MeV ultrafast electron diffraction and microscopy for the scientific frontier

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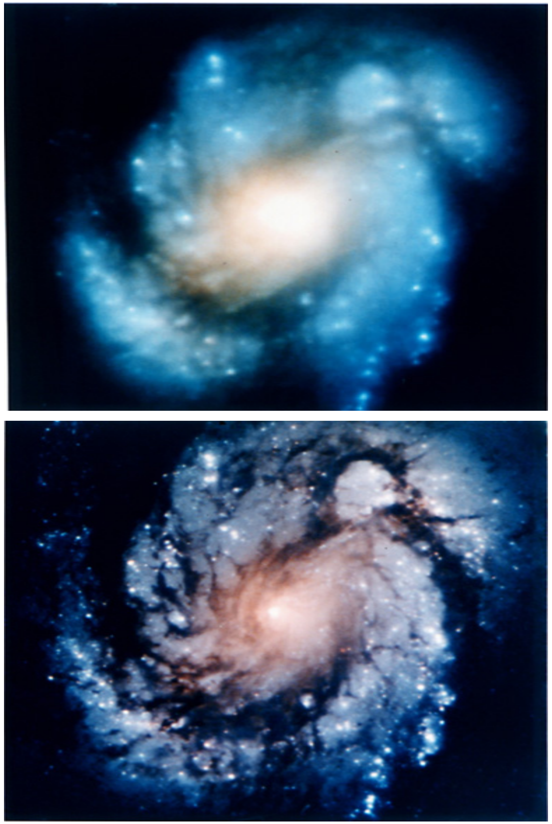
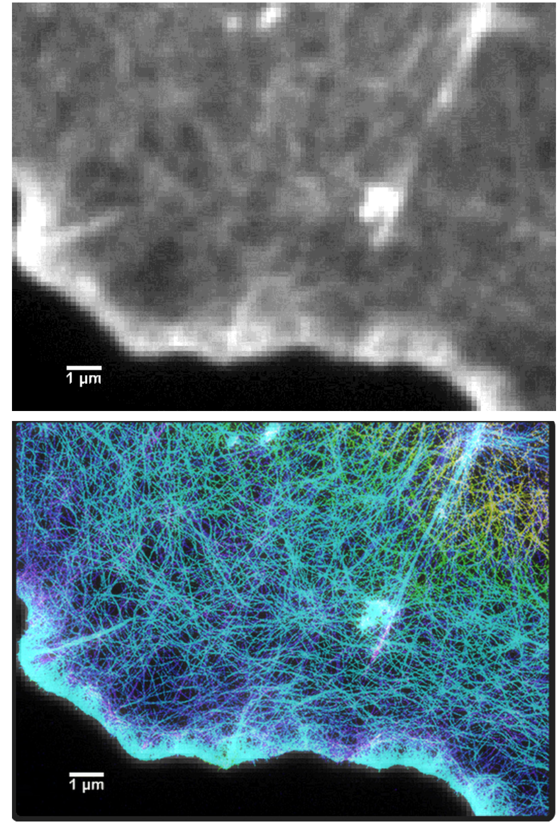
5/21/2019

The quest of resolution



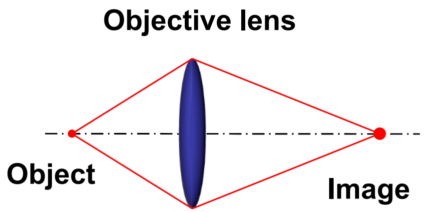
Galaxy by Hubble Space Telescope



Molecule by super resolution fluorescence microscopy

Spatial resolution: imaging and diffraction

Imaging

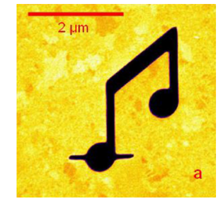


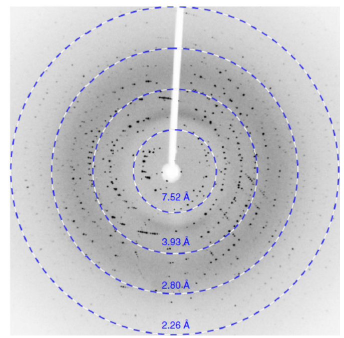
$$\Delta r \approx \frac{\lambda}{2n\sin\alpha}$$

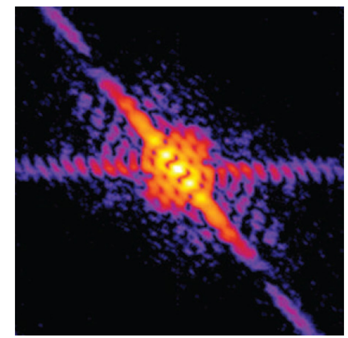
***λ*: wavelength of incident beam**
***n*·sin(*α*): Numerical Aperture**

Resolution: λ/2
(~200 nm for optical light)

Diffraction



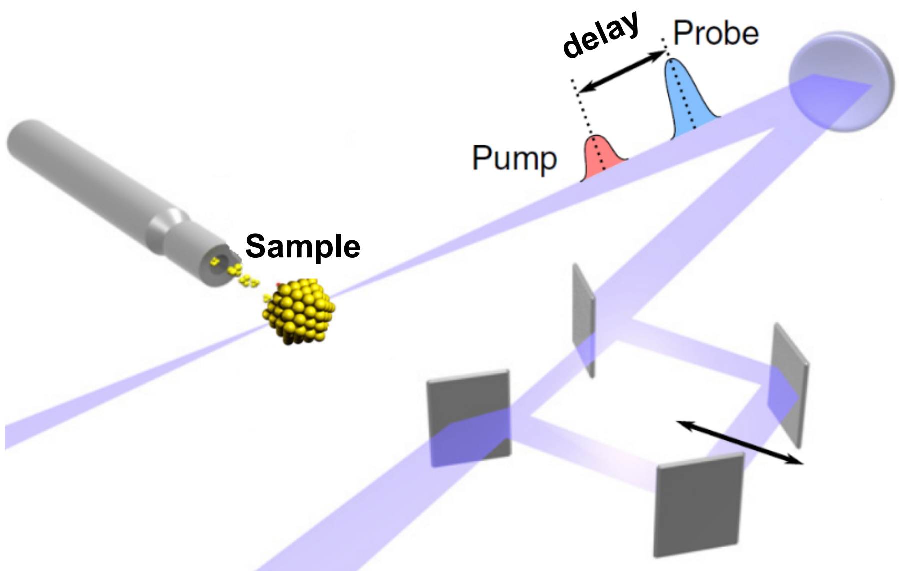


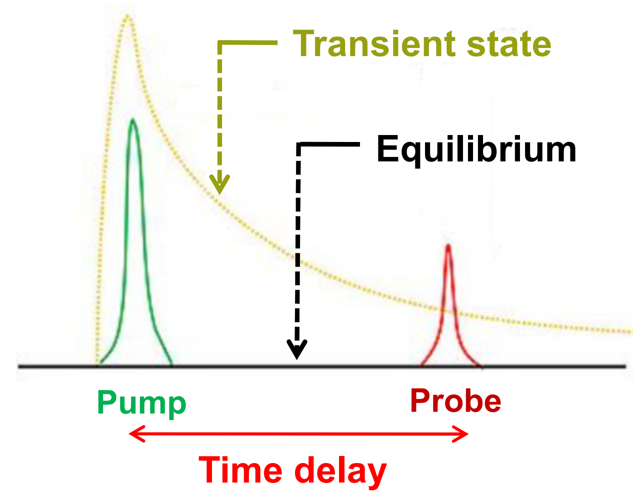


Crystallography

Coherent diffraction imaging

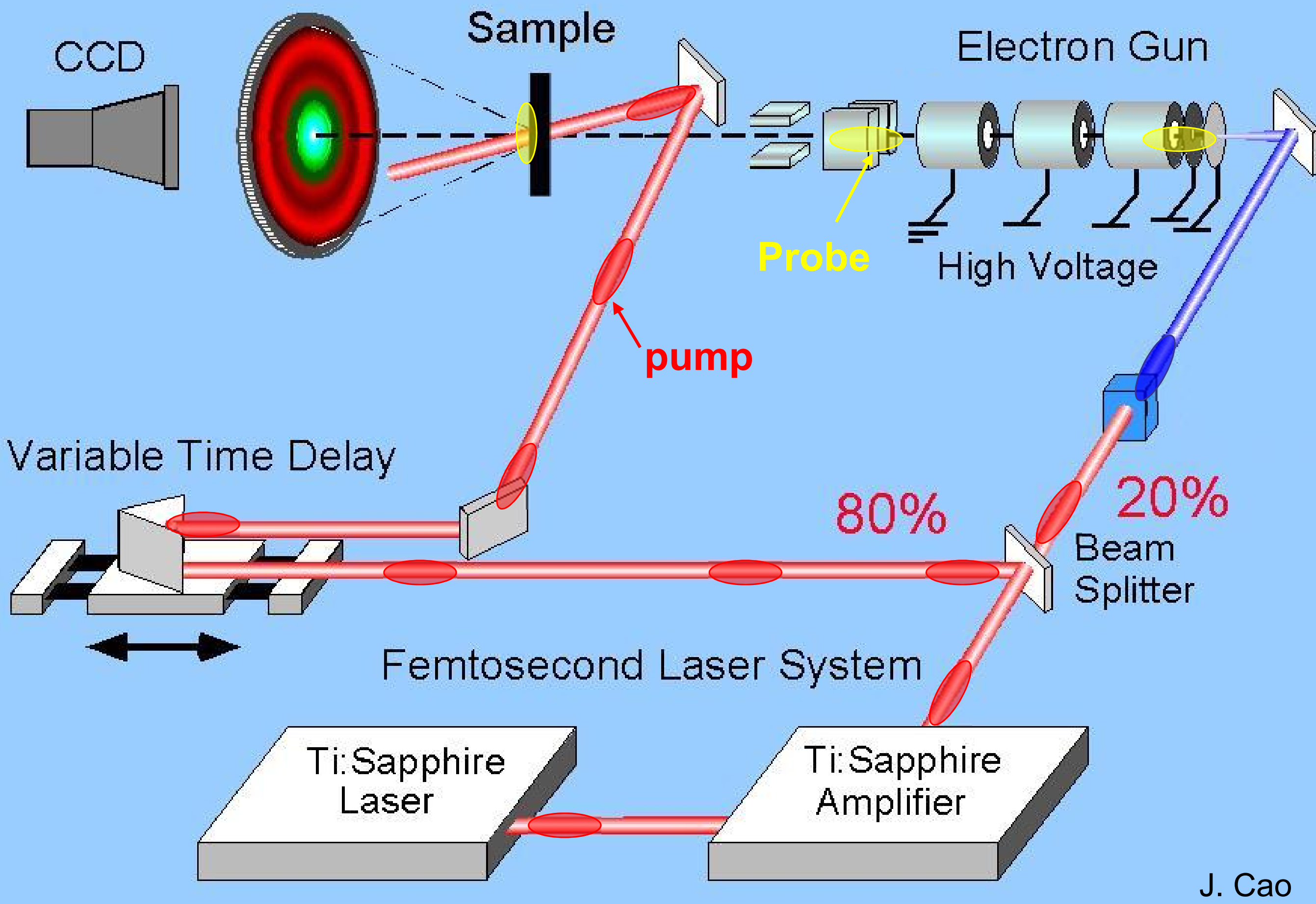
Temporal resolution: pump-probe technique



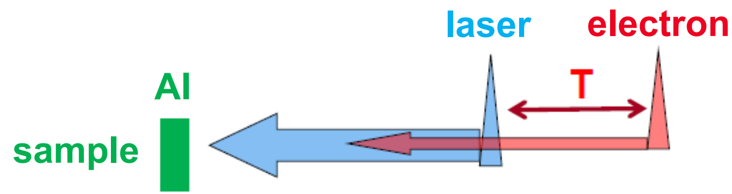


- A ‘pump’ pulse drives the system out of equilibrium state to initiate a dynamic process
- A ‘probe’ pulse measures the transient state following the excitation at a given delay time
- Changing time delay to map out the whole process by which the system relaxes back
- Pulsed x-ray or electron ‘probe’ beams provide both high spatial and temporal resolution
- Ultrafast Electron Diffraction (UED): laser-pump electron-probe technique

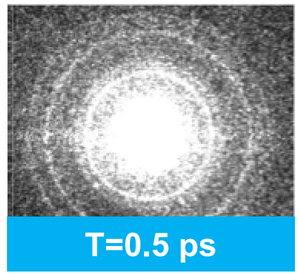
Ultrafast electron diffraction (UED): complementary to FELs

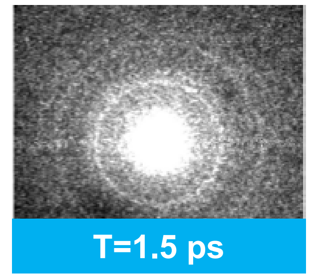


UED application: phase transition



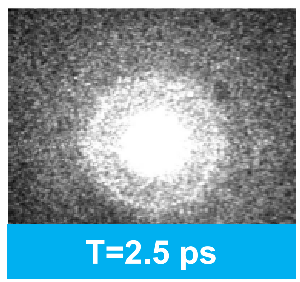
Still a crystal

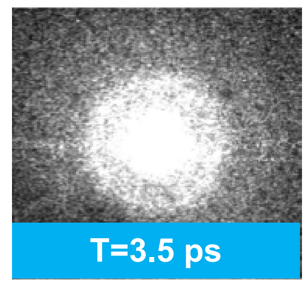




Start to lose long range order

Long range order almost lost





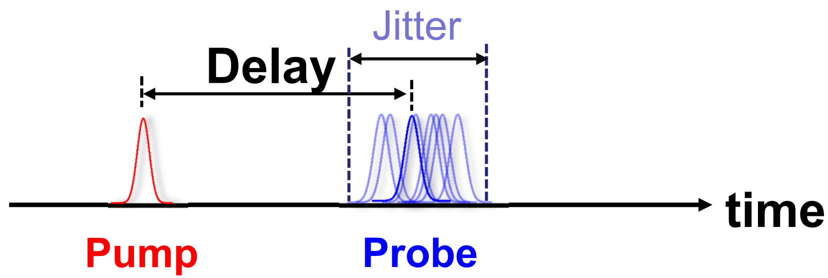
Now in liquid state

An atomic view of phase transition in Aluminium

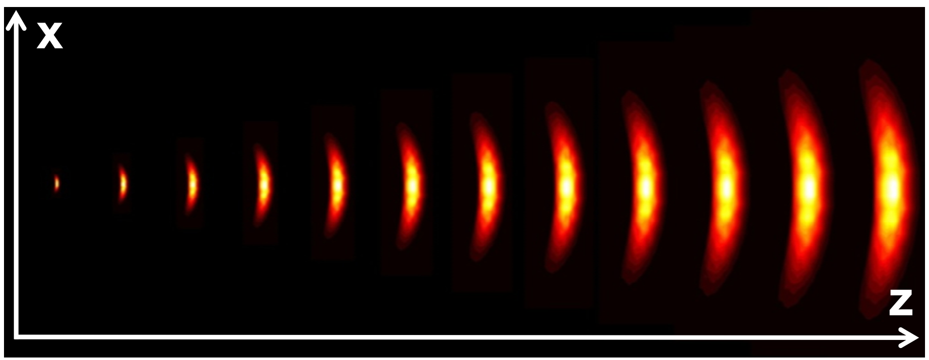
Science 302, 1382 (2003)

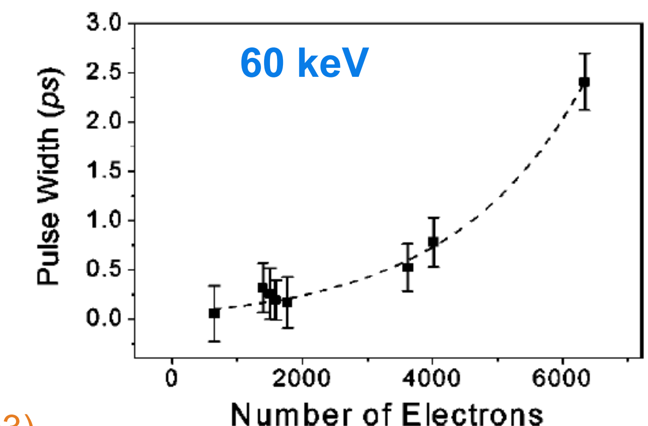
UED temporal resolution

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



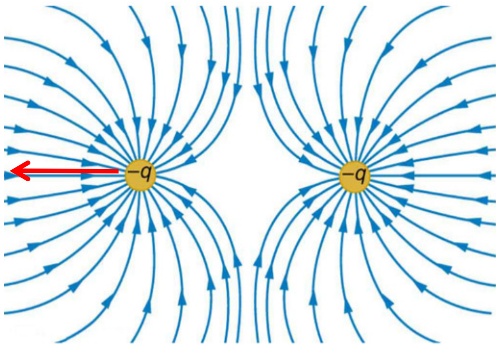
Electron beam pulse width limited by space charge effect



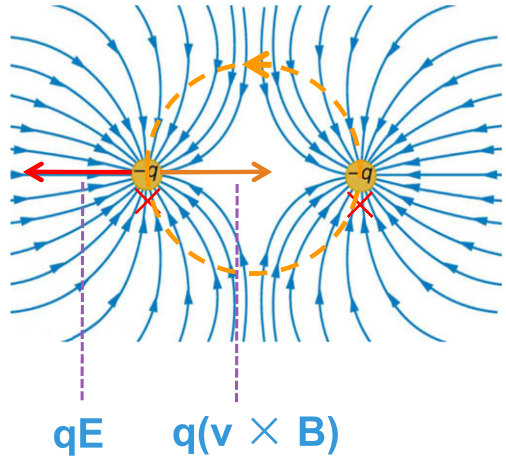


APL 83, 1044 (2003)

UED and UEM go relativistic

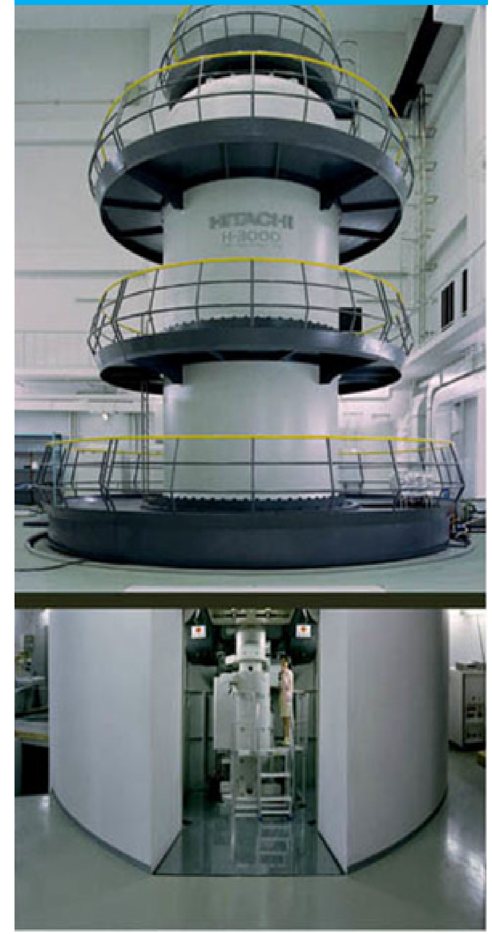


F=q[E+(v×B)]



- v = 0.99c for 3 MeV electron beam
- The electric force and magnetic force largely cancel out
- MeV beam from a photocathode rf gun
- High acceleration gradient increases beam brightness
- High acceleration gradient reduces cost and size

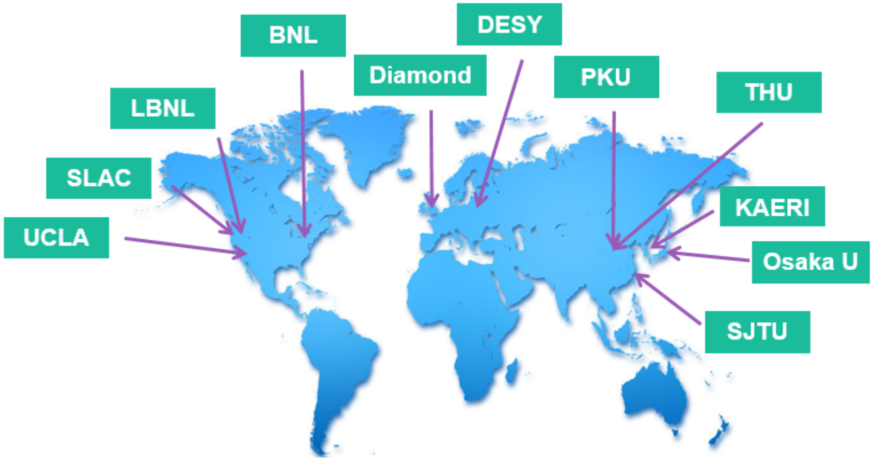
3 MeV TEM at Osaka

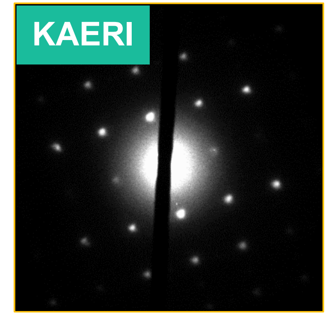


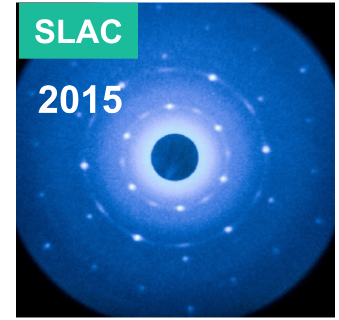
Outline

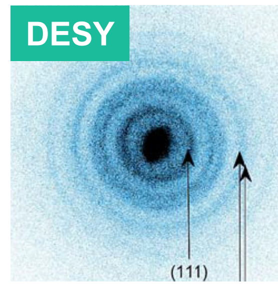
- Introduction
- MeV UED and UEM developments
- Breaking ~50 fs resolution barrier
- Summary

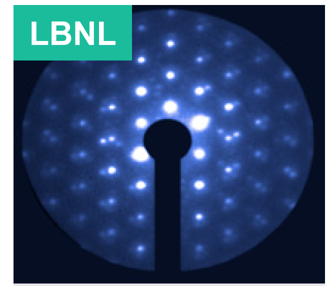
Accelerator-based MeV UED: world-wide efforts

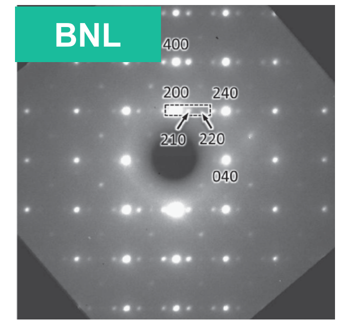


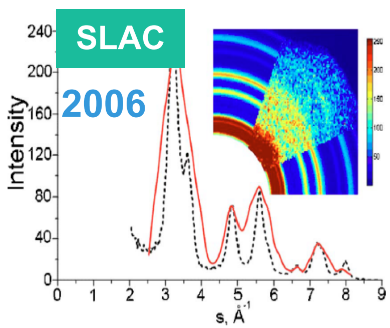


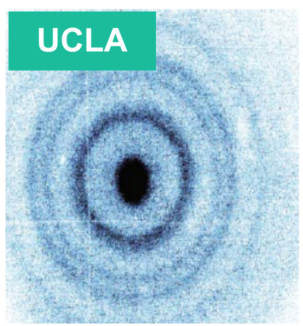


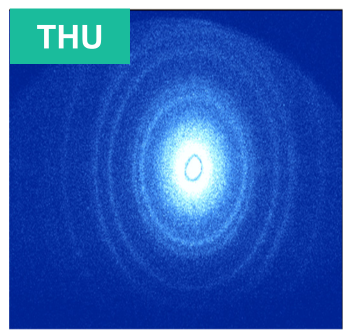


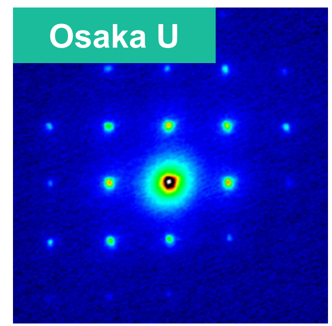


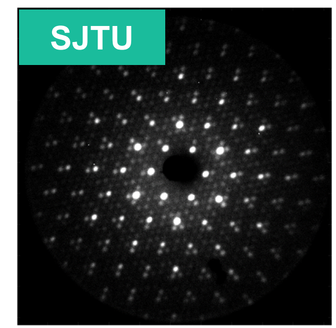






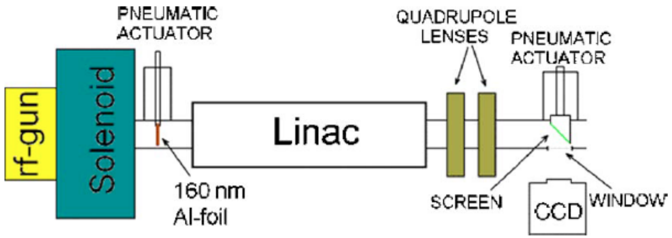


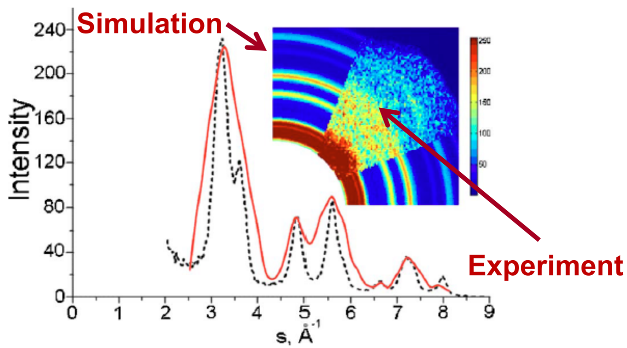




Stage 1: proof-of-principle demonstration

SLAC, 2006





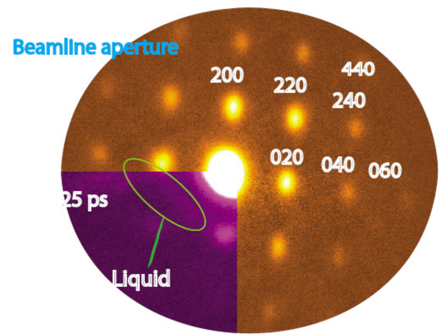
- First demonstration of MeV UED
- Single-shot diffraction obtained with a 5.4 MeV / 3 pC /500 fs beam
- No collimator to improve S/N ratio

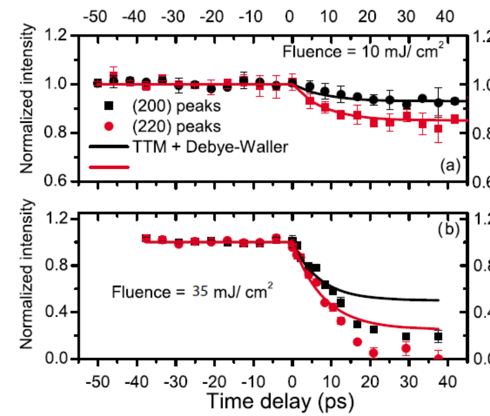
APL 89, 184109 (2006)

UCLA, 2010

$$C_e \frac{\partial T_e}{\partial t} = \frac{\partial}{\partial x}\left(k_e \frac{\partial T_e}{dx}\right) - G(T_e - T_l) + S$$

$$C_l \frac{\partial T_l}{\partial t} = \frac{\partial}{\partial x}\left(k_l \frac{\partial T_l}{dx}\right) + G(T_e - T_l)$$



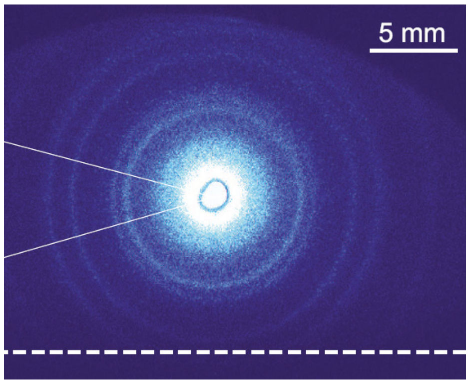


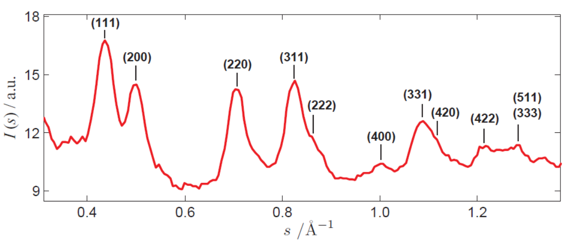
- For the first time MeV UED is used in a pump-probe experiment for studies of ultrafast dynamics
- Laser-induced Debye-Waller effect in Gold
- Collimator to improve S/N ratio

APL 97, 063502 (2010)

Stage 1: proof-of-principle demonstration

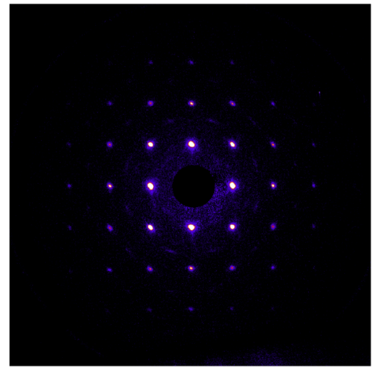
THU, 2009

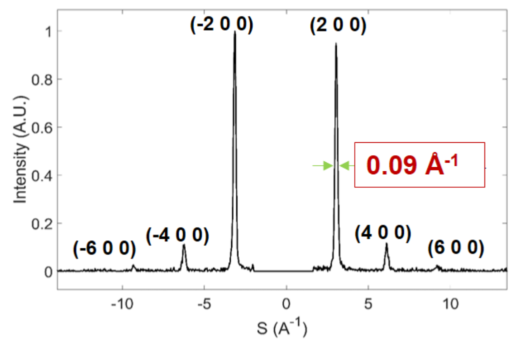




RSI 80, 083303 (2009)

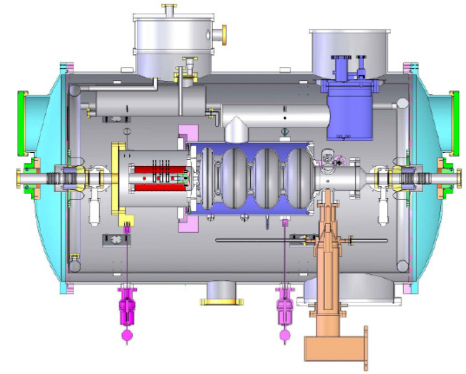
SJTU, 2014



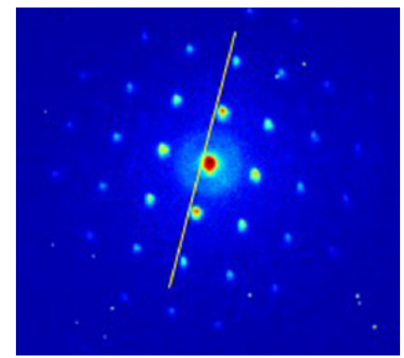


RSI 85, 083701 (2014)

PKU, 2015



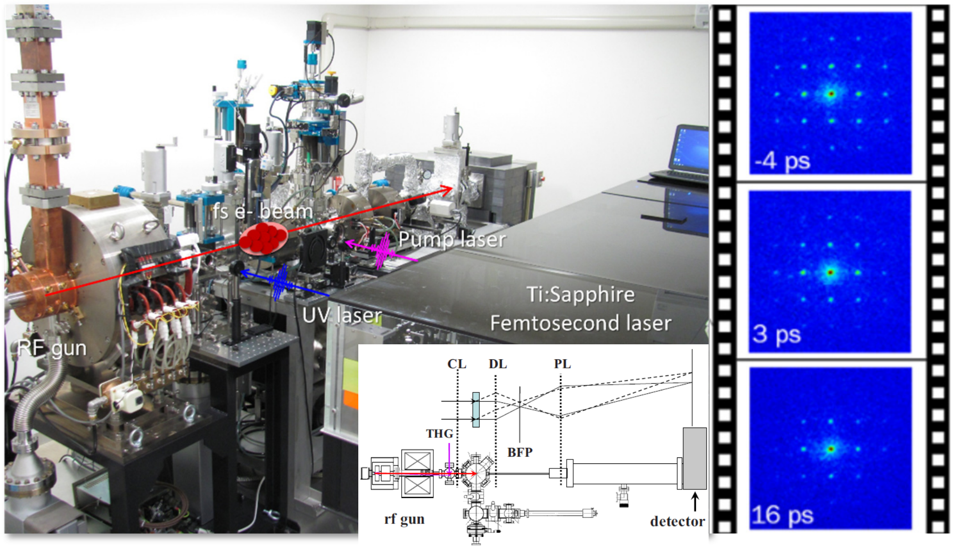
DC-SRF gun (~MHz)



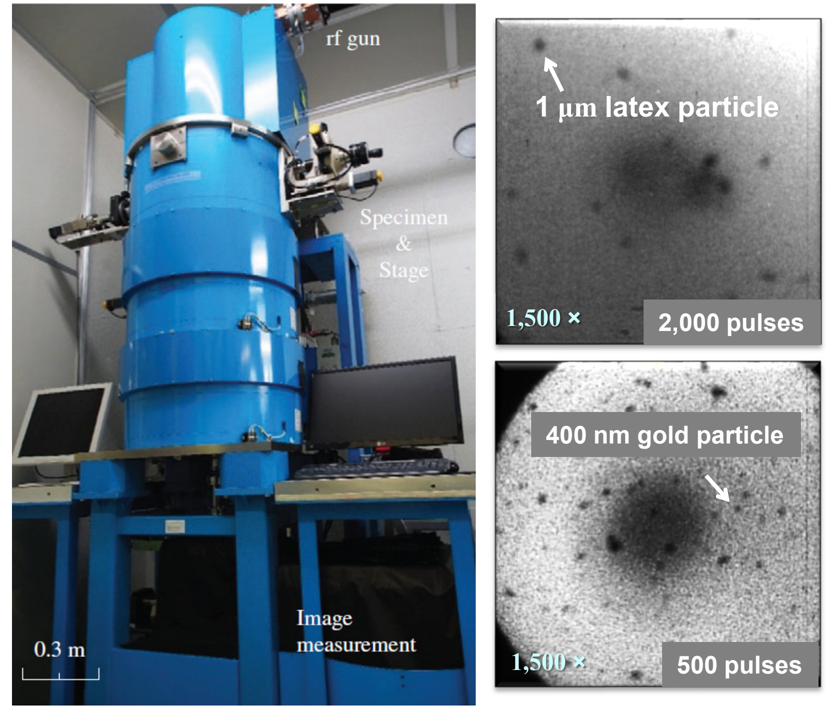
APL 107, 224101 (2015)

Stage 1: proof-of-principle demonstration

Osaka U, 2011



Compact diffractometer

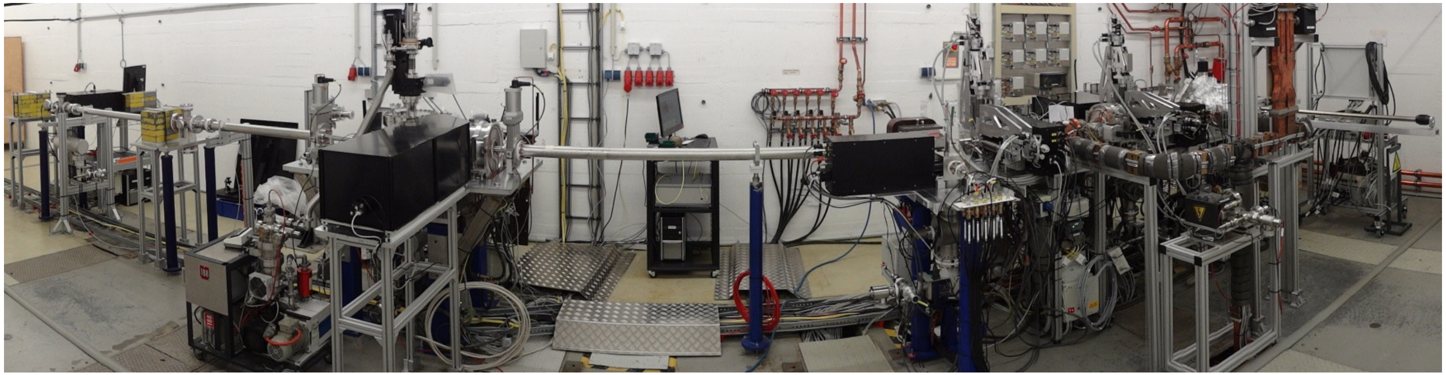


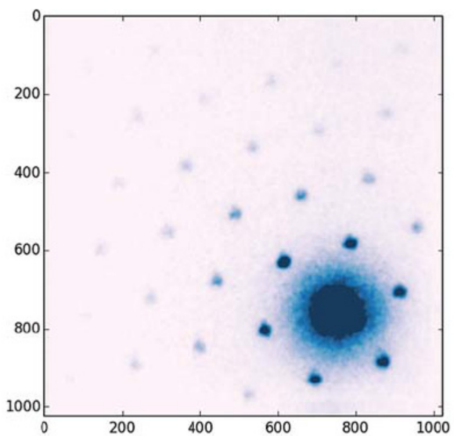
Ultrafast electron microscope

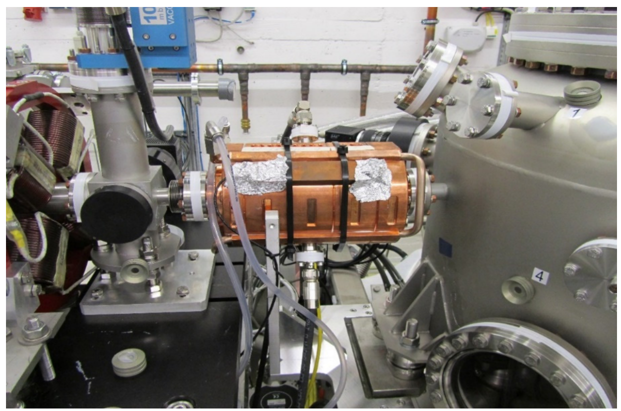
APL 98, 251903 (2011)   APL 103, 253107 (2013)   Microscopy 67, 291 (2018)

Stage 1: proof-of-principle demonstration

DESY/MPSD， 2015





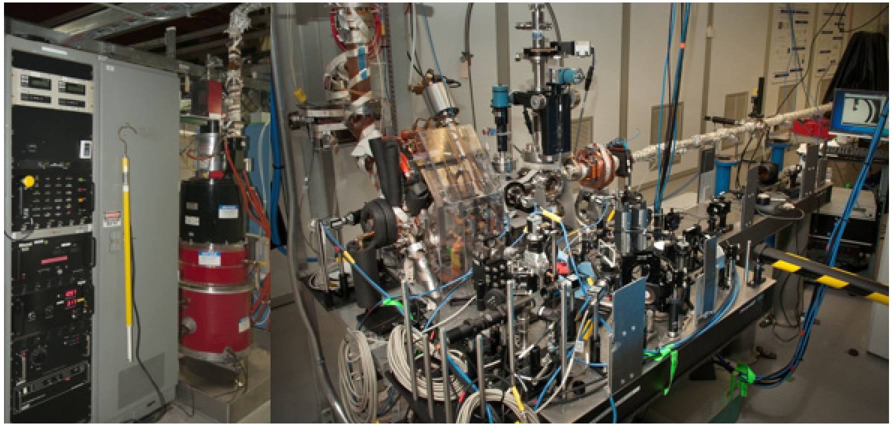


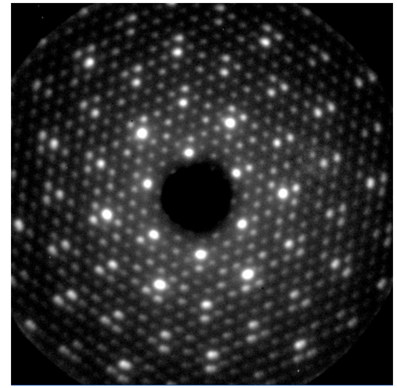
- **Static diffraction obtained**
- **Buncher and deflector to improve resolution**

Faraday Discuss., 177, 467 (2015)

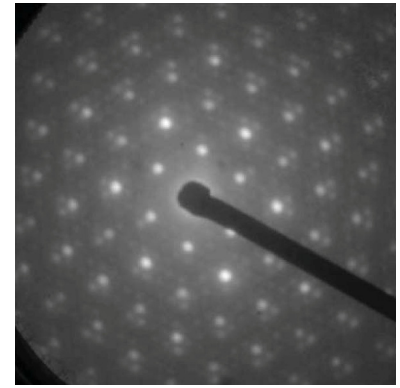
Stage 2: from test facility to user facility

BNL

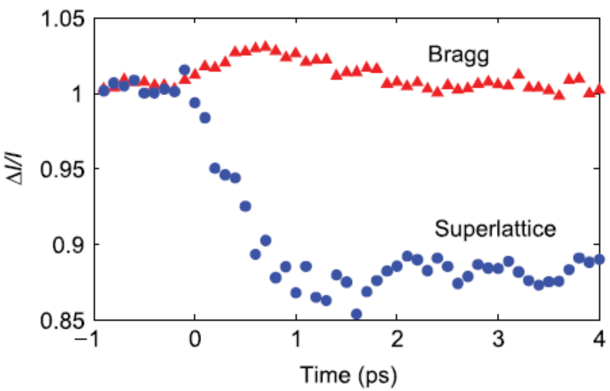


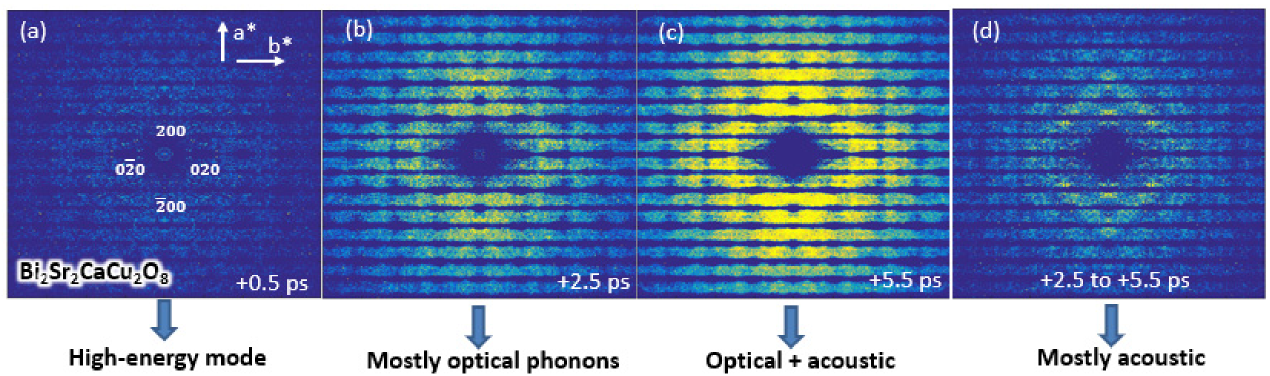


3 MeV UED



60 keV UED



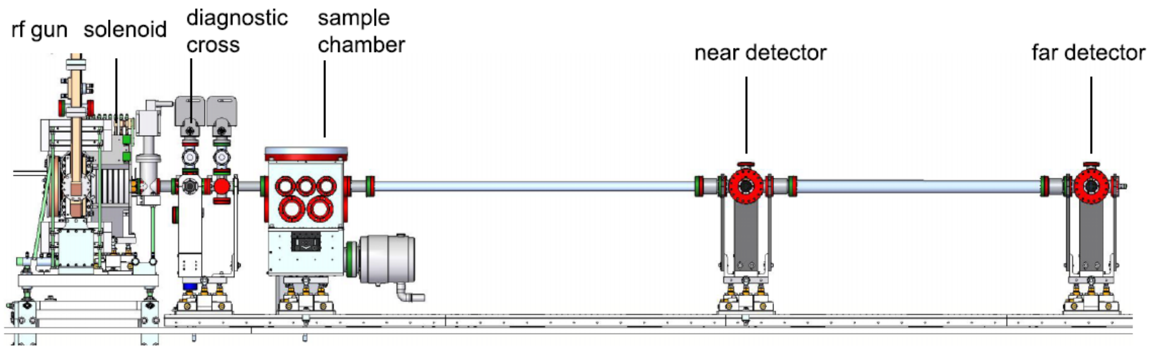


NJP 17, 063004 (2015); Sci. Adv., 4: ap7427 (2018)

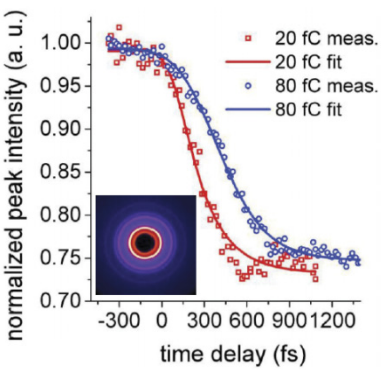
Separate optical and acoustic phonons

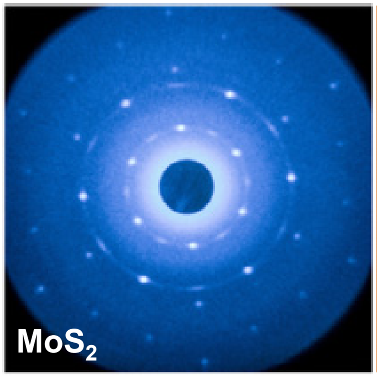
Stage 2: from test facility to user facility

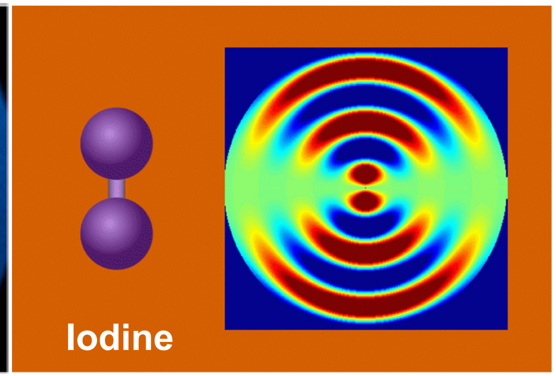
SLAC

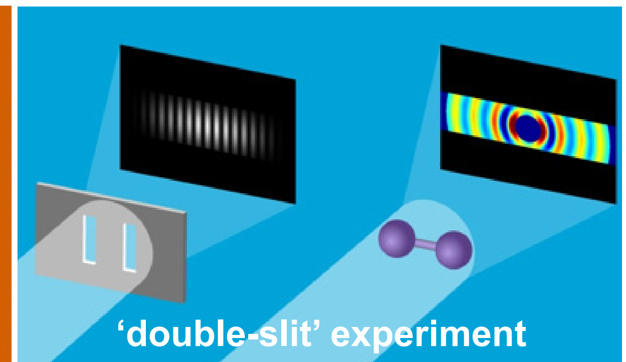


- **State-of-the-art**
- **180 Hz / 150 fs resolution (FWHM)**
- **Optical to THz pump pulse**
- **Solid / gas sample**
- **30 K – 400 K temperature control**
- **5-axis sample manipulation**
- **Now a DOE user facility**







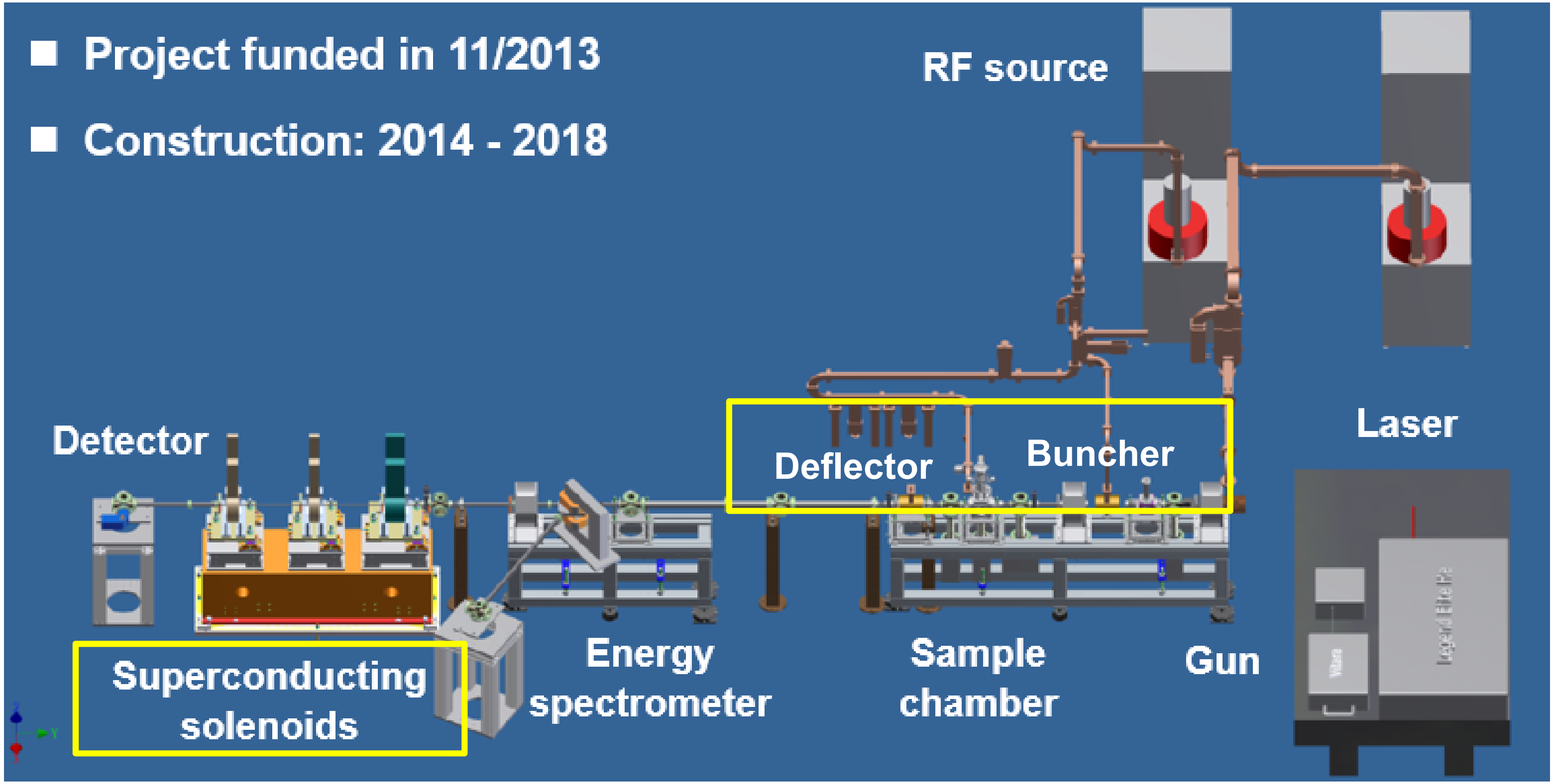


RSI 86, 073702 (2015); PRL 117, 153002 (2016); Science 360, 1451 (2018) / 361, 64 (2018); Nature 565, 61 (2019)

Stage 2: from test facility to user facility

SJTU

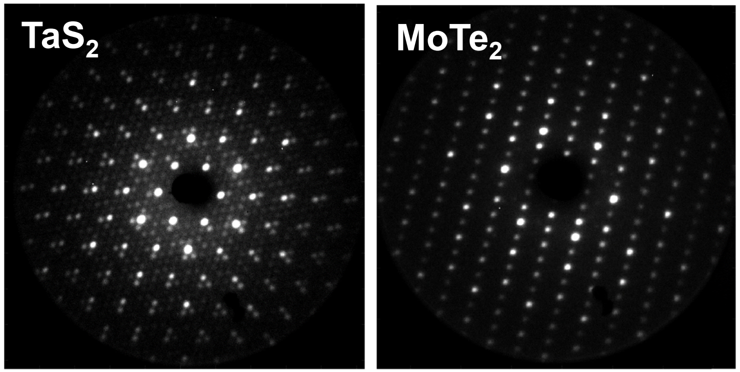
- Project funded in 11/2013
- Construction: 2014 - 2018



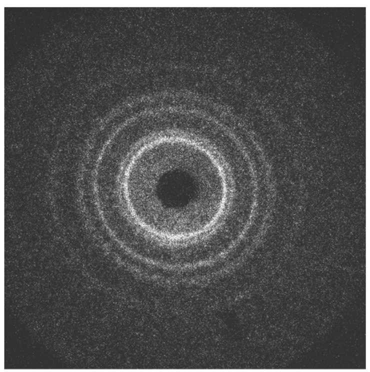
3 MeV ultrafast electron diffraction and microscope

Stage 2: from test facility to user facility

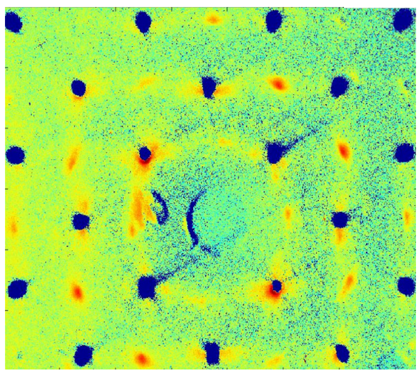
SJTU



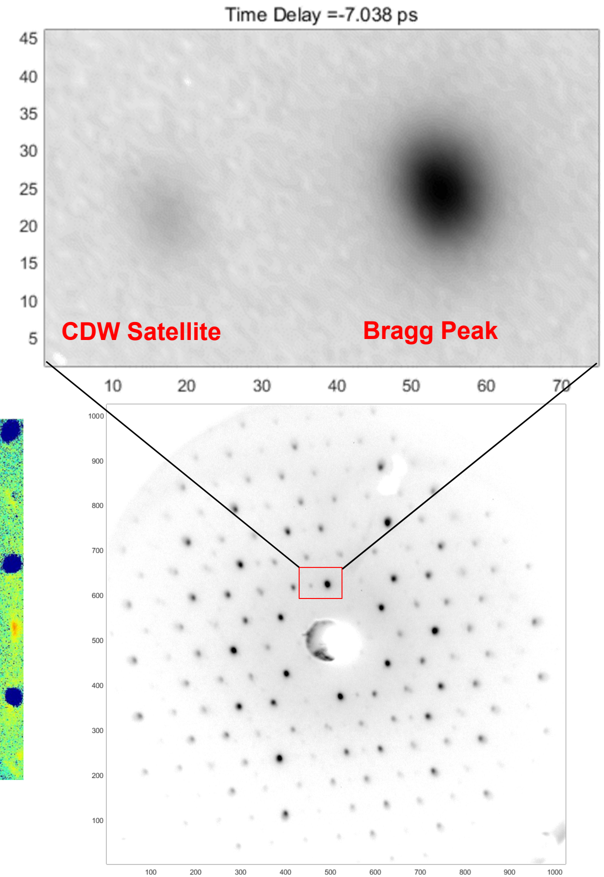
High quality electron diffraction

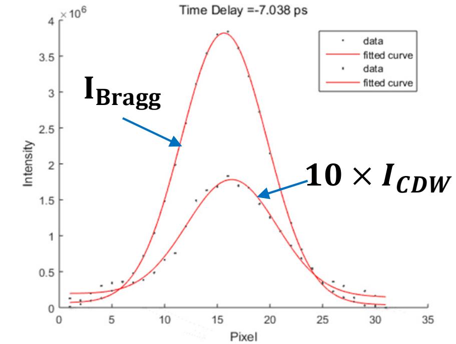


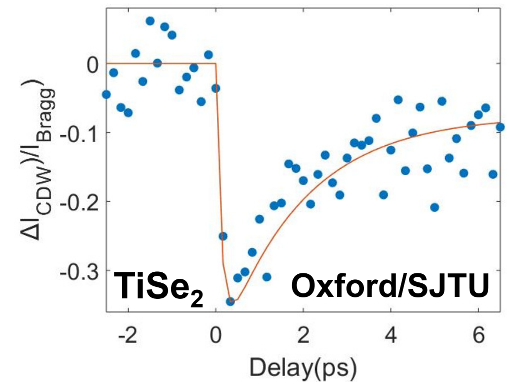
Single-shot with ~100 fs beam



Diffuse scattering with ~10^{10} electrons



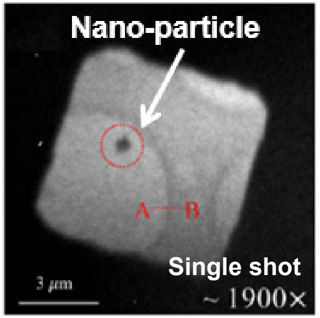


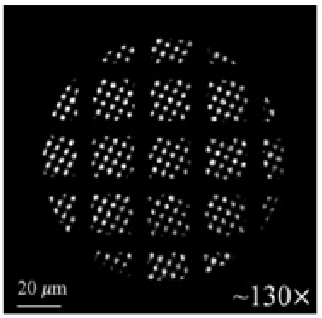


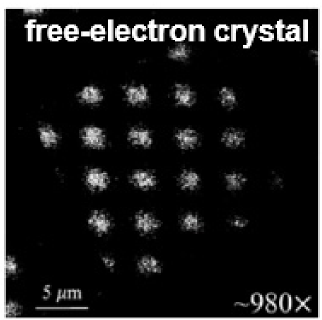
Charge density wave dynamics

Manuscript in preparation

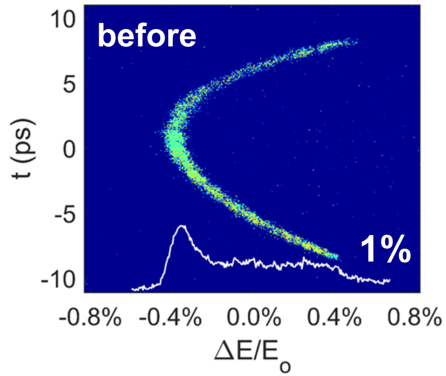
Stage 2: from test facility to user facility

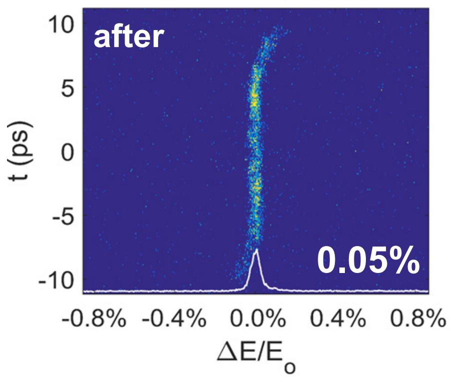






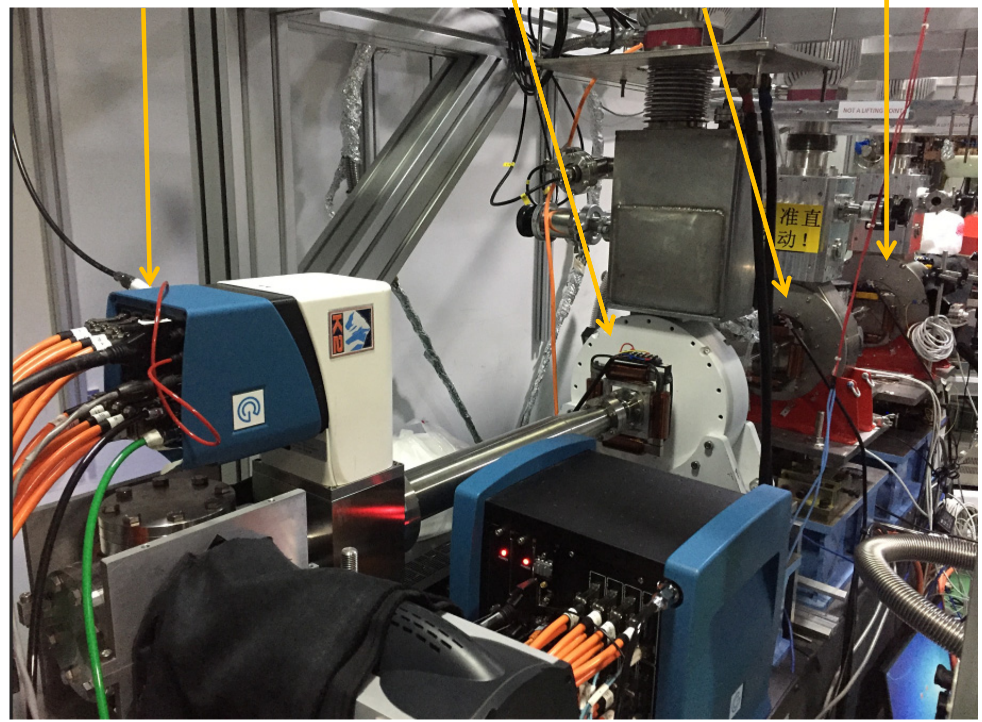
SJTU





Reduce energy spread with a harmonic cavity

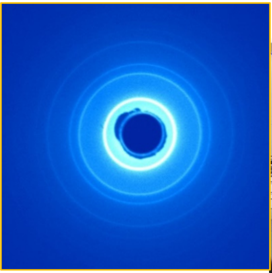
Appl. Phys. Lett. 112, 113102 (2018)

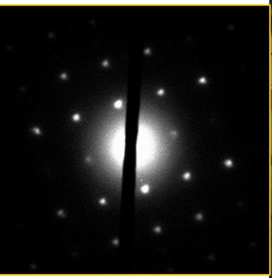


3 MeV ultrafast electron microscope

Stage 2: from test facility to user facility

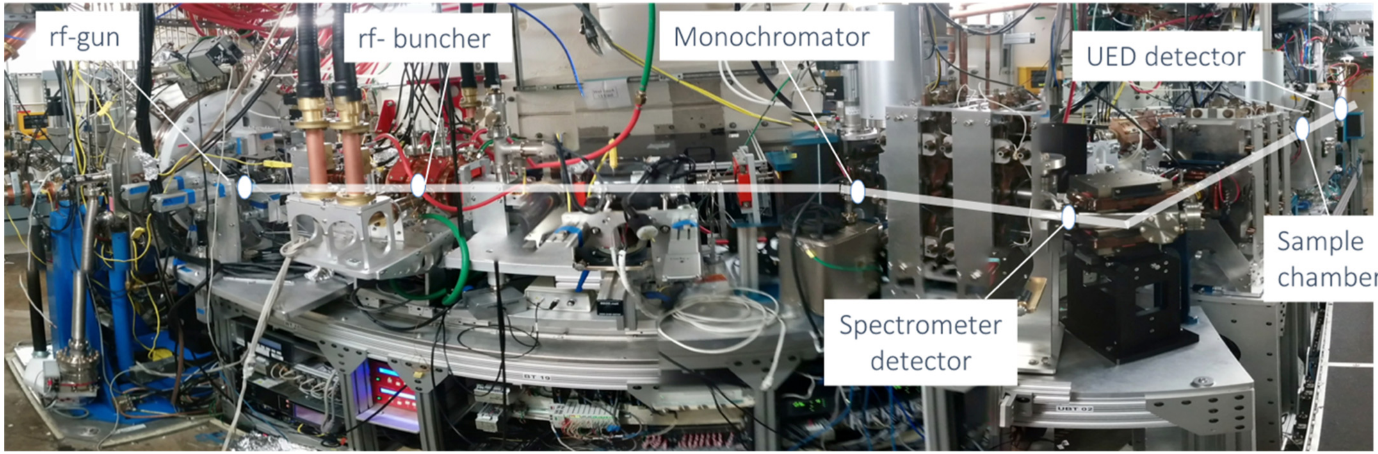
KAERI





Stage 2: from test facility to user facility

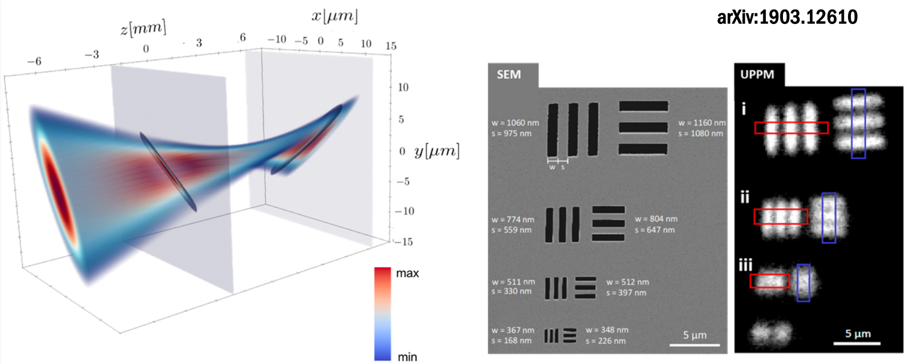
LBNL: High Repetition Rate Electron Scattering beamline (HiRES)



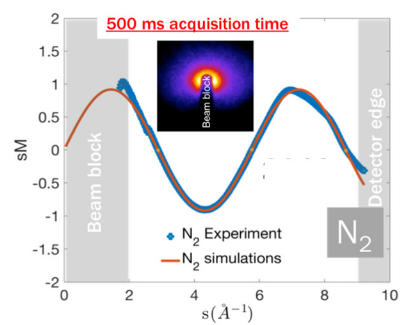
Electron beam energy	**700-900 keV**
Repetition rate	**1-10^6 Hz**
Temporal resolution	**200 fs-1000 ps**
Electrons per pulse	**1-10^8**
Relative energy spread	**10^{-3} 10^{-4}**

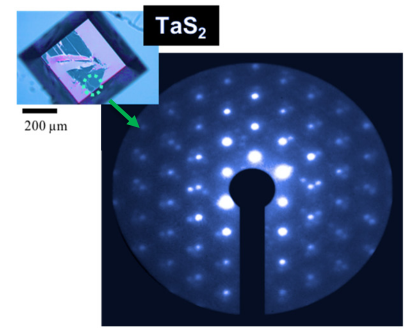
Nano-UED and UPPM

arXiv:1901.03443
arXiv:1903.12610



Gas and solid state experiments ongoing





Outline

- Introduction
- MeV UED and UEM developments
- Breaking ~50 fs resolution barrier
- Summary

break ~50 fs resolution barrier

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

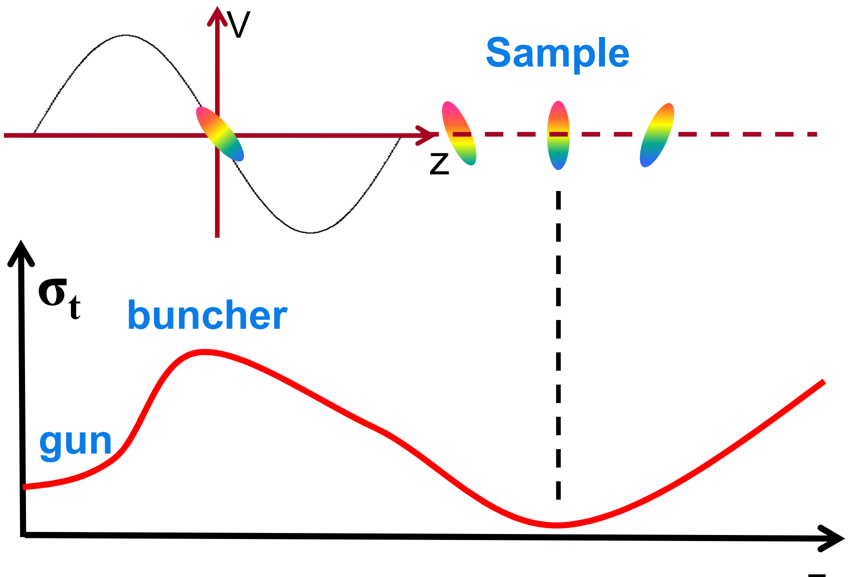
- **rf compression + time stamping**

  Produce short beam and correct timing jitter

- **Compression with space charge force**

  Produce short beam with small timing jitter

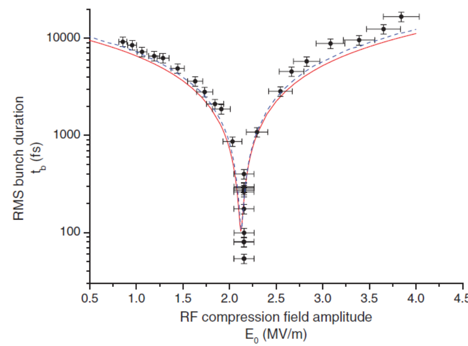
rf compression + time stamping

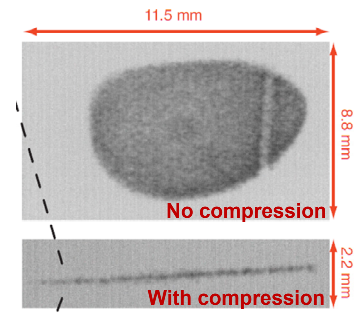


Bunch length vs z

- **Negative energy chirp**
- **Low energy electrons slow down**
- **High energy electrons catch up**

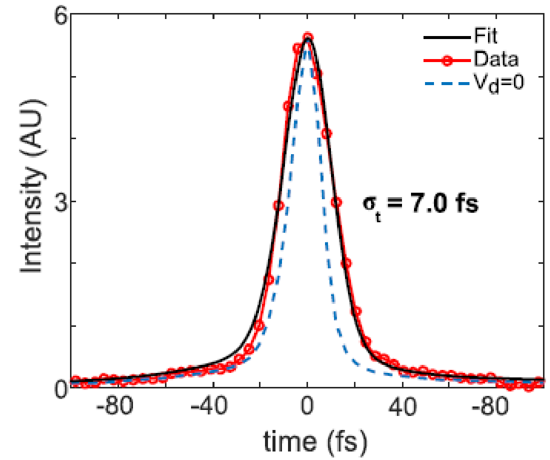
95 keV beam
10 ps -> 100 fs





PRL 105, 264801 (2010)

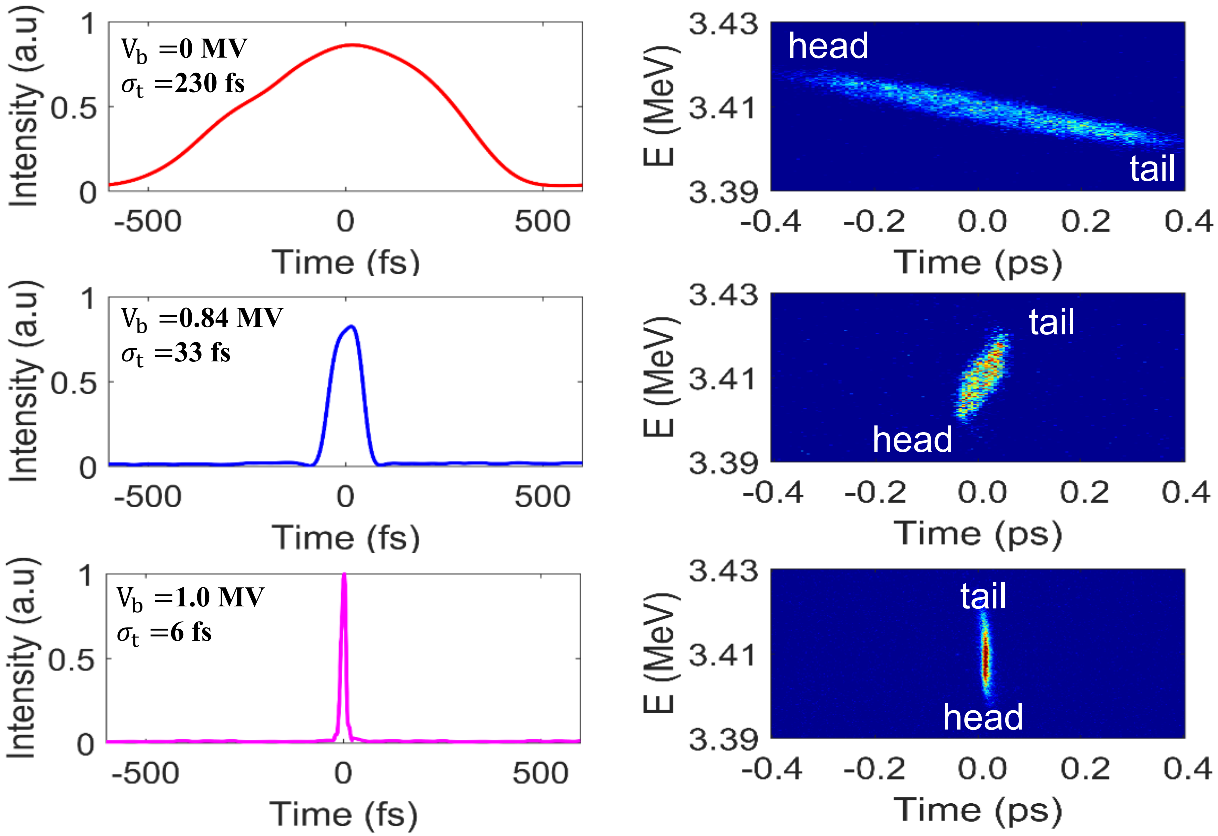
UCLA, 5 MeV
~100 fs -> ~7 fs



- **X-band buncher**
- **X-band deflector (400 kV)**

PRL 118, 154802 (2017)

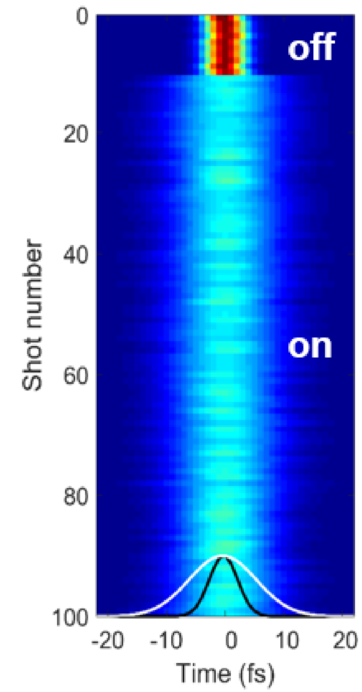
rf compression + time stamping



Bunch length and longitudinal phase space

PRX 8, 021061 (2018)

SJTU, 3 MeV
~200 fs -> 6 fs



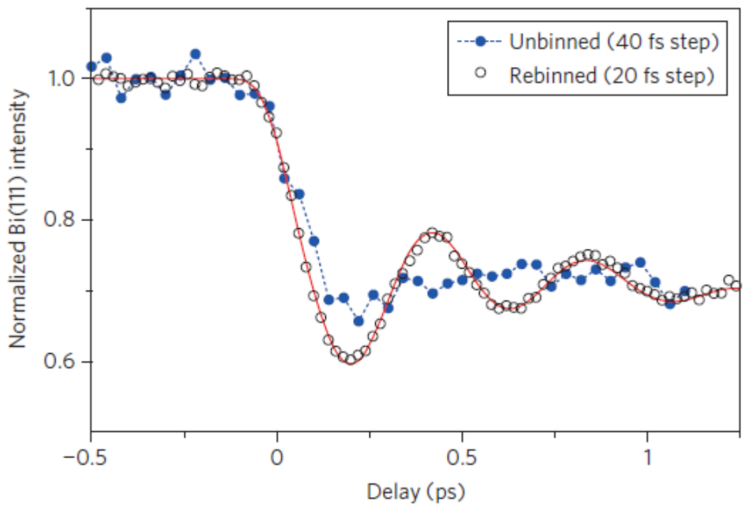
- **C-band buncher**
- **C-band deflector (2 MV)**

rf compression + time stamping

Measure and sort

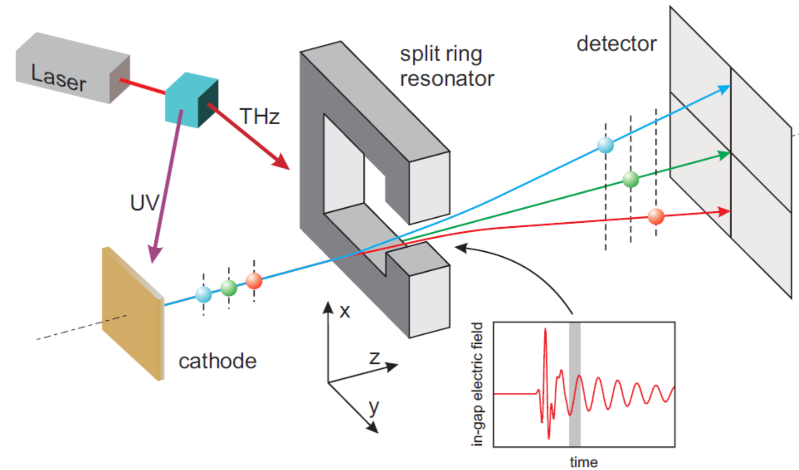
nature photonics | LETTERS
PUBLISHED ONLINE: 17 FEBRUARY 2013 | DOI: 10.1038/NPHOTON.2013.11

Achieving few-femtosecond time-sorting at hard X-ray free-electron lasers



7 papers published in Nature Photonics

THz deflector

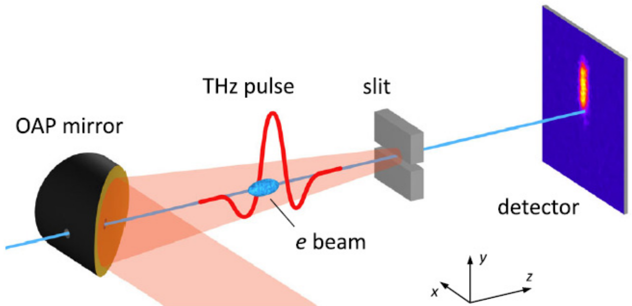


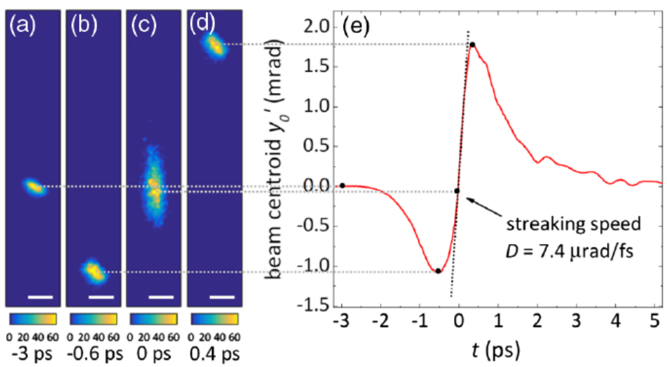
- **THz pulse in tight synchronization with laser**
- **Time-dependent angular kick**
- **E-field is not in phase with B-field in the gap**
- **Field enhancement in the narrow gap**

Sci Rep 4, 5645 (2014)

rf compression + time stamping

THz streaking at SLAC

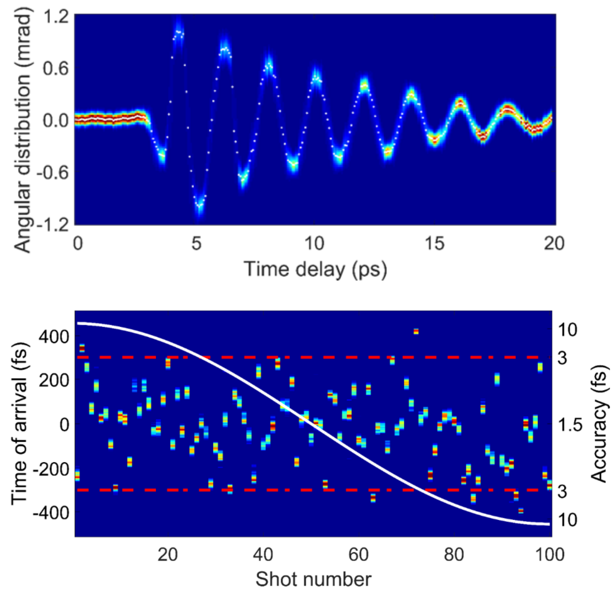




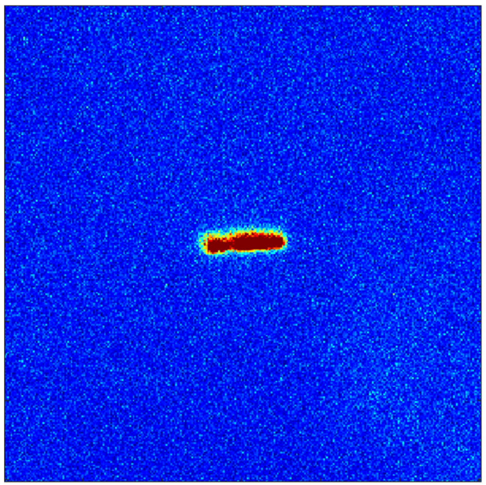
- 4 mm X 50 μm slit
- Single oscillation

PRAB 22, 012803 (2019)

THz streaking at SJTU



Time stamping of a 6 fs beam



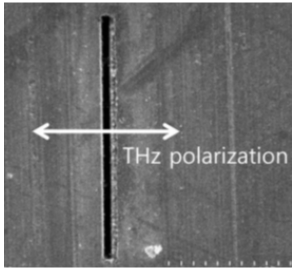
Deflection vs time delay

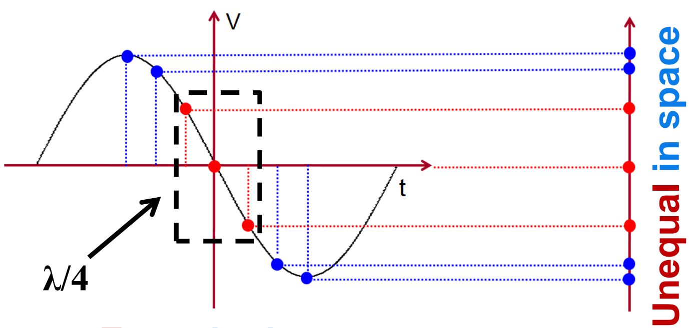
- 250 μm X 10 μm slit
- multipole oscillation
- 6 fs beam with jitter corrected with 1.5 fs accuracy

PRX 8, 021061 (2018)

rf compression + time stamping

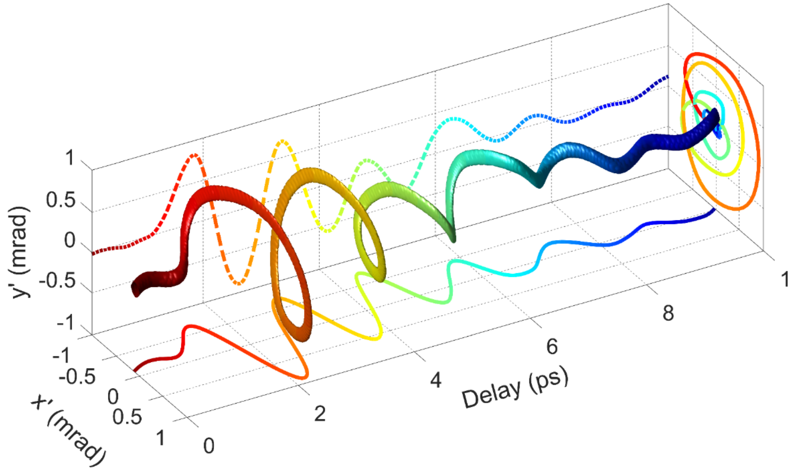
THz oscilloscope for recording time information

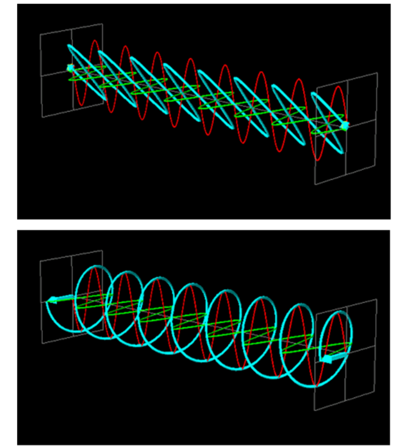


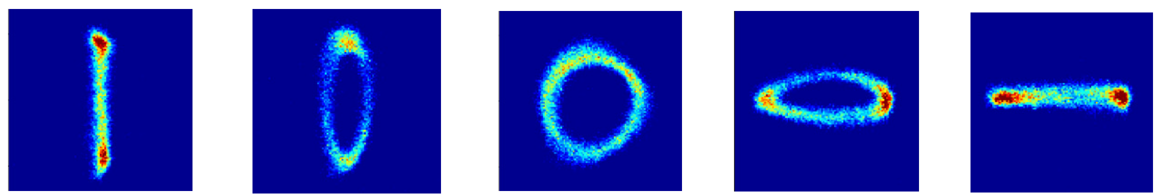


Equal in time

- **Small aperture**
- **Limited dynamic range**







$\Delta\varphi = 0$ $\Delta\varphi = \pi/4$ $\Delta\varphi = \pi/2$ $\Delta\varphi = 3\pi/4$ $\Delta\varphi = \pi$

- **Dielectric tube + two THz pulses with orthogonal polarization**
- **Large aperture + large dynamic range**

PRL 122, 144801 (2019) (Editors' Suggestion and Featured in Physics)

break ~50 fs resolution barrier

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

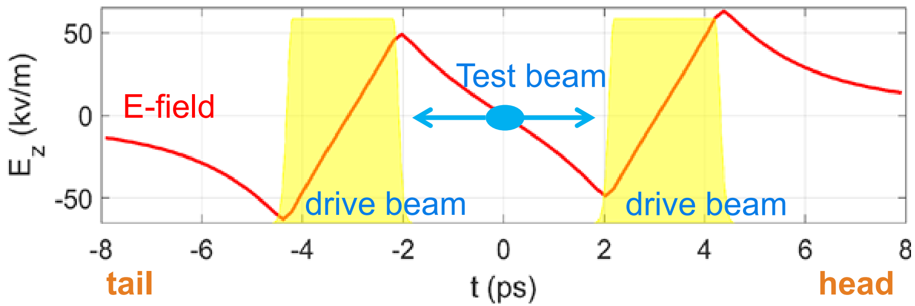
- **rf compression + time stamping**

  Produce short beam and correct timing jitter

- **Compression with space charge force**

  Produce short beam with small timing jitter

Compression with space charge force

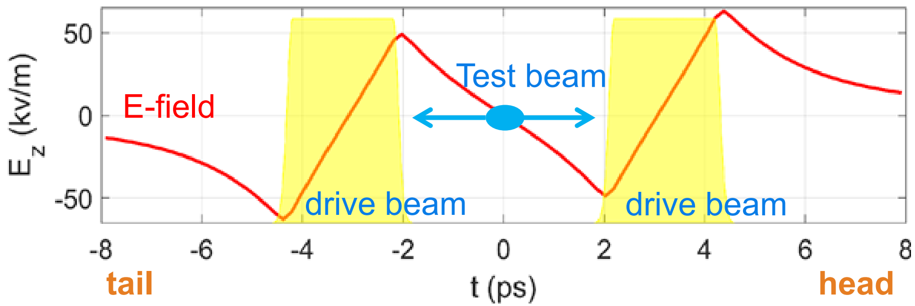


- **Test beam in the middle of two drive beams**
- **Negative energy chirp**
- **Centroid energy will not change**
- **Test beam will be compressed with negligible timing jitter**

- **The front drive beam pushes the test beam backward**
- **The back drive beam pushes the test beam forward**
- **The test beam stays in the middle with its pulse width reduced**

PRL 120, 044801 (2018) (Editors' Suggestion and Featured in Physics)

Compression with space charge force



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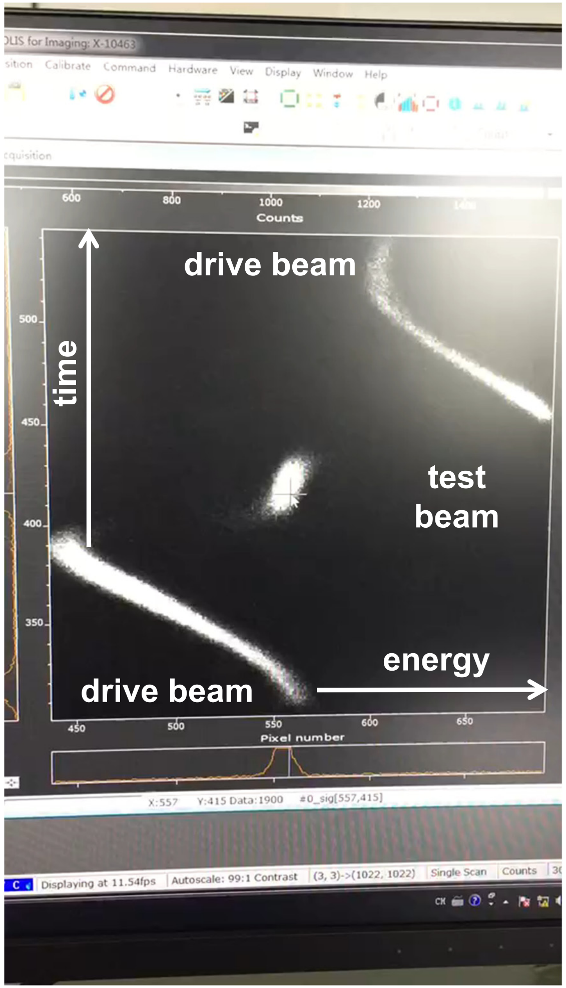
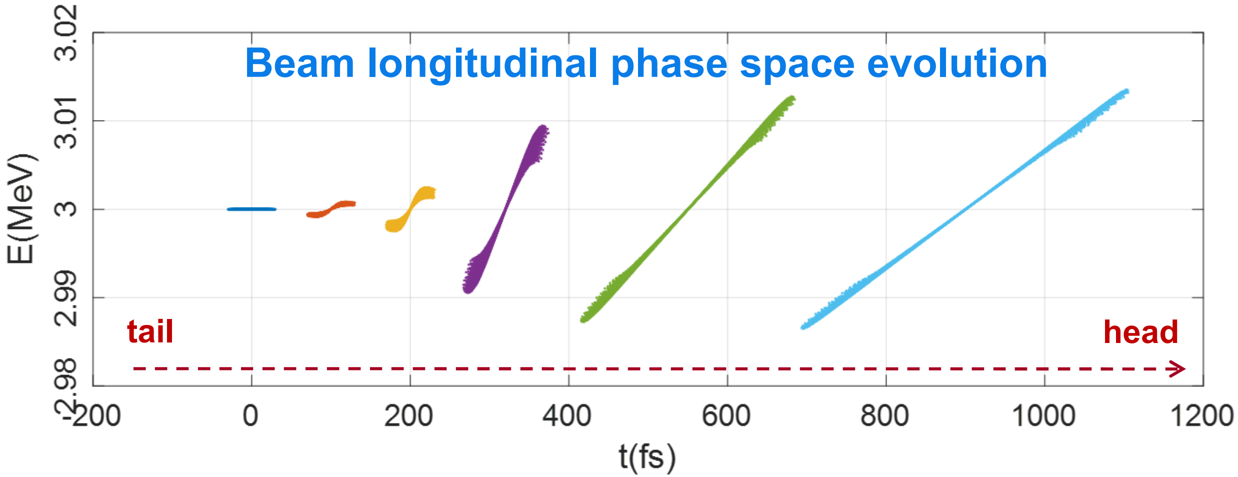


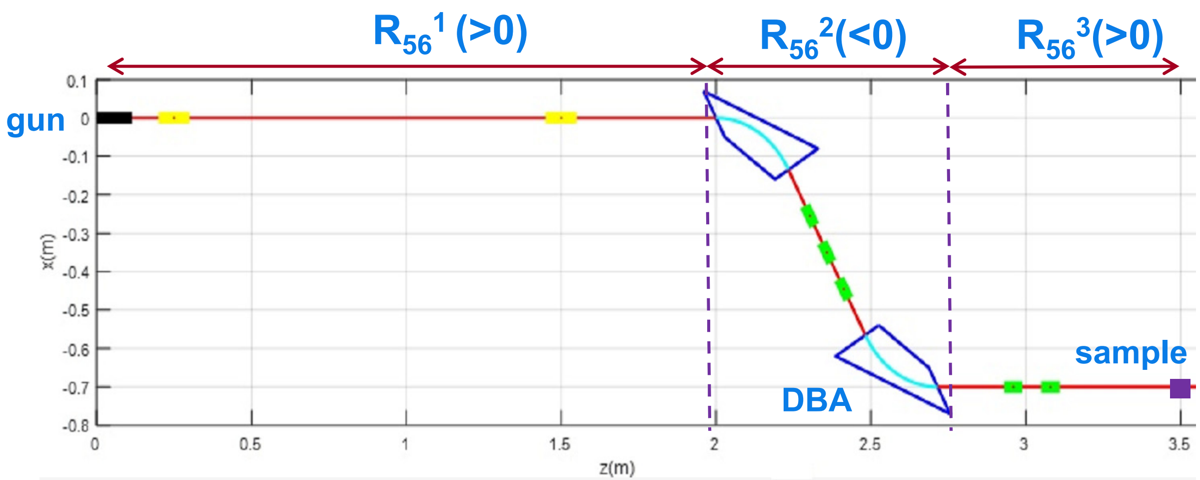
- The front drive beam pushes the test beam backward
- The back drive beam pushes the test beam forward
- The test beam stay in the middle with its pulse width reduced

PRL 120, 044801 (2018) (Editors' Suggestion and Featured in Physics)

Compression with a double-bend achromat (DBA)



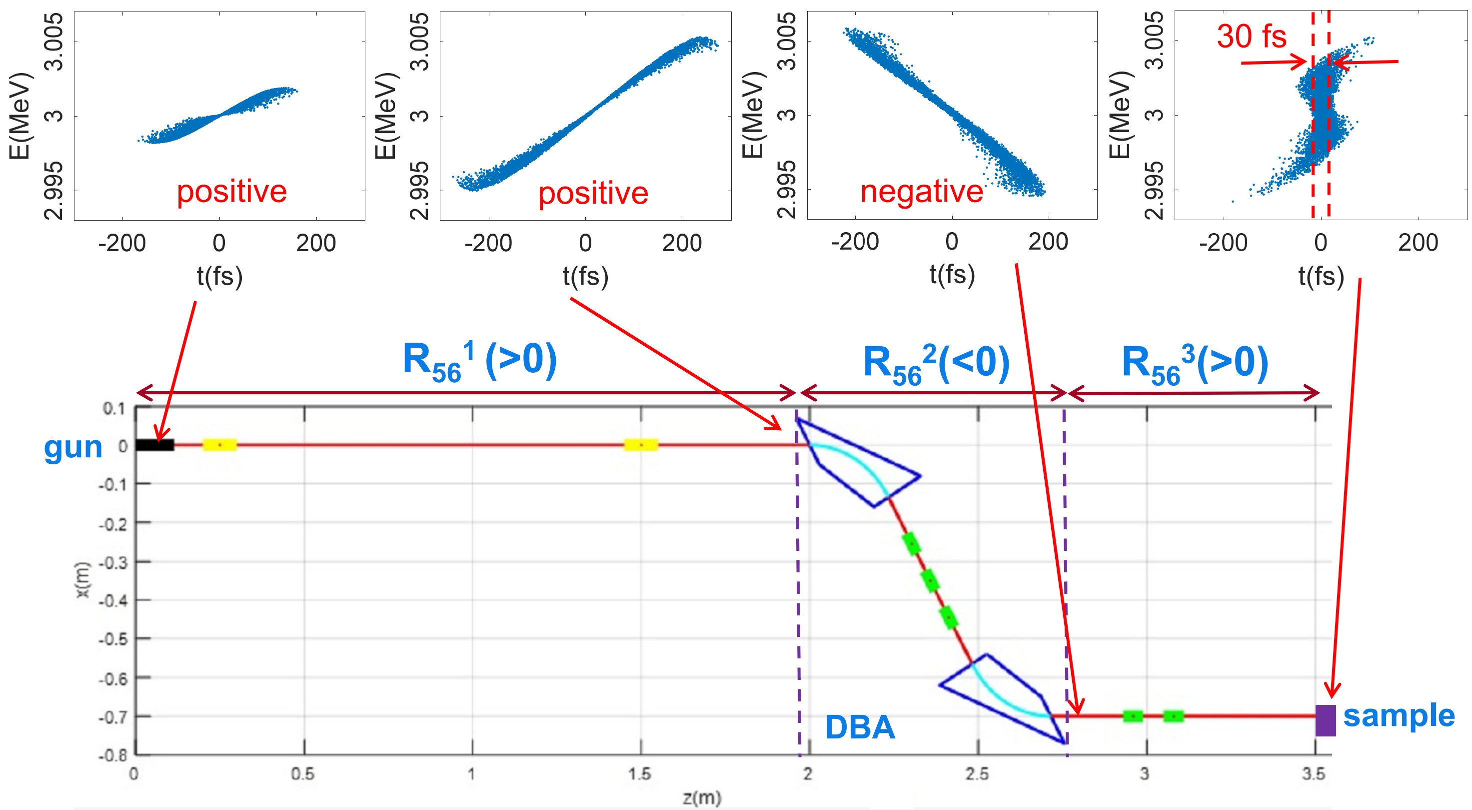
Space charge force induces positive energy chirp without changing beam centroid energy



- Isochronous: $R_{56}^{1}+R_{56}^{2}+R_{56}^{3}=0$
- Gun amplitude jitter won't convert to arrival timing jitter
- Space charge induced positive energy chirp leads to bunch compression ($R_{56}^{2}+R_{56}^{3}<0$)
- Jitter free bunch compression

Compression with a double-bend achromat (DBA)

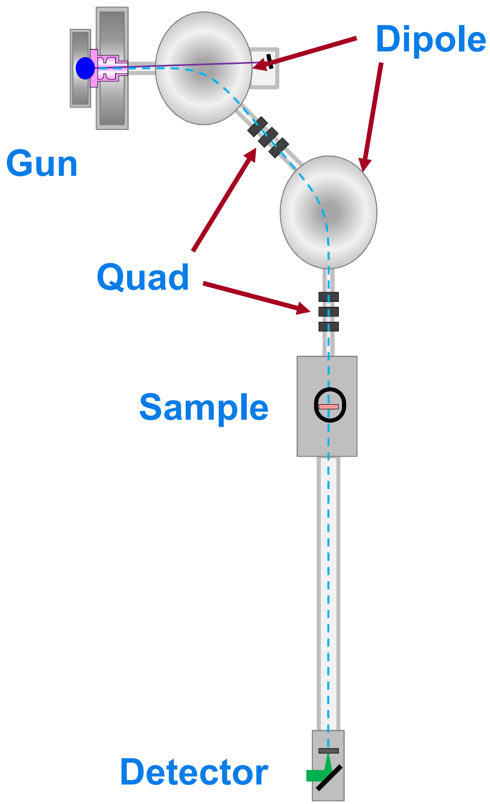
~30 fC beam compressed to ~30 fs (FWHM) with <5 fs timing jitter



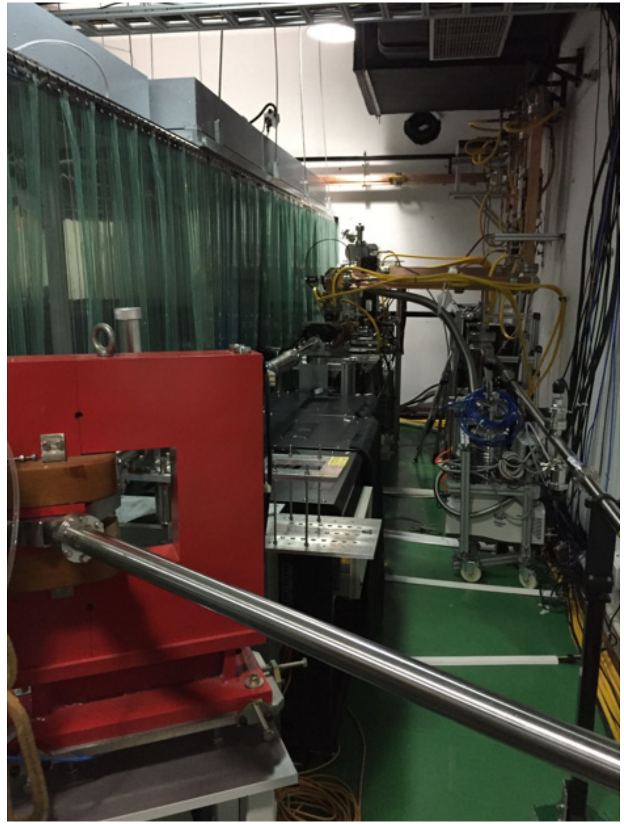
Manuscript in preparation

Compression with a double-bend achromat (DBA)

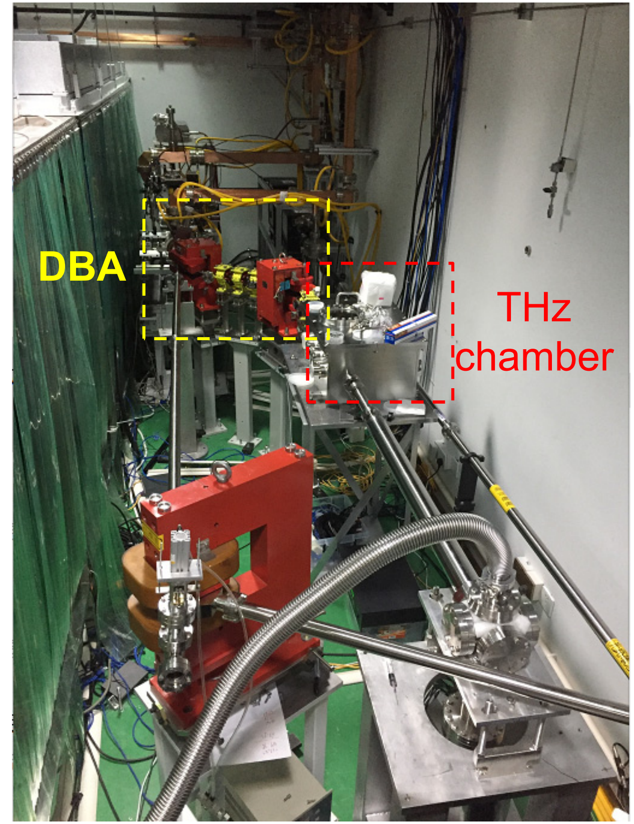
KAERI



SJTU

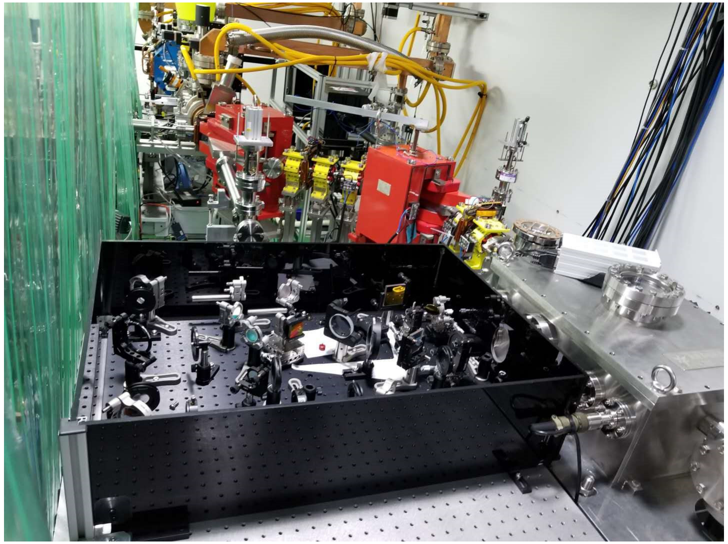


Before installation

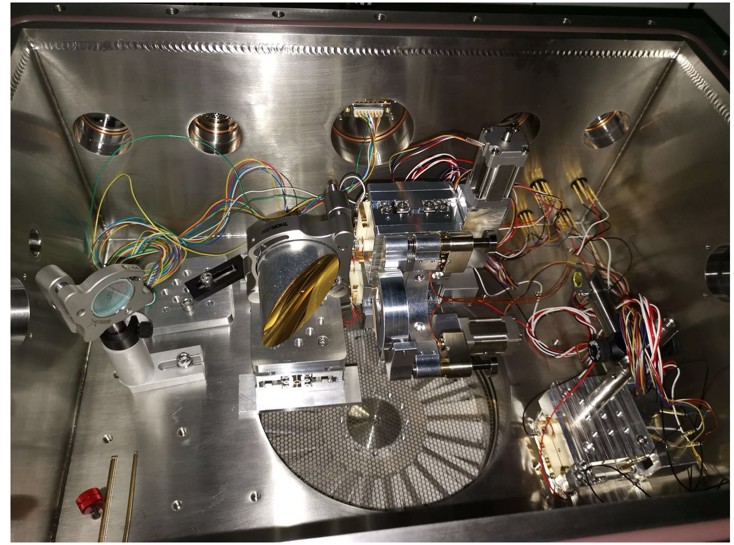


New DBA beamline

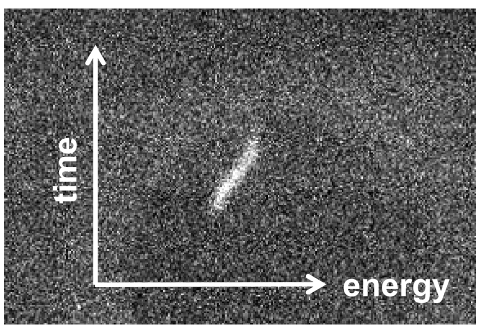
Compression with a double-bend achromat (DBA)

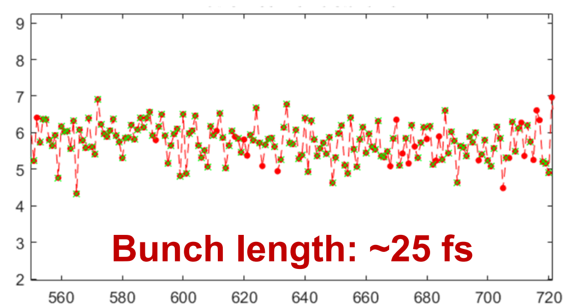


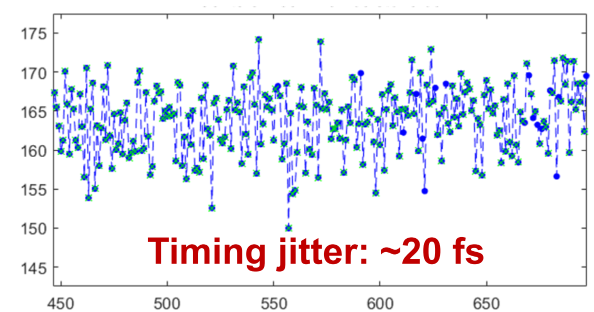
THz source for measuring electron bunch length and jitter



THz-electron interaction chamber







Outline

- Introduction
- MeV UED and UEM developments
- Breaking ~50 fs resolution barrier
- Summary

Summary

- Growing interest in using MeV UED/UEM to solve the grand challenges in probing matter at ultrafast temporal and ultrasmall spatial scales
- Compact facility, yet with rich physics and great potential
- Potential of MeV UED/UEM fully demonstrated
- Still room to improve and lots of possibilities to explore

Thanks!