization dynamics
Time
What mechanisms and timescales are involved in ultrafast magnetization?
- using a laser field, using external magnetic field, using spin injection
Can we engineer new materials for ultrafast control of magnetization
- control by electric fields – eg. multiferroic materials
How does energy flow in a magnetic system when changing the magnetization?
- how is energy coupled from the field to the spin system to the lattice
10⁻⁹ s 1 ns
thermal activation
100 ps
spin precession and damping
10 ps
10⁻¹² s 1 ps
100 fs
Spin-orbit coupling
The Key Tool:Time-Resolved X-ray Magnetic Circular Dichroism
- psec temporal resolution
- can be allied with x-ray microscopy
- gives us information per element in a multi-element system
- gives us spin and orbital magnetic moments
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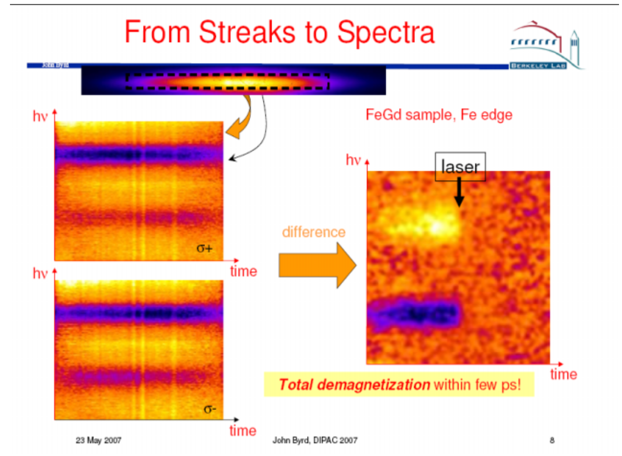
From Streaks to Spectra
hν
FeGd sample, Fe edge
σ+
time
difference
laser
σ-
time
Total demagnetization within few ps!
time
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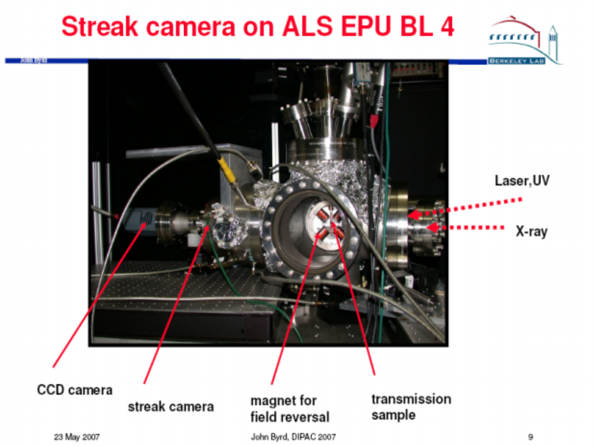
Streak camera on ALS EPU BL 4
Laser,UV
X-ray
CCD camera
streak camera
magnet for field reversal
transmission sample
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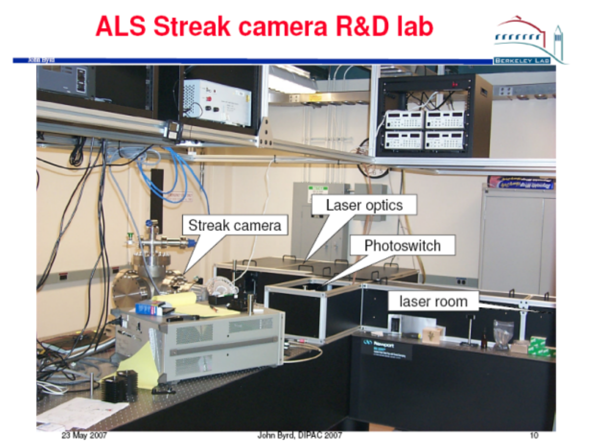
ALS Streak camera R&D lab
Laser optics
Streak camera
Photoswitch
laser room
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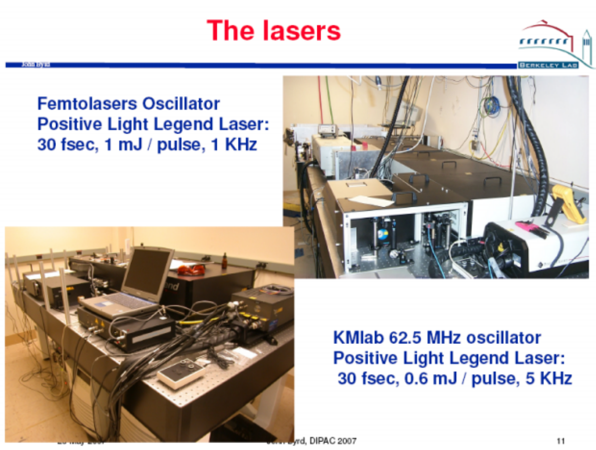
The lasers
Femtolasers Oscillator
Positive Light Legend Laser:
30 fsec, 1 mJ / pulse, 1 KHz
KMlab 62.5 MHz oscillator
Positive Light Legend Laser:
30 fsec, 0.6 mJ / pulse, 5 KHz
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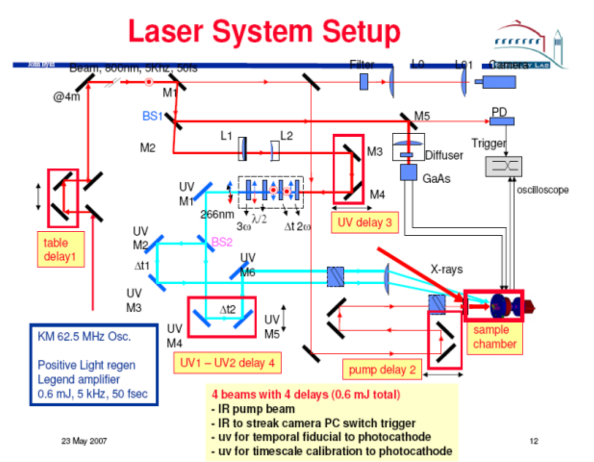
Laser System Setup
@4m
M1
BS1
M2
L1
L2
M3
M4
M5
PD
Diffuser
GaAs
Trigger
oscilloscope
table delay1
UV M1
266nm
3ω
λ/2
Δt 2ω
UV delay 3
UV M2
BS2
Δt1
UV M6
X-rays
UV M3
Δt2
UV M4
UV M5
sample chamber
KM 62.5 MHz Osc.
Positive Light regen Legend amplifier
0.6 mJ, 5 kHz, 50 fsec
UV1 – UV2 delay 4
pump delay 2
4 beams with 4 delays (0.6 mJ total)
- IR pump beam
- IR to streak camera PC switch trigger
- uv for temporal fiducial to photocathode
- uv for timescale calibration to photocathode
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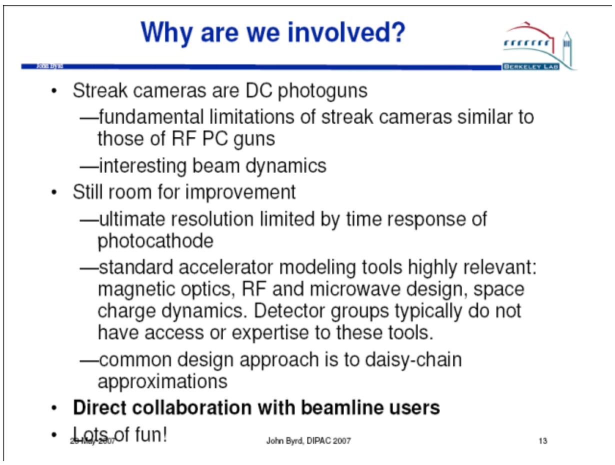
Why are we involved?
• Streak cameras are DC photoguns
—fundamental limitations of streak cameras similar to those of RF PC guns
—interesting beam dynamics
• Still room for improvement
—ultimate resolution limited by time response of photocathode
—standard accelerator modeling tools highly relevant: magnetic optics, RF and microwave design, space charge dynamics. Detector groups typically do not have access or expertise to these tools.
—common design approach is to daisy-chain approximations
• Direct collaboration with beamline users
• Lots of fun!
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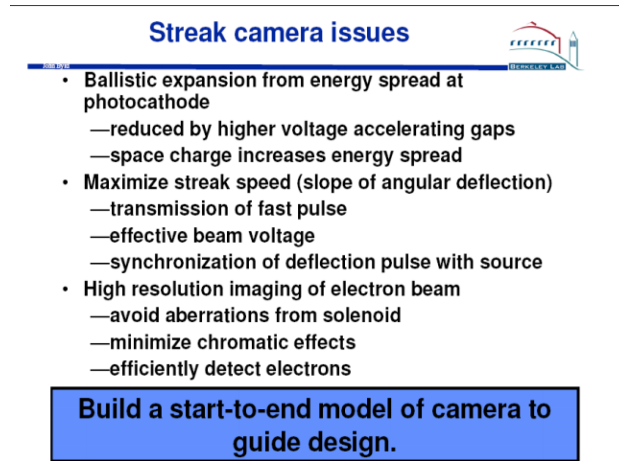
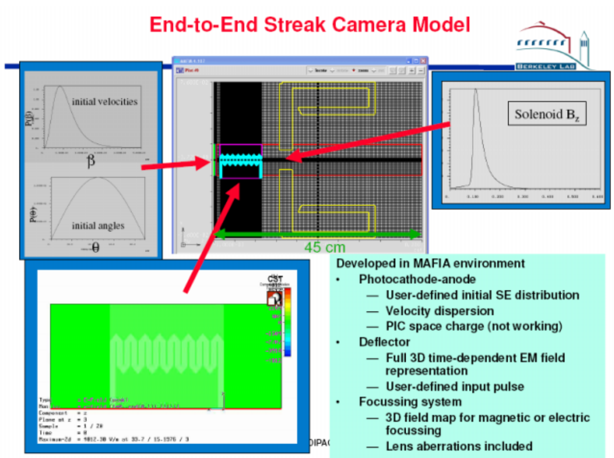
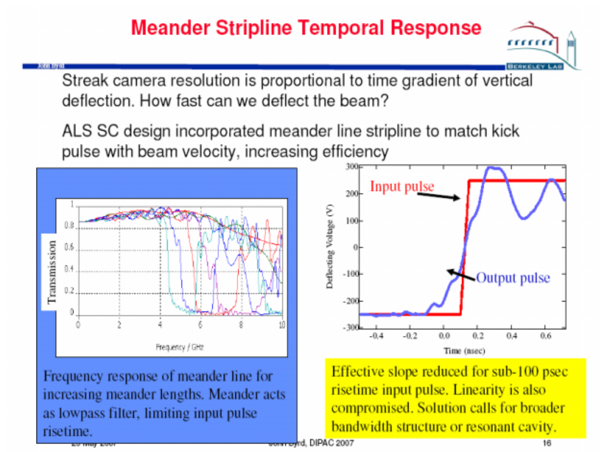

Streak camera issues
• Ballistic expansion from energy spread at photocathode
—reduced by higher voltage accelerating gaps
—space charge increases energy spread
• Maximize streak speed (slope of angular deflection)
—transmission of fast pulse
—effective beam voltage
—synchronization of deflection pulse with source
• High resolution imaging of electron beam
—avoid aberrations from solenoid
—minimize chromatic effects
—efficiently detect electrons
Build a start-to-end model of camera to guide design.


End-to-End Streak Camera Model
initial velocities
β
initial angles
θ
45 cm
Solenoid B_z
Developed in MAFIA environment
• Photocathode-anode
— User-defined initial SE distribution
— Velocity dispersion
— PIC space charge (not working)
• Deflector
— Full 3D time-dependent EM field representation
— User-defined input pulse
• Focussing system
— 3D field map for magnetic or electric focussing
— Lens aberrations included


Meander Stripline Temporal Response
Streak camera resolution is proportional to time gradient of vertical deflection. How fast can we deflect the beam?
ALS SC design incorporated meander line stripline to match kick pulse with beam velocity, increasing efficiency
Transmission
Frequency / GHz
Input pulse
Output pulse
Deflecting Voltage (V)
Time (nsec)
Frequency response of meander line for increasing meander lengths. Meander acts as lowpass filter, limiting input pulse risetime.
Effective slope reduced for sub-100 psec risetime input pulse. Linearity is also compromised. Solution calls for broader bandwidth structure or resonant cavity.
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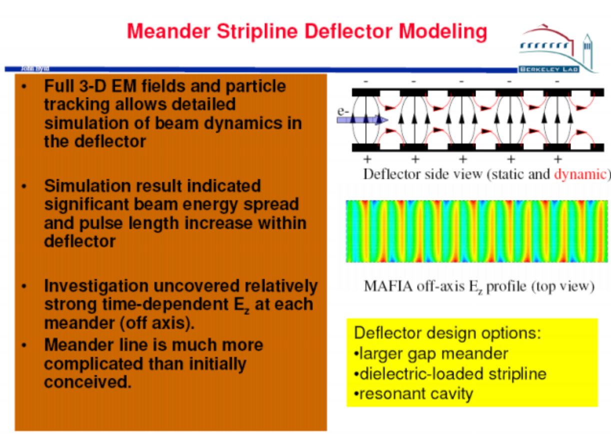
Meander Stripline Deflector Modeling
• Full 3-D EM fields and particle tracking allows detailed simulation of beam dynamics in the deflector
• Simulation result indicated significant beam energy spread and pulse length increase within deflector
• Investigation uncovered relatively strong time-dependent E_z at each meander (off axis).
• Meander line is much more complicated than initially conceived.
e-
Deflector side view (static and dynamic)
MAFIA off-axis E_z profile (top view)
Deflector design options:
•larger gap meander
•dielectric-loaded stripline
•resonant cavity
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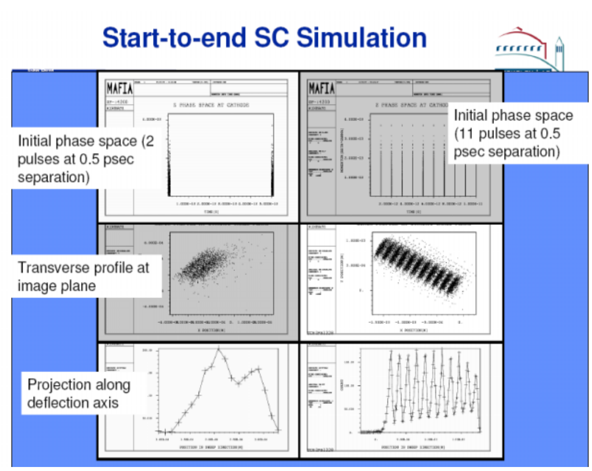
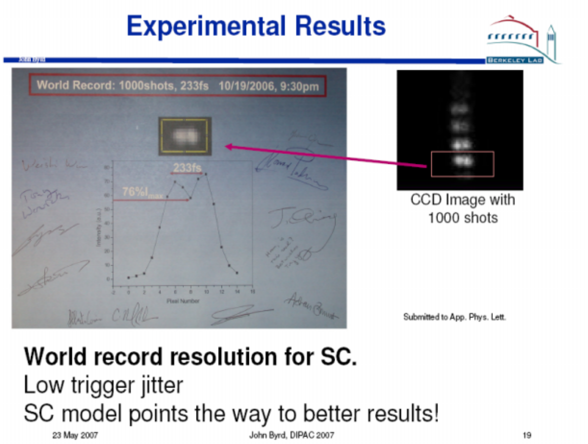

Start-to-end SC Simulation
MAFIA
Initial phase space (2 pulses at 0.5 psec separation)
Initial phase space (11 pulses at 0.5 psec separation)
Transverse profile at image plane
Projection along deflection axis


Experimental Results
World Record: 1000shots, 233fs 10/19/2006, 9:30pm
233fs
76%
CCD Image with
1000 shots
Submitted to App. Phys. Lett.
World record resolution for SC.
Low trigger jitter
SC model points the way to better results!
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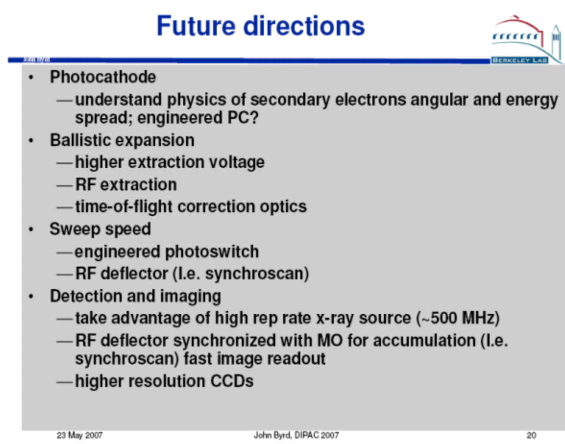
Future directions
• Photocathode
—understand physics of secondary electrons angular and energy spread; engineered PC?
• Ballistic expansion
—higher extraction voltage
—RF extraction
—time-of-flight correction optics
• Sweep speed
—engineered photoswitch
—RF deflector (I.e. synchroscan)
• Detection and imaging
—take advantage of high rep rate x-ray source (~500 MHz)
—RF deflector synchronized with MO for accumulation (I.e. synchroscan) fast image readout
—higher resolution CCDs
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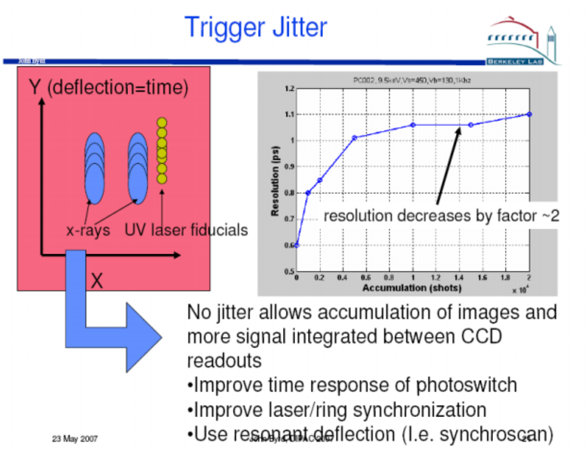
Trigger Jitter
Y (deflection=time)
x-rays
UV laser fiducials
X
Resolution (ps)
resolution decreases by factor ~2
Accumulation (shots)
No jitter allows accumulation of images and more signal integrated between CCD readouts
•Improve time response of photoswitch
•Improve laser/ring synchronization
•Use resonant deflection (I.e. synchroscan)
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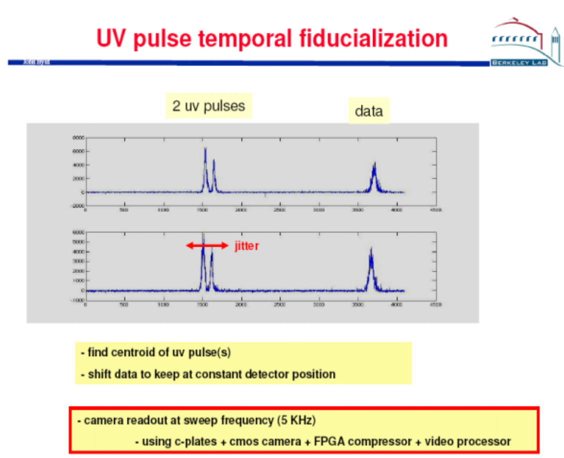
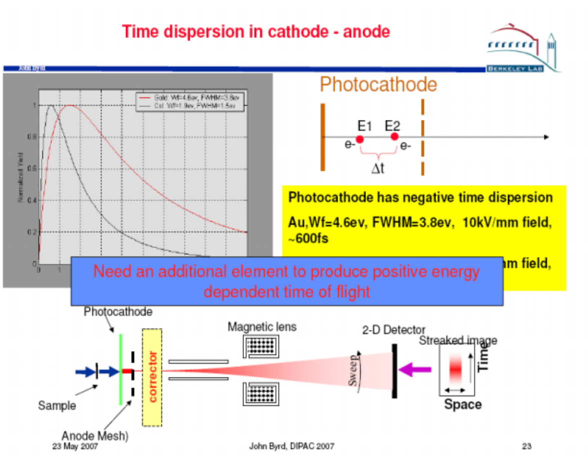

UV pulse temporal fiducialization
2 uv pulses
data
jitter
- find centroid of uv pulse(s)
- shift data to keep at constant detector position
- camera readout at sweep frequency (5 KHz)
- using c-plates + cmos camera + FPGA compressor + video processor


Time dispersion in cathode - anode
Photocathode
E1 E2
e-
e-
Δt
Photocathode has negative time dispersion
Au,Wf=4.6ev, FWHM=3.8ev, 10kV/mm field, ~600fs
Need an additional element to produce positive energy dependent time of flight
Photocathode
Magnetic lens
2-D Detector
Streaked image
corrector
Sweep
Time
Space
Sample
Anode Mesh)
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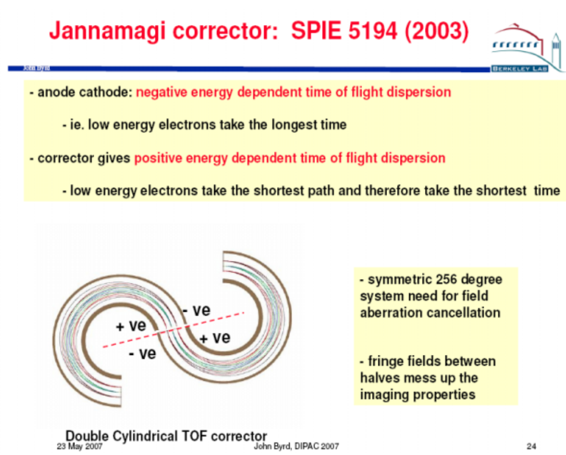
Jannamagi corrector: SPIE 5194 (2003)
- anode cathode: negative energy dependent time of flight dispersion
- ie. low energy electrons take the longest time
- corrector gives positive energy dependent time of flight dispersion
- low energy electrons take the shortest path and therefore take the shortest time
+ ve
- ve
- ve
+ ve
- symmetric 256 degree system need for field aberration cancellation
- fringe fields between halves mess up the imaging properties
Double Cylindrical TOF corrector
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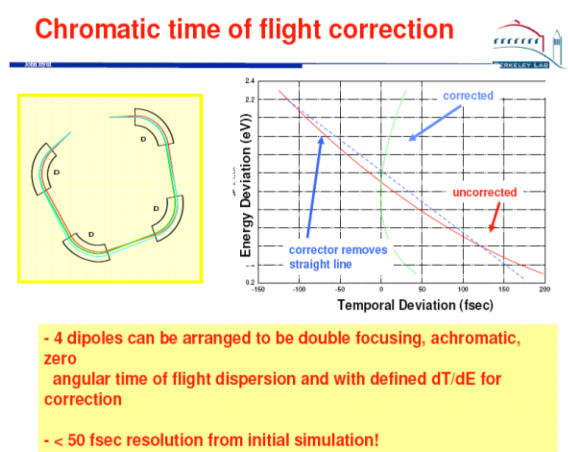
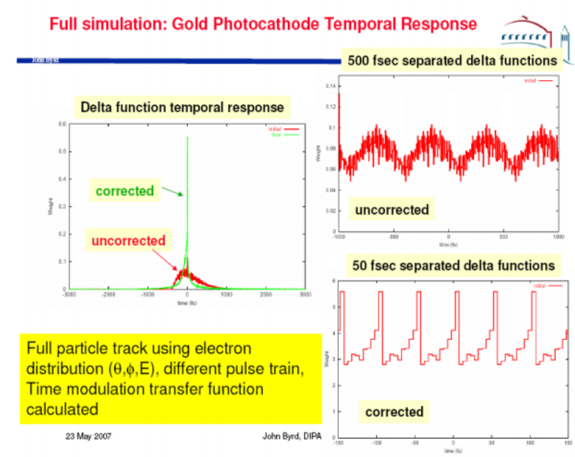

Chromatic time of flight correction
corrected
uncorrected
corrector removes straight line
Energy Deviation (eV)
Temporal Deviation (fsec)
- 4 dipoles can be arranged to be double focusing, achromatic, zero angular time of flight dispersion and with defined dT/dE for correction
- < 50 fsec resolution from initial simulation!


Full simulation: Gold Photocathode Temporal Response
500 fsec separated delta functions
Delta function temporal response
corrected
uncorrected
uncorrected
50 fsec separated delta functions
corrected
Full particle track using electron distribution (θ,φ,E), different pulse train, Time modulation transfer function calculated
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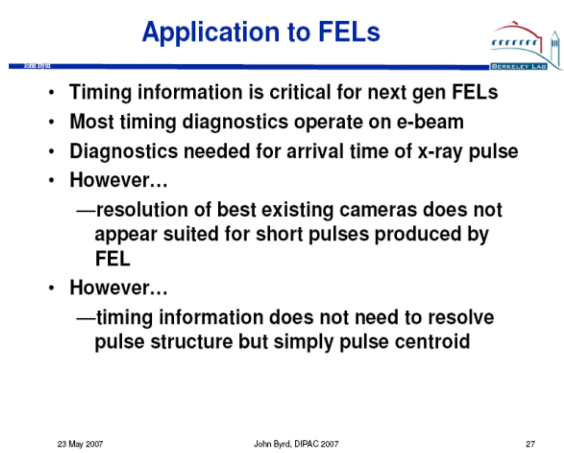
Application to FELs
• Timing information is critical for next gen FELs
• Most timing diagnostics operate on e-beam
• Diagnostics needed for arrival time of x-ray pulse
• However…
—resolution of best existing cameras does not appear suited for short pulses produced by FEL
• However…
—timing information does not need to resolve pulse structure but simply pulse centroid
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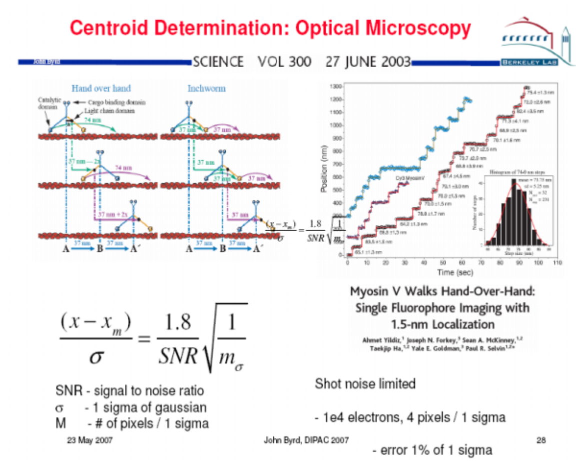
Centroid Determination: Optical Microscopy
SCIENCE VOL 300 27 JUNE 2003
Hand over hand
Inchworm
Position (nm)
Time (sec)
$$\frac{(x-x_m)}{\sigma} = \frac{1.8}{SNR}\sqrt{\frac{1}{m_\sigma}}$$
Myosin V Walks Hand-Over-Hand: Single Fluorophore Imaging with 1.5-nm Localization
SNR - signal to noise ratio
σ - 1 sigma of gaussian
M - # of pixels / 1 sigma
Shot noise limited
- 1e4 electrons, 4 pixels / 1 sigma
- error 1% of 1 sigma
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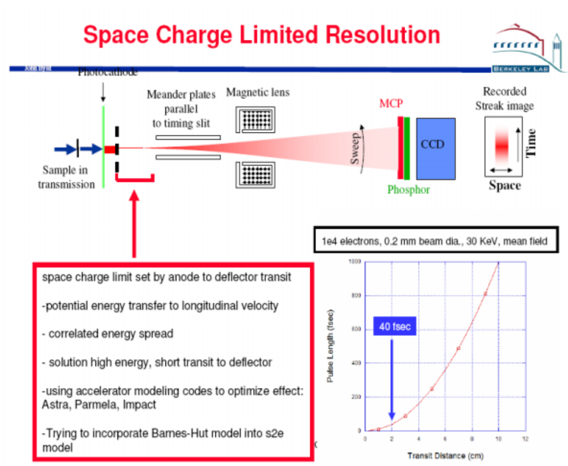
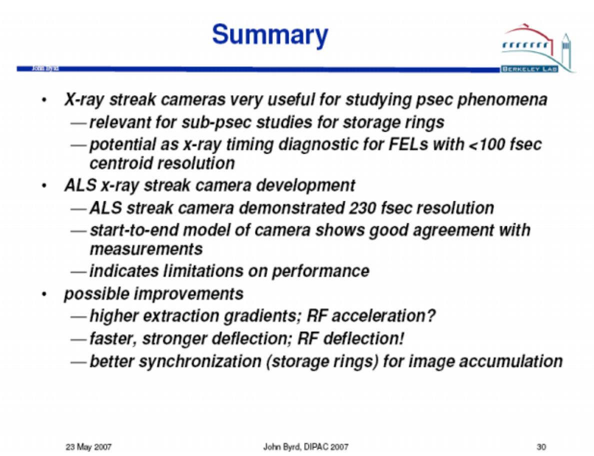

Space Charge Limited Resolution
Photocathode
Meander plates parallel to timing slit
Magnetic lens
MCP
Recorded Streak image
Sweep
CCD
Time
Sample in transmission
Phosphor
Space
1e4 electrons, 0.2 mm beam dia., 30 KeV, mean field
space charge limit set by anode to deflector transit
-potential energy transfer to longitudinal velocity
- correlated energy spread
- solution high energy, short transit to deflector
-using accelerator modeling codes to optimize effect: Astra, Parmela, Impact
-Trying to incorporate Barnes-Hut model into s2e model
40 fsec
Pulse Length (fsec)
Transit Distance (cm)


Summary
• X-ray streak cameras very useful for studying psec phenomena
—relevant for sub-psec studies for storage rings
—potential as x-ray timing diagnostic for FELs with <100 fsec centroid resolution
• ALS x-ray streak camera development
—ALS streak camera demonstrated 230 fsec resolution
—start-to-end model of camera shows good agreement with measurements
—indicates limitations on performance
• possible improvements
—higher extraction gradients; RF acceleration?
—faster, stronger deflection; RF deflection!
—better synchronization (storage rings) for image accumulation
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