# Beam Dynamics in a High-Gradient RF Streak Camera

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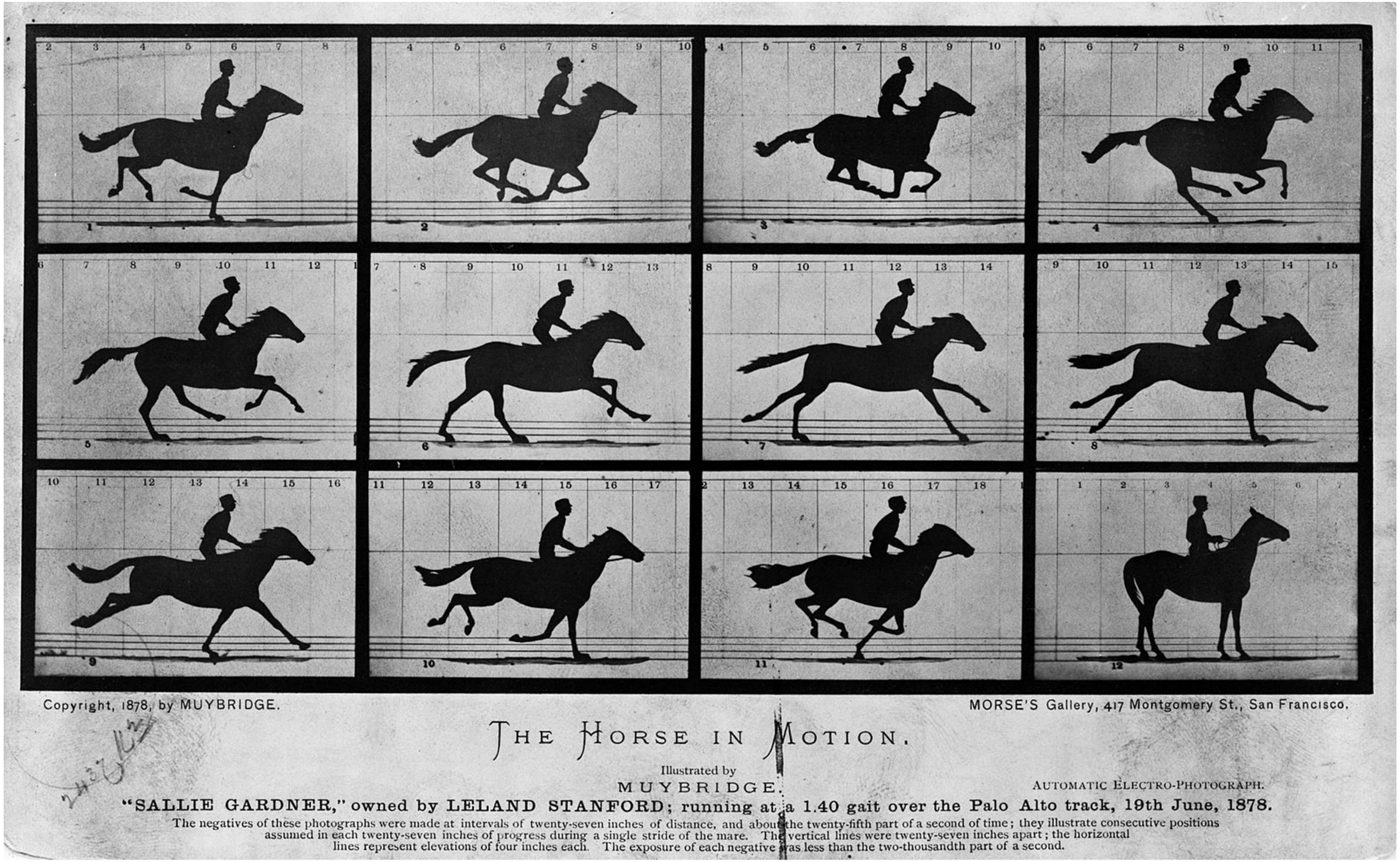
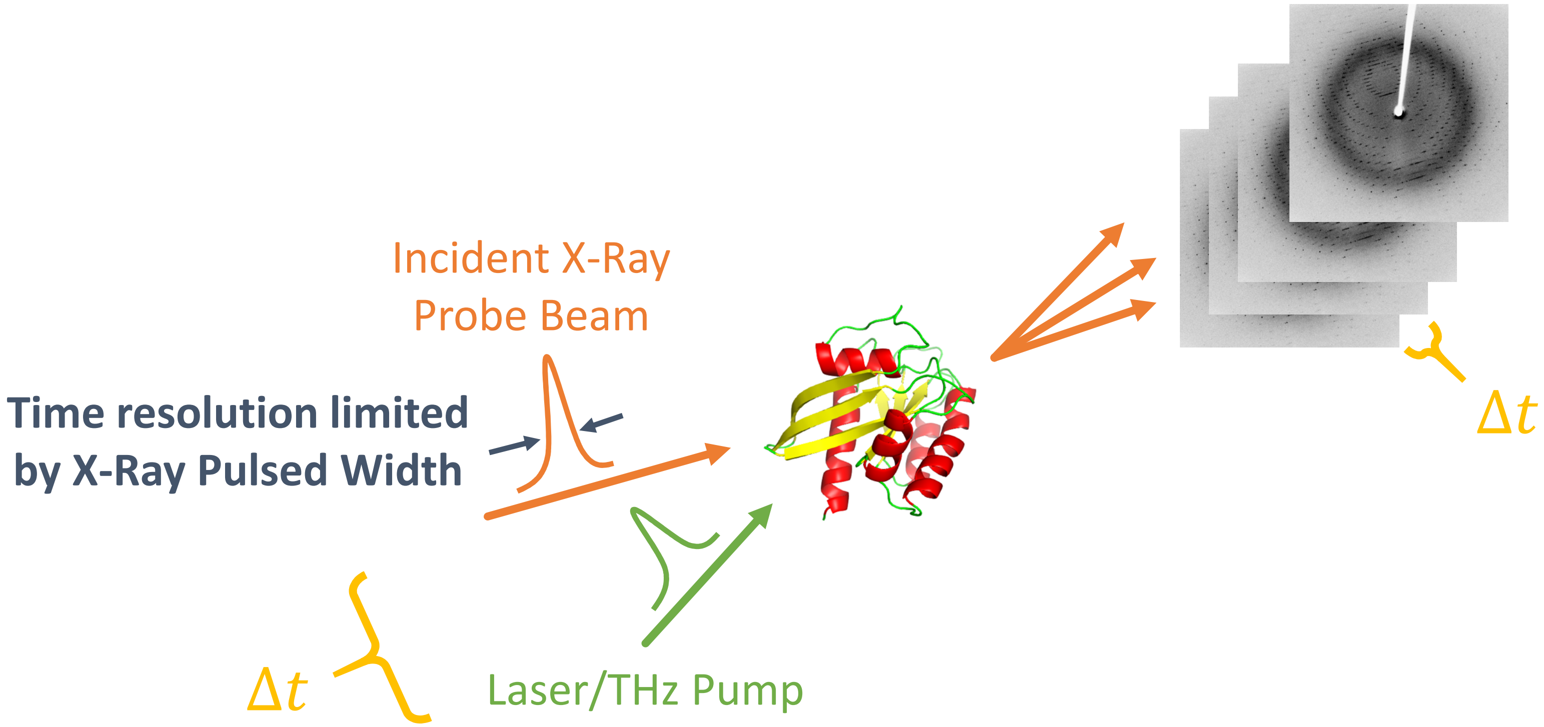
SLAC




Source: Provided directly by Library of Congress Prints and Photographs Division

# Time-Resolved Experiments in Synchrotrons & FELs



# Time Resolution Determined by X-Ray Pulse Width

## Storage Ring-based Light Sources

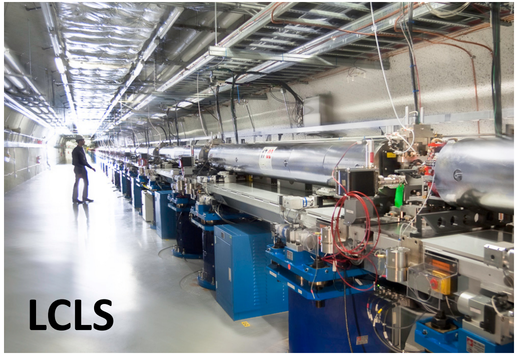
**20 picosecond RMS (2ps with crab cavities)**

**Can study sub-nanosecond phenomena**


## Free-Electron Lasers

**5-200 femtosecond RMS**

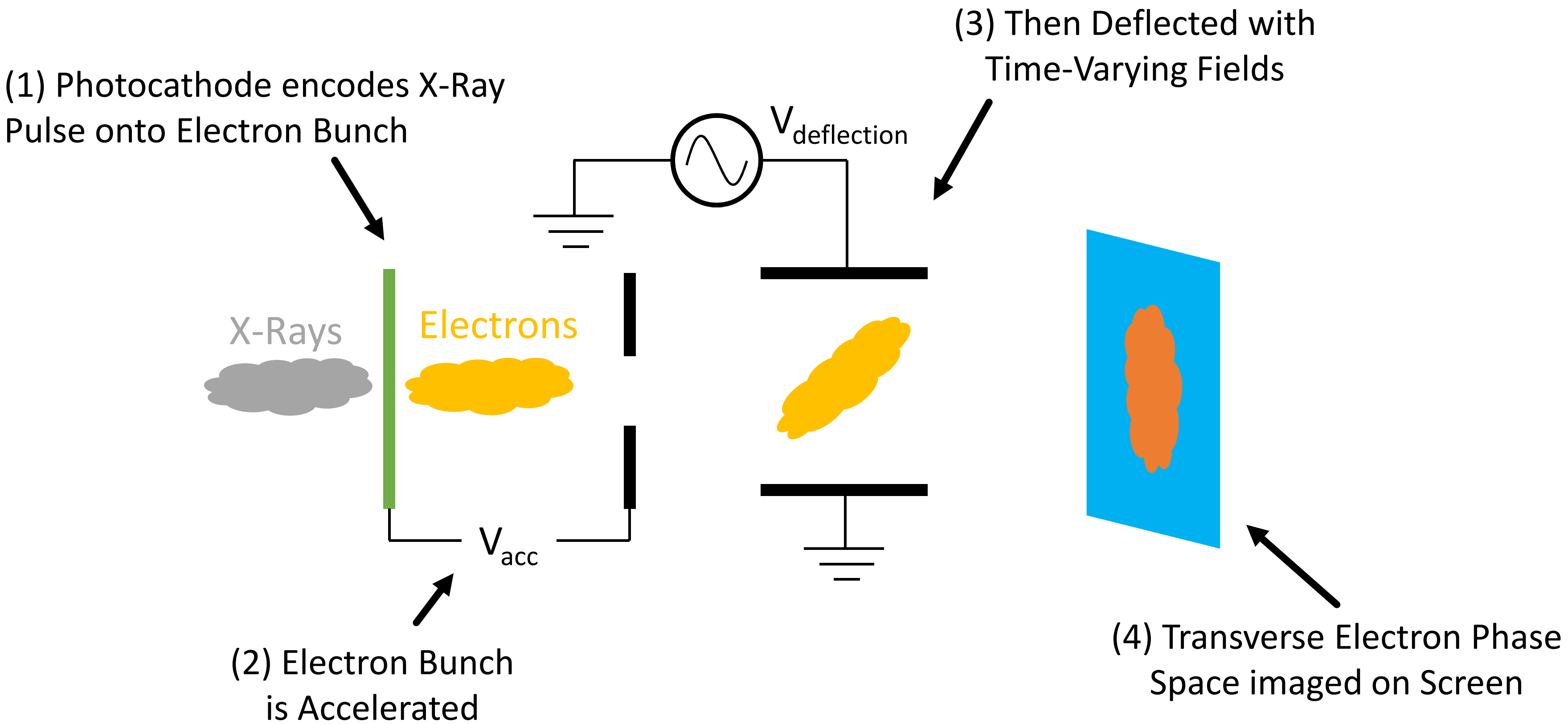
**Can study sub-picosecond phenomena**




**Can we do sub-picosecond time resolved experiments?**

**How do we measure time-of-arrival for pump-probe?**

# Imaging with Long Pulses – Streak Camera



# X-Ray Streak Cameras have > 1ps resolution

## Visible Light / Ultraviolet

- Low energy photons
  - Interactions at cathode surface
  - Very fast emission
- Low energy spread electrons

- **100 fsec resolution**

## X-Rays

- Very high energy photons
  - Interactions inside cathode
  - Electrons emitted for long time
- High energy spread electrons
  - Bunch lengthening during acceleration

- **Several psec resolution**

# Time Resolution Limits in Streak Cameras

Time jitter for accumulation mode

Time spread of secondary photo-electrons

Bunch lengthening due to drift

Bunch lengthening due to space charge

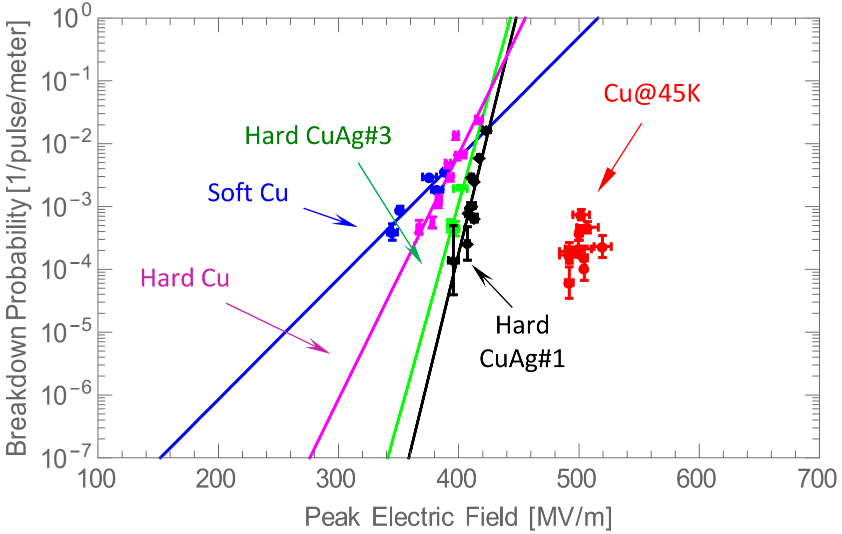
$$\Delta t = \sqrt{\Delta t_j^2 + \Delta t_e^2 + \Delta t_a^2 + \Delta t_d^2 + \Delta t_s^2 + \Delta t_{sc}^2}$$

Bunch lengthening due to initial energy spread and accelerating gradient

$$\Delta t_a(ps) = \frac{3.5\sqrt{W(eV)}}{E_{acc}(kV/mm)}$$

Time error due to finite transverse emittance and deflection speed

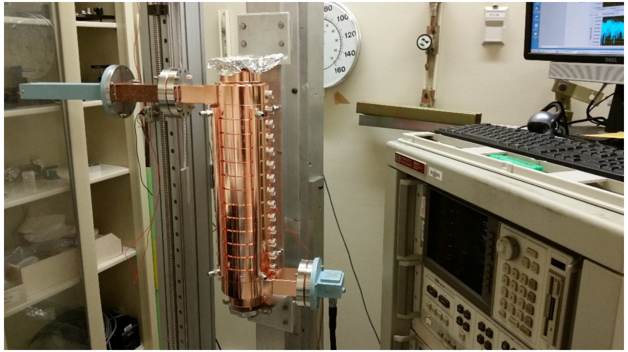
# High Gradients in X-Band Accelerating Cavities



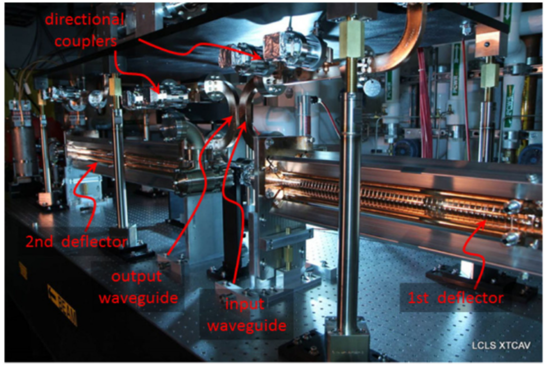

Breakdown rate vs. gradient and peak surface electric for first rf breakdowns, 1C-A2.75-T2.0 structures, shaped rf pulse with 150 ns flat part

Source: A. Cahill *et al.*, “Ultra High Gradient Breakdown Rates in X-Band Cryogenic Normal Conducting Rf Accelerating Cavities,” IPAC 17

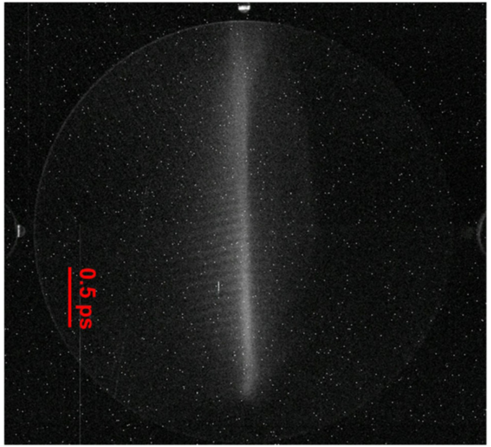
# High-Gradient RF Deflectors



S-Band LCLS Deflector



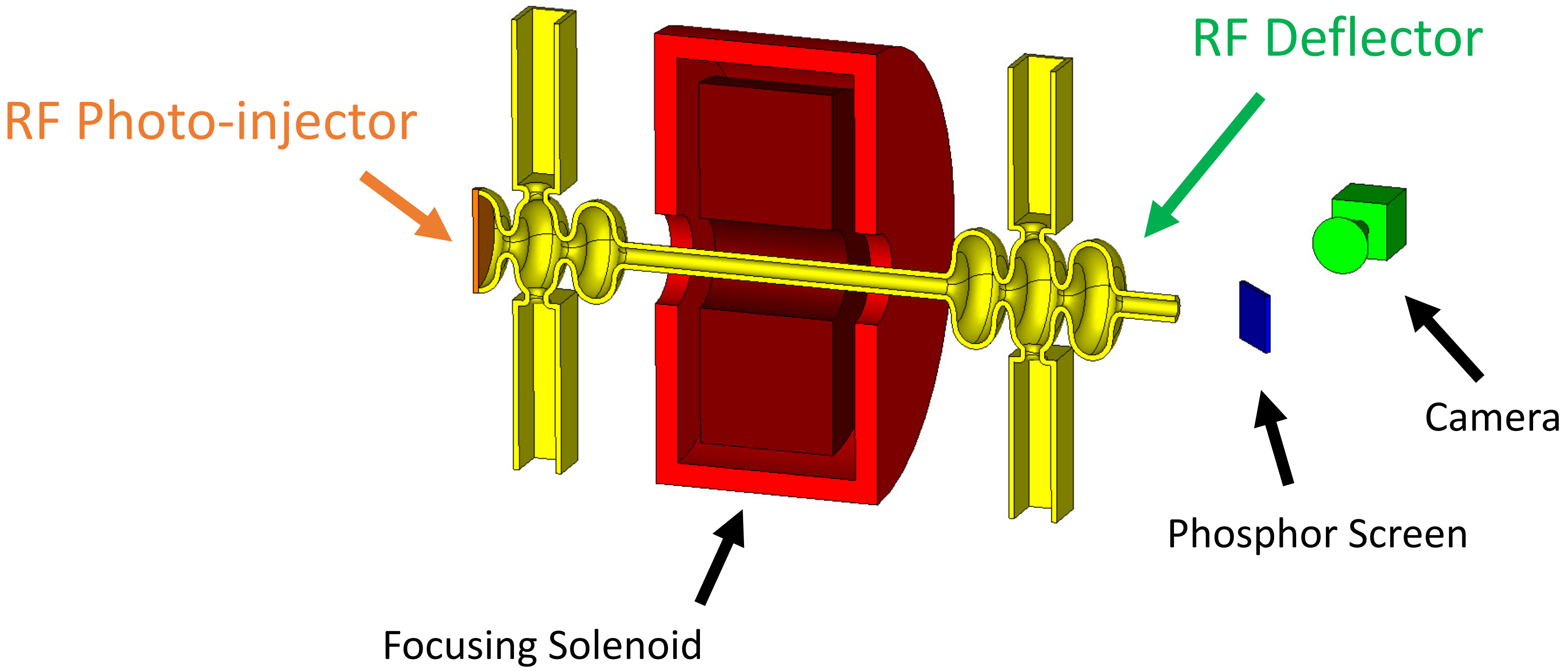

**2 m LCLS X-Band Deflector**
**Resolution: 1 - 4 fs RMS**




Streaked Image at NLCTA
20 cm X-Band deflector

Source: V. A. Dolgashev, G. Bowden, Y. Ding, P. Emma, P. Krejcik, J. Lewandowski, C. Limborg, M. Litos, J. Wang, and D. Xiang, "Design and application of multimegawatt X-band deflectors for femtosecond electron beam diagnostics," Phys. Rev. ST Accel. Beams, vol. 17, no. 10, p. 102801, Oct. 2014.

# Our solution: High-Gradient RF Streak Camera



# Our solution: High-Gradient RF Streak Camera

Traditional Streak Cameras
~**10 kV** beam energy

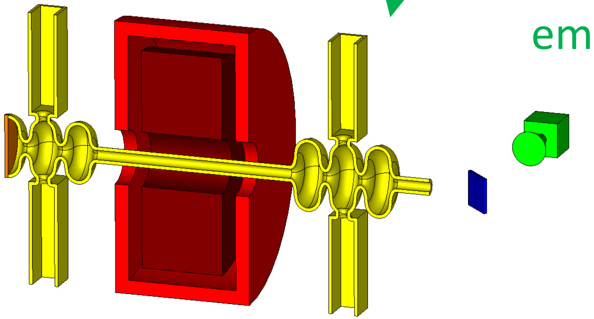
Zeroed due to few
**MeV** beam energy

Zeroed due to few
**MeV** beam energy

$$\Delta t = \sqrt{\Delta t_j^2 + \Delta t_e^2 + \Delta t_a^2 + \Delta t_d^2 + \Delta t_s^2 + \Delta t_{sc}^2}$$

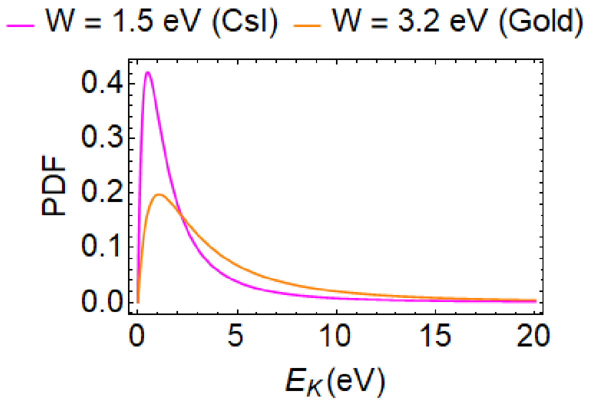
1 - 4 fs resolution achieved with RF deflectors and low emittance electron beam

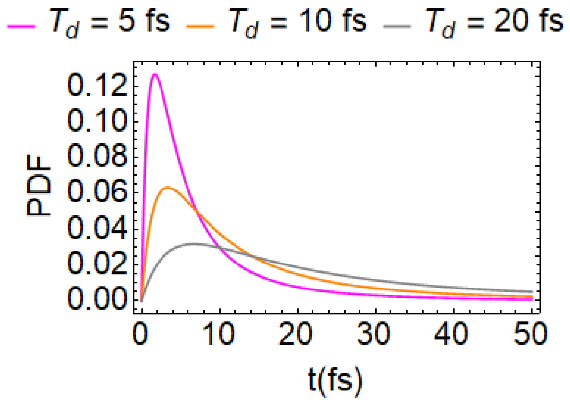
Traditional Streak Camera **10 MV/m**
Warm S-Band (3 GHz) up to **130 MV/m**
Warm X-Band (11 GHz) up to **200 MV/m**
Cryogenic X-Band @ 45 K up to **500 MV/m**
**Up to 50x improvement in resolution**



# X-Ray Photo-emission Model Determines Time Structure of Photo-electrons

- No 6D photo-electron emittance data in the literature
- Modelled photo-emission process as follows*:
    - Peak energy ~ 2 eV
    - Energy FWHM < 10 eV
    - **Time spread estimated on the order of 10 fs**



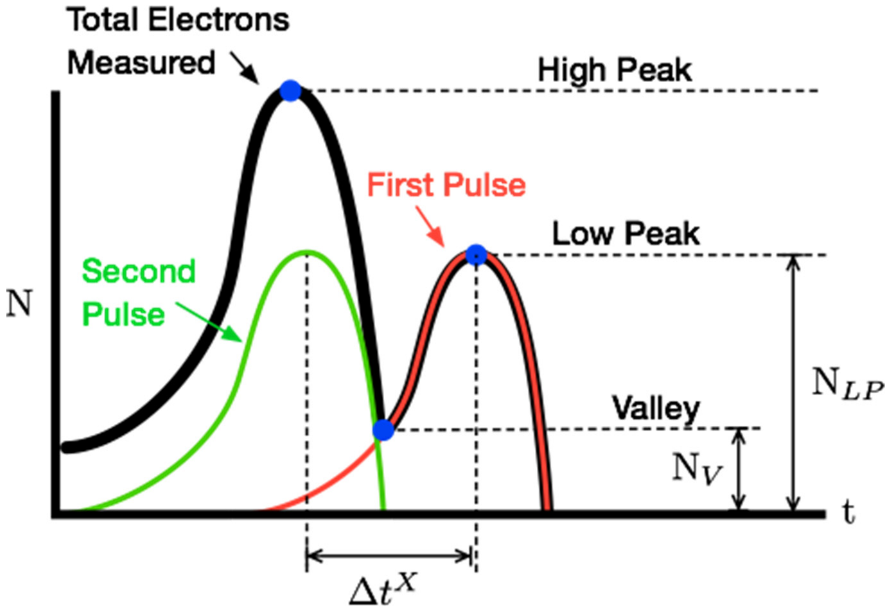

* B. L. Henke, J. A. Smith, and D. T. Attwood, "0.1–10-keV x-ray-induced electron emissions from solids—Models and secondary electron measurements," *Journal of Applied Physics*, vol. 48, no. 5, pp. 1852–1866, 1977.

# Resolution Definition

- Typically FWHM of one pulse used
  - May not be representative

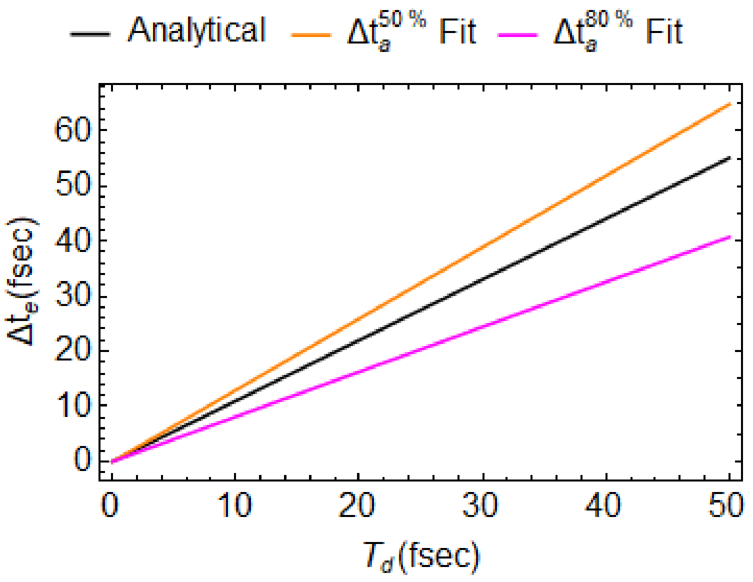
- We use two pulses
  - Look at the valley with respect to peak
  - $\Delta t^X$ so that $\frac{N_V}{N_{LP}} = X$

- Similar approach to optics



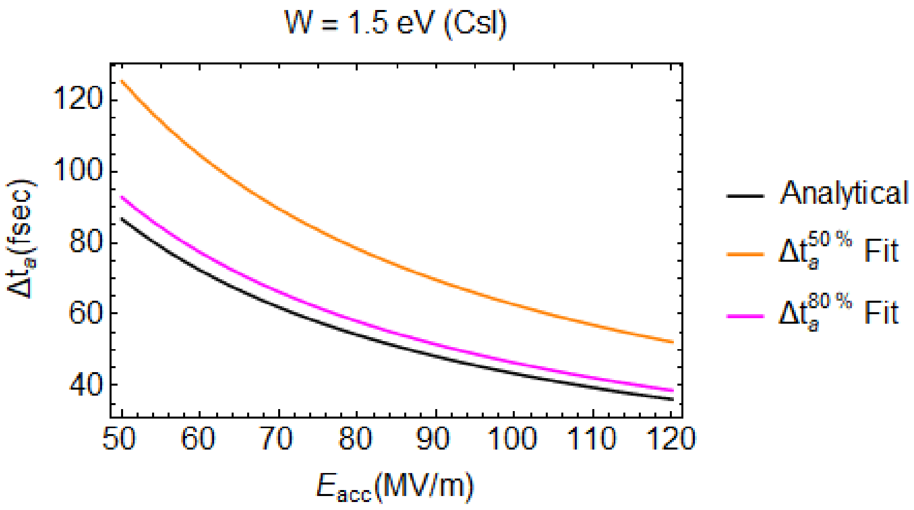
# Effect of the Initial Time Spread

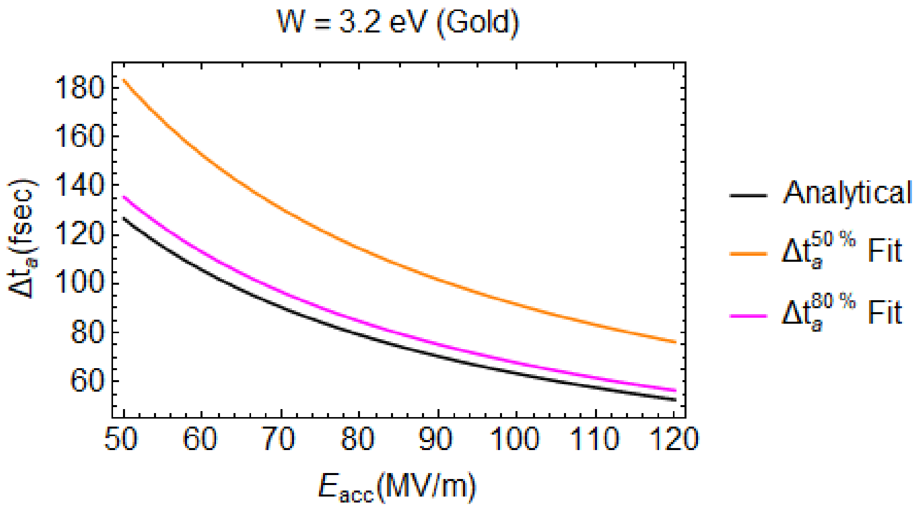
- Analytically: $\Delta t_e = 1.1\ T_d$
  - $T_d$ is the distribution parameter
- Fundamental limitation
- **Needs to be quantified experimentally**




$$\Delta t = \sqrt{\Delta t_j^2 + \boldsymbol{\Delta t_e^2} + \Delta t_a^2 + \Delta t_d^2 + \Delta t_s^2 + \Delta t_{sc}^2}$$

# Effect of Initial Energy Spread

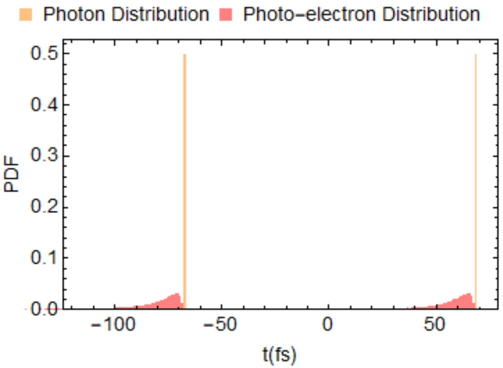



$$\Delta t_a \approx \frac{1}{E_{acc}}\sqrt{\frac{2m_e\delta E}{q_e}} \approx \frac{3.5\sqrt{W}}{E_{acc}}$$

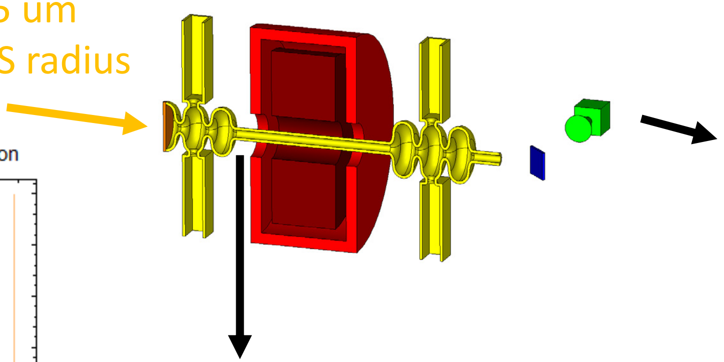
$$\Delta t = \sqrt{\Delta t_j^2 + \Delta t_e^2 + \boldsymbol{\Delta t_a^2} + \Delta t_d^2 + \Delta t_s^2 + \Delta t_{sc}^2}$$

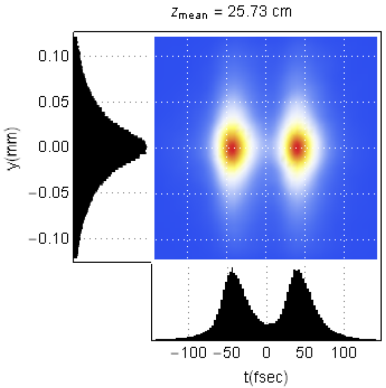
# Near-100 fs Resolution demonstrated in Beam Dynamics Simulation

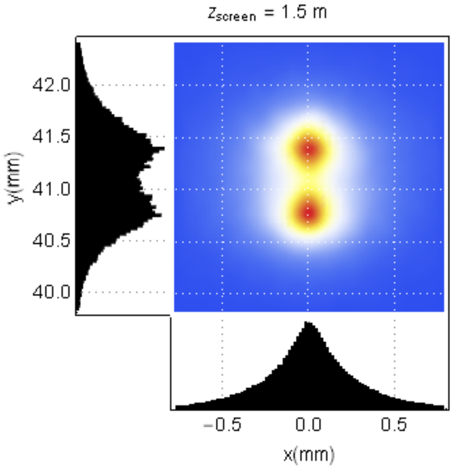



Two 0-length pulses
136 fs apart
the 80% resolution

5 um
RMS radius






**Pulses clearly distinguished on screen**

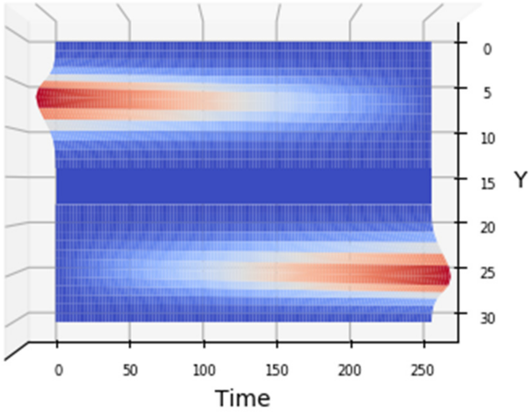
Assumptions:

- Gold W = 3.2 eV / 10 fs initial time spread
- 120 MV/m on the cathode
- 3.5 MV peak deflecting voltage

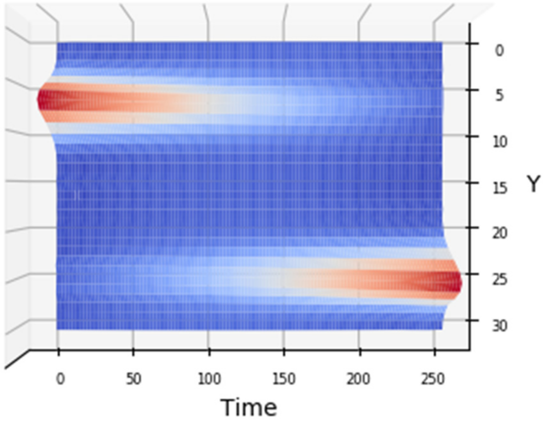
# Open Questions & Next Steps

- No 6D emittance of photo-electrons
  - Need measurements, especially time spread
- Engineer high-gradient compatible cathode materials to improve resolution
- Tolerance analysis for the whole system
- Low effective photon flux in a Storage Ring
  - Effect of Dark Current
  - Find sweet spot between gradient and duty cycle
  - Jitter
- Movie reconstruction

# Movie Reconstruction Preliminary Tests



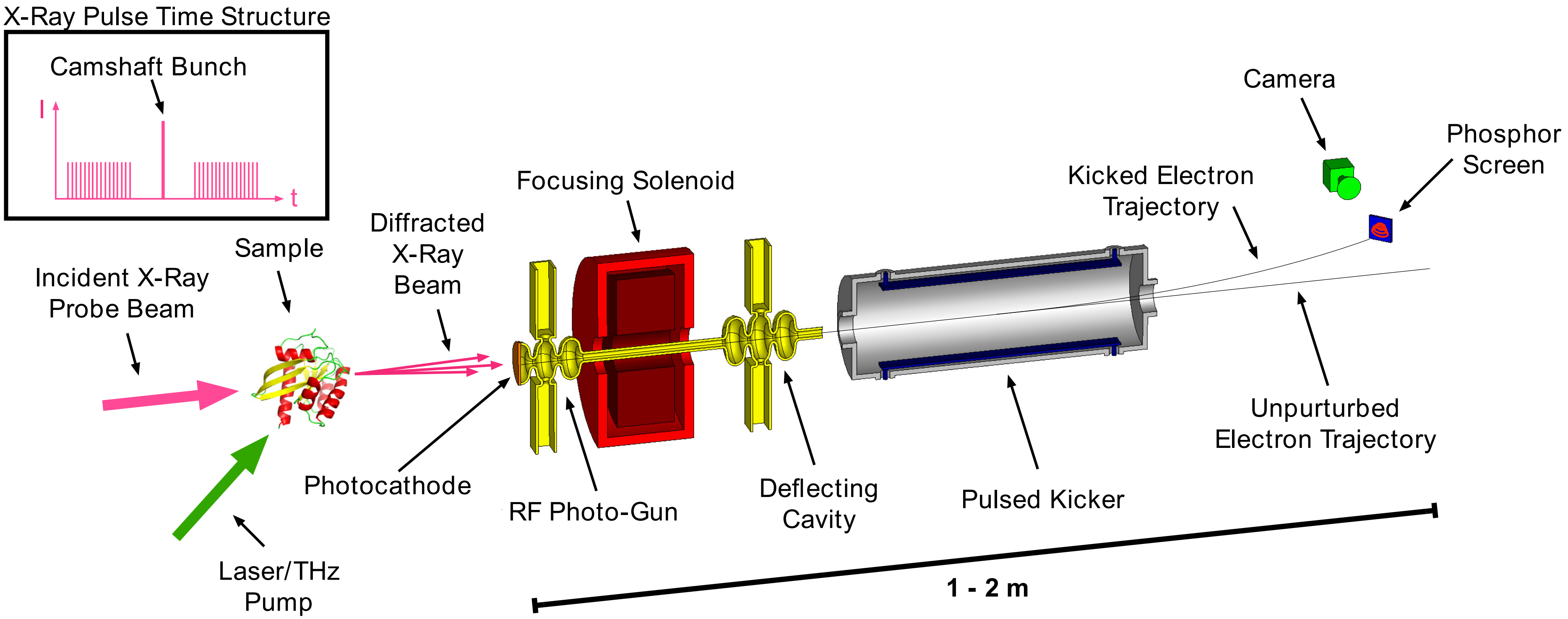





**Input:**
- 2 spots in Y
- One fading
- One lightening up

**Streaked Image in Y**

**Reconstructed**


X-Ray Pulse Time Structure
Camshaft Bunch
I
t
Incident X-Ray
Probe Beam
Sample
Diffracted
X-Ray
Beam
Focusing Solenoid
Photocathode
RF Photo-Gun
Deflecting
Cavity
Pulsed Kicker
Kicked Electron
Trajectory
Camera
Phosphor
Screen
Unpurturbed
Electron Trajectory
Laser/THz
Pump
1 - 2 m