Optical and x-ray streak cameras for pulse length measurement

John Byrd

Overview

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

Principle of the Streak Camera

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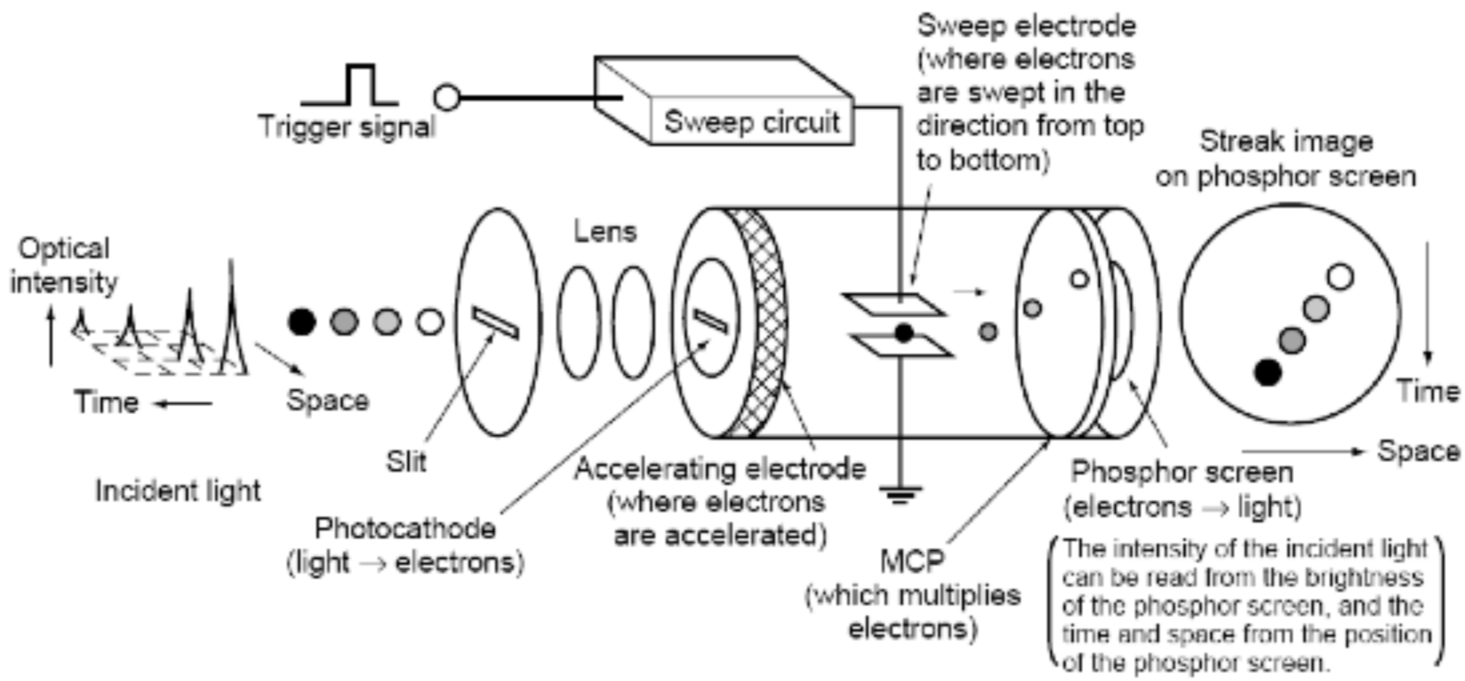

- Compare streak camera to gated camera:
  - Light→Photocathode→Electrons→MCP→Screen→CCD as before, but…
  - Remove: Vertical spatial information, with a tight focus and a thin slit.
  - Add: Accelerating electrode after the photocathode
    Fast vertical sweep in drift space before the MCP
  - Vertical coordinate now displays the arrival time of the photons.

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Single Bunch, Triggered Sweep

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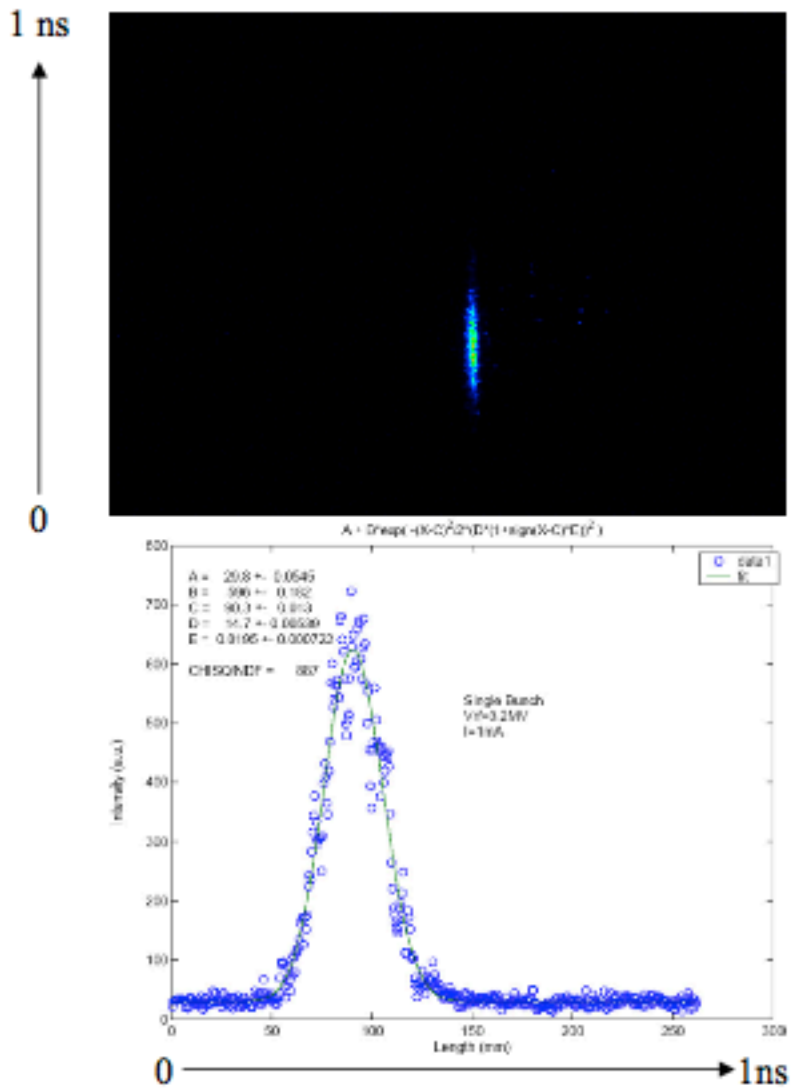

- Single bunch in the LER (low-energy ring) of PEP-II
- Projection along the vertical axis gives the profile in time.
  - Beam fits an asymmetric Gaussian (faster rise than fall)
  - Studied variation with ring current and RF voltage.

Focus Mode: Effect of finite spot size

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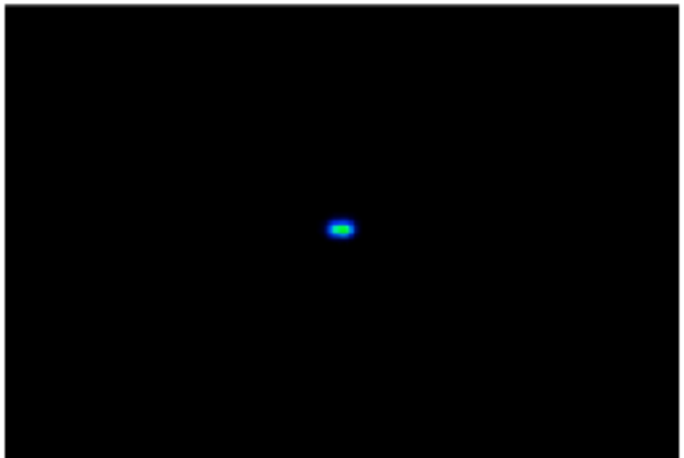

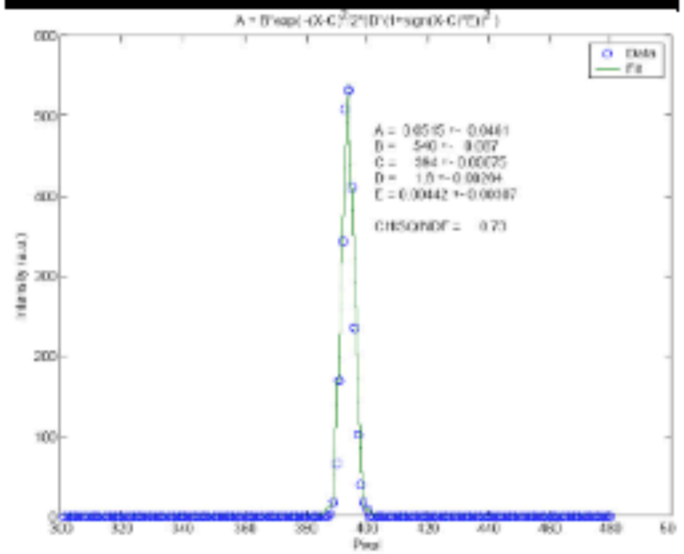

- A big spot with the sweep off degrades time resolution.
  - Once sweep is on, source's height and time spread will mix.
- Check setup in Focus Mode.
  - Use a narrow entrance slit.
    - Typically 10 to 30 μm
  - With sweep off, focus all optics, both external and within the camera, to get the smallest spot on the CCD.
  - Measure RMS spot size in pixels.
- Correct streak data for resolution.
  - Convert pixels to time scale of streak.
  - Subtract resolution in quadrature from beam's measured RMS length.

$$\sigma = \sqrt{\sigma_{\text{meas}}^2 - \sigma_{\text{res}}^2}$$

Signal/Noise

John Byrd

- How much light?
  - Too little gives shot noise and more error in the fit, as shown in the previous single-bunch streak image.
  - Too much:
    - Space charge between the photocathode and the MCP spreads out the electron pulse, broadening the measured temporal profile
    - Damage to the photocathode, MCP, and phosphor screen.
    - **Warning!** The screen is easily damaged in Focus Mode, since without the sweep, the light is concentrated in a small spot. Always attenuate the light heavily (~ 40 dB, also called an optical density of 4) before opening the shutter in Focus Mode.
  - The best time resolution is found with visible noise in the image. Optimize by varying the attenuation and MCP gain.

Timing Jitter

- One cure for noise is to add images from several measurements.
  - But if the sweep time is not fixed relative to the beam, the sum will be broader than any one fit.
  - Jitter in sweep (~ 20 ps) can be close to bunch length.
  - Jitter in trigger can be worse: DG535 has 50 ps.
  - And any synchrotron oscillation will add to this spread.
- First find the mean of the time profile of each image, and then overlap them at their means.

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Synchroscan

- For stable bunches stored in a ring, there is an alternative way to beat noise.
- Since the bunch is locked to the ring's RF, an RF sine wave can sweep the beam without jitter.
  - Want only the linear part of the sine, near the zero crossing.
    - Good for sweeps spanning short time scales: $\Delta t_{sweep} << 1/f_{sweep}$
  - Deflection plates incorporated in a high-Q resonator tuned to f_{sweep} to get enough field to sweep the full MCP in Δt_{sweep}
  - Upper limit to drive frequency for the resonator
    - $f_{sweep} < 125$ MHz for our Hamamatsu C5680
    - Low compared to typical ring RF: $f_{RF} \approx 500$ MHz
    - PEP-II and SPEAR-3 use $f_{RF} = 476$ MHz, and so our camera uses a subharmonic: $f_{sweep} = 476/4 = 119$ MHz

Etalon calibration

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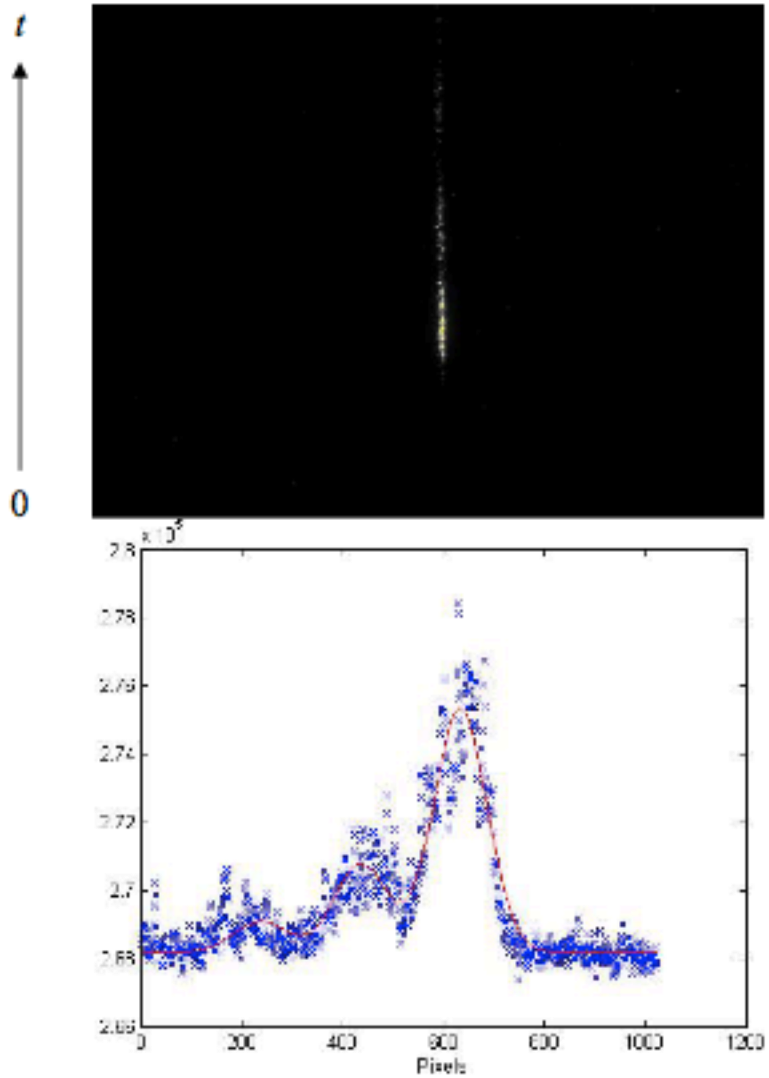

- Etalon: two parallel, partially reflective surfaces
  - We use a fused silica window, L=15.00 mm thick. Both sides have reflectivity $R=1-T \approx 0.5$.
- Insert near streak camera.
  - Main peak is reduced by T^2 .
  - Internal reflection produces a series of echoes
    - Each smaller by factors of R^2
    - Each delayed by nL/c
    - n is the index of refraction (~1.5) at the wavelength used
  - Fit to series of delayed Gaussians to calibrate ps/pixel

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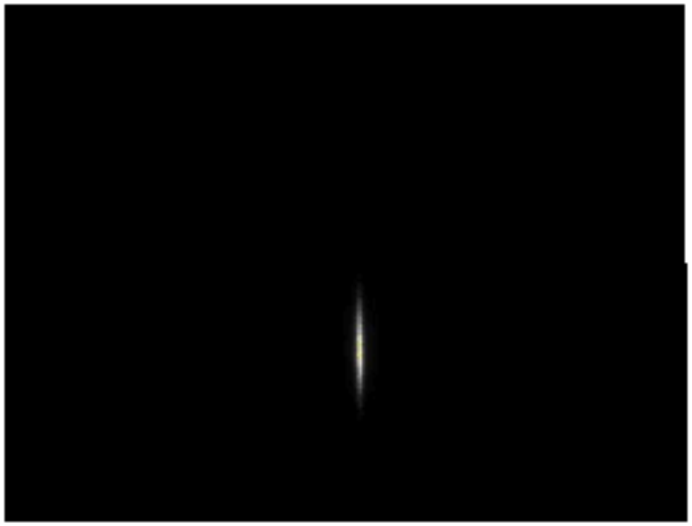
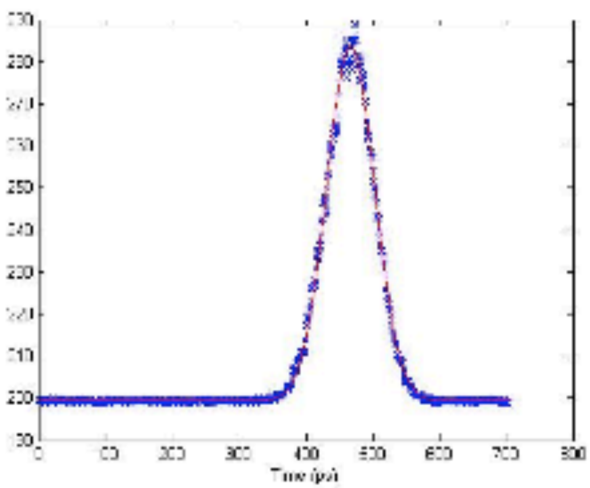
Dual-sweep synchroscan

- Horizontal axis has interesting spatial information.
  - Reveals *xt* (or *yt*) coupling: head-tail instability.
- But what if the instability changes along a bunch train or over several turns?
  - Add a second set of plates to sweep the beam horizontally.
  - This deflection is slow, spanning ns, μs, or even ms.
  - Makes a stripe of consecutive bunches.
    - Like the rotating mirror, but on a faster time scale, and displaying longitudinal rather than transverse behavior.

Single bunch with synchroscan

John By

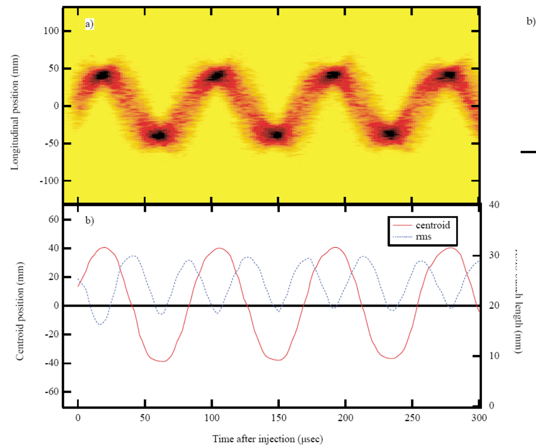




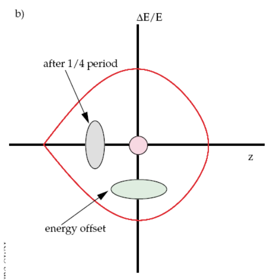
- Less noise in this image and profile than in single sweep.
- CCD accumulates signal over many sweeps (ms), and so the space charge is low.
  - Bright image without broadening or risk of damage.
- Direction of time in the image depends on the sine phase as the light arrives.
  - Sine sweeps up and down.
  - Camera remains on, capturing signal in both directions.

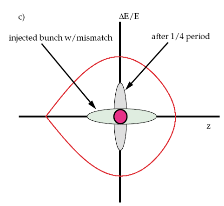
ALS study of longitudinal beam dynamics at injection

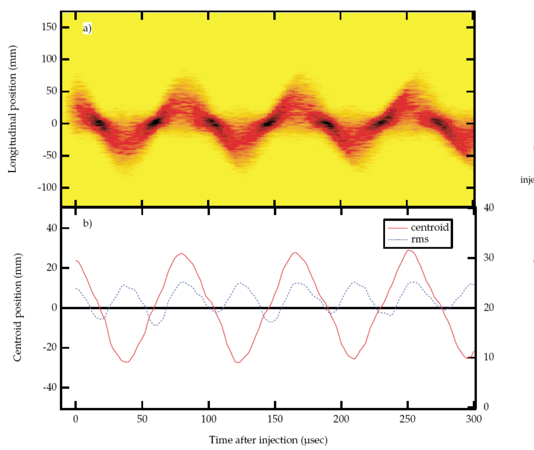
John Byrd



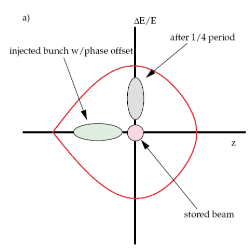
olor) (a) Injection transient with an energy offset. (b) Centroid and rms of the bunch di:

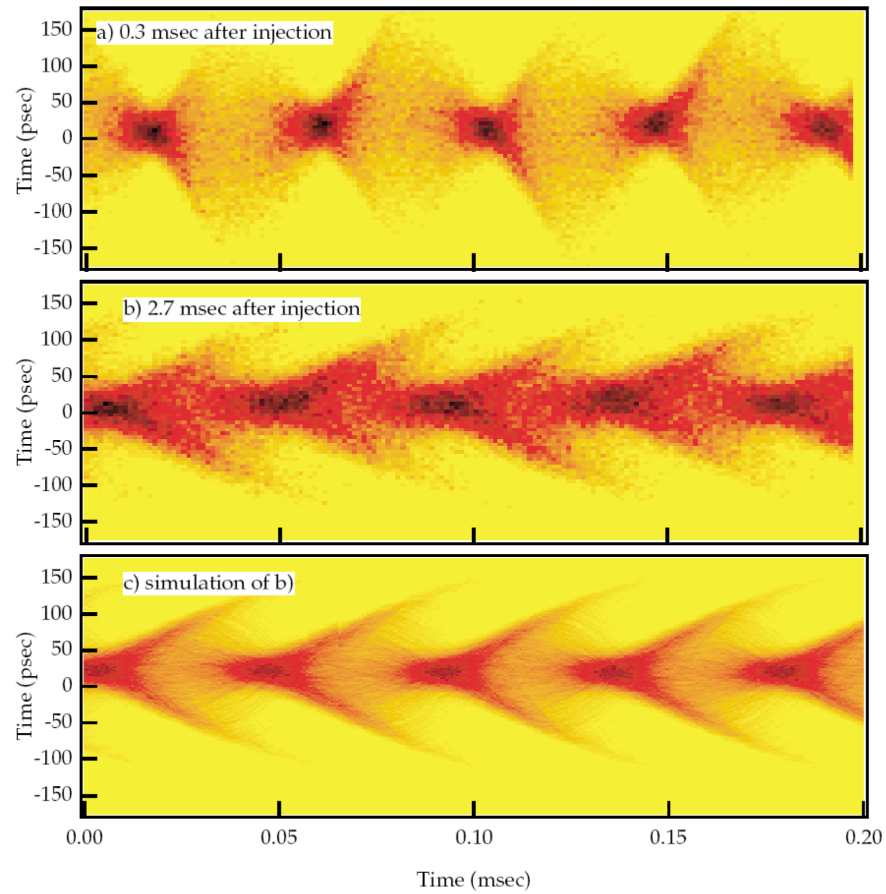






Color) (a) Injection transient with a phase offset. (b) Centroid and rms of the bunch dist





SC image 0.3 ms following injection showing modulation of the bunch length. (b) SC image 2.7 ms
ı of the large amplitude particles. (c) A computer simulated image found from tracking.

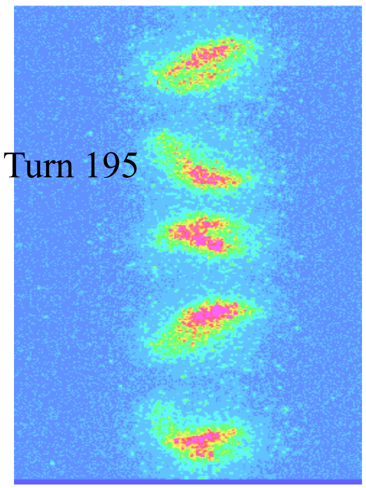
J. M. Byrd and S. De Santis, “Longitudinal injection transients in an electron storage ring,” Phys. Rev. ST AB 4, 024401(2001)

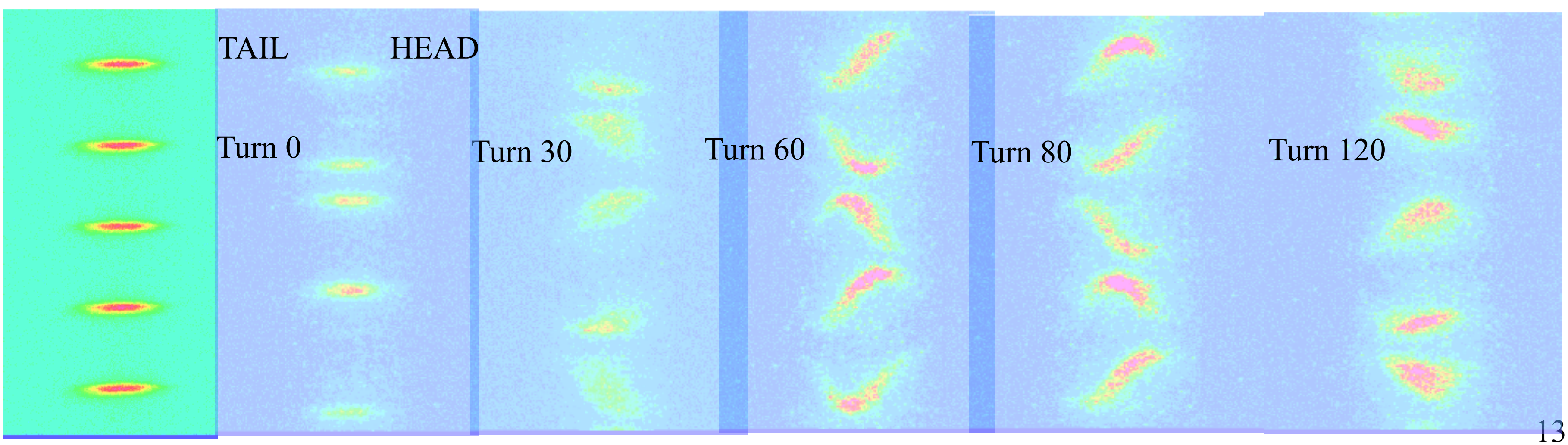
Synchro-betatron coupled motion - 1

John Byrd

Excited Head-Tail Oscillation

- **Synchro-betatron coupled motion excited by a transverse kicker**
- **The motion has major contribution to decoherence of betatron motion**
- **Proposal by Weiming Guo to generate ps x-ray pulse. To date, we have produced 6 ps photon bunch from 25 ps electron bunches.**





Imaging in the longitudinal phase space

John Byrd

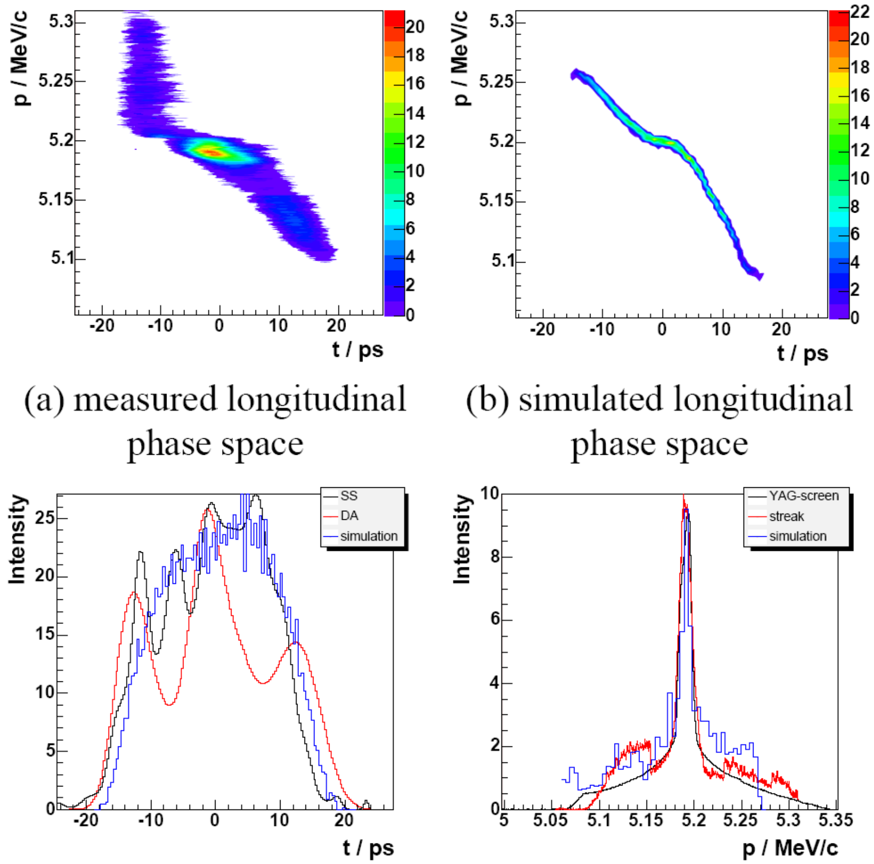
On streak camera monitor, the location of an electron's image point is given by

$$x = x_\beta + \eta\delta$$

$$y = y_\beta + v_{streak} t$$

At a highly dispersive section, using a fast sweep, the energy and time terms dominate in the expressions, and we have an approximate longitudinal phase space map.

In linac, such map can be obtained at the spectrometer.



(a) measured longitudinal phase space (b) simulated longitudinal phase space

(c) longitudinal distribution (d) momentum distribution

J. Rönsch, et al, "Longitudinal phase space studies at PITZ," FEL'05, p 552.

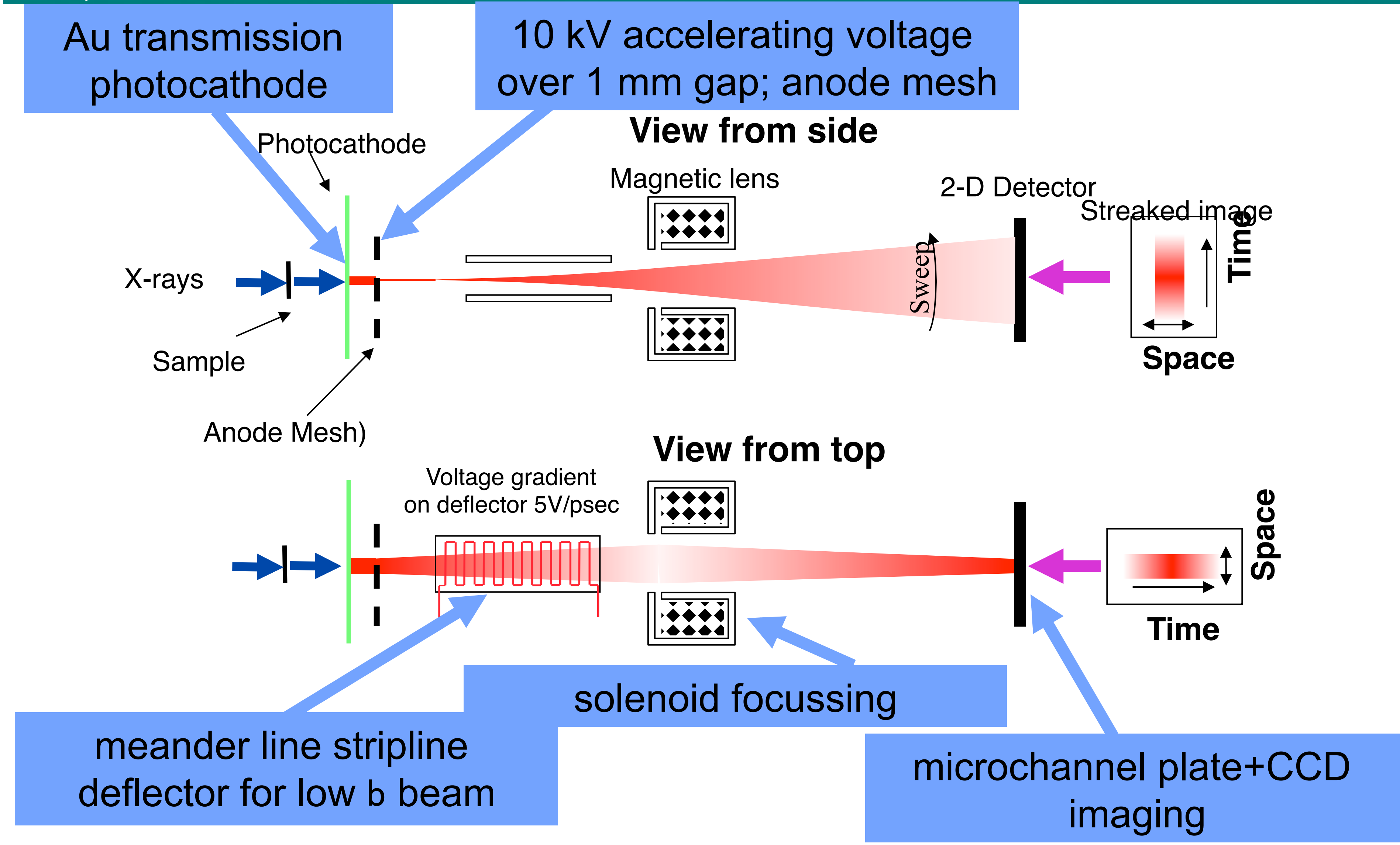
ALS x-ray streak camera development

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"

ALS X-ray streak camera

John Byrd

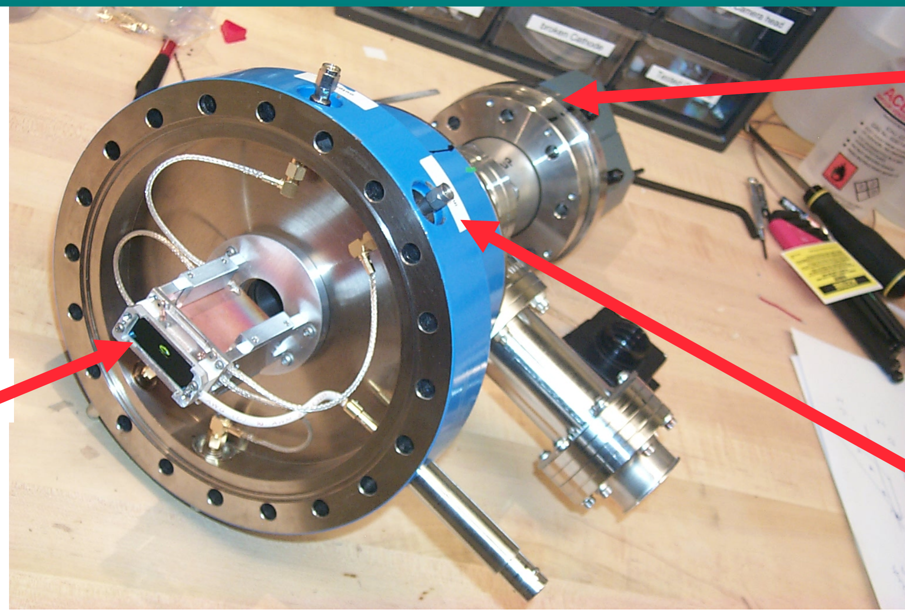


ALS x-ray streak camera

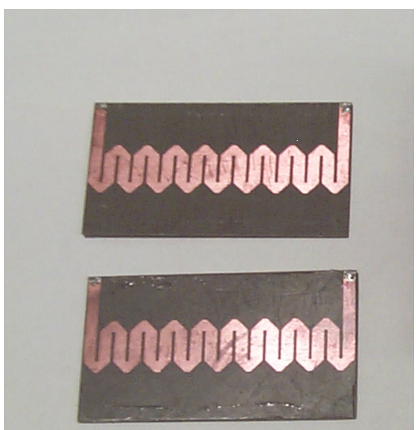
John Byrd

microchannel plates and imaging CCD

Photocathode / slit



Solenoid magnet



Meander strip line

Photoconductive GaAs switch for triggering

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Motivation: Ultrafast magnetization dynamics

John Byrd

What mechanisms and timescales are involved in ultrafast magnetization?

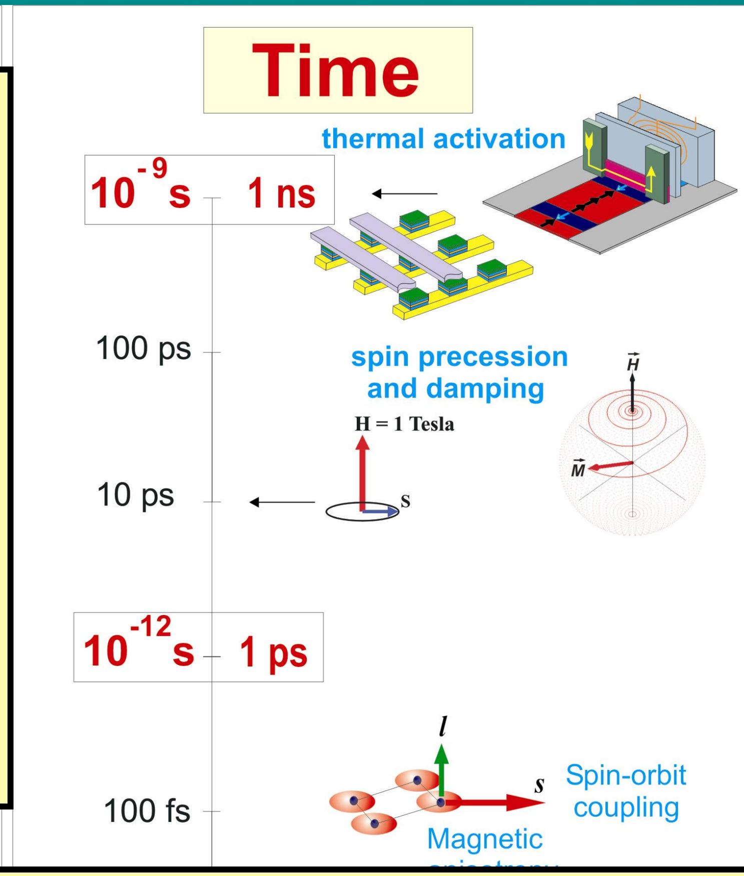
- using a laser field, using external magnetic field, using spin injection

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

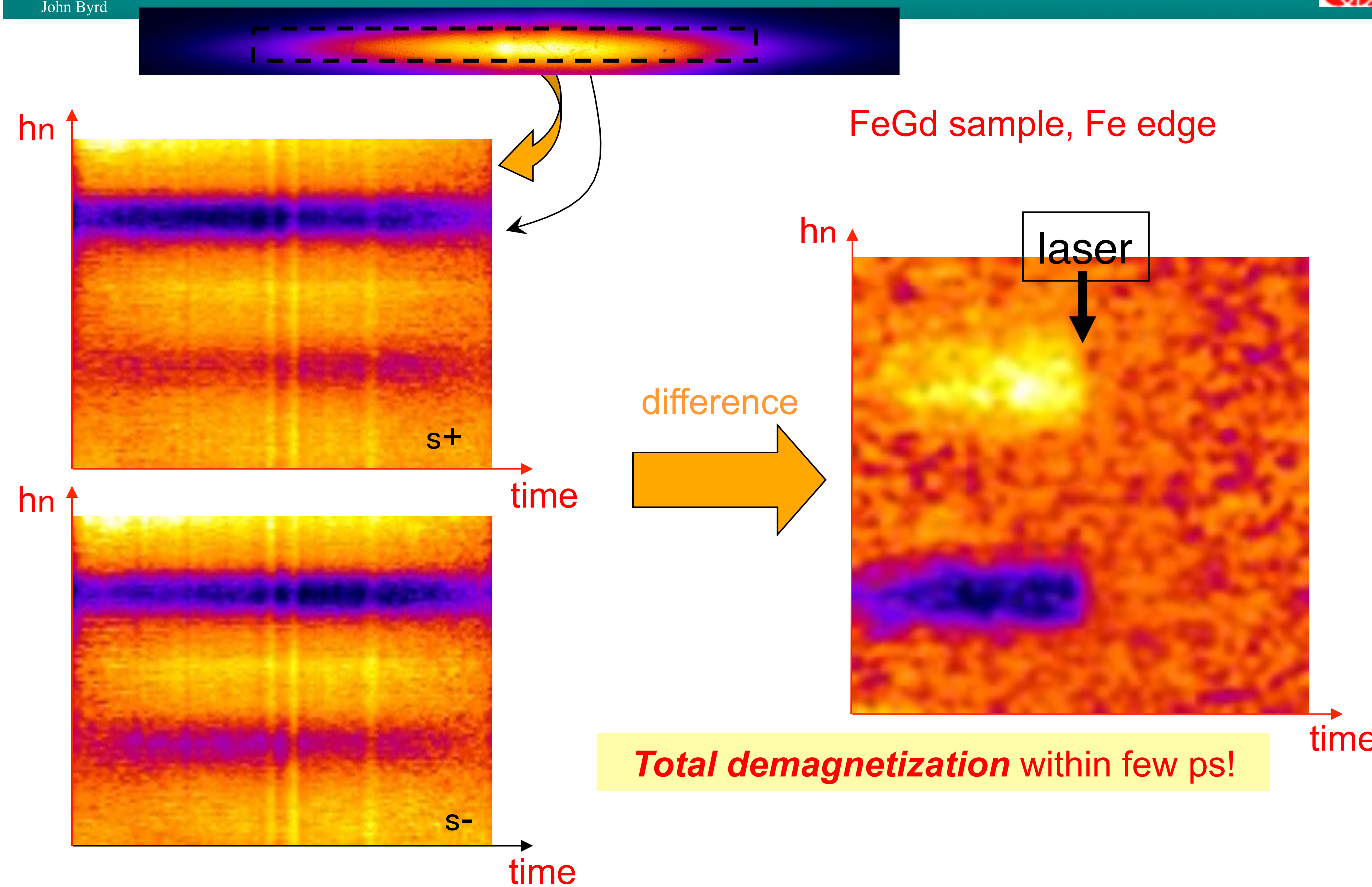


The Key Tool:Time-Resolved X-ray Magnetic Circular Dichroism

- **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**

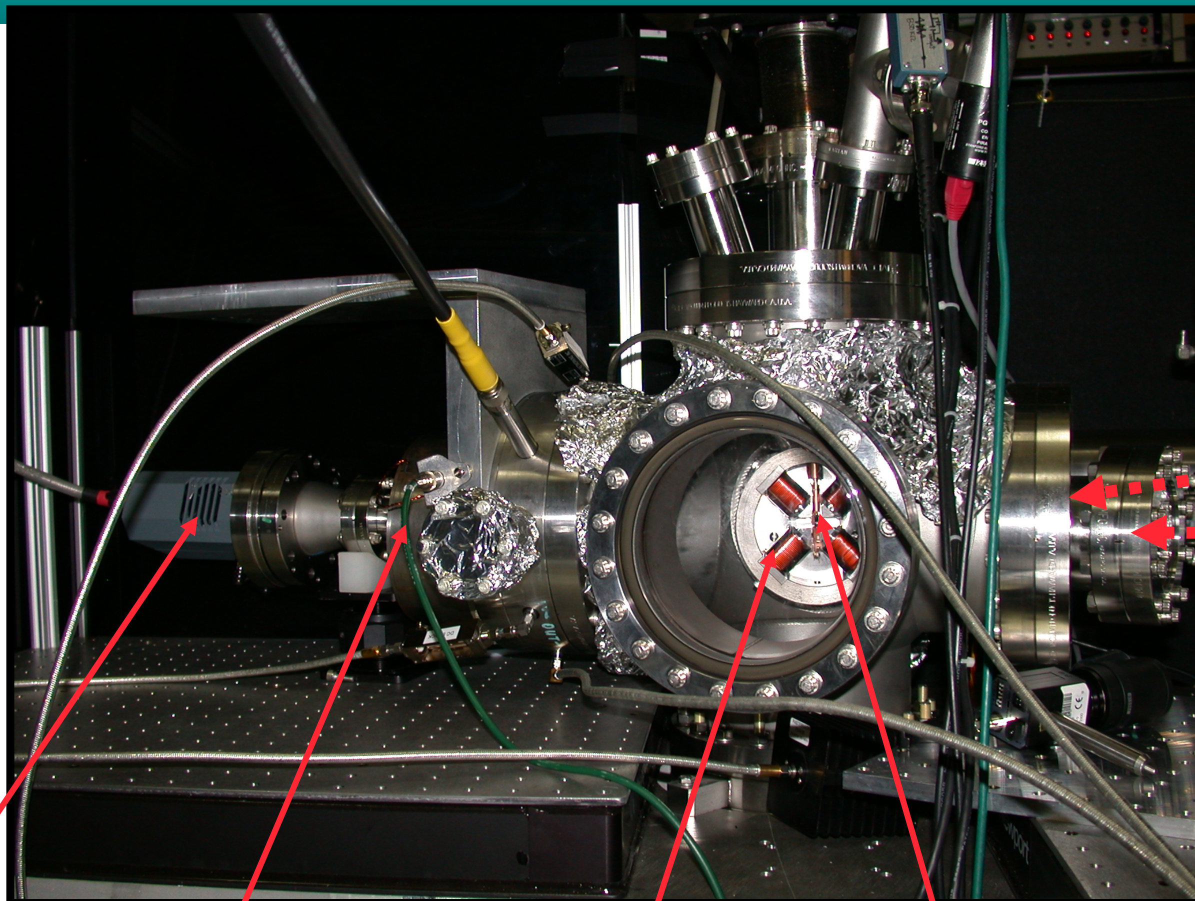
From Streaks to Spectra

John Byrd



Total demagnetization within few ps!

Streak camera on ALS EPU BL 4



CCD camera

streak camera

magnet for
field reversal

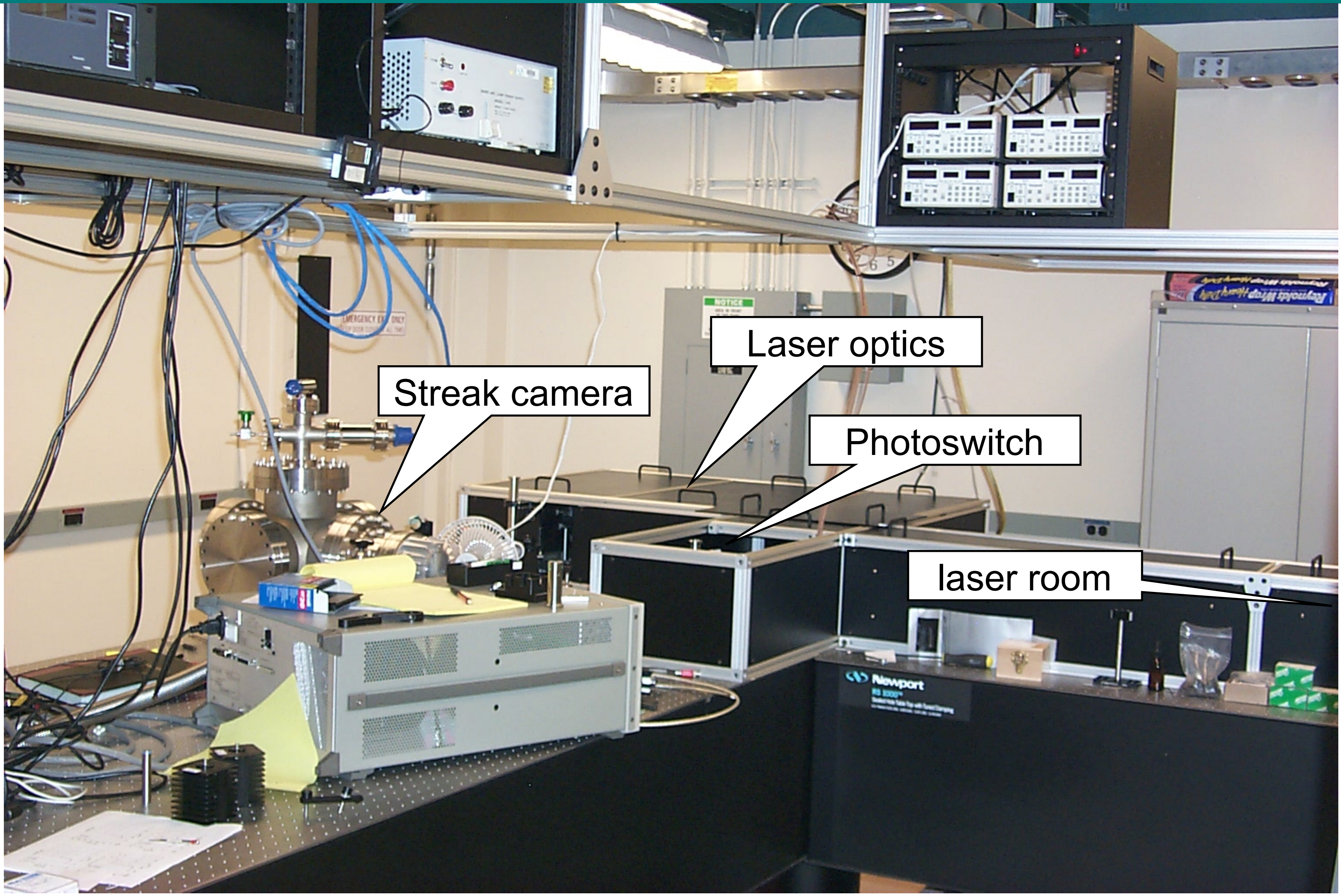
transmission
sample

Laser,UV

X-ray

ALS Streak camera R&D lab

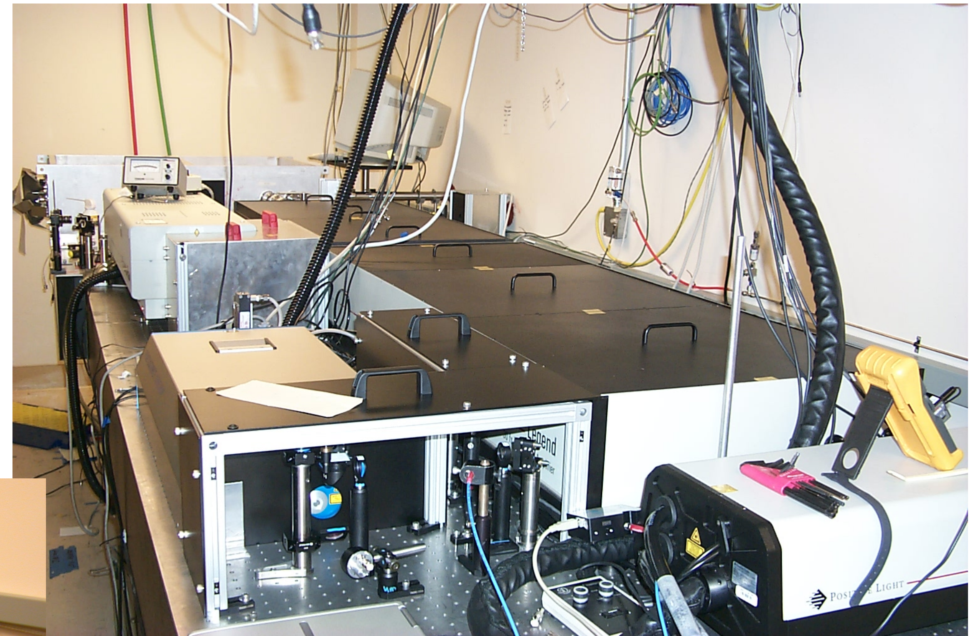
John Byrd

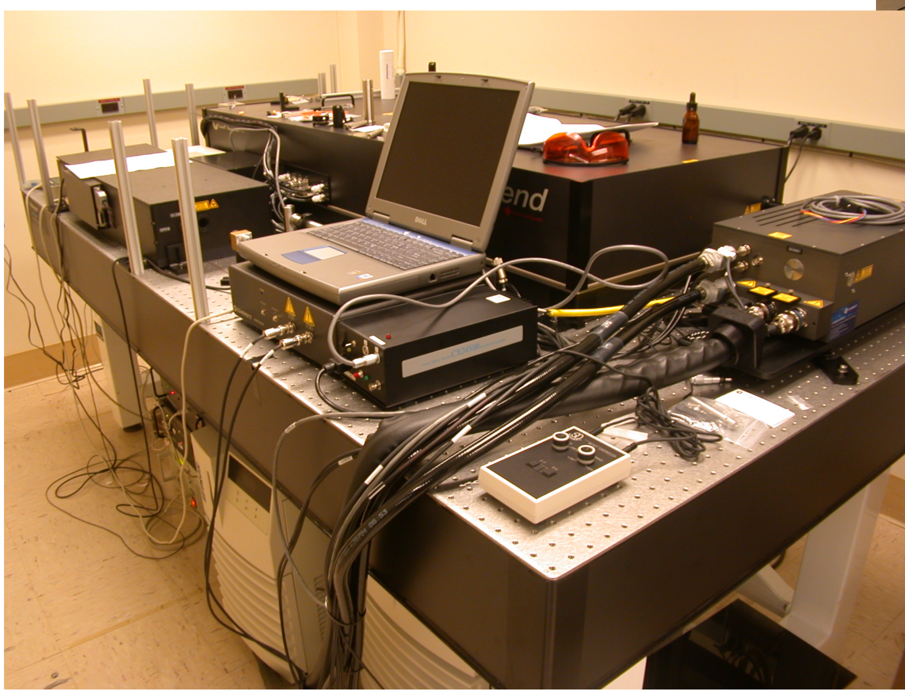


The lasers

John Byrd

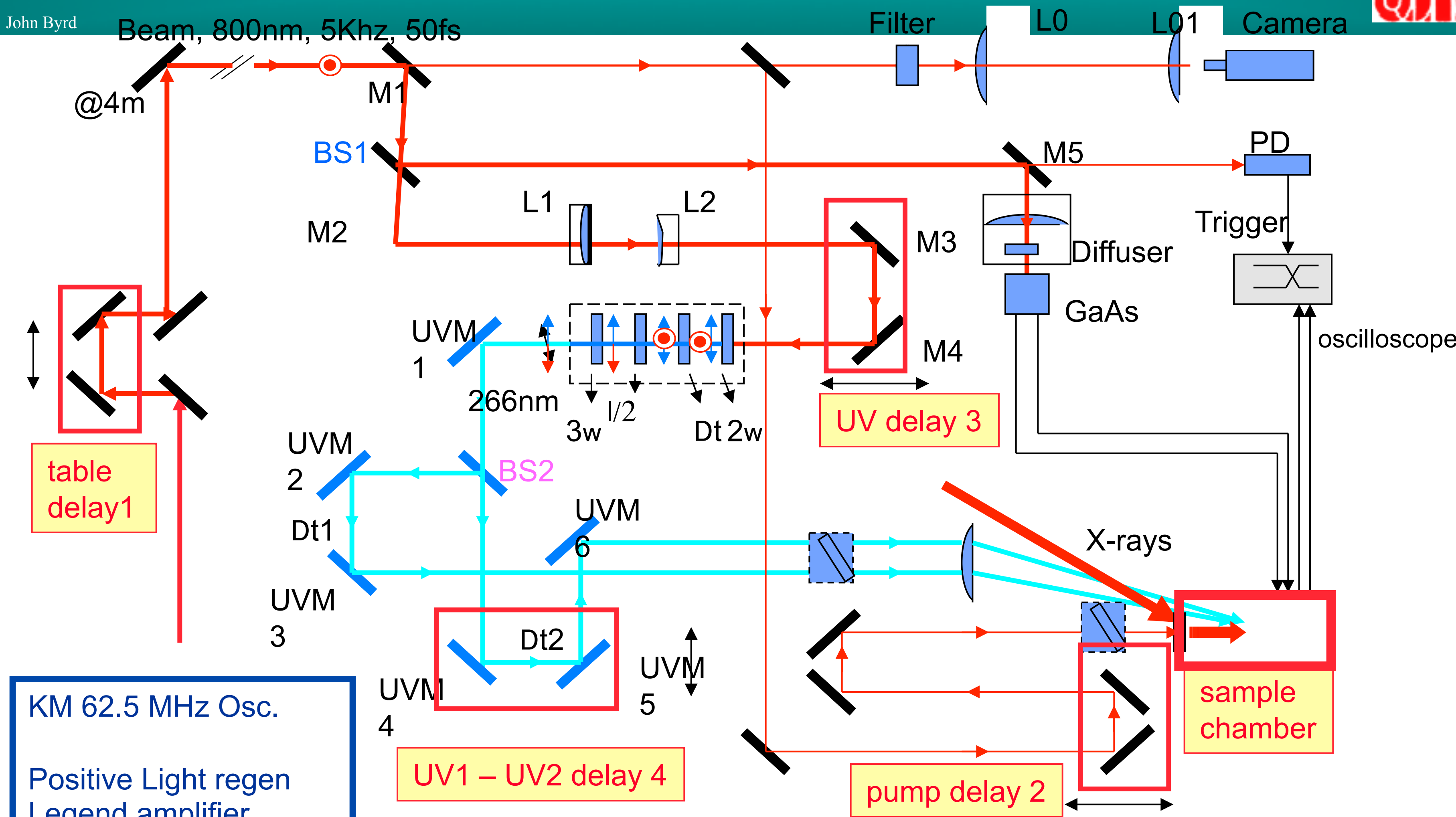
Femtolasers Oscillator
Positive Light Legend Laser:
30 fsec, 1 mJ / pulse, 1 KHz





KMlab 62.5 MHz oscillator
Positive Light Legend Laser:
30 fsec, 0.6 mJ / pulse, 5 KHz

Laser System Setup



KM 62.5 MHz Osc.

Positive Light regen
Legend amplifier
0.6 mJ, 5 kHz, 50 fsec

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**

Why are we involved?

John Byrd

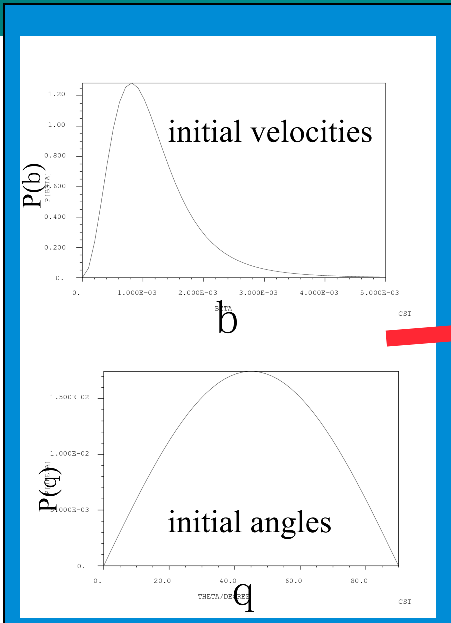
- Streak cameras are DC photoguns
  - —fundamental limitations of streak cameras similar to those of RF PC guns
  - —interesting beam dynamics
- Still room for improvement
  - —ultimate resolution limited by time response of photocathode
  - —standard accelerator modeling tools highly relevant: magnetic 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!

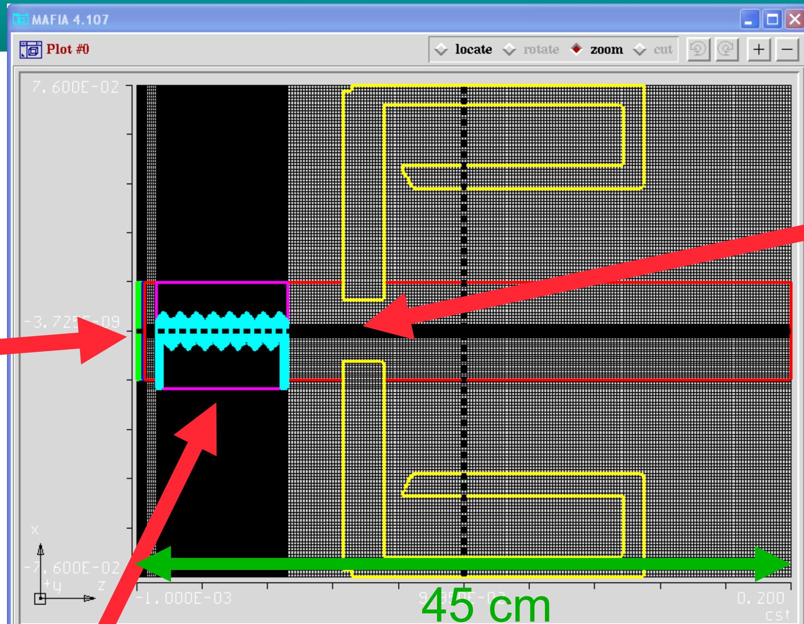
Streak camera issues

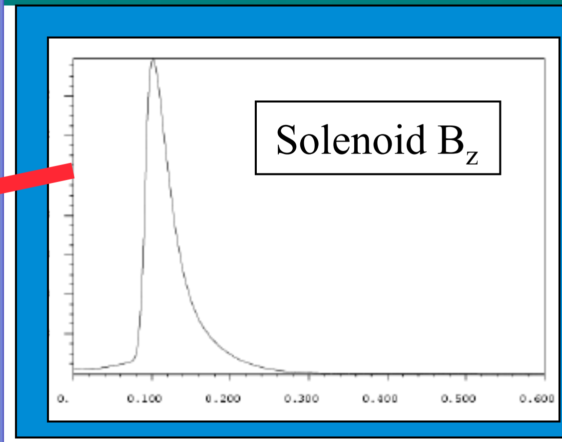
- Ballistic expansion from energy spread at photocathode
  —reduced by higher voltage accelerating gaps
  —space charge increases energy spread
- Maximize streak speed (slope of angular deflection)
  —transmission of fast pulse
  —effective beam voltage
  —synchronization of deflection pulse with source
- High resolution imaging of electron beam
  —avoid aberrations from solenoid
  —minimize chromatic effects
  —efficiently detect electrons

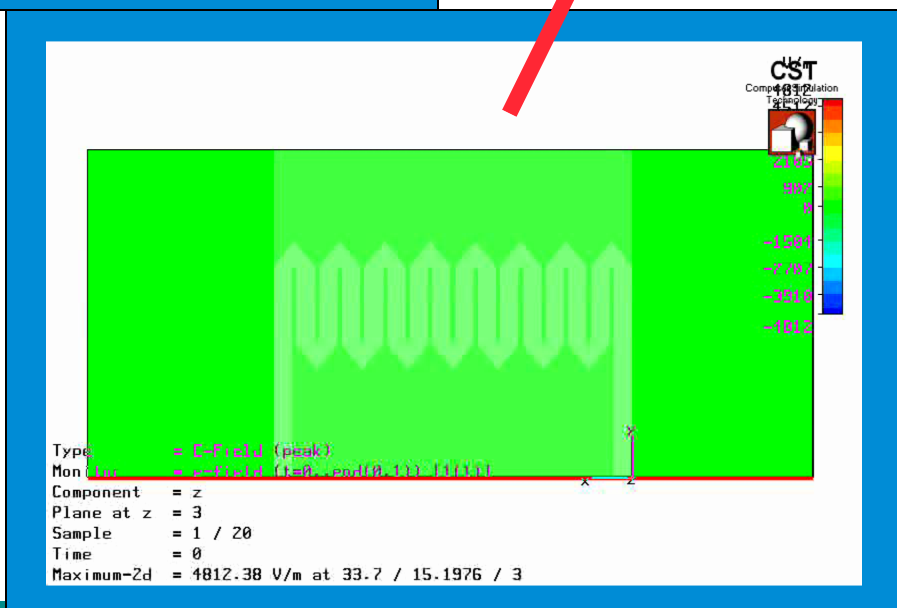
Build a start-to-end model of camera to guide design.

End-to-End Streak Camera Model









Developed in MAFIA environment

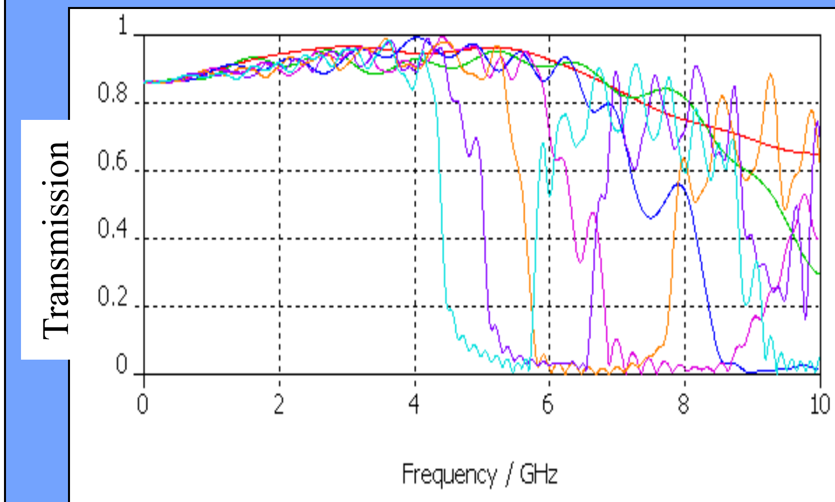
- **Photocathode-anode**
  - **User-defined initial SE distribution**
  - **Velocity dispersion**
  - **PIC space charge (not working)**
- **Deflector**
  - **Full 3D time-dependent EM field representation**
  - **User-defined input pulse**
- **Focussing system**
  - **3D field map for magnetic or electric focussing**
  - **Lens aberrations included**

Meander Stripline Temporal Response

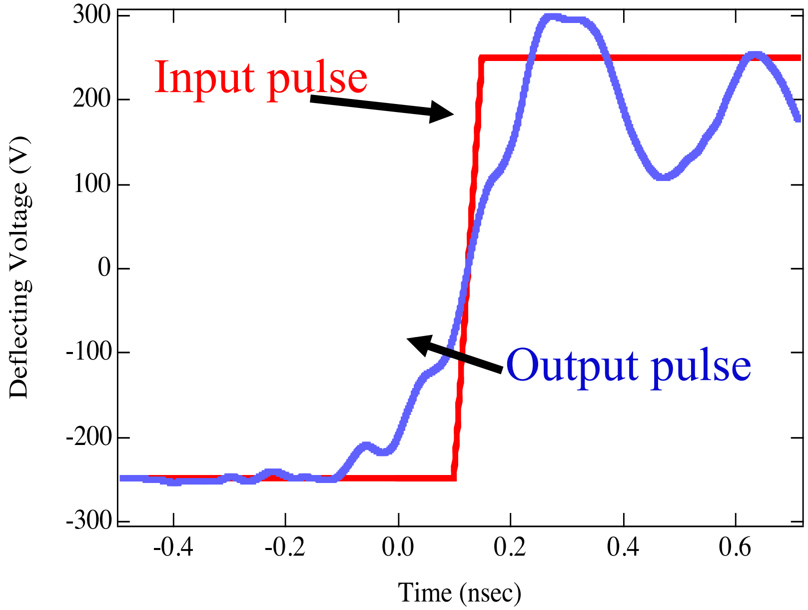
John Byrd

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



Frequency response of meander line for increasing meander lengths. Meander acts as lowpass filter, limiting input pulse risetime.

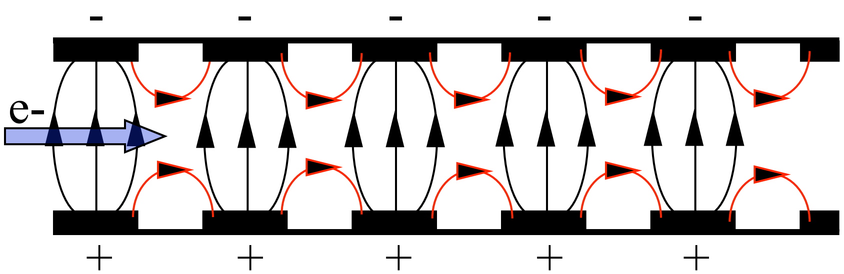


Effective slope reduced for sub-100 psec risetime input pulse. Linearity is also compromised. Solution calls for broader bandwidth structure or resonant cavity.

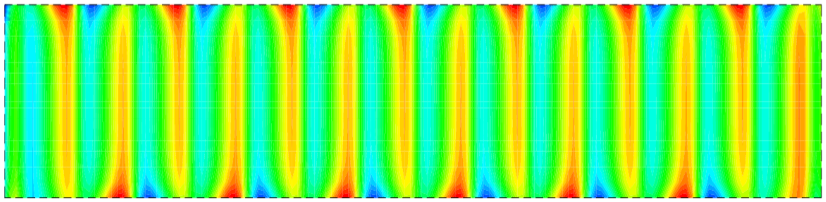
Meander Stripline Deflector Modeling

John Byrd

- 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.



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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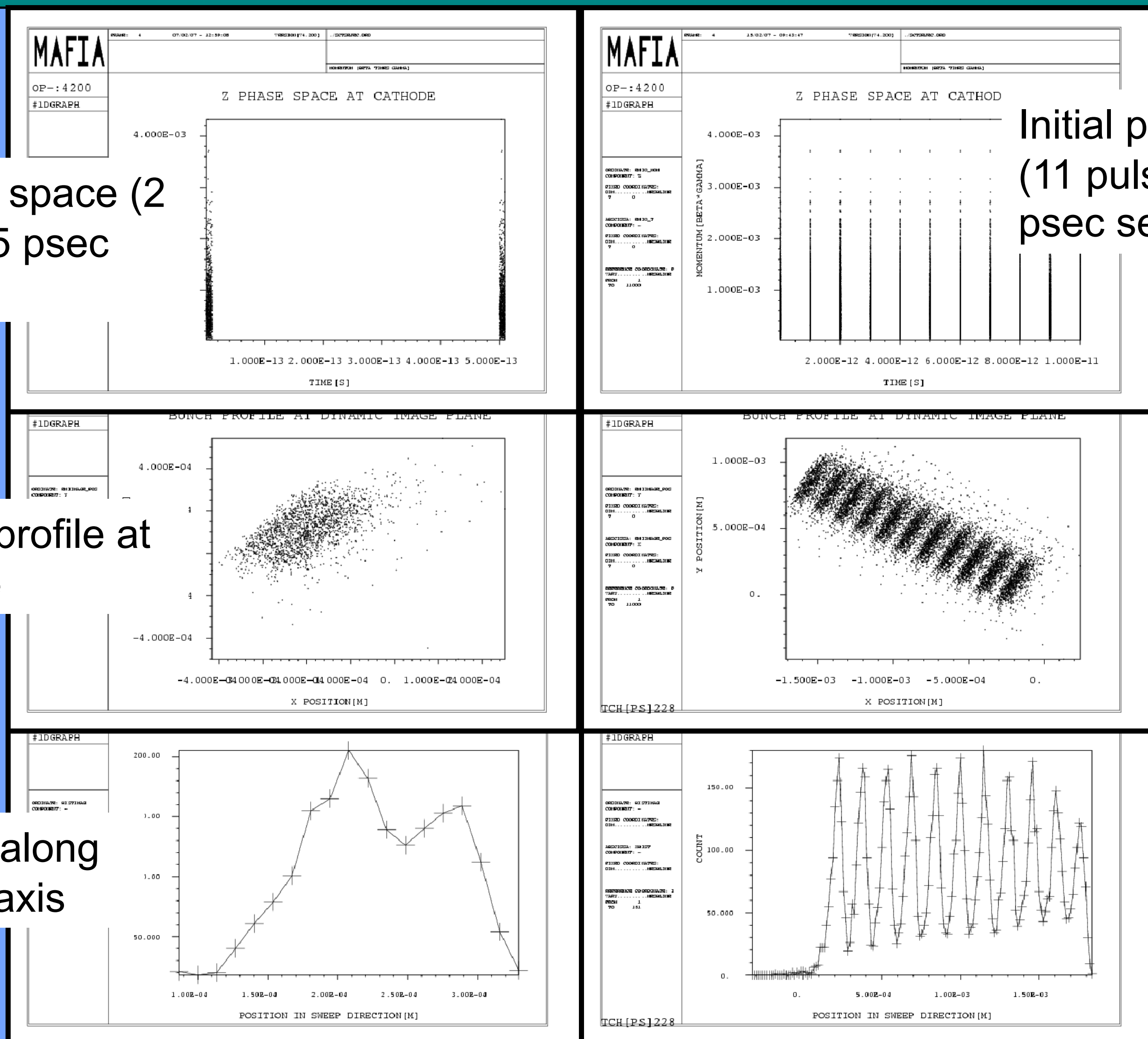
Start-to-end SC Simulation



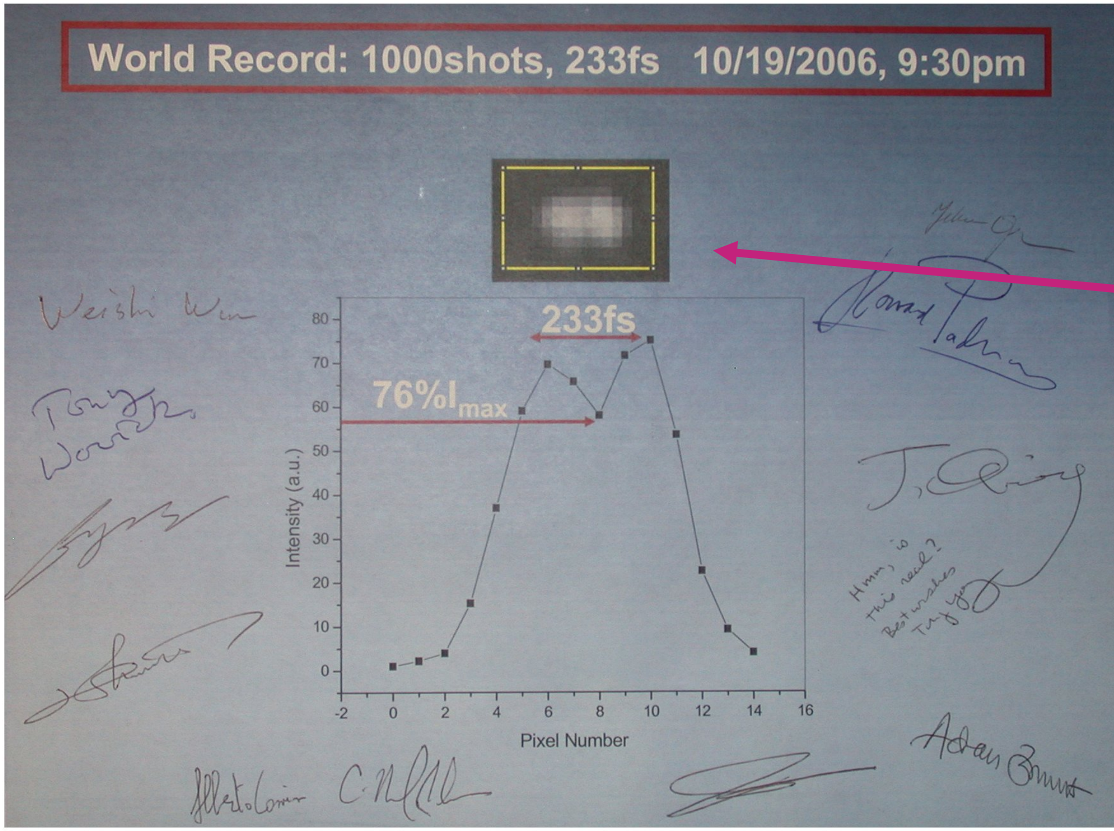
Initial phase space (2 pulses at 0.5 psec separation)

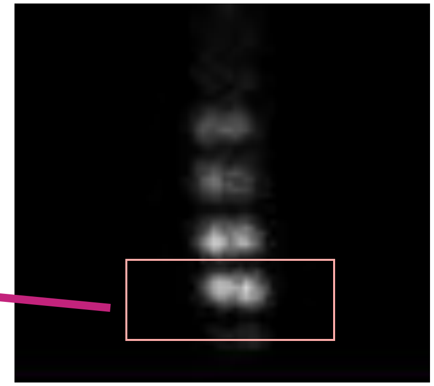
Initial phase space (11 pulses at 0.5 psec separation)

Transverse profile at image plane

Projection along deflection axis

Experimental Results





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!

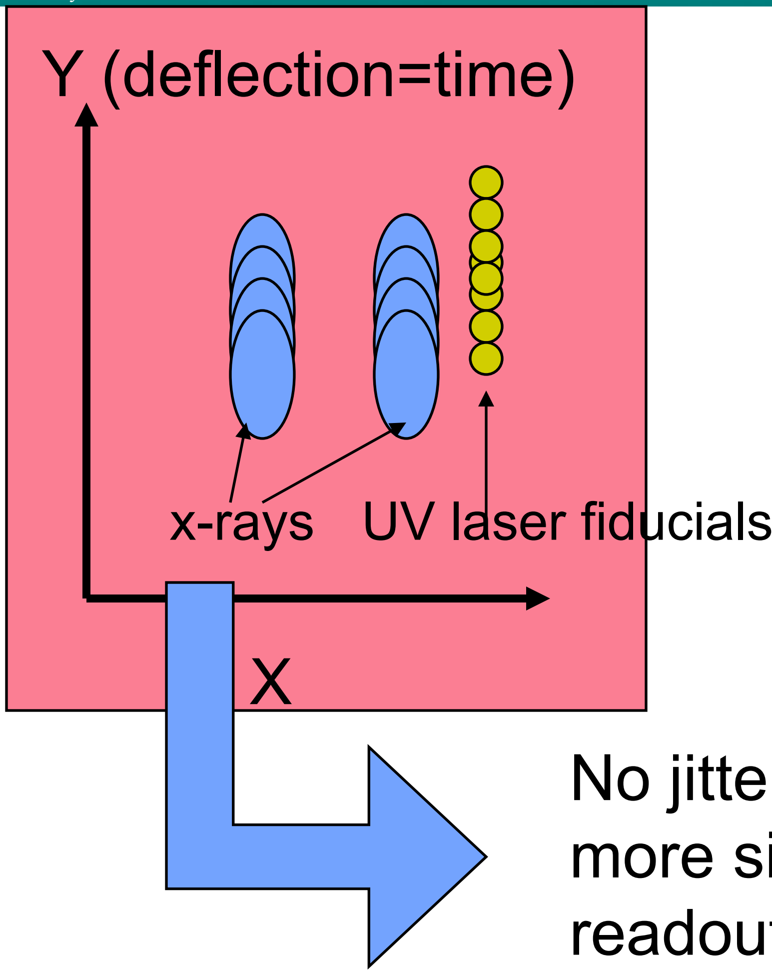
Future directions

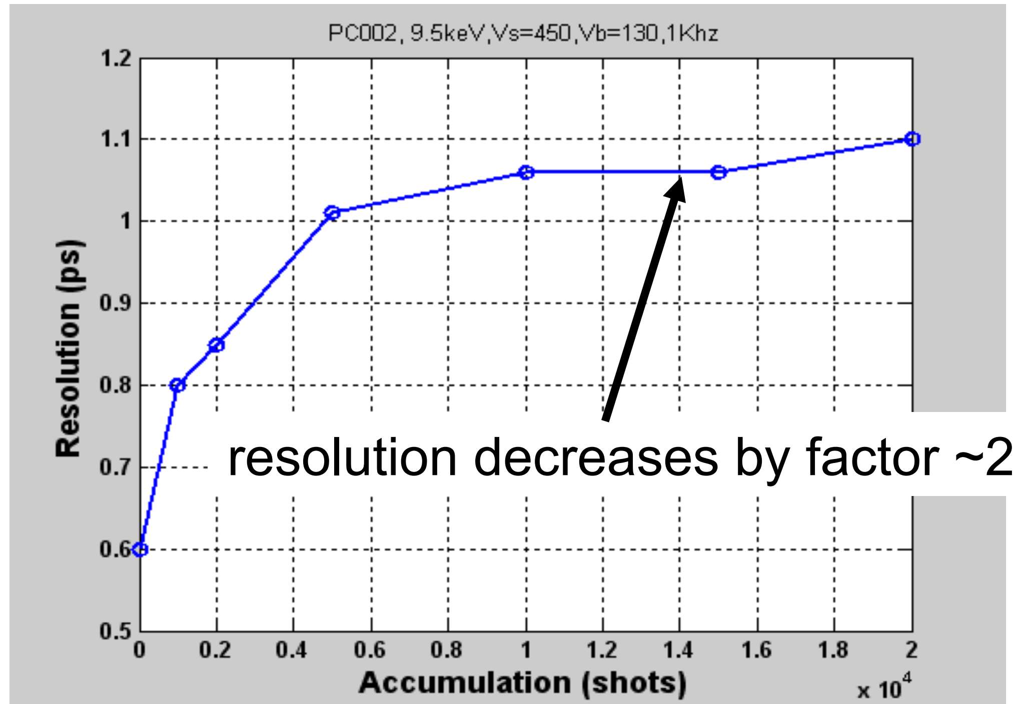
John Byrd

- 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

Trigger Jitter

John Byrd



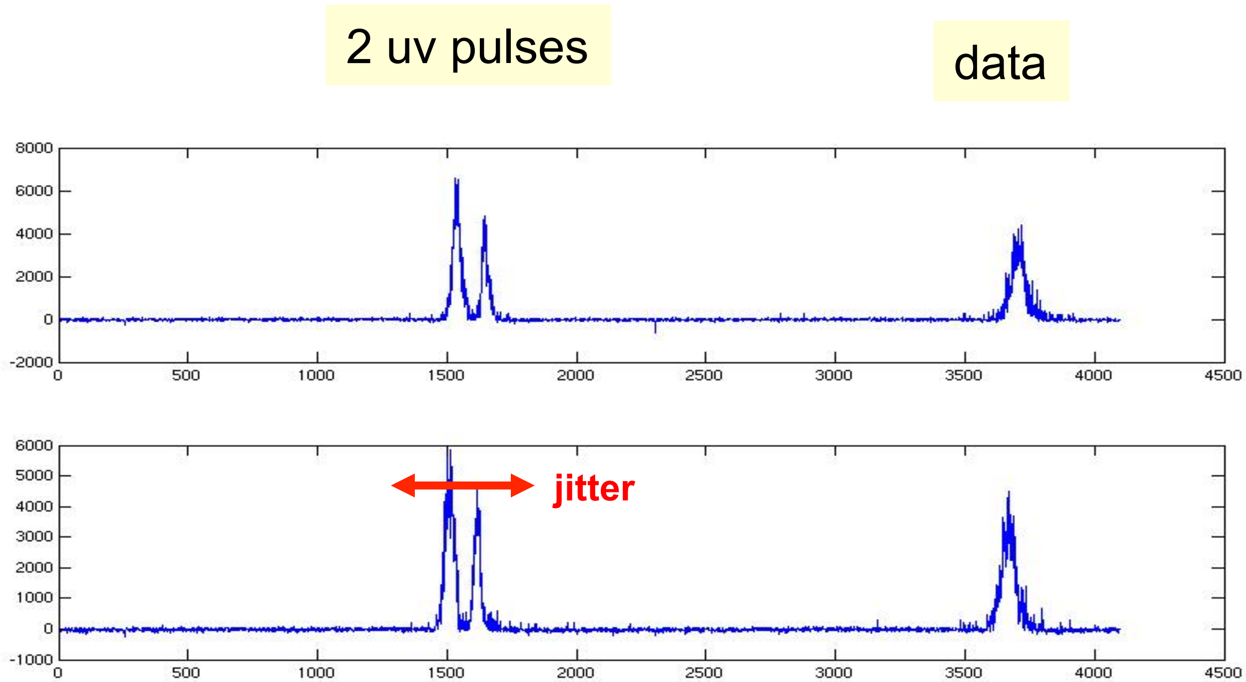


No jitter allows accumulation of images and more signal integrated between CCD readouts

- Improve time response of photoswitch
- Improve laser/ring synchronization
- Use resonant deflection (I.e. synchroscan)

UV pulse temporal fiducialization

John Byrd

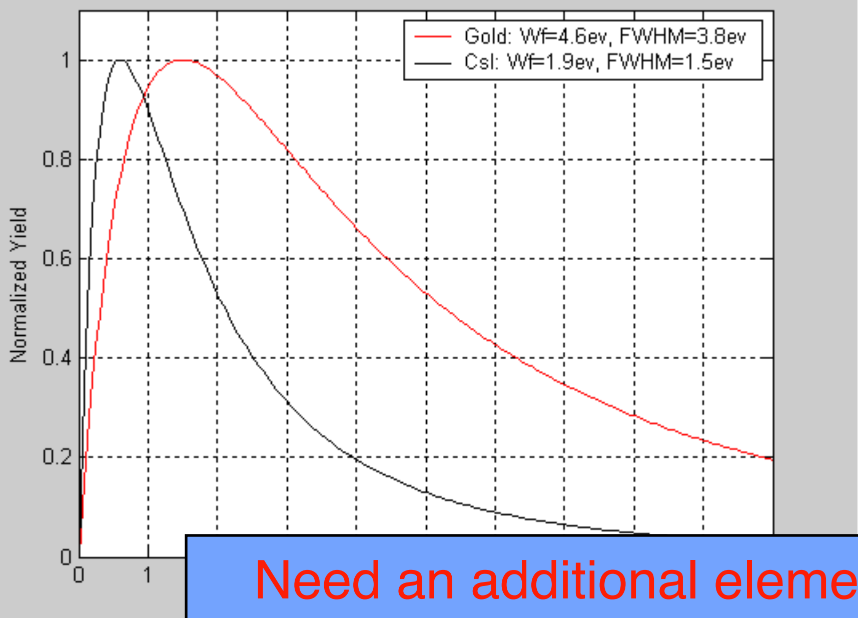


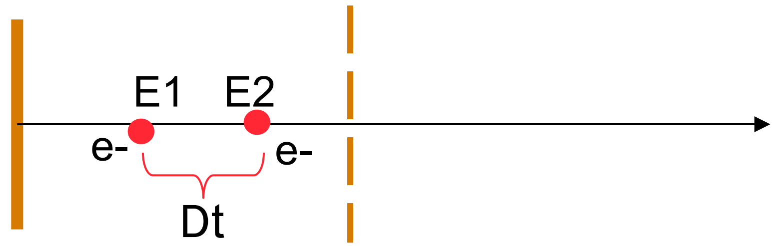
- find centroid of uv pulse(s)
- shift data to keep at constant detector position

- camera readout at sweep frequency (5 KHz)
  - using c-plates + cmos camera + FPGA compressor + video processor

Time dispersion in cathode - anode

John Byrd



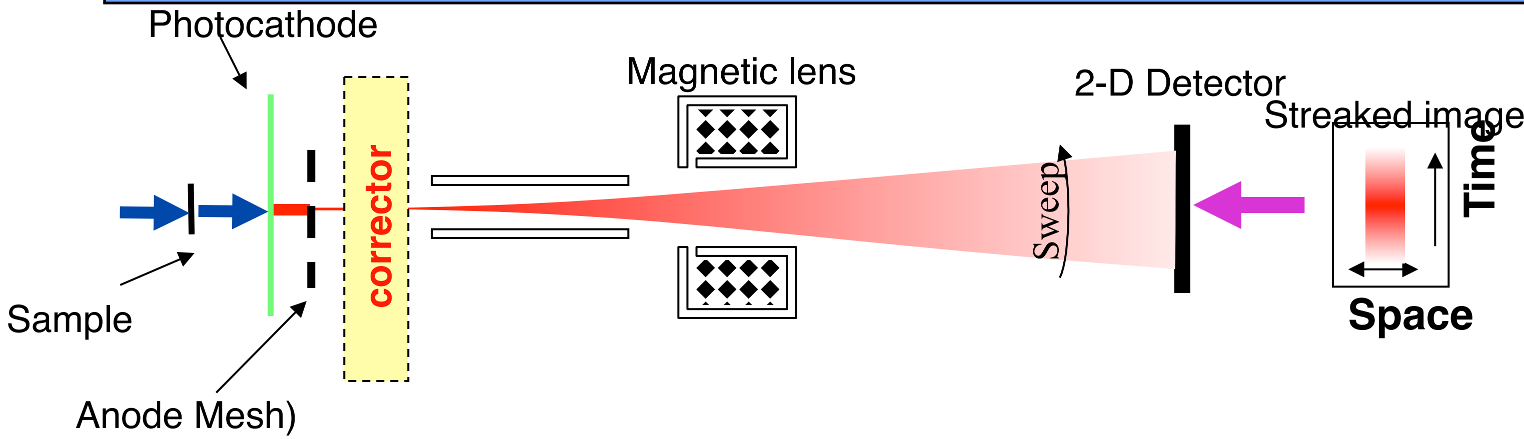


Photocathode has negative time dispersion

Au,Wf=4.6ev, FWHM=3.8ev, 10kV/mm field, ~600fs

m field,

Need an additional element to produce positive energy dependent time of flight



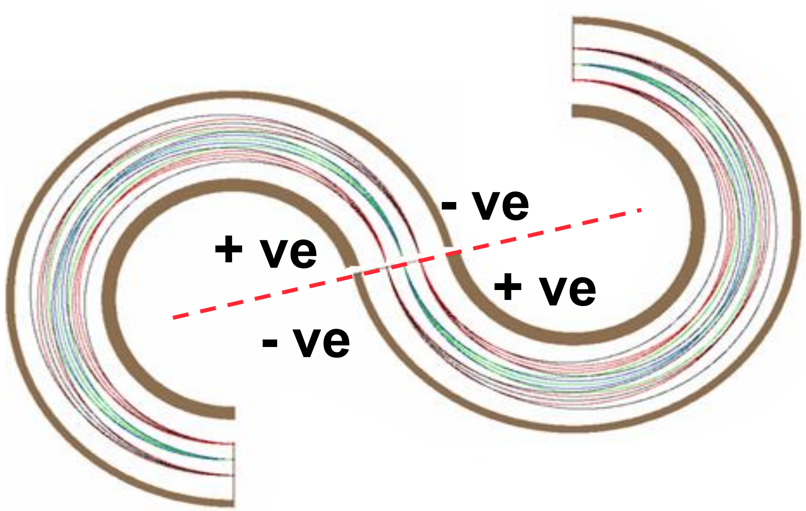
Jannamagi corrector: SPIE 5194 (2003)

- 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



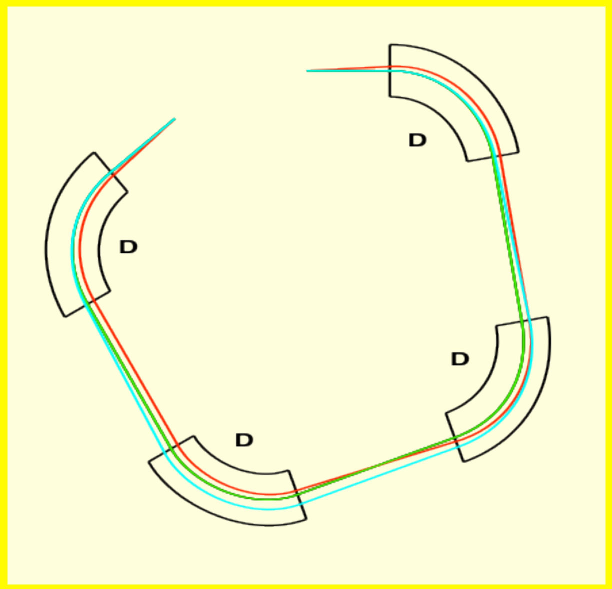
- symmetric 256 degree system need for field aberration cancellation

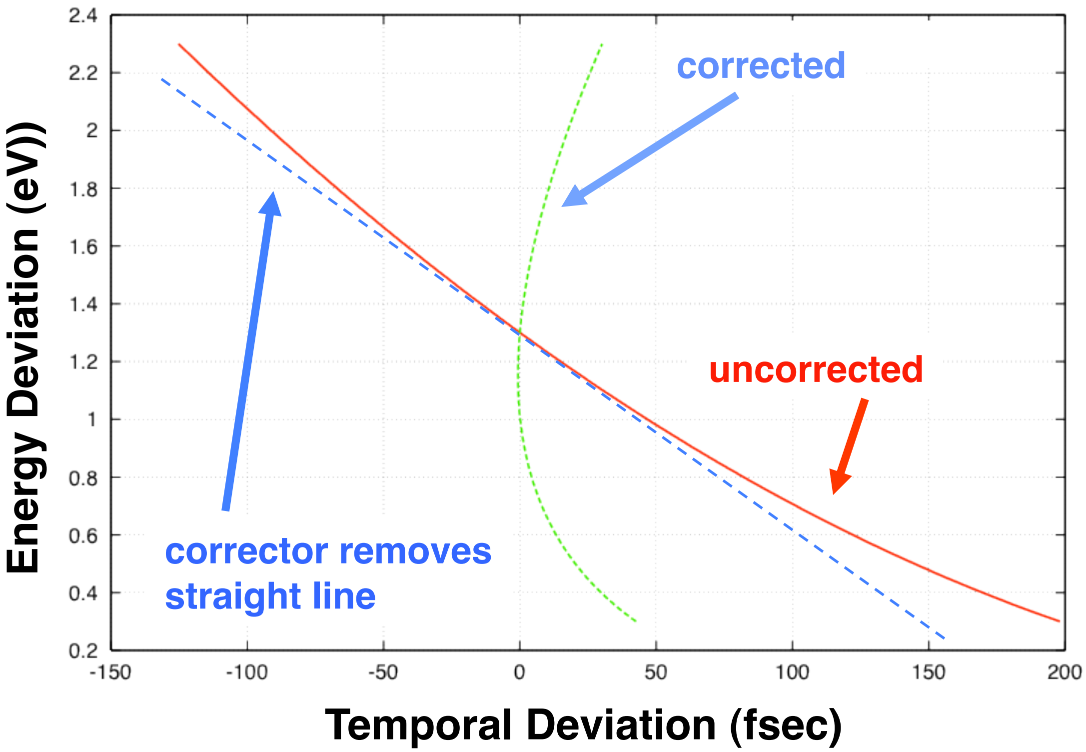
- fringe fields between halves mess up the imaging properties

Double Cylindrical TOF corrector

Chromatic time of flight correction

John Byrd



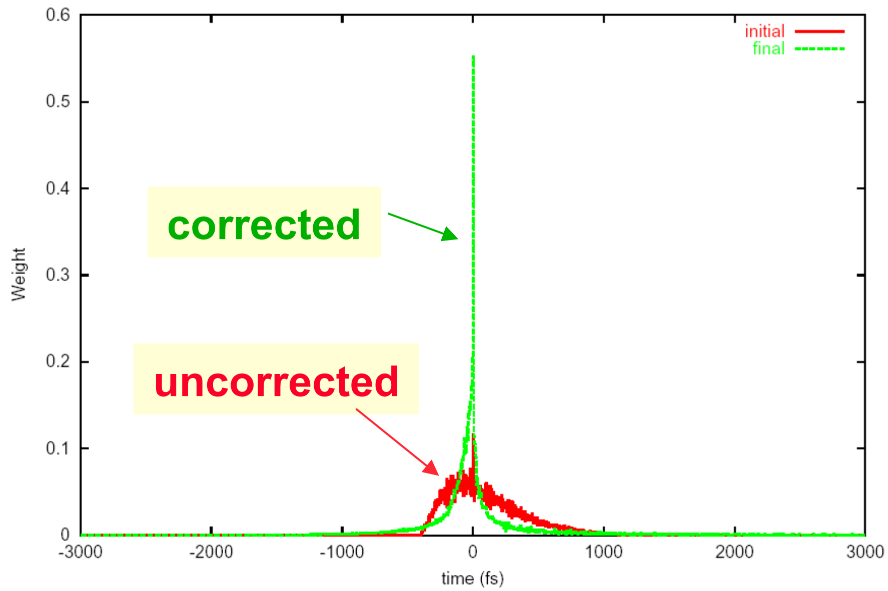


- 4 dipoles can be arranged to be double focusing, achromatic, zero
  angular time of flight dispersion and with defined dT/dE for correction

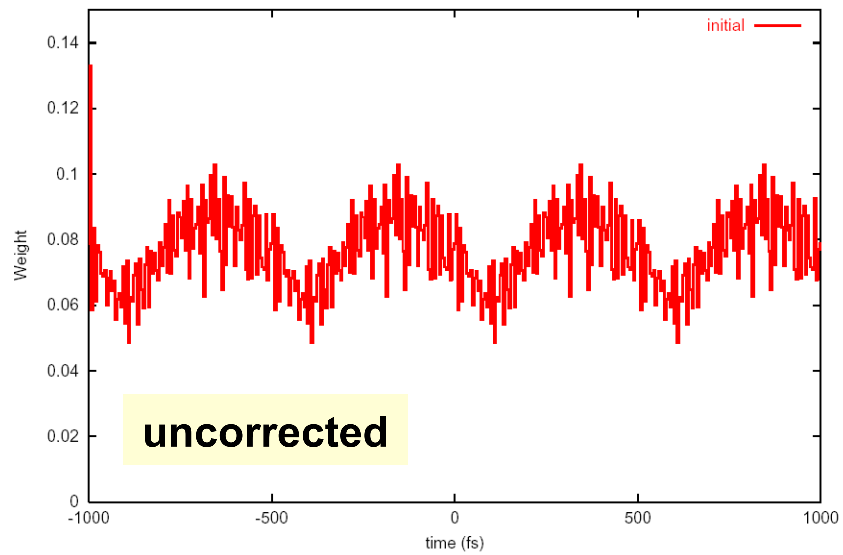
- < 50 fsec resolution from initial simulation!

Full simulation: Gold Photocathode Temporal Response

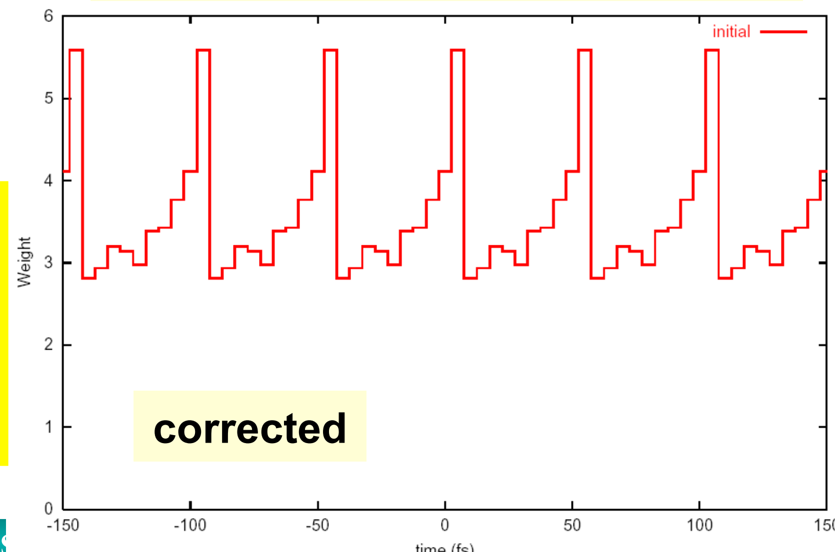
Delta function temporal response



500 fsec separated delta functions



50 fsec separated delta functions



Full particle track using electron distribution (q,f,E), different pulse train, Time modulation transfer function calculated

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

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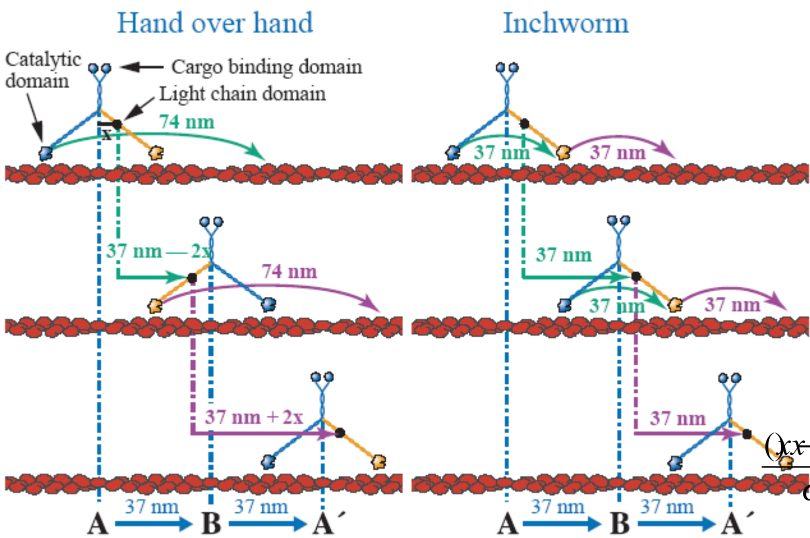
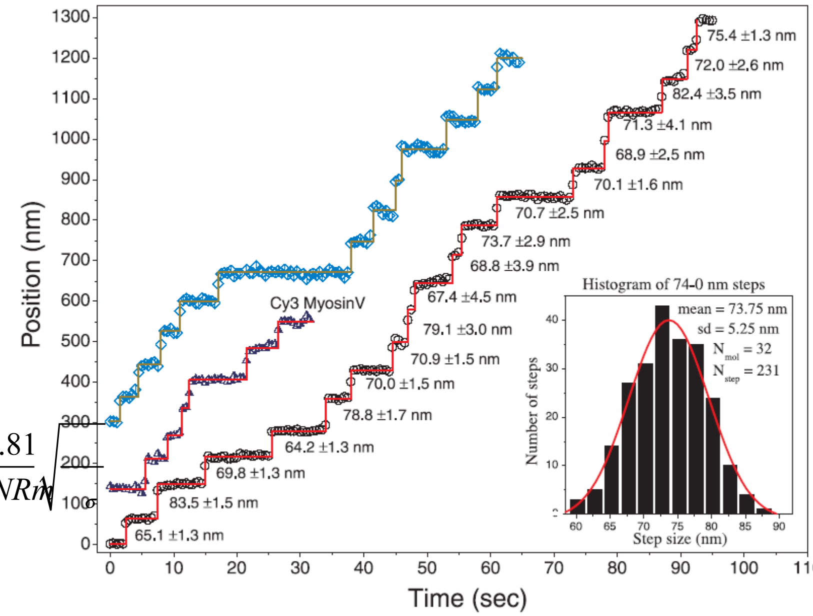




Myosin V Walks Hand-Over-Hand: Single Fluorophore Imaging with 1.5-nm Localization

Ahmet Yildiz,[1] Joseph N. Forkey,[3] Sean A. McKinney,[1,2] Taekjip Ha,[1,2] Yale E. Goldman,[3] Paul R. Selvin[1,2]*

$$\frac{(x - x_m)}{\sigma} = \frac{1.8}{SNR}\sqrt{\frac{1}{m_\sigma}}$$

SNR - signal to noise ratio
s - 1 sigma of gaussian
M - # of pixels / 1 sigma

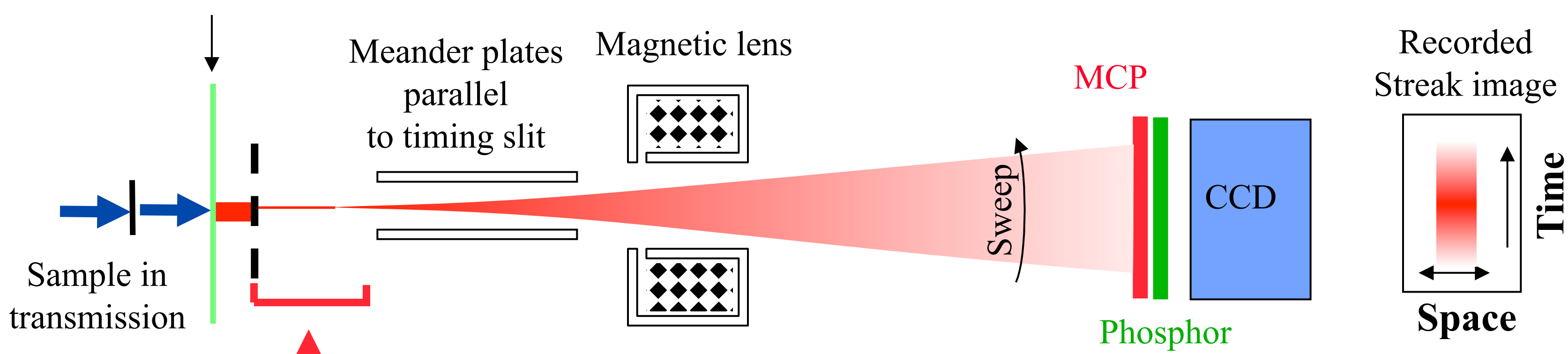
Shot noise limited

- 1e4 electrons, 4 pixels / 1 sigma

- error 1% of 1 sigma

Space Charge Limited Resolution

John Byrd



space charge limit set by anode to deflector transit

-potential energy transfer to longitudinal velocity

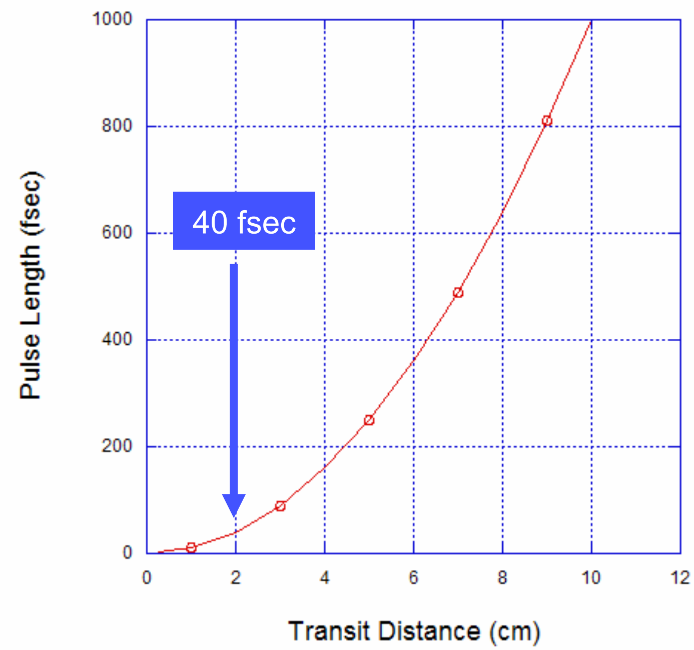
- correlated energy spread

- 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

1e4 electrons, 0.2 mm beam dia., 30 KeV, mean field



Summary

John Byrd

- *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*