FEMTOSECOND RF GUN BASED MEV ELECTRON DIFFRACTION

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Ultrafast electron diffraction(UED)

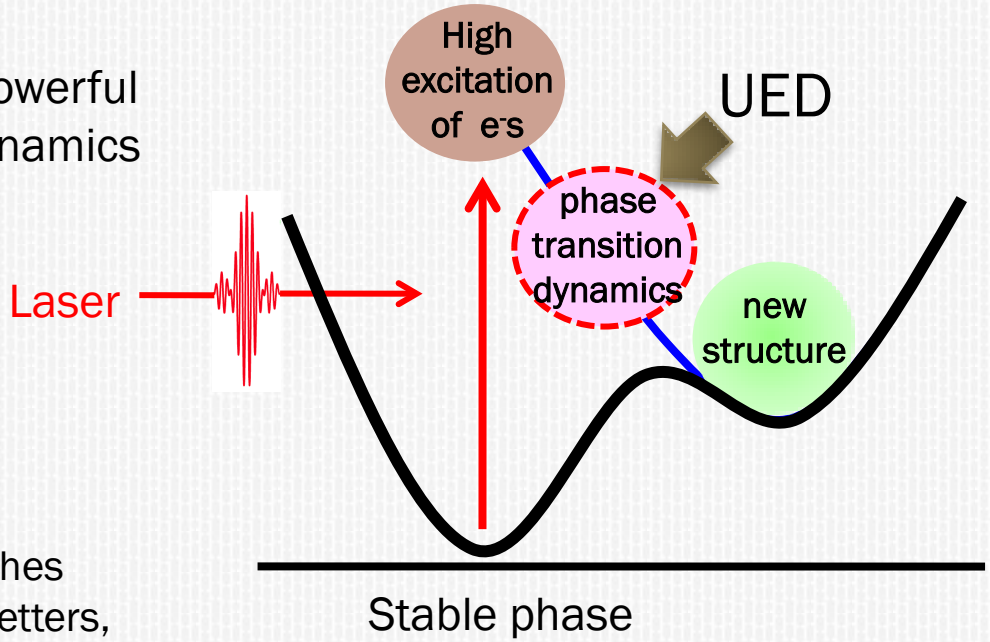
----- a pump-probe technique -----

Short-pulse photon beam: pump source,
short-bunch electron beam: probe source

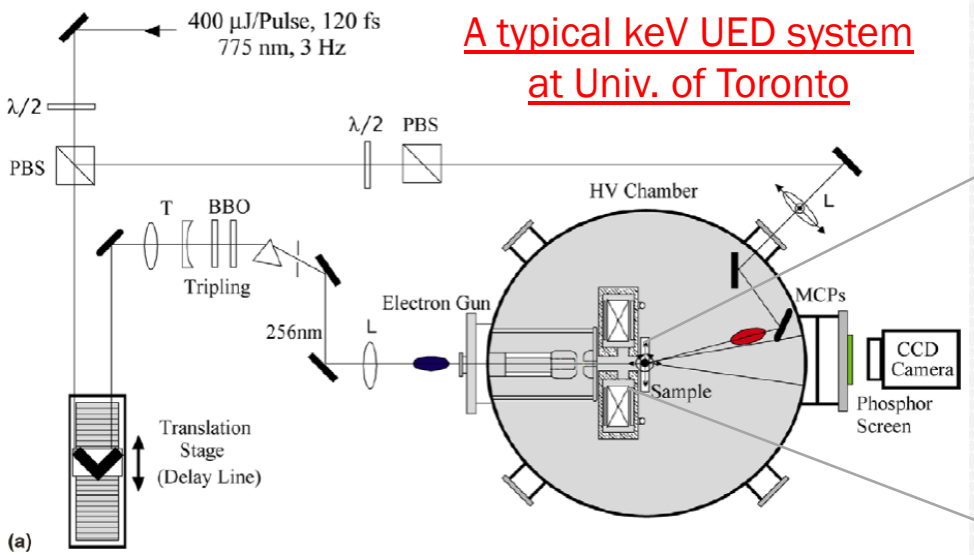
The ultrafast electron diffraction is a powerful tool for the study of photon-induced dynamics in materials, i.e.

structure transformation,
melting,
phase transition,
...

In the recent ten years, a lot of UED researches were reported in Science, PRL, APL, Nano Letters, ...

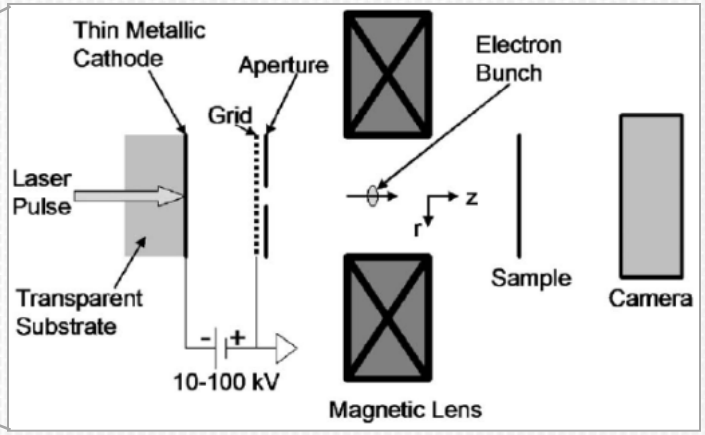


keV-e^- based UEDs

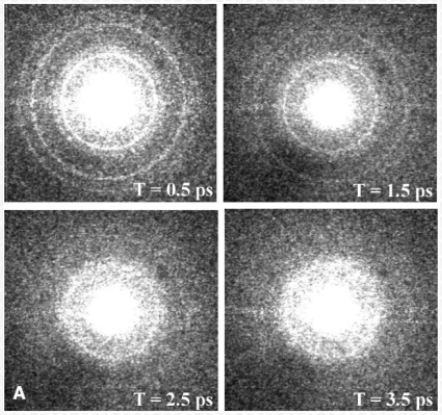


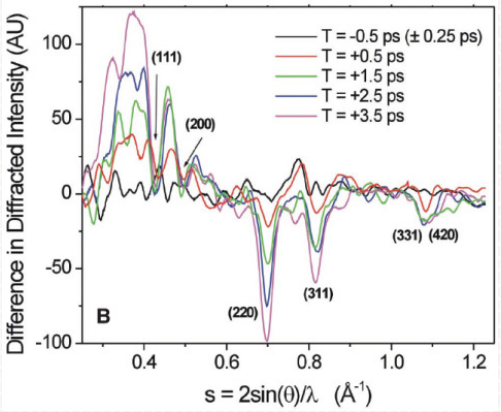
A typical keV UED system at Univ. of Toronto

DC electron gun



B. J. Siwick, *et al*. Science 302, 1382(2003)





view of melting in Al on picosecond time scale

Typical Parameters:

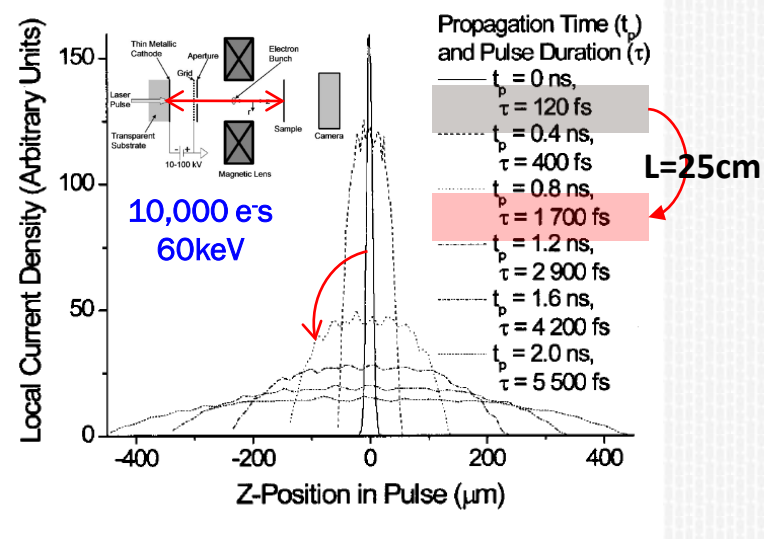
e^- beam energy: 60 keV,
photocathode-to-sample: 4.5 cm,
bunch length: 600±100fs,
e^- number: 6,000 e^-'s /pulse
(>100 shots for measurement)

Why MeV UED?

Problem using DC gun: electron pulse broadening due to space-charge effect!

①shorten the distance between gun and sample

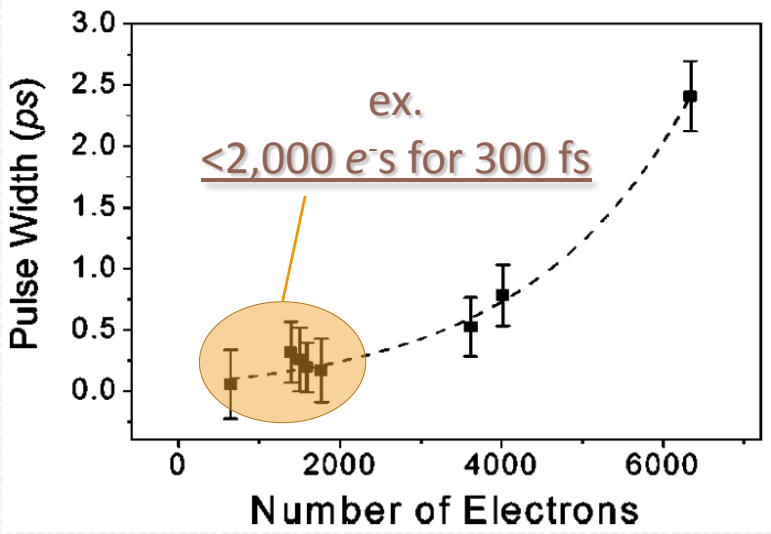
photocathode-to-sample: 4.5 cm



B. J. Siwick et al., JAP 92, 1643 (2002)

②decrease electron charge

It is impossible for single-shot meas.!



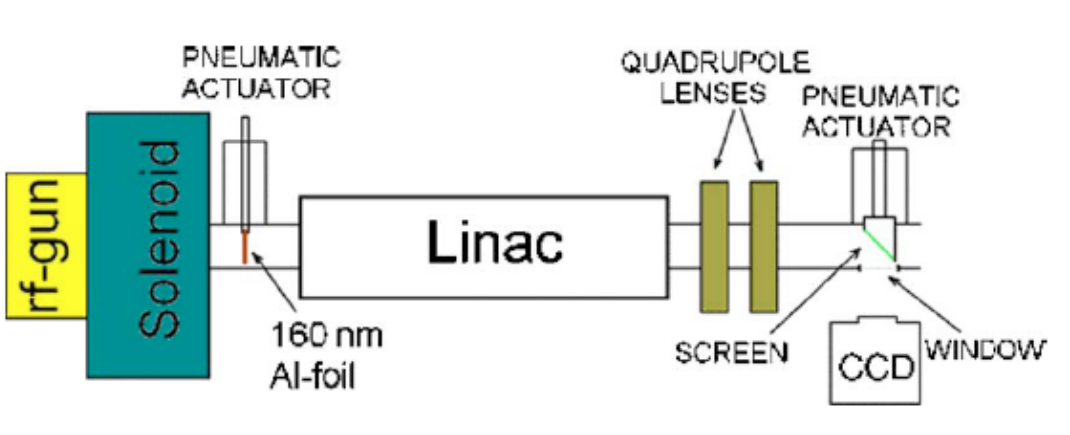
J. Cao et al., APL 83, 1044 (2003)

It is difficult to generate 100 fs electron bunch or less due to space-charge effect in DC gun.

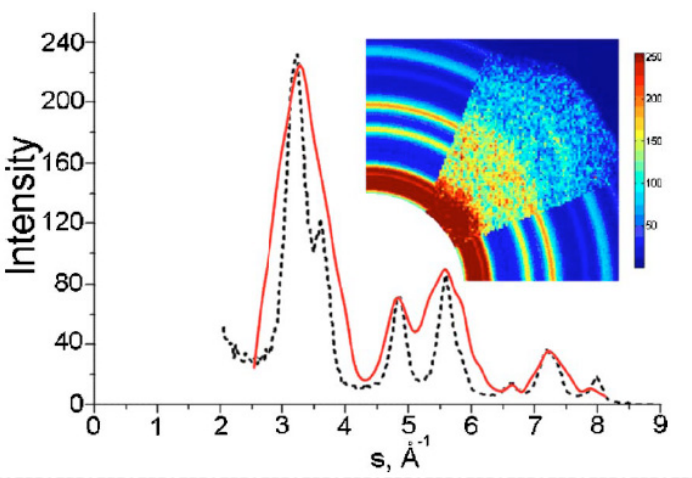
A good choice to use photocathode rf gun generating 100 fs MeV electron beam for UED!

First UED demonstration using RF gun

First MeV UED experiment at SLAC in 2006: Hastings, *et al.* APL 89, 2006



MeV e- diffraction from 160-nm Al



Beam energy: 5.4MeV

Bunch charge: 2.9pC

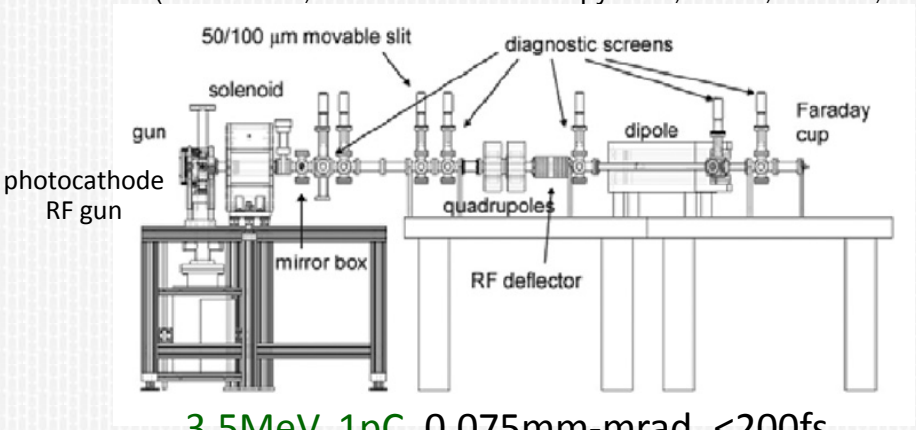
Emittance: 0.85mm-mrad

Energy spread: 0.65%

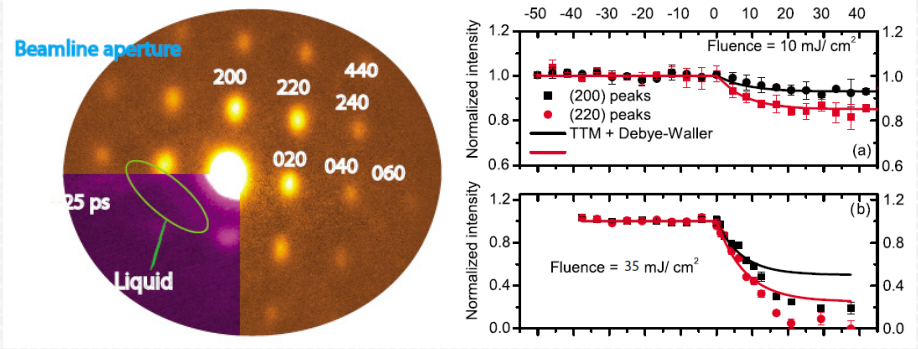
recent progress on MeV UED

①MeV UED at UCLA in 2008

(Musumeci, *et al.* Ultramicroscopy 108, 2008; APL 97, 2010)



3.5MeV, 1pC, 0.075mm-mrad, <200fs

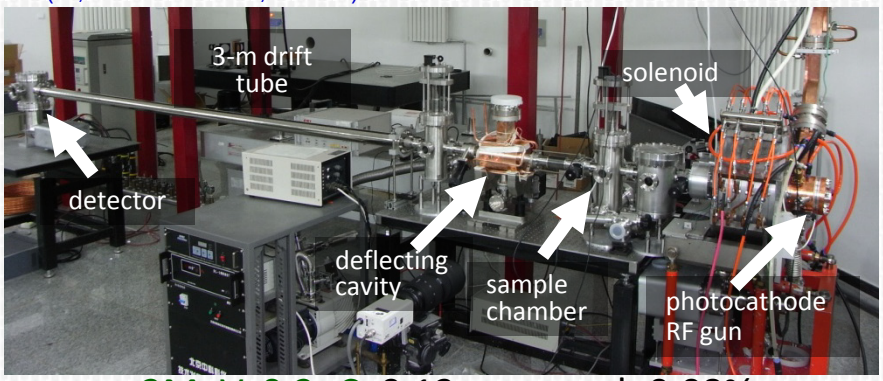


MeV e⁻ diffraction and time-resolved meas. from a single crystal 20-nm thick gold sample

②MeV UED at Tsinghua Univ. in 2009

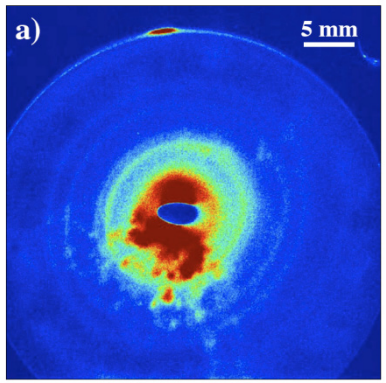
清華大學 Tsinghua University

(Li, *et al.* RSI 80, 2009)

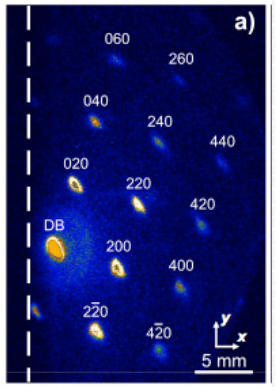


2MeV, 0.2pC, 0.13mm-mrad, 0.08%

MeV e⁻ diffractions



100 nm polycrystalline Al

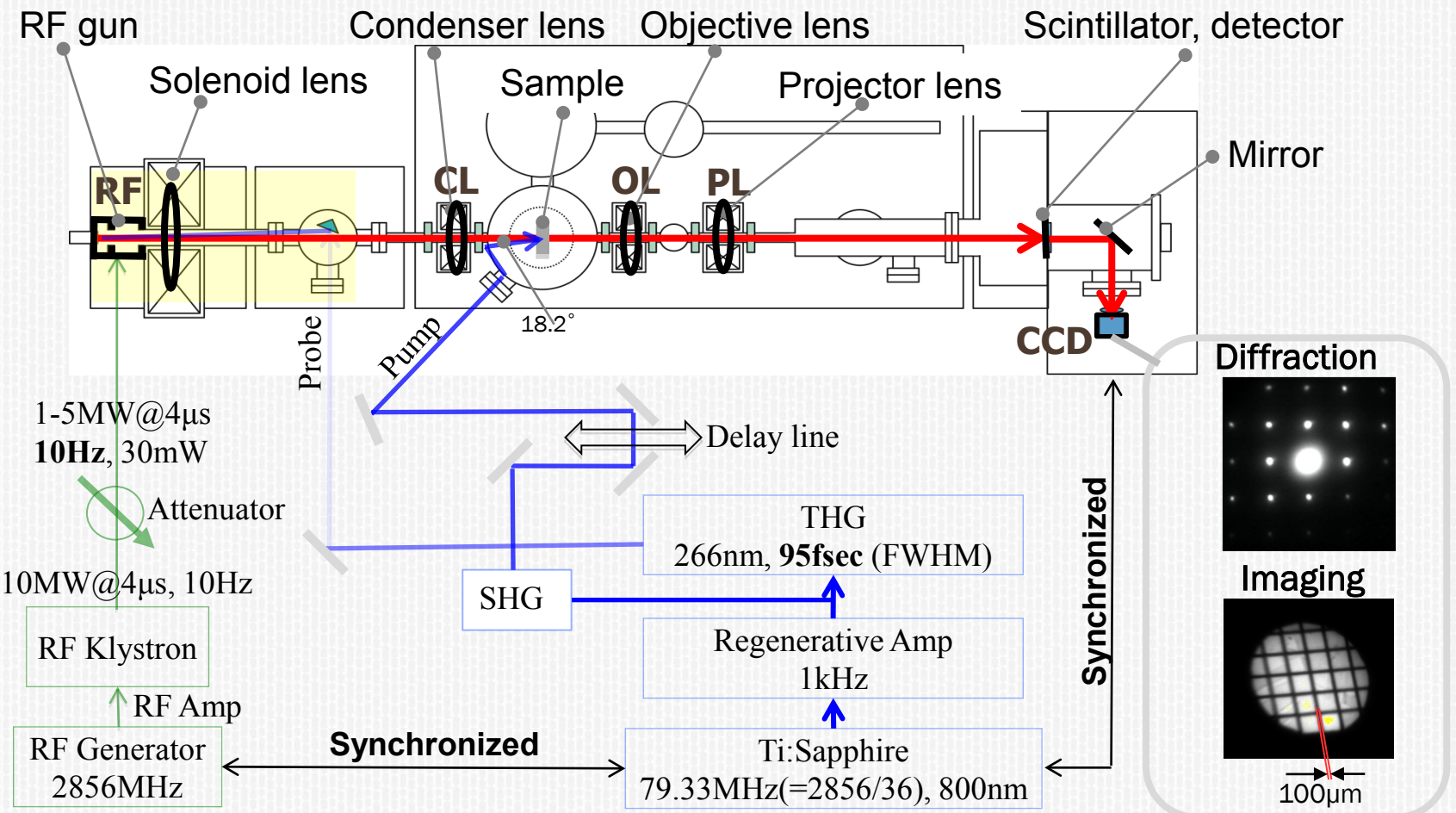


single crystal gold

Both experiments show that the RF gun is useful for MeV electron diffraction!

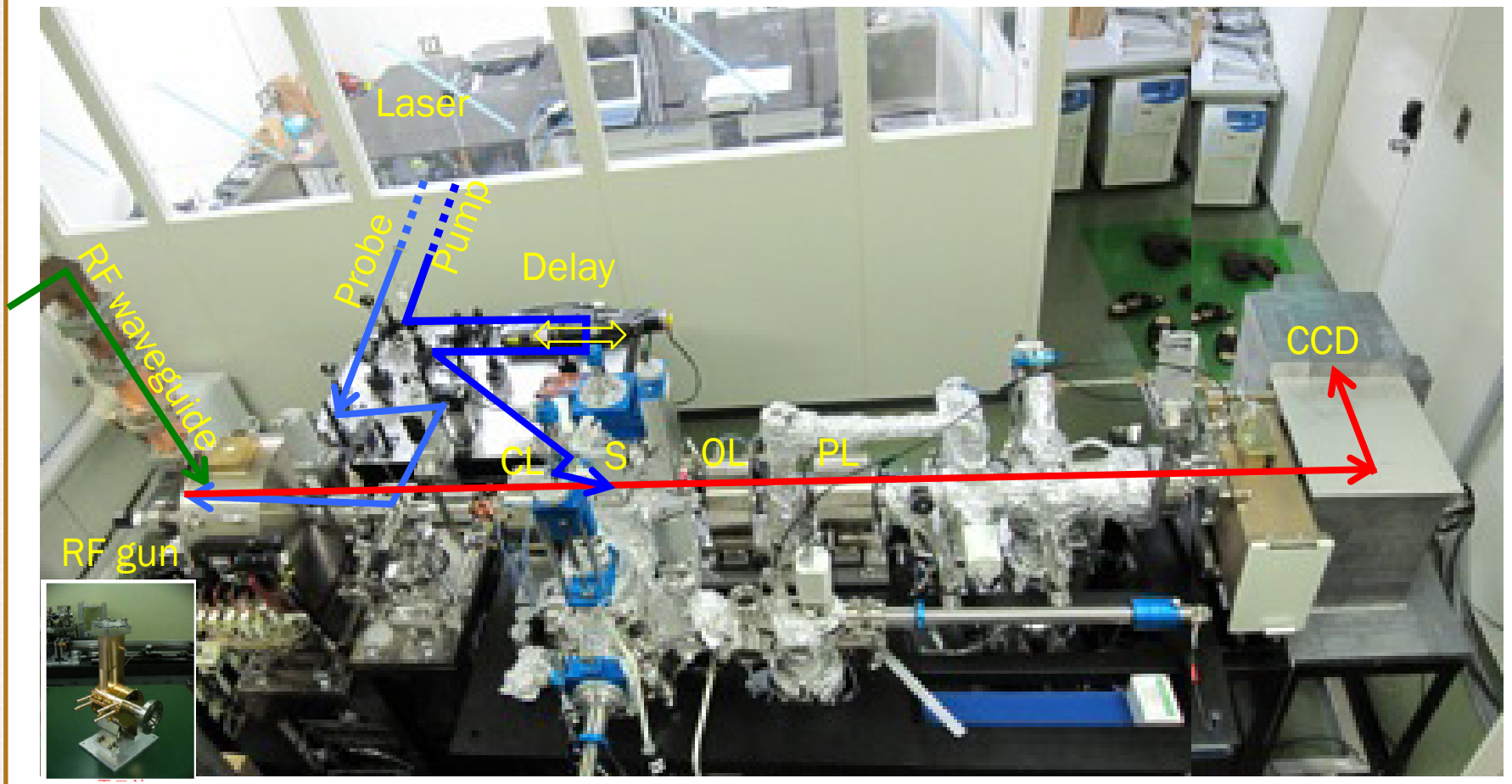
MeV electron diffraction in Osaka Univ.

We develop a femtosecond time-resolved electron diffraction at Osaka Univ., since 2009.

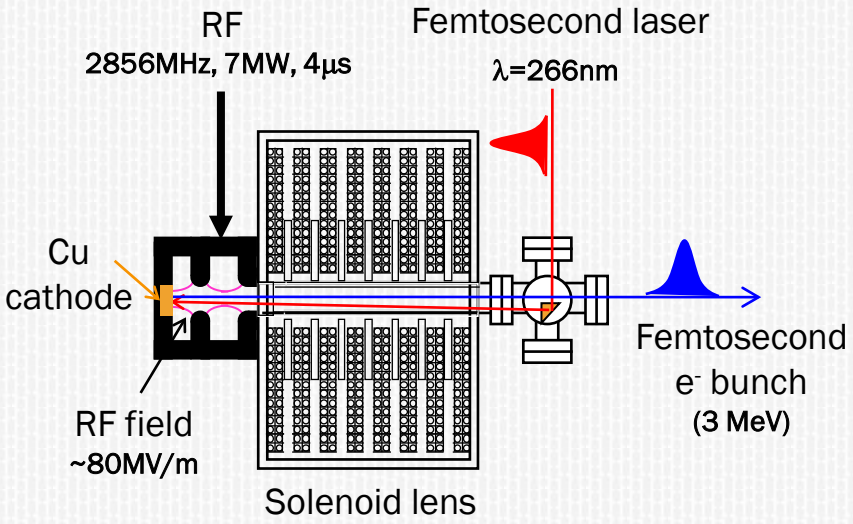


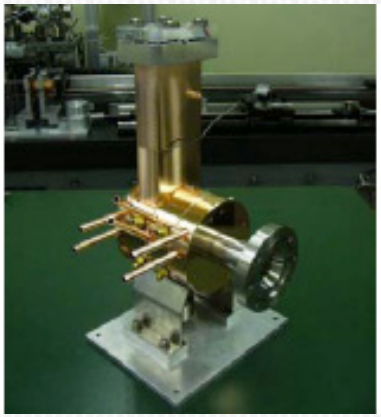
Difference with other UED facilities (i.e. UCLA, Tsinghua Univ.):

use of Cond. Lens, Object. Lens and Proj. Lens, therefore, compact & more efficient!


Laser
Probe
Pump
Delay
RF waveguide
CL
S
QL
PL
CCD
RF gun

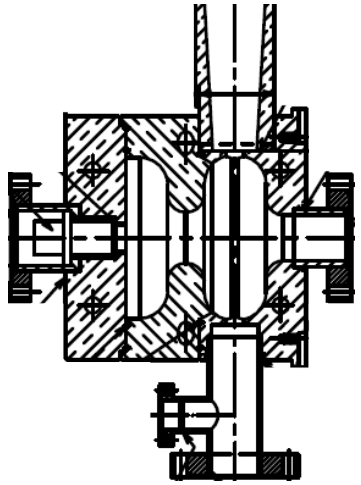
Femtosecond electron RF gun





developed under the collaboration with KEK

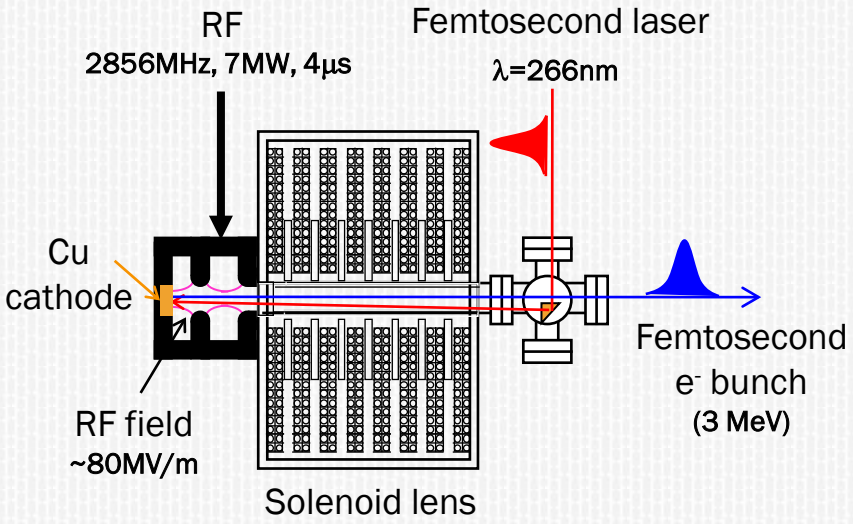
New structure

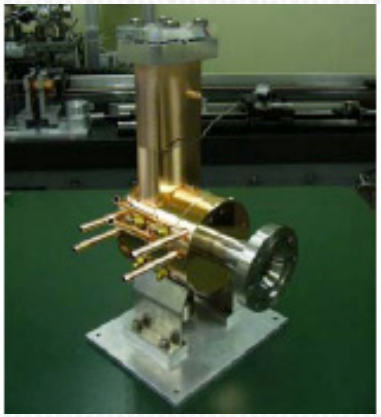


Some improvements:

- **a new structure cavity**
- **remove two laser injection ports**
- **a new turner system**
- **a new insertion function of photocathode**
  (The photocathode is removable)

Femtosecond electron RF gun





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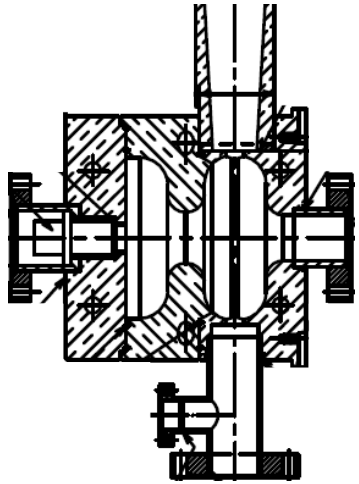
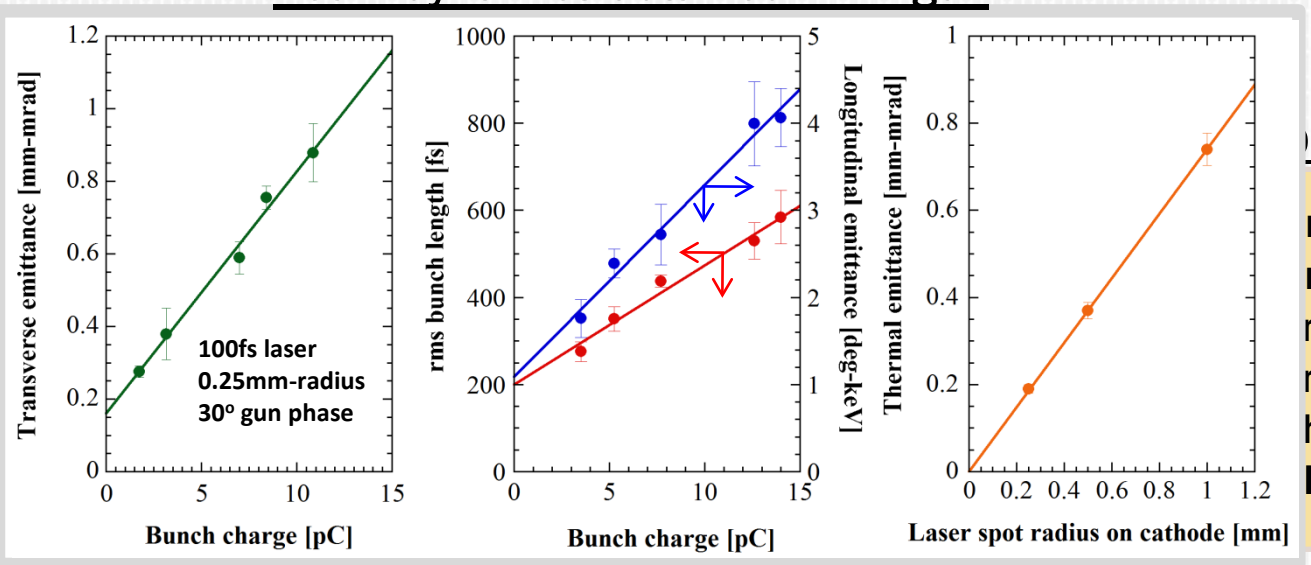


Beam dynamics obtained in RF gun



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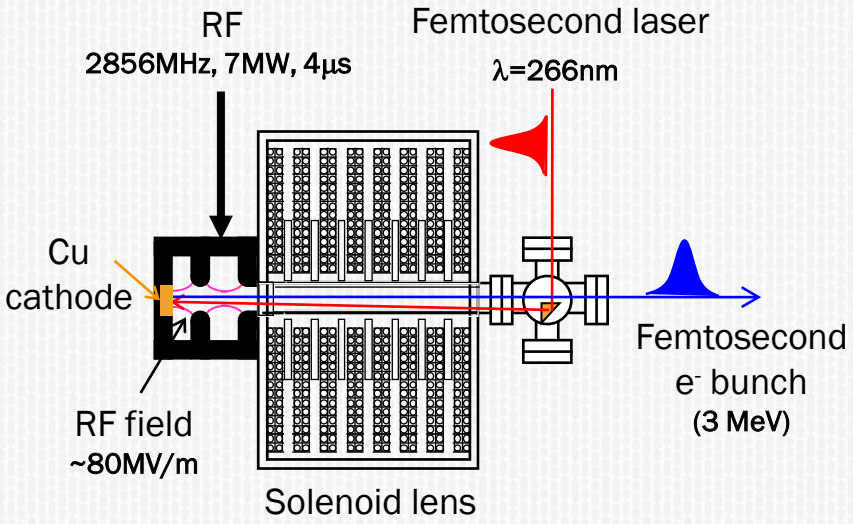

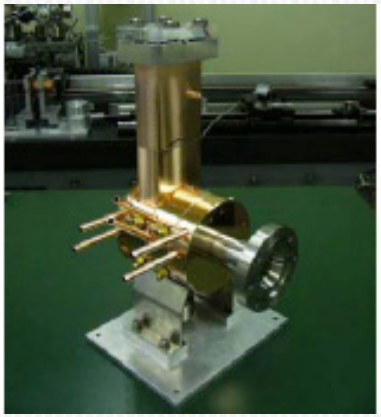

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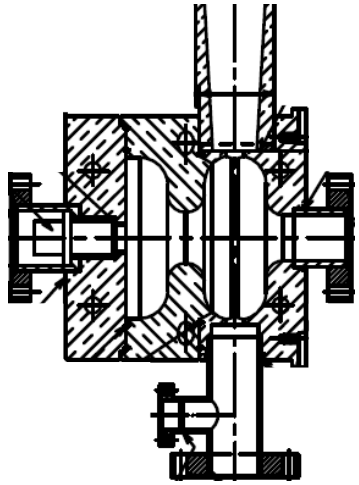

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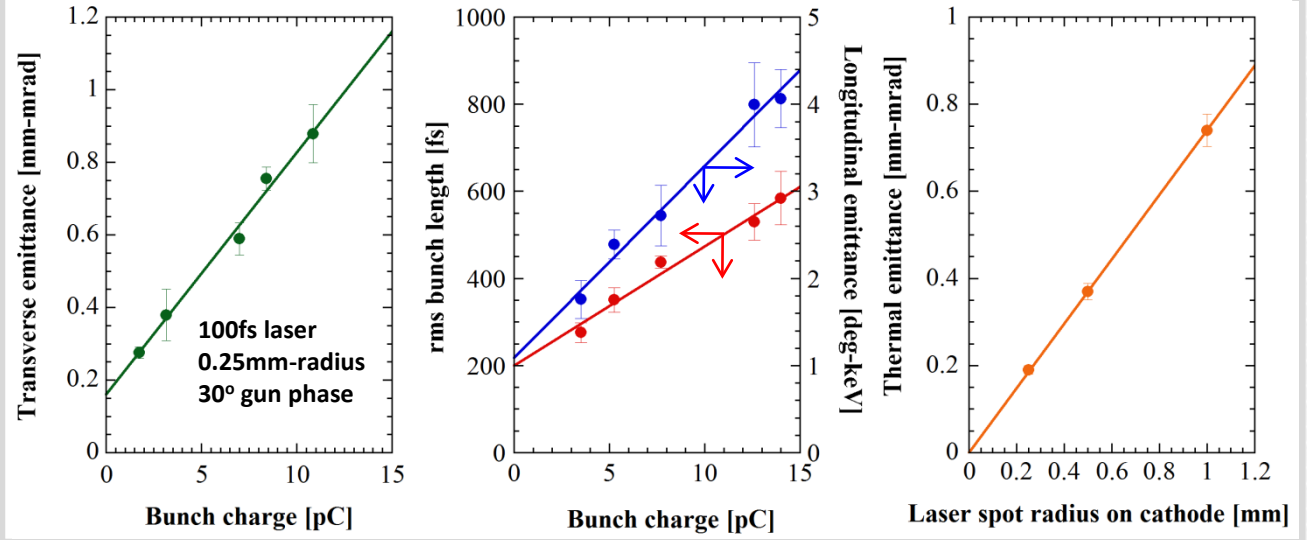
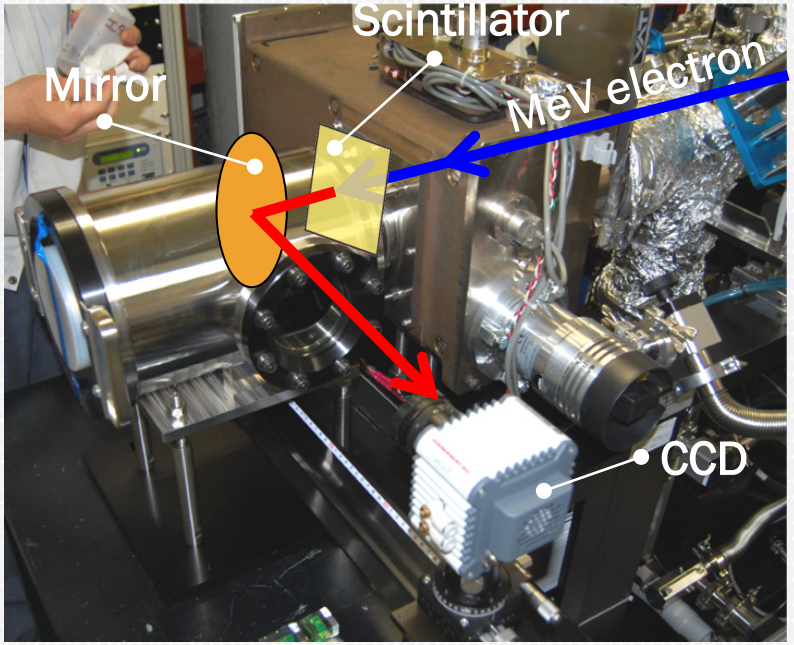


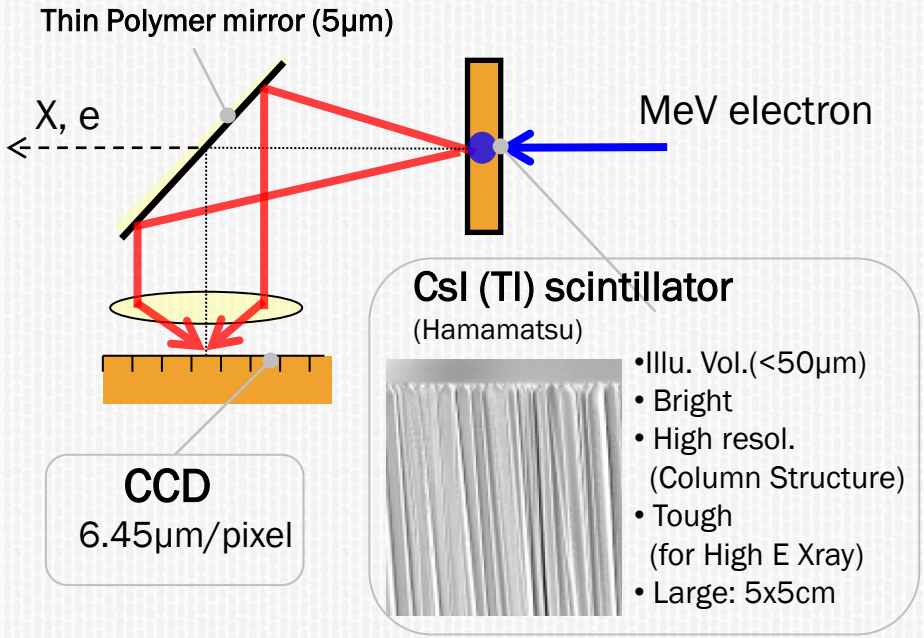
Electron energy : 3 MeV
Bunch length : 200fs
Emittance : 0.2~0.3 mm-mrad
Energy spread : 10^{-3}
Bunch charge : 2 pC

200fs UV laser with a radius spot size of 250 μm on cathode

Detection of MeV electron diffraction

Requirements of detector: high resolution, high efficiency, no damage





Problems

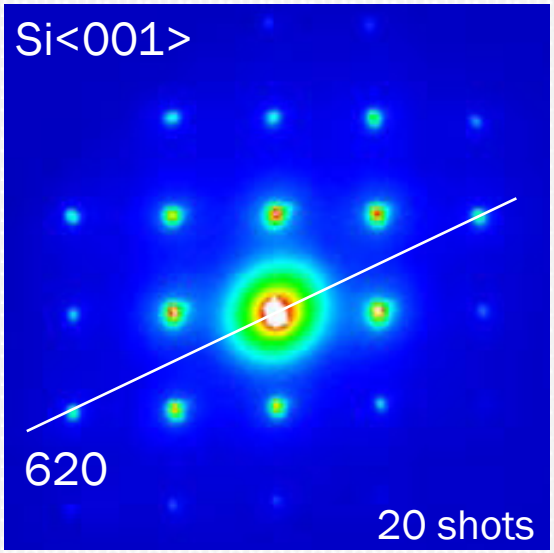
- Very low current, i.e. ~pA
- Small scattering angle, i.e. 0.1mrad
- Strong X-ray emissions,
  i.e. Backgnd, pixel defect
- Damage by MeV electron,
  i.e. scintillator, fiber
- Diff. Pattern to be magnified/shifted

Solution

- CsI: Small Illumination volume size-matched to CCD pixel
- Indirect exposure
  Thin mirror + Lens coupling
- No pixel defect observed yet
- Large detection area, i.e. 5x5cm^2

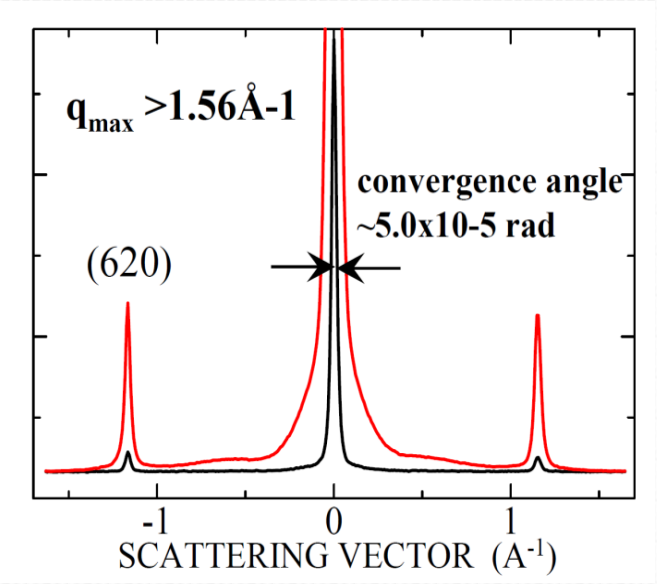
Quality of MeV electron diffraction

Electron beam: 3 MeV, 0.3 pC
Sample: 180nm-thick single crystal Si



A high-quality MeV ED was observed!

Intensity profile of 620 pattern



- Beam convergence angle: 50 μrad
- Maximum scattering vector : q_{max} >1.56Å^{-1}
- Requirement of the e$^-$ number: $10^{6\text{-}8}$

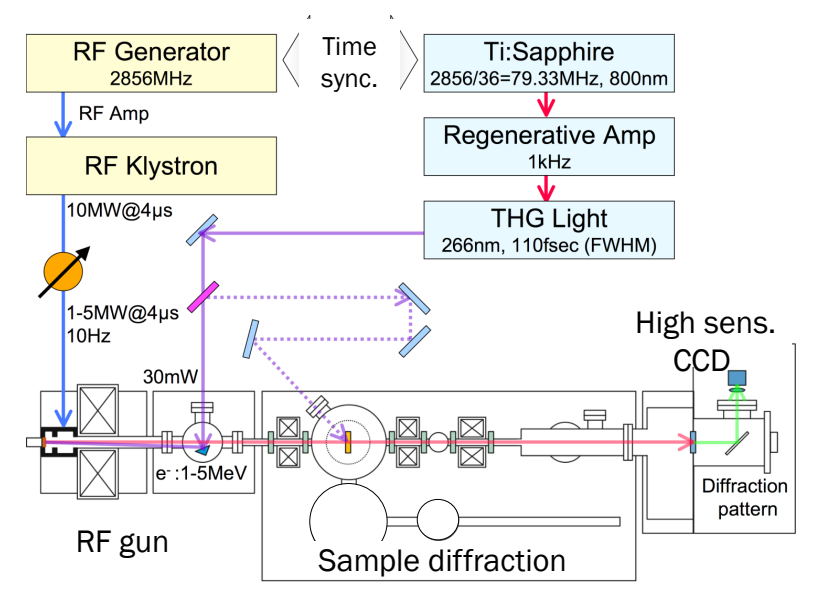
- Bragg law

$$2d\sin\theta = n\lambda$$

$$\tan\theta = \frac{D}{L}$$

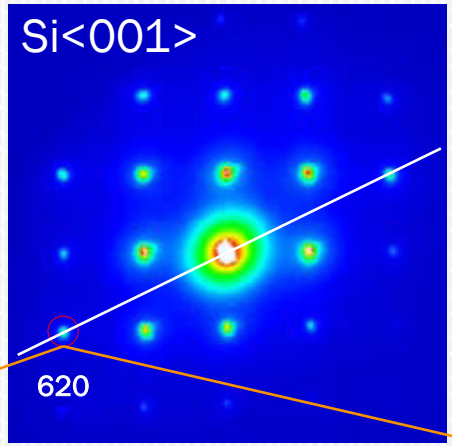
The RF gun is useful to observe a high-quality MeV electron diffraction!

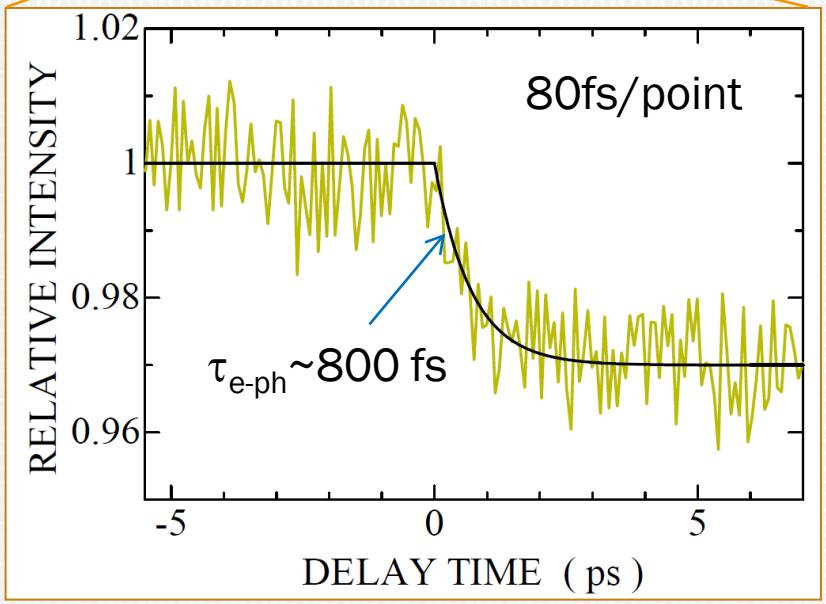
Time-resolved measurement



Sample:
180-nm-thick single crystal Si

Time-dependence of the 620 diffraction intensity in single-crystal Si





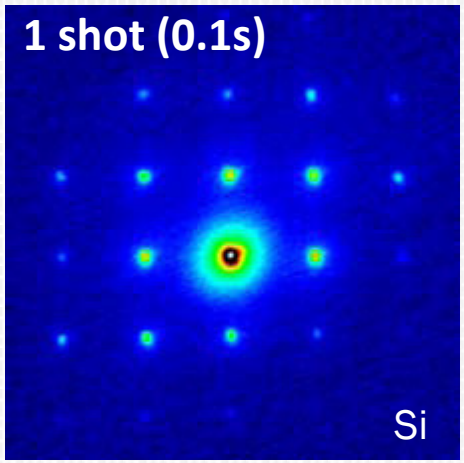
Probe electron beam:
- bunch charge: 3 pC
- bunch length: ~110 fs
- beam energy: 3 MeV

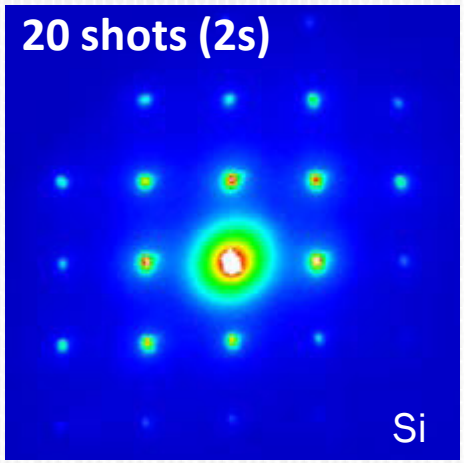
Pump laser:
- wavelength: 385 nm
- pulse width: 110 fs
- intensity: 3.5mJ/cm^2

$\tau_{e\text{-}ph}$~800 fs for the excited electron thermalization in lattice of Si crystal.

Power of the technique: static diffractions

- Single-shot measurement





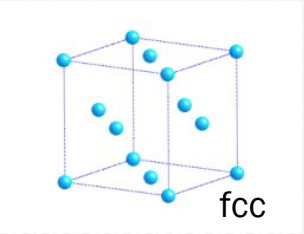
Electron beam: 3 MeV, 0.3 pC

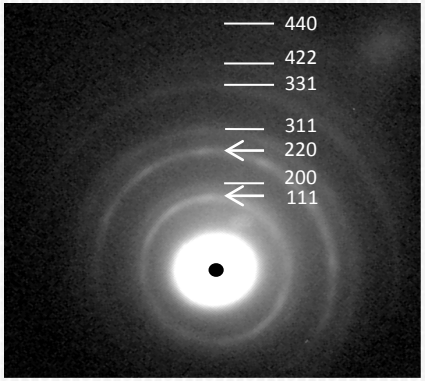
Sample: single crystal Si

The single-shot measurement is available.

The excellent statistics are observed in 2 second!

- **Metal** (Al)
  - polycrystal (100nm)



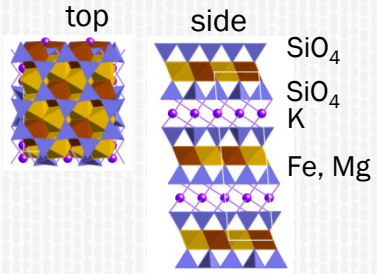


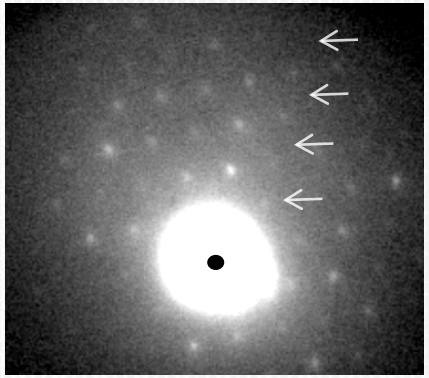
Large scattering vector

q_{max}

- **Insulator** (Mica)
  - Single crystal (~100s nm)

$K(Fe,Mg)_3(AlSi_3O_{10})(OH,F)_2$





No charging effect

(Difficult at Low Voltage)

Conclusion

We have developed successfully a femtosecond MeV electron diffraction system based on photocathode RF gun at Osaka University.

Both the single-shot and time-resolved measurements were succeeded. The high-quality MeV electron diffractions were observed from the semiconductor, the insulator and the metal.

The experiments suggest that the photocathode rf gun is very useful for the ultrafast electron diffraction/microscopy.

A time-resolved MeV electron microscopy based on photocathode RF gun is being developed in Osaka University.

Acknowledgments

Co-workers at Osaka University:

Nobuyasu Naruse

Yoshie Murooka

Katsumi Tanimura

Koichi Kan

Takafumi Kondoh

Yoichi Yoshida

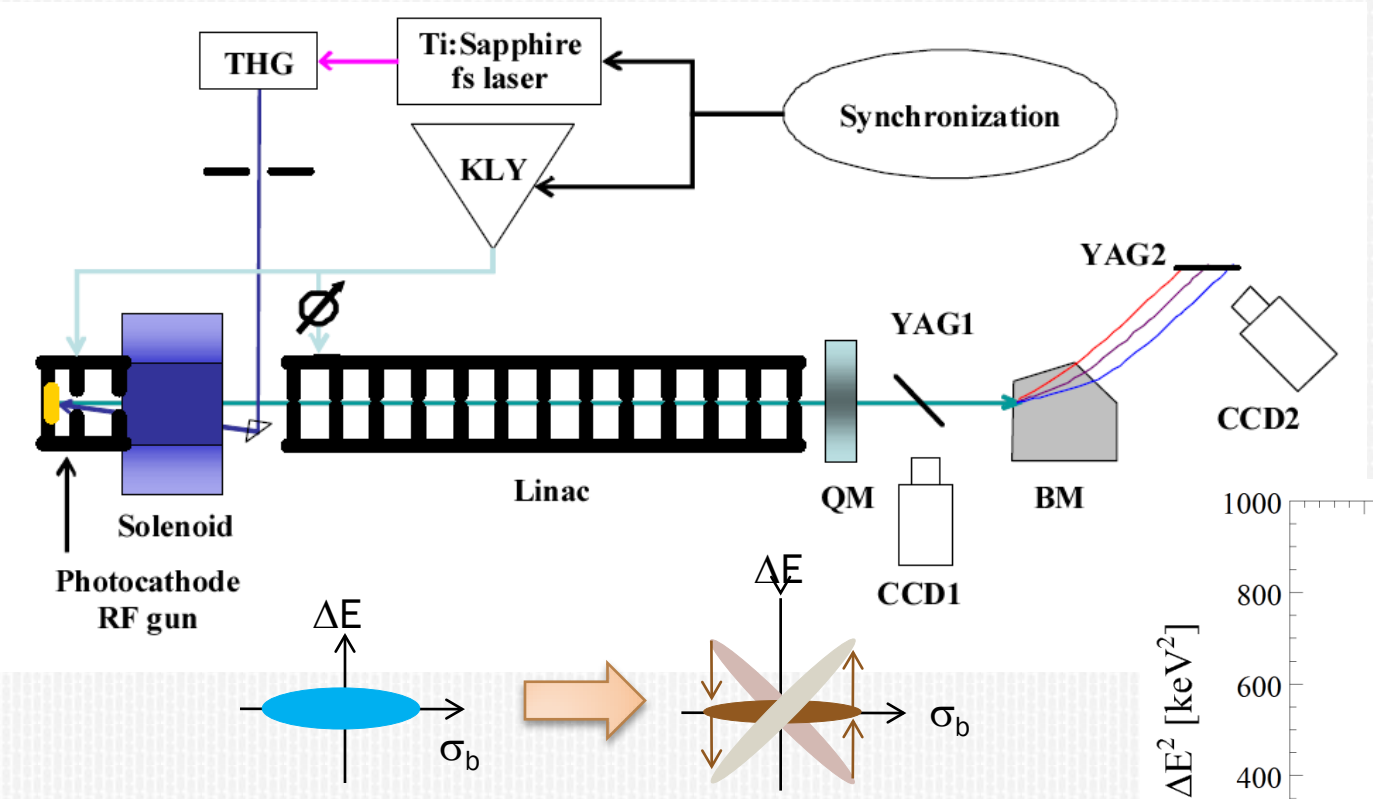
Collaboration member in KEK:

Junji Urakawa

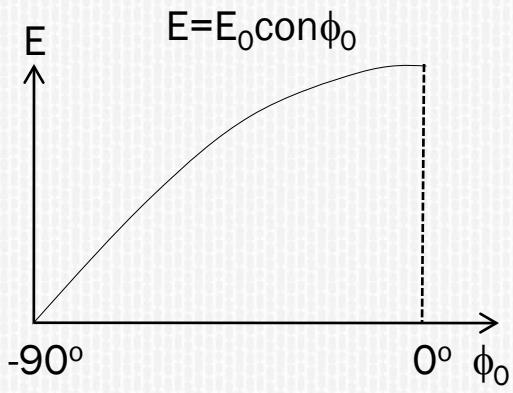
Toshikazu Takatomi

fs bunch length at exit of rf gun

A phase-scan technique

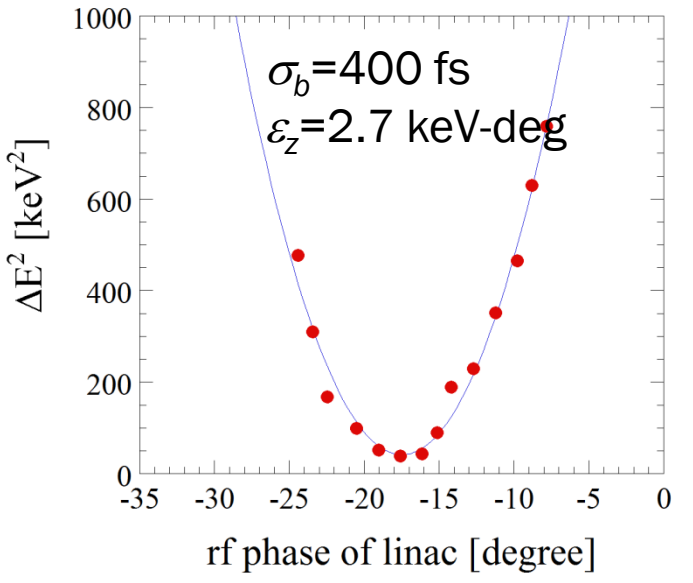


Waveform of rf

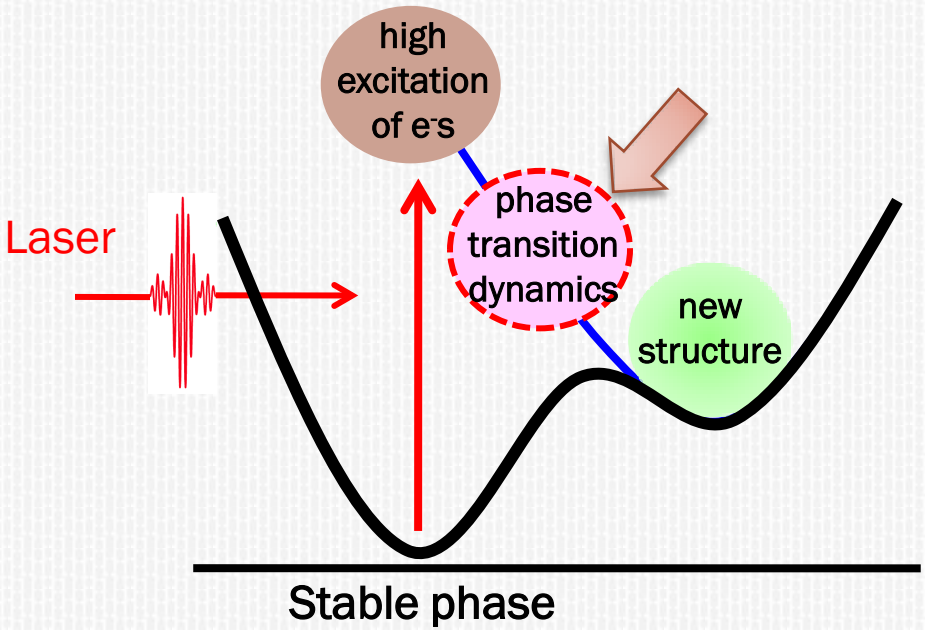


Rotating bunch in the linac

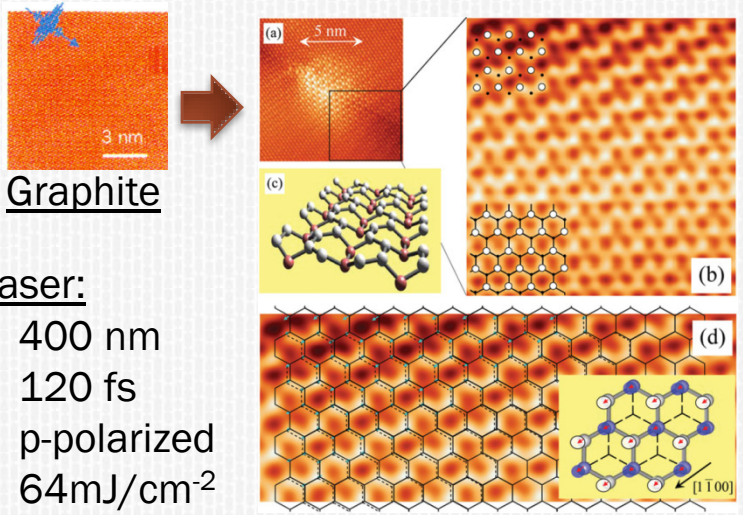
$$\Delta E^2 = \sigma_b^2\left(\frac{2\pi}{360}V_l\sin(\phi_0)\right)^2 - 2\sigma_{12}\left(\frac{2\pi}{360}V_l\sin(\phi_0)\right) + \sigma_{\Delta E}$$



Purpose: Study of phase transition dynamics



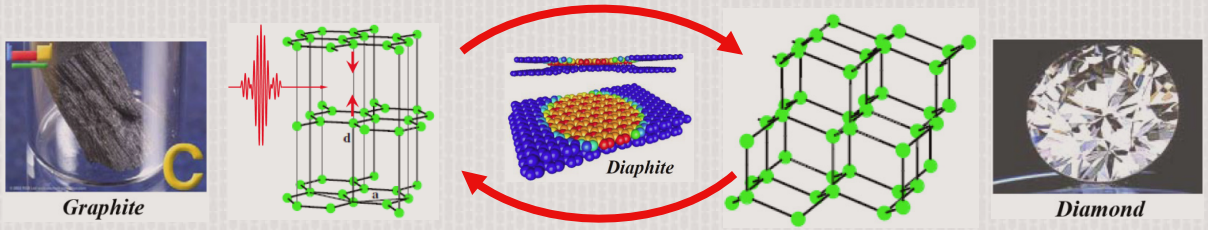
Formation of diamond(sp^3-bonded carbon) nanostructures on graphite by femtosecond laser excitation



Laser:
400 nm
120 fs
p-polarized
64mJ/cm^{-2}

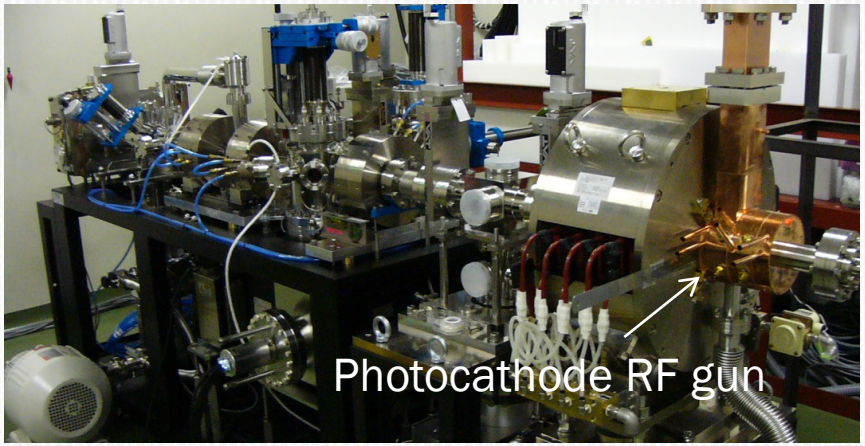
J. Kanasaki, et al. PRL 102, 087402(2009)

What dynamics of structure change from Graphite to Diamond?



recent progress on MeV UED

④ MeV UED at Osaka Univ. in 2009

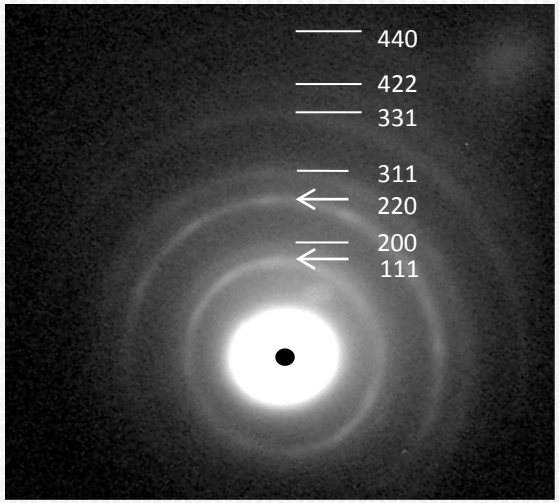


Beam energy: 3 MeV
Bunch charge: 1 pC
Emittance: 0.2~0.3mm-mrad
Energy spread: 0.3%

sample: Al thin foil

- polycrystalline
- 100nm-thick

MeV electron diffraction rings



Compared with 300keV TEM