Single-shot Ultrafast Electron Microscopy

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UCLA

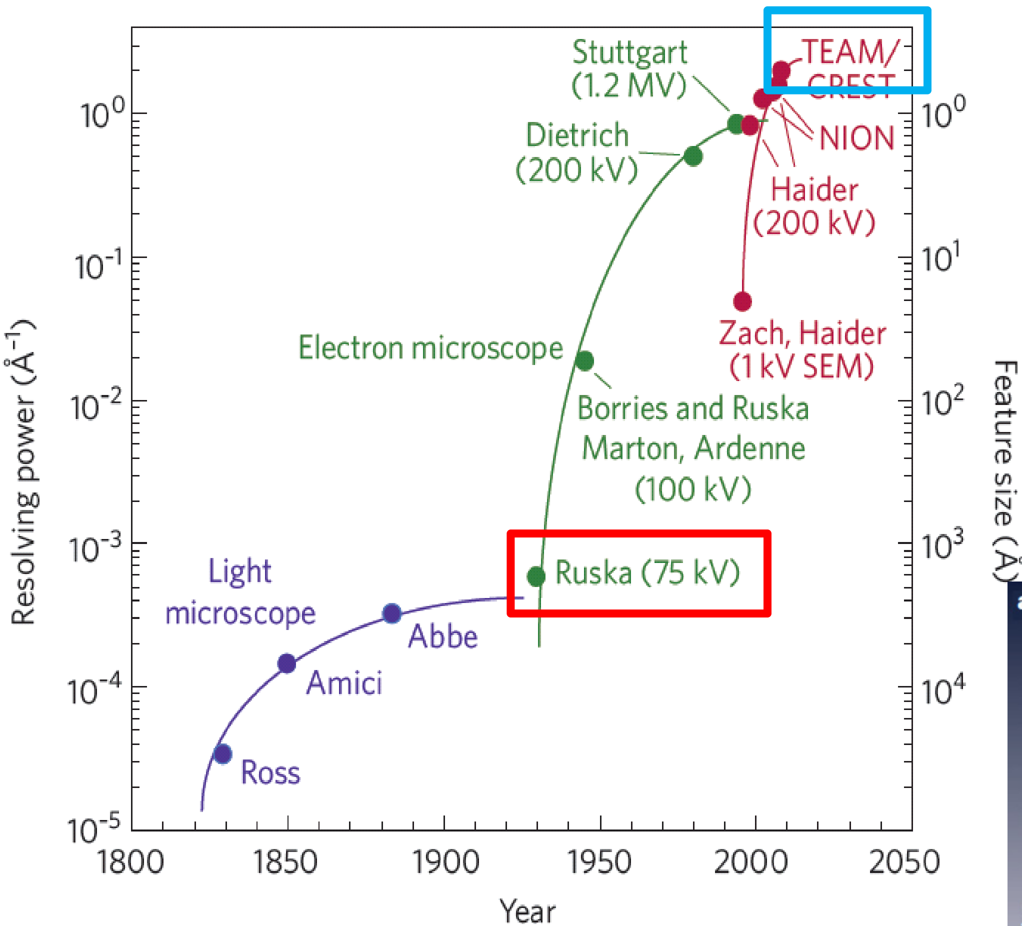
PBPL

Outline

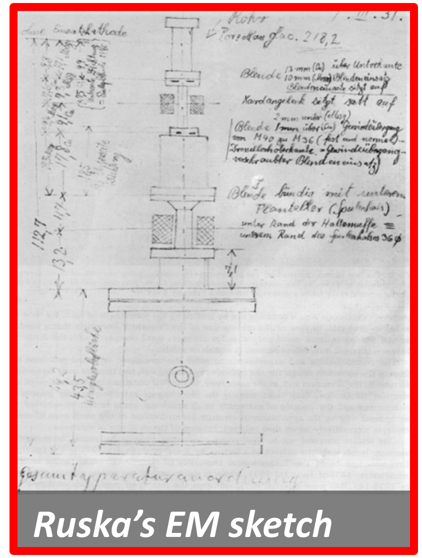
- transmission electron microscopes go '4D'
- stroboscopic and single-shot approaches
- single-shot, picosecond-temporal resolution UEM based on photocathode rf guns
  - ultralow emittance: cigar-shape beam
  - ultralow energy spread: rf curvature regulation
  - novel electron optics: PMQ and μ-quads
- summary and outlook

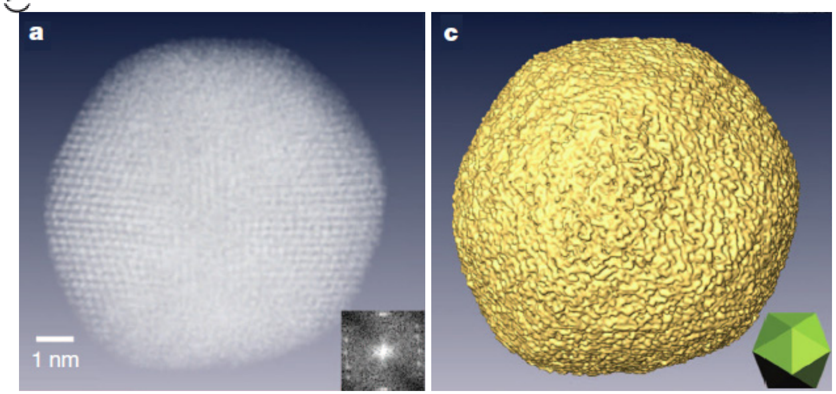
Transmission electron microscopies

- *primary tool for material science, chemistry, physics, biology, and industry*
- *sub-Ångström spatial resolution with aberration correction*



D. A. Muller, Nat. Mater. 8, 263 (2009)
Adapted from H. H. Rose (2009)

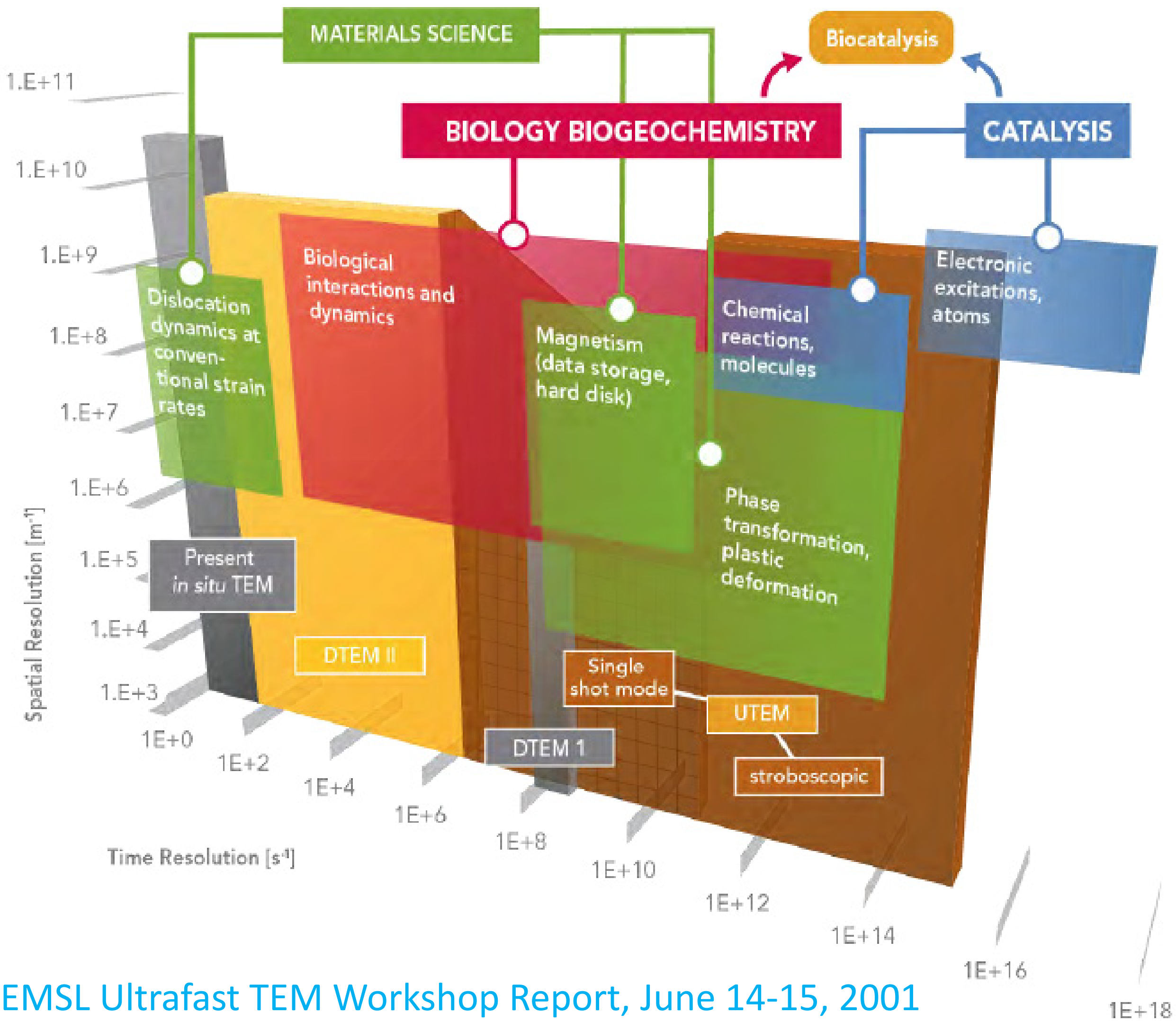


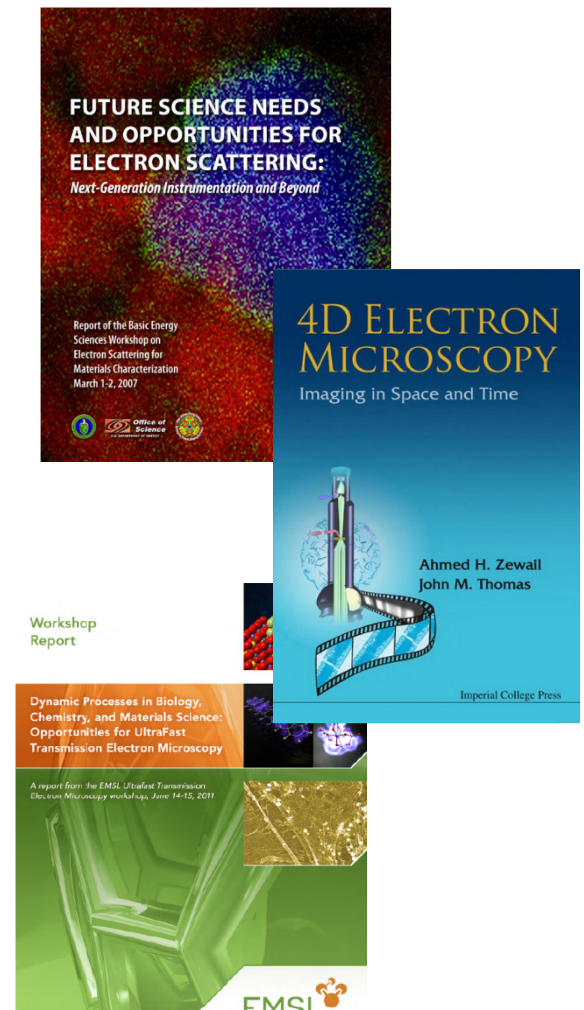


3D electron tomography at ångström resolution
M. C. Scott, Nature 444, 483 (2012)

Resolution in the 4th dimension – time domain

- *Conventional TEMs need millisecond to second exposure time*
- *many reasons to see structural **changes** in time, rather than static images*

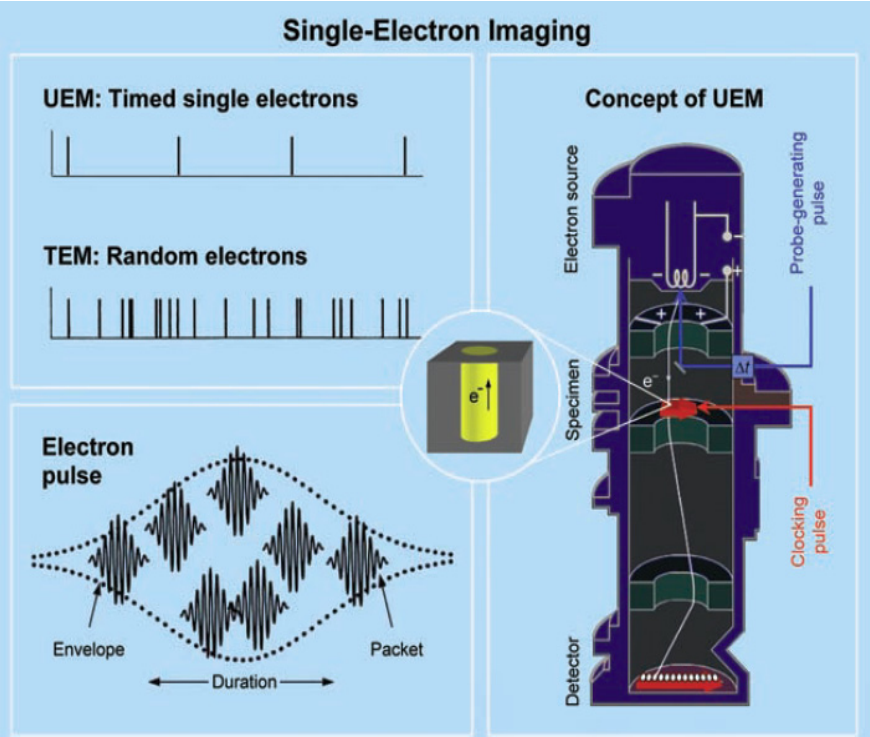




EMSL Ultrafast TEM Workshop Report, June 14-15, 2001

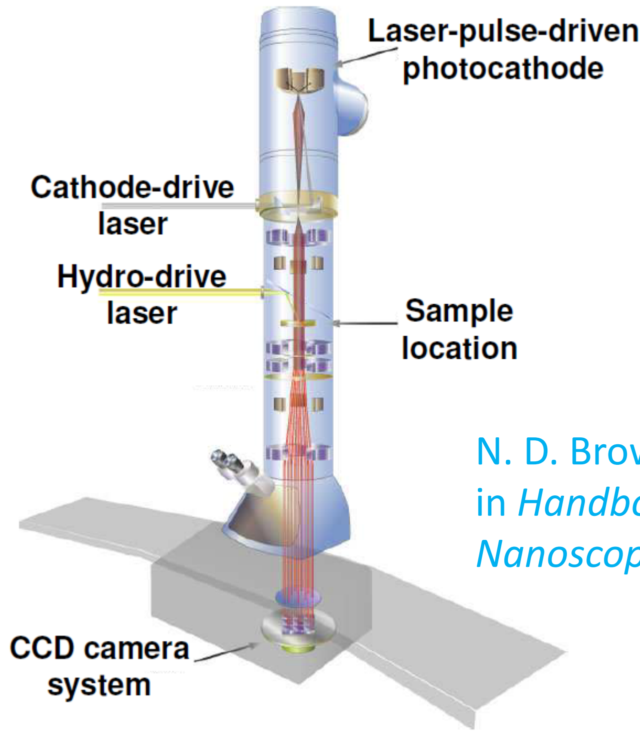
Ultrafast TEM: stroboscopic and single-shot approaches

Stroboscopic: UEM at Caltech



A. H. Zewail, Science 328, 187 (2010)

Single-shot: DTEM at LLNL



N. D. Browning et al., in *Handbook of Nanoscopy*, 2012

O. Bostanjoglo, in *Advan in Imag Elect Phys*,121 (2002)

- *use photocathode in conventional 200 kV TEMs, pump-probe scheme*
- *Stroboscopic: 1 e^-/pulse, atomic scale resolutions, reversible processes*
- *Single-shot: 10^8 e^-/pulse, 10 nm – 15 ns resolution, irreversible processes*

Single-shot UEM using photocathode rf guns

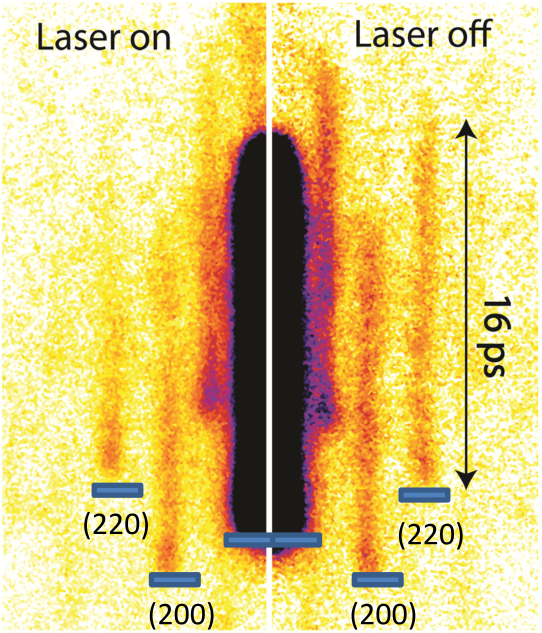
- *DTEM limited by beam brightness and space charge effects*
  - *modified conventional TEM gun, low gradient of 1 MV/m*
  - *low beam energy of 200 keV, high charge density close to sample area*

Are the low gradient gun design and low beam energy the optimal solution for ultrafast imaging applications?

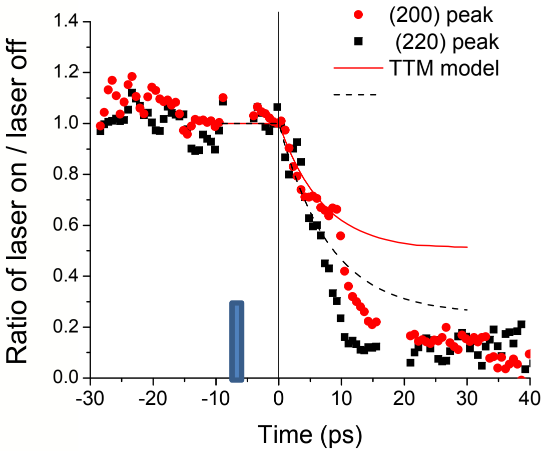
- *Photocathode rf guns*
  - *high gradient 100 MV/m, help improve beam brightness*
  - *high beam energy 3-5 MeV, greatly suppress space charge effects*

Using the beam from photocathode rf guns, it is possible to build picosecond-temporal resolution UEMs.

an exciting new field: UED and UEM



gold melting, streak-mode,
full history with one *e*- beam



P. Musumeci et al. JAP, **108**, 114513 (2010)

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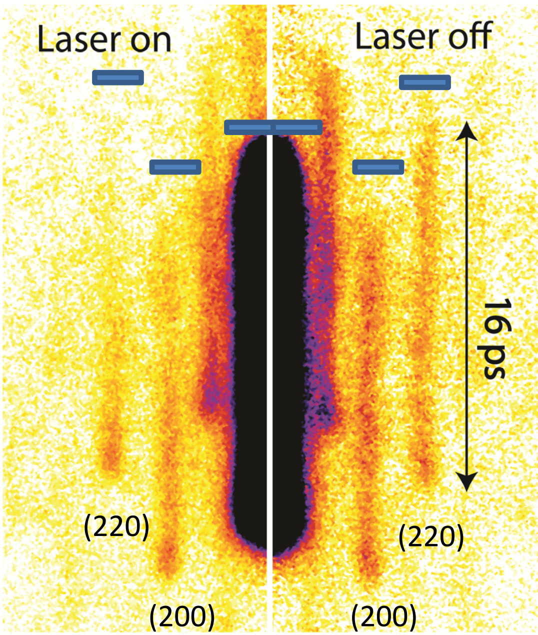

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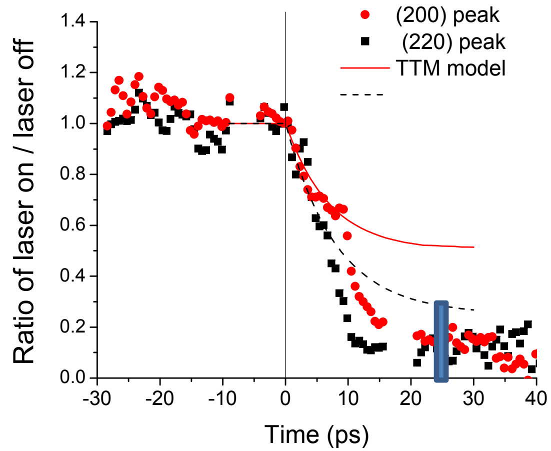
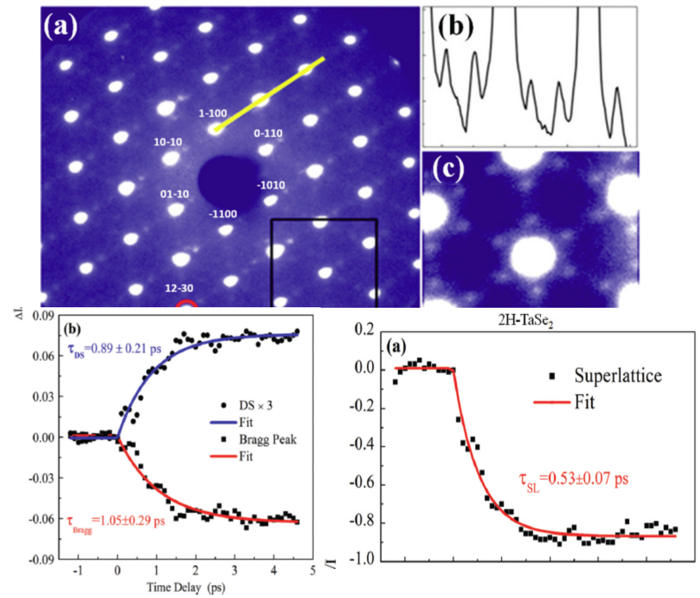


P. Musumeci et al. JAP, **108**, 114513 (2010)

CDW, very high pattern quality



P. F. Zhu et al. APL 103, 071914 (2013)

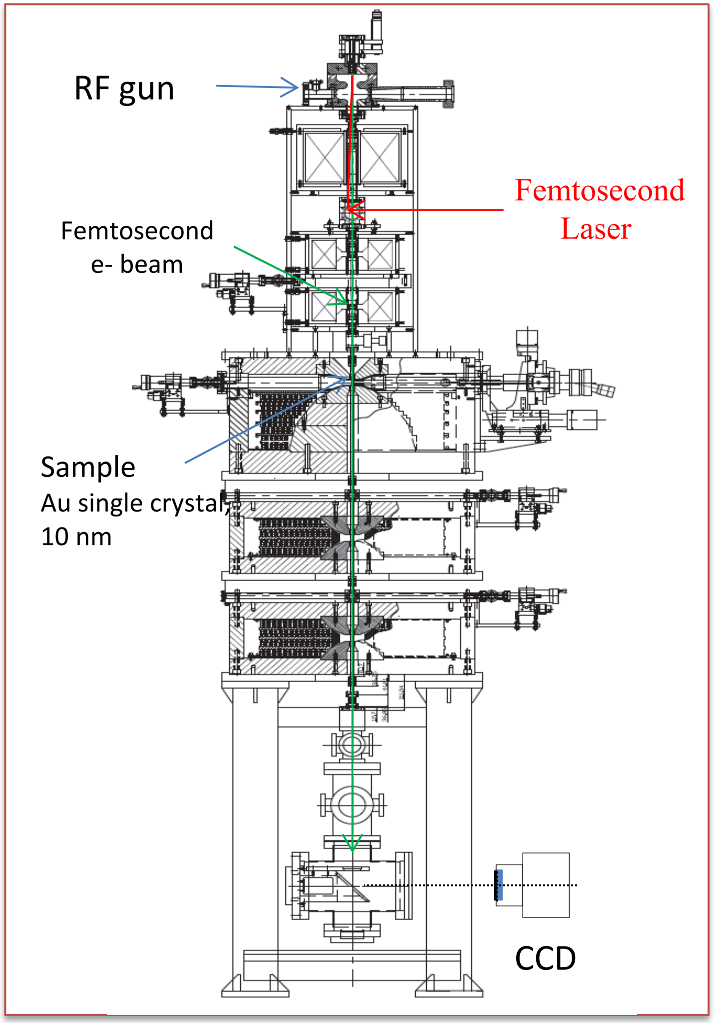
Courtesy of Xijie Wang

Recent and upcoming workshops

- *Dec. 2012, Workshop on Ultrafast Electron Sources for Diffraction and Microscopy Applications* http://pbpl.physics.ucla.edu/UESDM_2012/
- *July 2013, Workshop on Femtosecond Transmission Electron Microscopy* http://lumes.epfl.ch/page-93264-en.html
- *Dec. 2013, FEIS 2013 - Femtosecond Electron Imaging and Spectroscopy* http://www.feis2013.org/

prototype rf gun based UEM at Osaka Univ.

Courtesy of Prof. Jinfeng Yang



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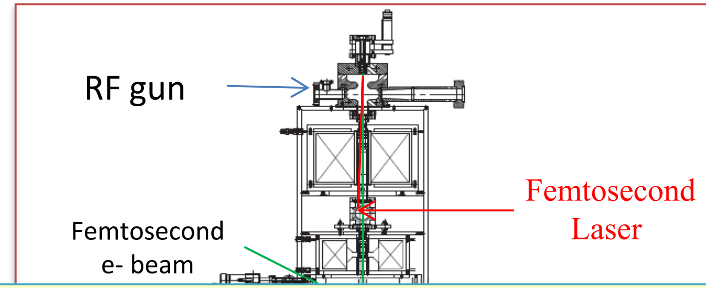

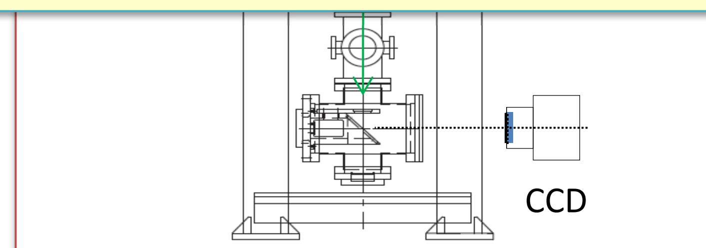

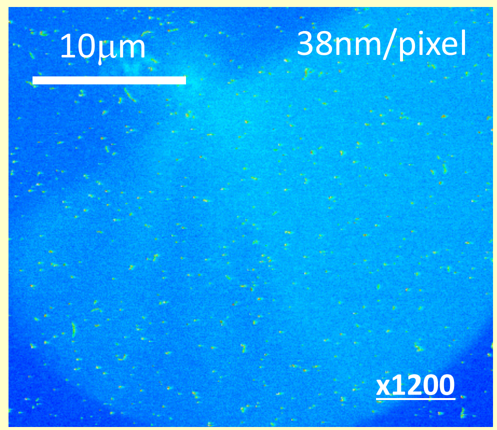

Electron charge:
~10 fC/pulse
(10^5 e-'s/pulse)

Measurement time:
~10 min

~10^8 e-'s/image

similar UEM projects in China and Germany!

beam requirements for single-shot ps UEM

$$B = \frac{N}{4\pi^2\sigma_x^2\sigma_{x'}^2 \cdot \Delta t \cdot \Delta\gamma/\gamma}$$

- *temporal resolution (a few ps):*
  - *ps bunch length:* $\Delta t \sim 1\ ps$
  - *sub-ps timing between laser and electron beams*
- *spatial resolution (a few tens of nm):*
  - *high flux at the sample (Rose' criterion):* $N \sim 10^6$-10^8, $\sigma_x \sim 1\ \mu m$
  - *low angular divergence (related to spherical aberration):* $\sigma_{x'} \sim 1\ mrad$
  - *low energy spread (related to chromatic aberration):* $\frac{\Delta\gamma}{\gamma} \sim 10^{-4}$ -10^{-5}

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  $\epsilon_n = 10\, nm\text{-}rad$
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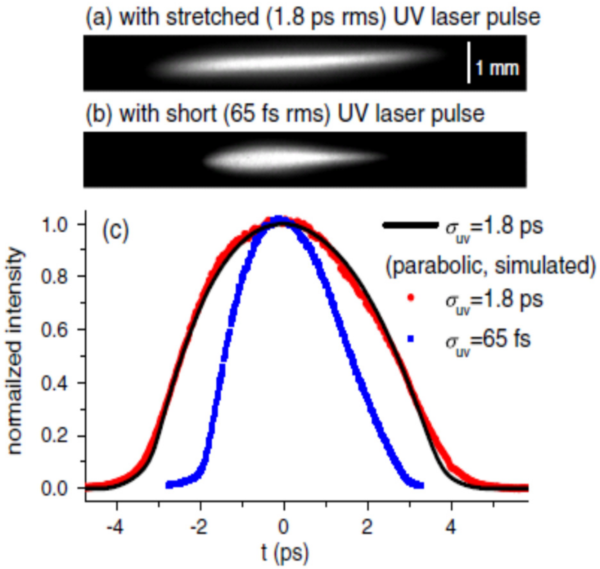
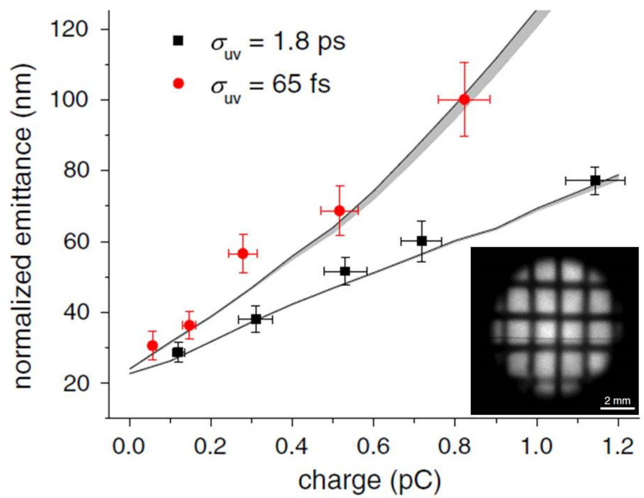
a few pC charge, ultralow emittance: Cigar-beam

- *Cigar-aspect-ratio beam: long (10 ps) and narrow (<50 μm spot size)*
  - *the aspect-ratio can beat the 'virtual cathode limit'* *D. Filippetto et al., submitted*
  - *very small intrinsic emittance from the cathode*
  - *transverse and longitudinal dynamics are essentially decoupled*

Simulation shows we can generate 5 MeV, 2 pC charge, 10 ps full width, <10 nm normalized emittance, <1 um rms spot size at the sample.

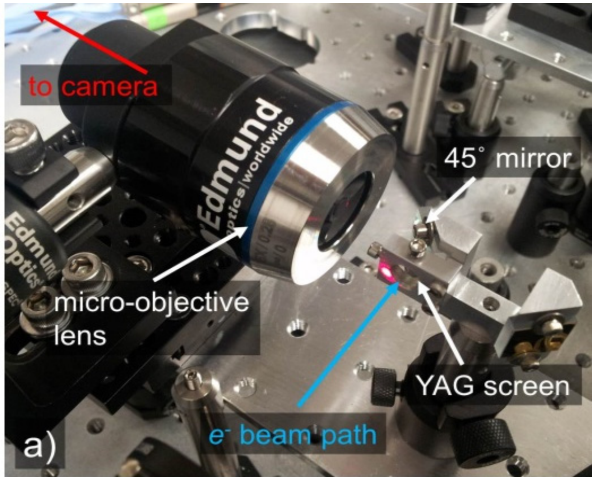
- *measurement of ultralow emittance and small spot size*





'grid method' measure very low (~1 nm) geometric emittance

R. K. Li et al, PRSTAB 15, 090702 (2012)



B. Jacobson's talk, **TUOBB4**

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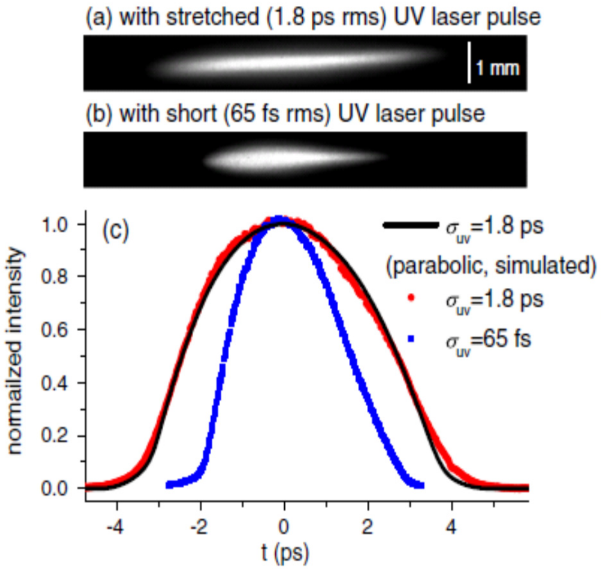

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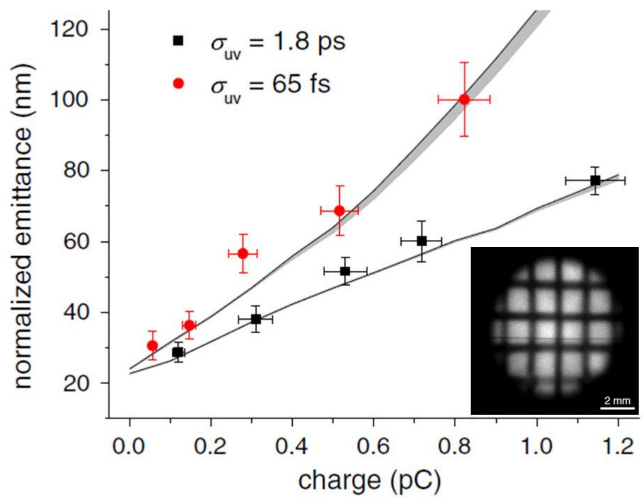

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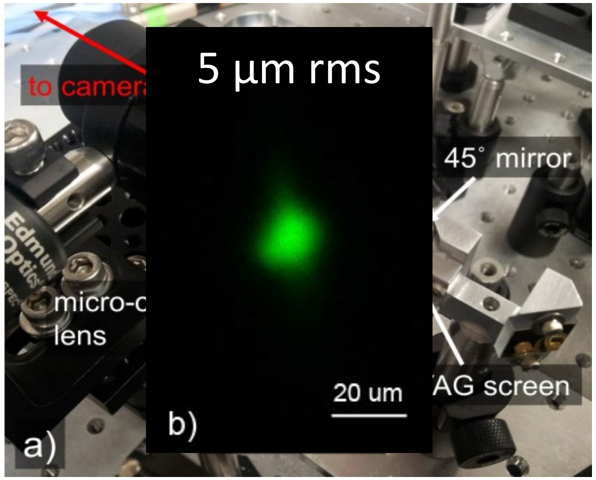

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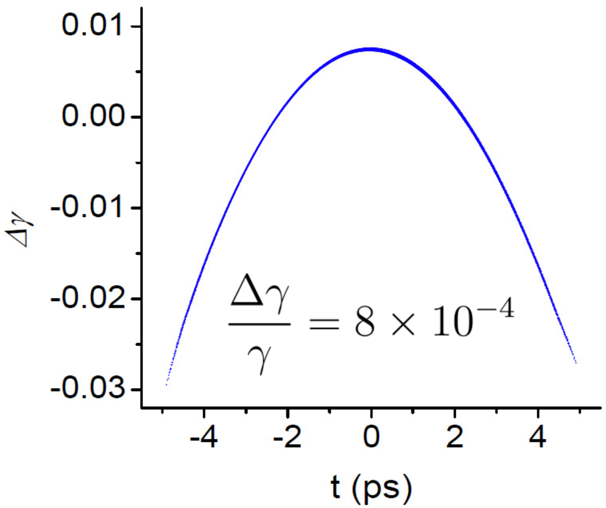
low energy spread: rf curvature regulation

- *beam rf curvature from rf guns*
  - *beam energy depends on launching phase (time)*
  - *beam energy spread dominated by the rf curvature*
  - *slice energy spread much smaller*

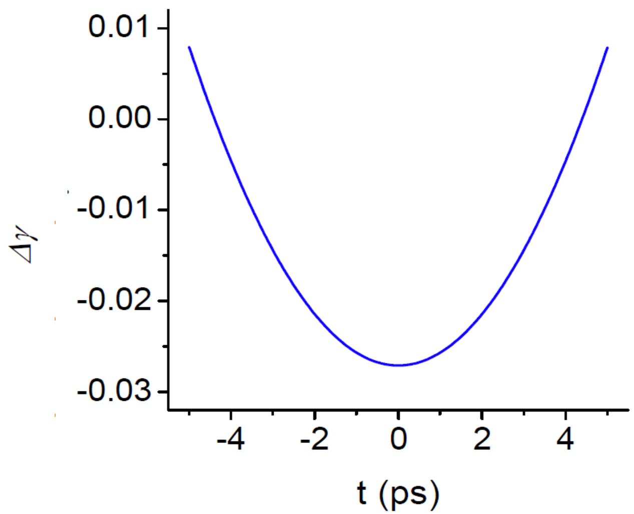
γ-t at S-band gun exit

$$\gamma(t) = \gamma_0 \cos\omega_0 t = \gamma_0 (1 - \frac{\omega_0^2 t^2}{2})$$



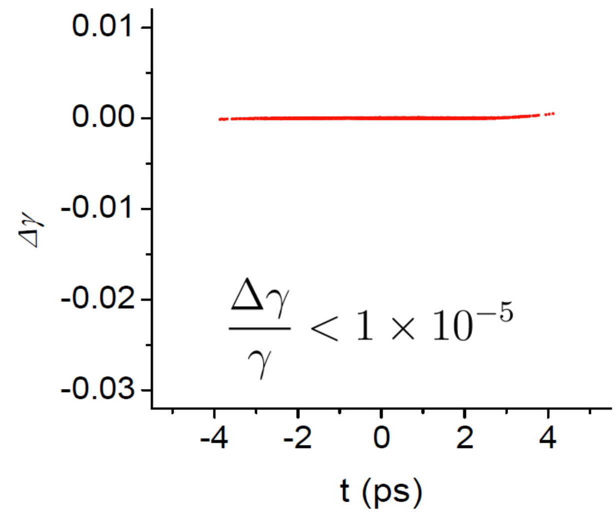
deceleration in X-band cavity

$$\gamma_X(t) = -\gamma_X (1 - \frac{k^2 \omega_0^2 t^2}{2})$$



final γ-t distribution

$$\gamma_X = \gamma_0 / k^2$$



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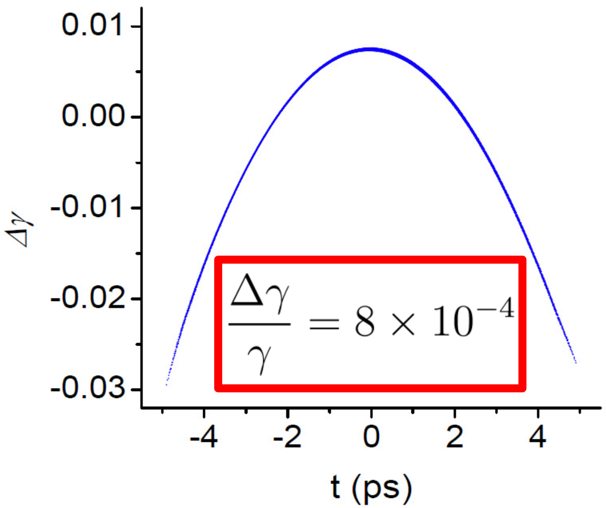

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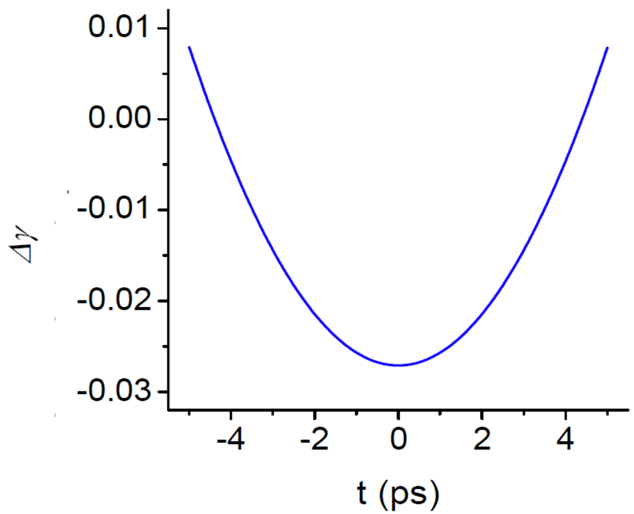

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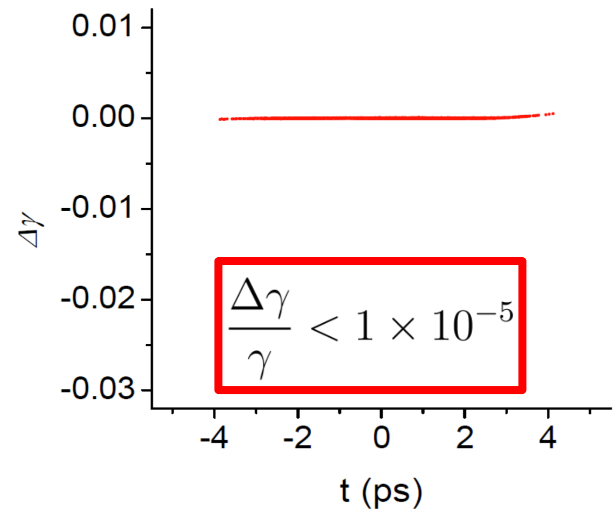
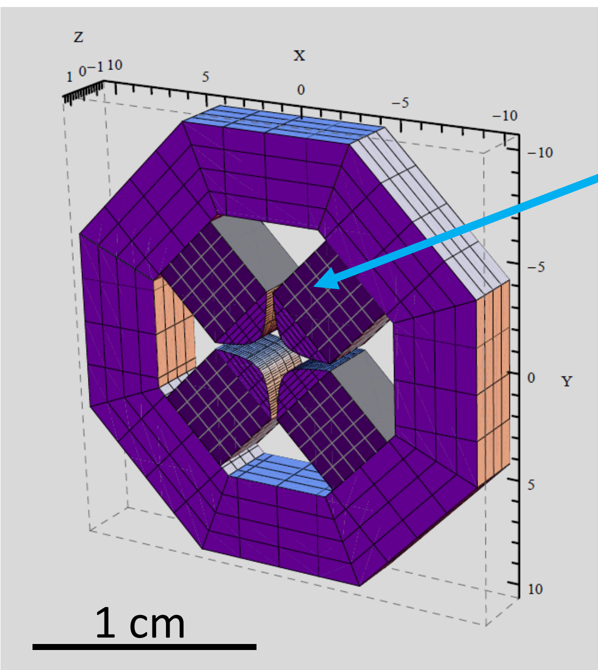


- *larger $k \equiv \omega_X/\omega_0$ works better (less deceleration)*
- *performances limited by rf amplitude and phase stabilities*

strong lenses for MeV beams

- *for conventional TEMs (<300 keV), solenoid lenses are used*
- *solenoid is symmetric, but very ineffective for high energy electrons*
- *Cs and Cc are roughly equal to the focal length*
- *heavy and bulky NC solenoid (≤2.2 T), or SC solenoid can be used*
- *or, using quadrupoles which are strong and compact*

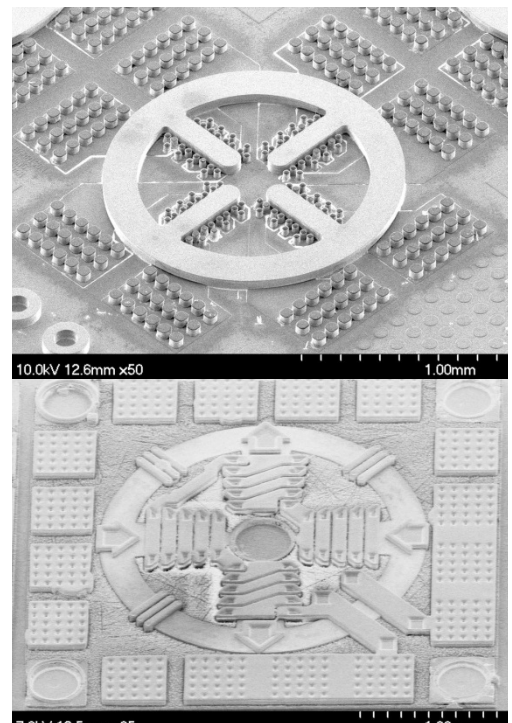
permanent magnet quadrupoles



permanent magnets, B_0=1.40 T

gradient G~500 T/m

nanofabricated micro-quads



1) gradient G>1000 T/m

2) tunable strength!!

Courtesy of J. Harrison, UCLA

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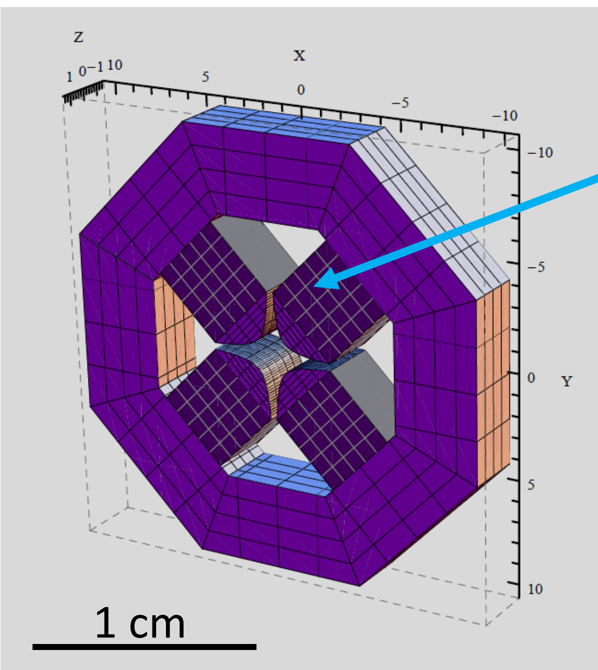

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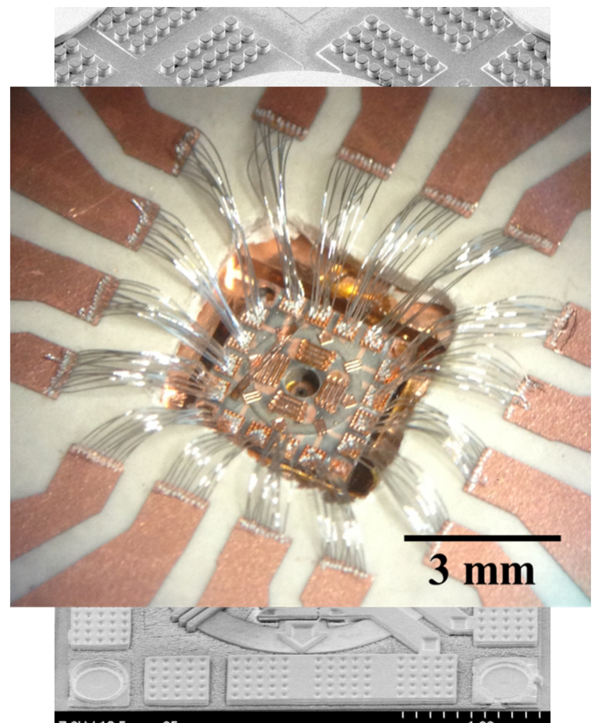

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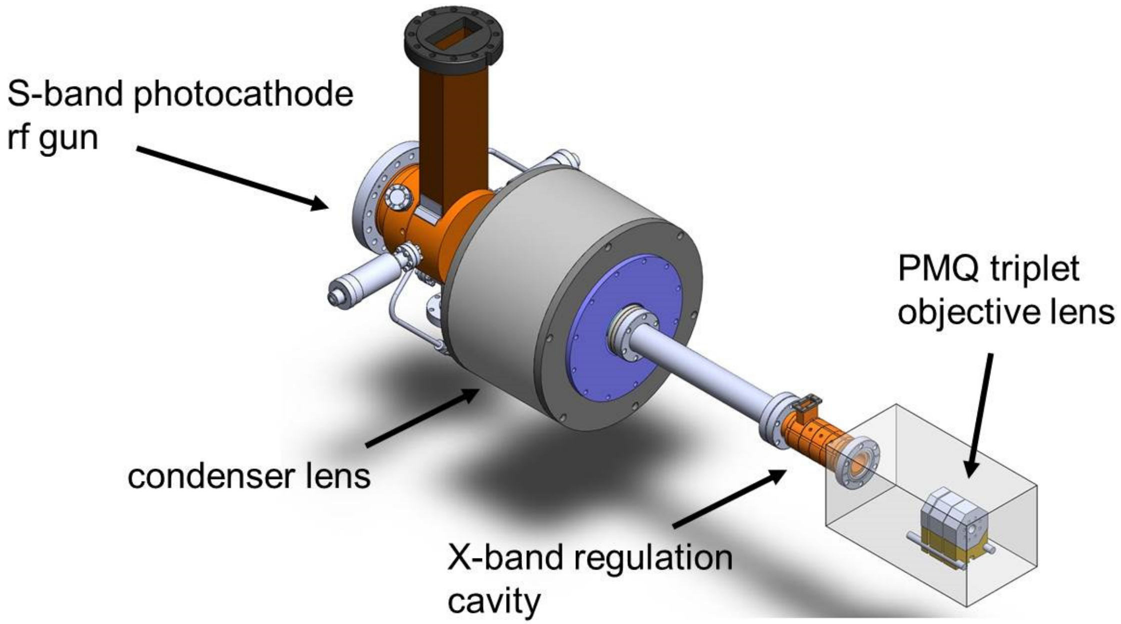
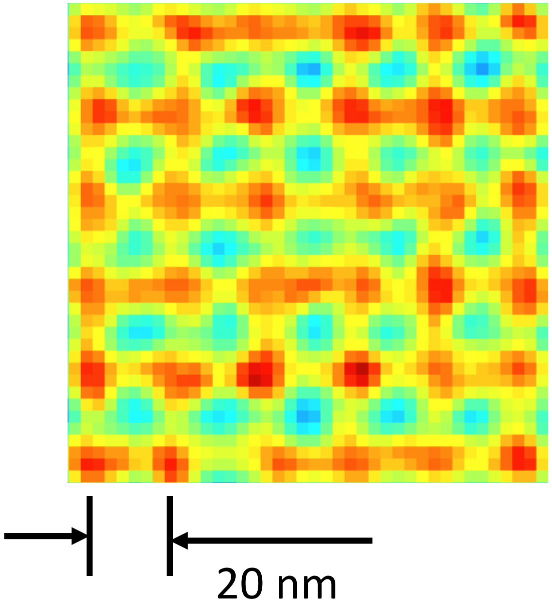
key components of a single-shot ps UEM



start-to-end simulation with point-to-point tree code



- *high gradient S-band rf gun* *see L. Faillace HBEB Workshop 2013*
- *X-band rf regulation cavity*
- *strong electron lens*
- *high efficiency detection of MeV electrons* *R. K. Li et al., JAP 110, 074512 (2011)*
- *rf amplitude and phase control*

Acknowledgement

- funding agencies: DOE-BES, DOE-HEP, JTO-ONR

- UCLA Pegasus Laboratory members
- O. Williams and P. Frigola on PMQ
- helpful discussions with M. Mecklenburg, B. W. Reed, J. C. H. Spence, and W. Wan

Summary

- strong motivation, clear path towards a single-shot ps UEM
- many scientific opportunities
- relatively compact and low cost facility fit into university labs
- technical approaches well defined, new technologies will help
- key parameters (emittance, energy stability and spread) challenging but within reach
- precise control and advanced diagnosis
- R&D will also benefit light source applications

Thank you for your attention!