RF gun based MeV TEM

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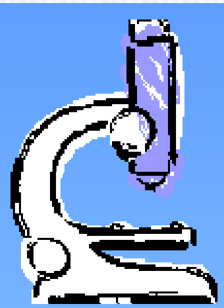
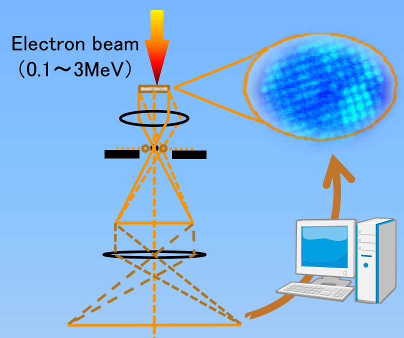
UEM and its applications



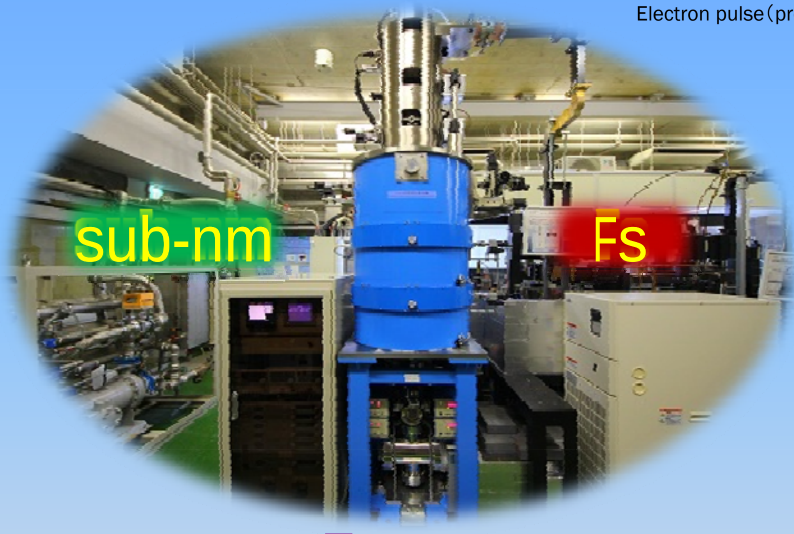
Imaging Technology

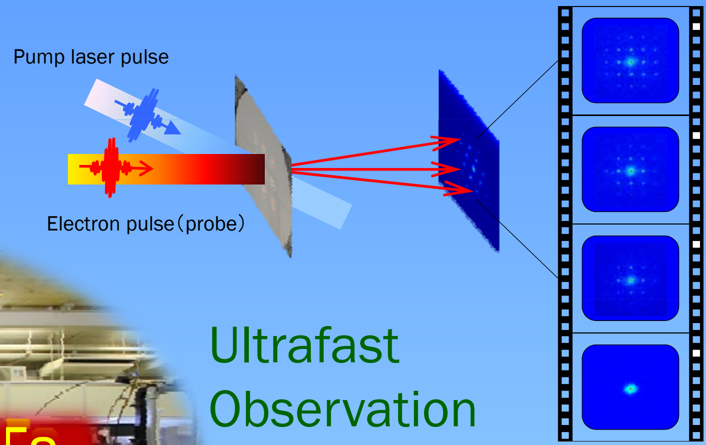
Structural observation and imaging in "real space" with atomic-scale spatial resolution using high-energy electron beam.



Imaging in "real space"

Methods





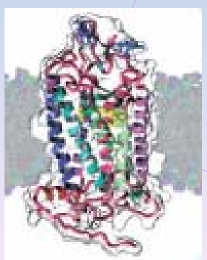
Ultrafast Observation

Observations of fundamental dynamic processes in matter occurring on femto-second time scales over atomic spatial dimensions.

Observation in "real time"

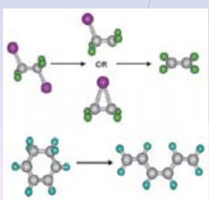
Targets

Protein Structural Dynamics



- Protein structural dynamics
- Macromolecular structure
- Reveal of functioning processes
- New technologies and applications in medical biology.

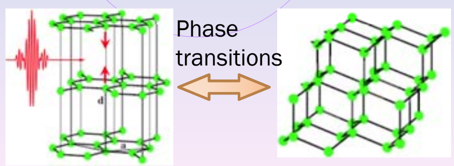
Making Molecular Movie



- Observation of single molecule motion.
- Ultrafast chemical reactions
- Solvation dynamics
- Discovery of transition states and reaction intermediates.

Nano-technology/science

- Transformation dynamics of novel nano-scale materials.
- Creation of new functional materials and devices for nanotechnology.



Why use RF gun in microscopy?

✓The space-charge effect can be reduced.

RF gun is operated with a high acceleration electric field up to 100 MV/m, which is x10 higher than that in DC electron gun.

✓A femtosecond relativistic-energy electron beam with high charge is available.

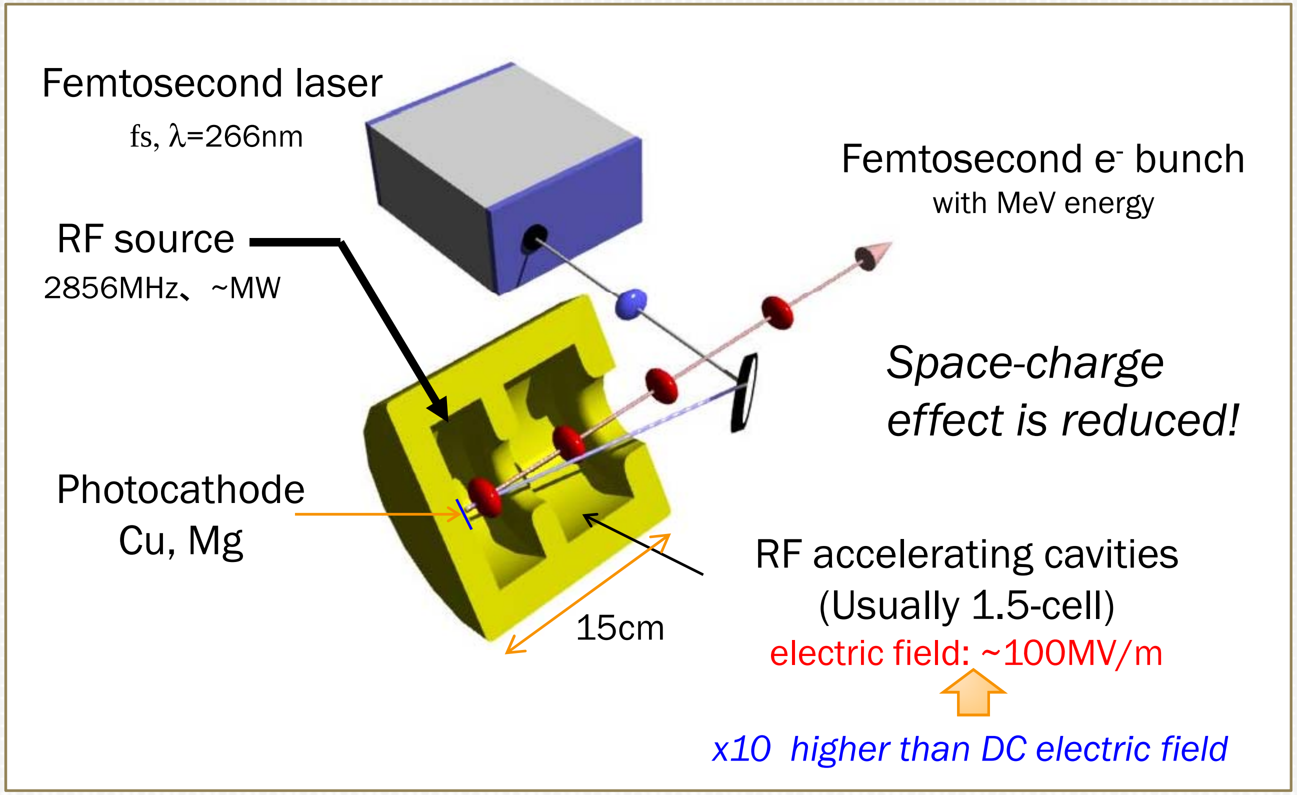
ex. 100-fs electron pulses with energy of 1~3MeV and charge of 1~10pC.

✓Femtosecond single-shot imaging may be achieved.

100-fs time-resolution & sub-nanometer spatial resolution in microscopy *(goal for the scientists)*

Challenge !

What RF electron gun?



The expected beam parameters:

Electron energy:	1~3 MeV
Bunch length:	100 fs
Emittance:	0.1 mm-mrad
Energy spread:	10^{-4} (10^{-5} for challenge)
Charge:	10^{7}~10^{8} e⁻'s/pulse

Key parameters for EM! (Emittance, Energy spread)

How to generate such beam?

Beam dynamics in RF gun

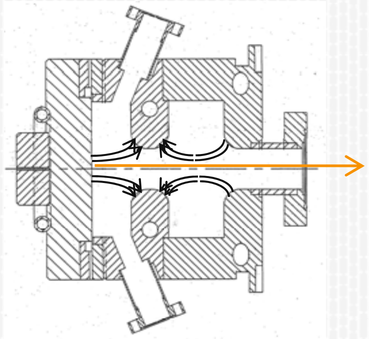
1) Longitudinal dynamics

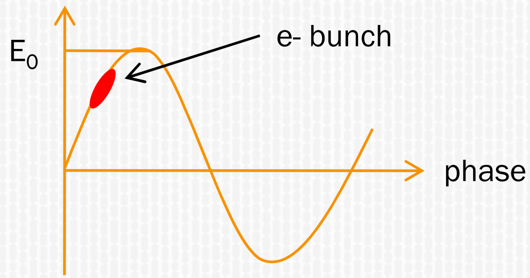
RF field in longitudinal direction:

$$E_z = E_0 \cos kz \sin(\omega t + \phi_0)$$

$$\phi = \omega t - kz - \phi_0 = k\int_0^z \left(\frac{\gamma}{\sqrt{\gamma^2-1}} - 1\right) dz + \phi_0$$

$$\frac{d\gamma}{dz} = \frac{eE_0}{2mc^2}\left[\sin\phi + \sin(\phi + 2kz)\right]$$





Solution of eqs.

Kim, NIM A275, 201-218(1989)
Travier, NIM A340, 26-39(1994)

$$\gamma = 1 + (n+0.5)\alpha\pi = 1 + 146.8(n+0.5)\frac{E_0[MV/m]}{f[MHz]}$$

$$\sigma_{\Delta\gamma}(rms) = 2\pi\alpha f \sigma_z = 2.9\times10^{-4} E_0[MV/m]\sigma_z[ps]$$

$$\left.\frac{\Delta E}{E}\right|_{RF}(rms) = \frac{\sigma_{\Delta\gamma}}{\gamma - 1} = 2\times10^{-6}\frac{f[MHz]\sigma_z[ps]}{n+0.5}$$

$$\alpha = \frac{eE_0}{2mc^2k} = 46.7\frac{E_0[MV/m]}{f[MHz]}$$

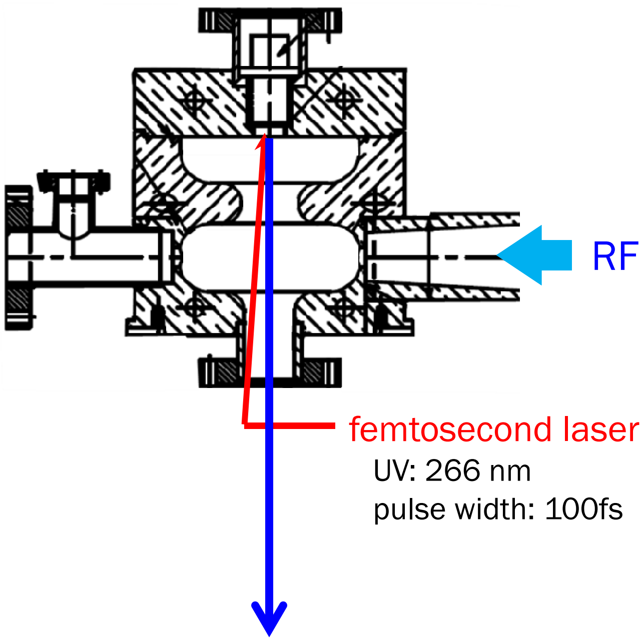
Example:

E_0=25~100MV/m, f=2856MHz, 1.5-cell

Energy: 1~4 MeV

- using 100fs laser,
  $\Delta E/E_{RF} \sim 10^{-4}$
- using 10fs laser,
  $\Delta E/E_{RF} \sim 10^{-5}$

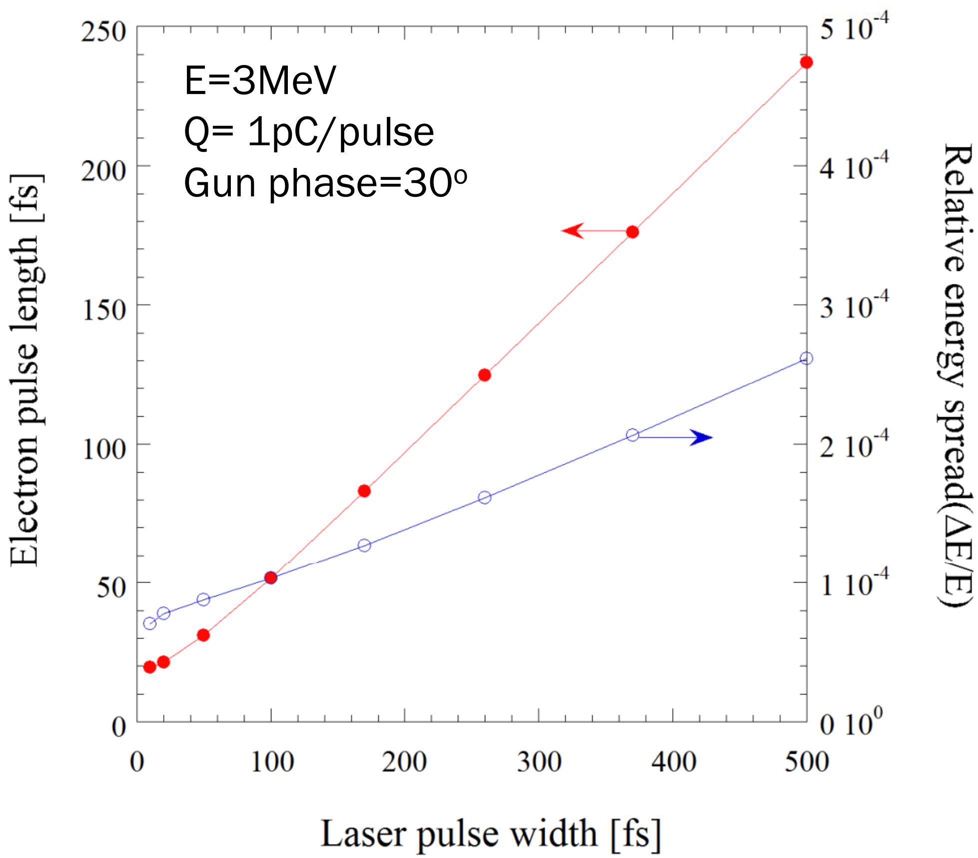
Simulation of low-energy spread e^- beam



Femtosecond electron beam

Energy spread: 10^{-4}

Energy spread as a function of laser pulse width



✓reduce energy spread due to RF effect with short-pulse laser

$\Delta E/E|_{RF}$ ~10^{-4} or less at σ_z<100 fs

Beam dynamics in RF gun

2) Transverse dynamics

➢ **Emittance due to space-charge effect:**

$$\varepsilon_{x,z}^{sc} = \frac{\pi}{4}\frac{1}{\alpha k}\frac{1}{\sin\phi_0}\frac{I_p}{I_A}\mu_{x,z}$$

$$\mu_x = \sqrt{\langle\Gamma_x^2\rangle\langle x^2\rangle - \langle\Gamma_x x\rangle^2} = \frac{1}{3\sigma_x/\sigma_z + 5}$$

for a Gaussian distribution beam

$$\varepsilon_x^{sc}[mm-mrad] = \frac{3.76\times Q[pC]}{E_0[MV/m](2\sigma_x[mm]+\sigma_z[ps])}$$

E_0~100MV/m in RF gun

➢ **Emittance due to RF effect:**

$$\varepsilon_x^{rf} = \sqrt{\langle p_x^2\rangle\langle x^2\rangle - \langle p_x x\rangle^2} = \alpha k\langle x^2\rangle\sqrt{\langle\sin^2\phi_f\rangle - \langle\sin\phi_f\rangle^2}$$

$$\phi_f \to \langle\phi_f\rangle + \Delta\phi, \quad \langle\phi_f\rangle = 90^o$$

$$\varepsilon_x^{rf} = 2.73\times10^{-11}E_0 f^2\sigma_x^2\sigma_z^2$$

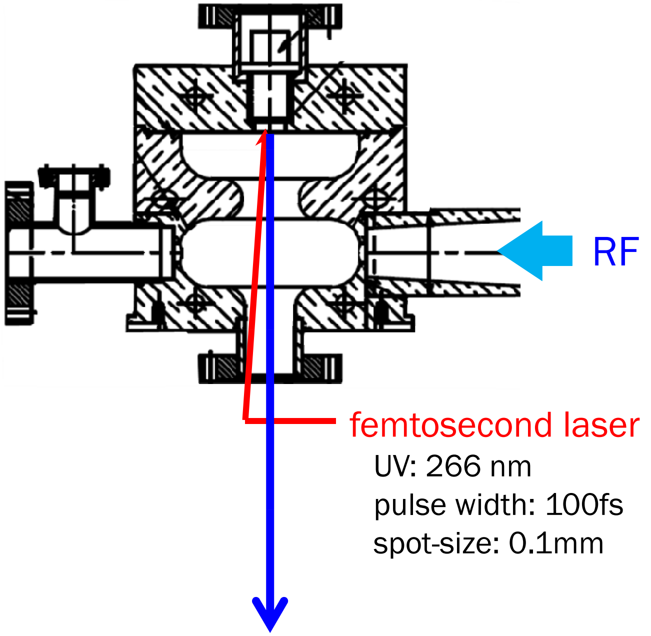
Example:

E_0=100MV/m, f=2856MHz, Q=1pC,
σ_x=0.1mm, σ_z=100fs

ε^{sc} ~ 0.1 mm-mrad
ε^{rf} ~ negligible

However, for the case of low-charge e^- beam, the emittance is dominated by thermal emittance on photocathode!

Generation of low-emittance e⁻ beam with RF gun



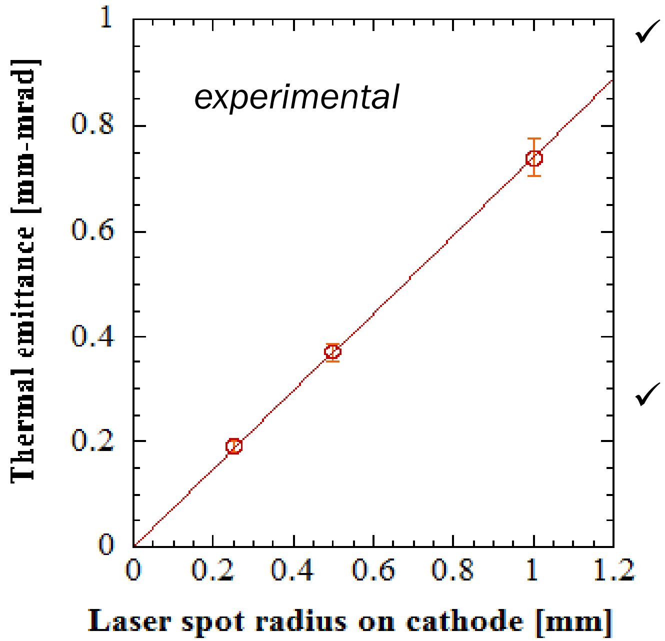
UV: 266 nm
pulse width: 100fs
spot-size: 0.1mm

Femtosecond electron beam

Emittance: 0.1 μm
Energy spread: 10^{-4}

E=3MeV
Q= 0.1pC/pulse

Emittance as a function of laser spot radius on Cu cathode



✓ Thermal emittance as a function of laser spot radius and kinetic energy of electrons,

$$\varepsilon_{th} = \sigma_r \sqrt{\frac{E_{kin}}{m_0 c^2}} \cong 0.75\sigma_r$$

✓ Kinetic energy of electrons emitted from Cu cathode

$$E_{kin} \cong 0.26eV$$

✓reduce thermal emittance with small size laser

ε_{th}~0.1 mm-mrad at σ_r=0.1mm

✓Initial energy spread emitted from Cu cathode

$$\left.\frac{\Delta E}{E}\right|_{in} = \frac{E_{kin}}{E} \frac{0.26eV}{3MeV} \approx 10^{-4}$$

RF gun based UED facilities

- Recently, the RF gun has been successfully used/proposed in UED facilities at BNL, SLAC, UCLA, Tsinghua Univ. , Osaka Univ., DESY, Shanghai Jiaotong Univ., KAERI, ...
- The UED experiments indicate that the RF gun based MeV UED is a useful tool for the study of ultrafast dynamics with time resolution of 100 fs or less.

However,

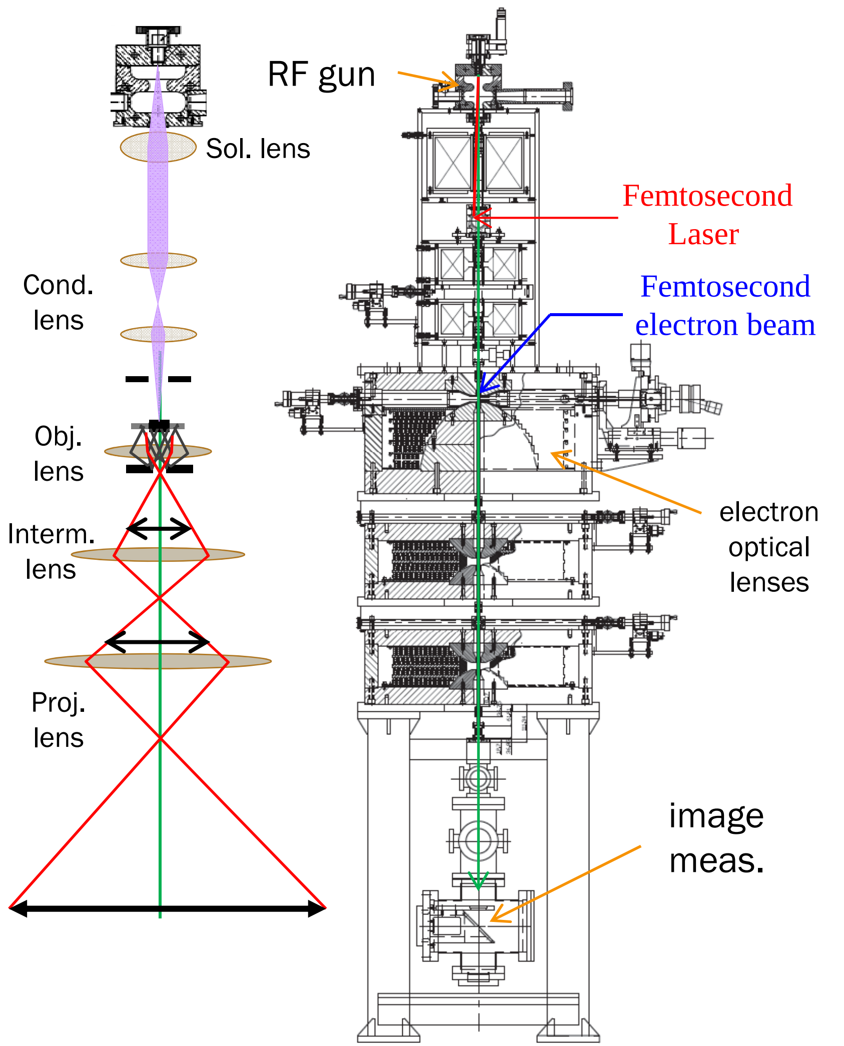
- Can RF gun be used in electron microscopy?
- What kind efforts and challenges are needed?

To understand,
we developed a prototype of time-resolved TEM using RF gun.

RF gun based electron microscopy

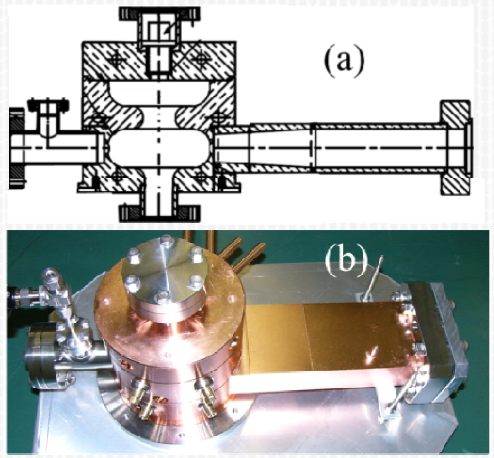
(under development at Osaka Univ.)

Concept of RF gun based TEM



Prototype of MeV UEM

Femtosecond photocathode electron gun



Electron energy：	1~3 MeV
Bunch length ：	100 fs
Emittance：	0.1 mm-mrad
Energy spread：	10^{-4} (10^{-5} for challenge)
Charge：	10^{7}~10^{8}e’s/pulse

Time resolution: 100 fs

Spatial resolution: 10 nm

Challenge !

First prototype of RF gun based electron microscopy

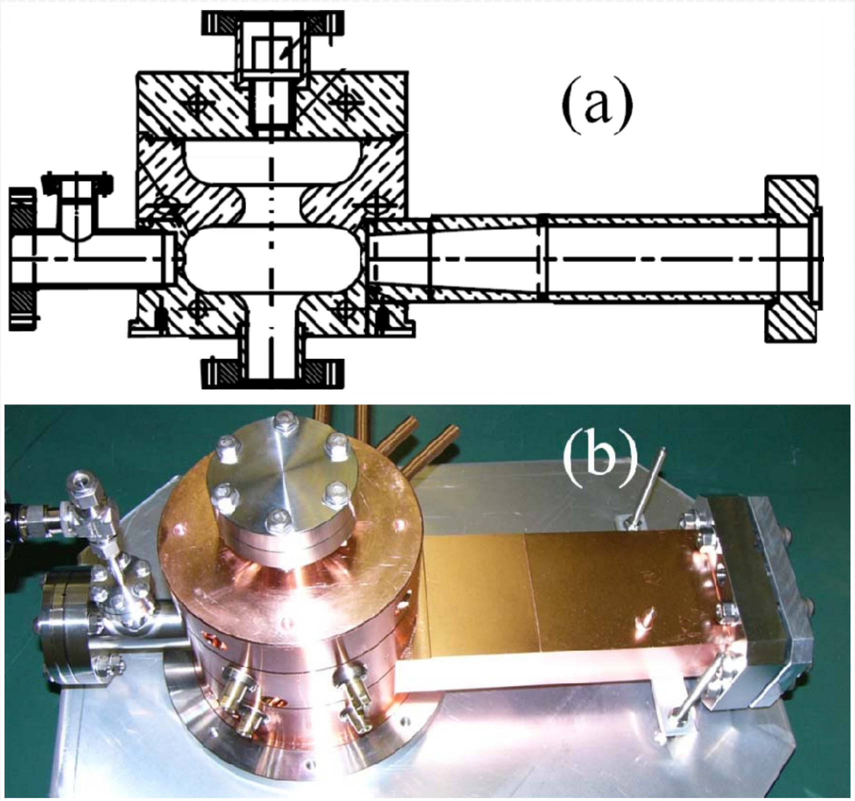
Prototype of MeV UEM at Osaka Univ.

(height: 3m, diameter: 0.7m)

- The prototype was constructed at the end of Oct. 2012.

Femtosecond RF gun at Osaka Univ.

Developed under the collaboration with KEK

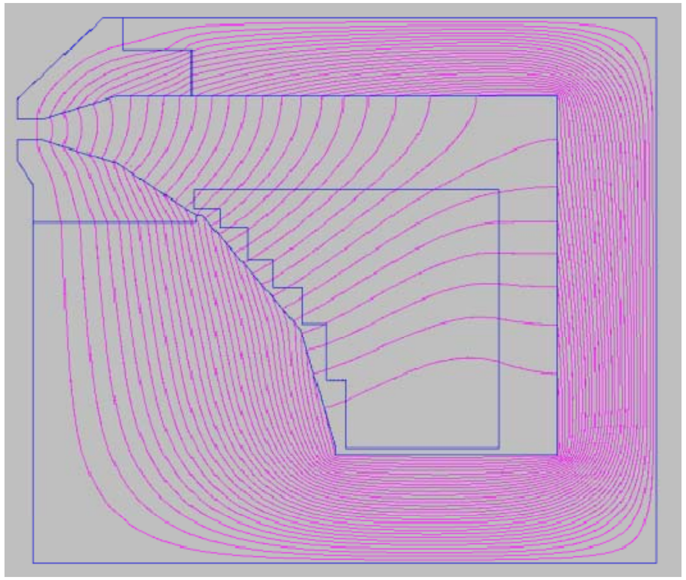


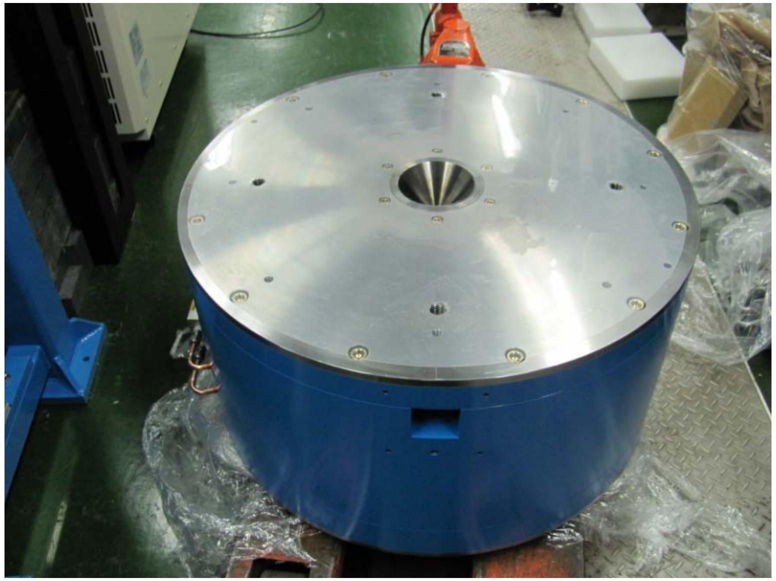
Improvements:

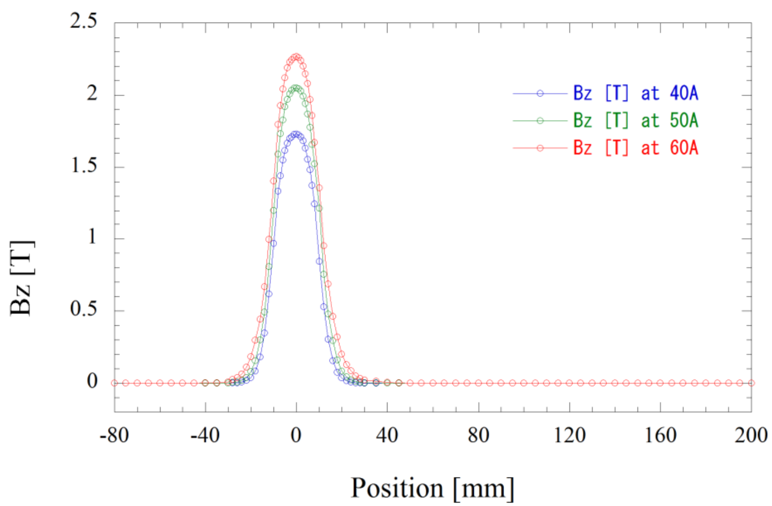
- •remove two laser injection ports
- •a new turner system
- •new structure cavities
- •a new insertion function of photocathode (The photocathode is removable)

- ➢reduce the asymmetric field in RF cavities.
- ➢generate low-emittance and low-energy-spread electron beam.

Design of 2T objective lens







Bore diameter: 13mm
Magnetic field: 2.2Tesla
Ampere-turn: 35,000

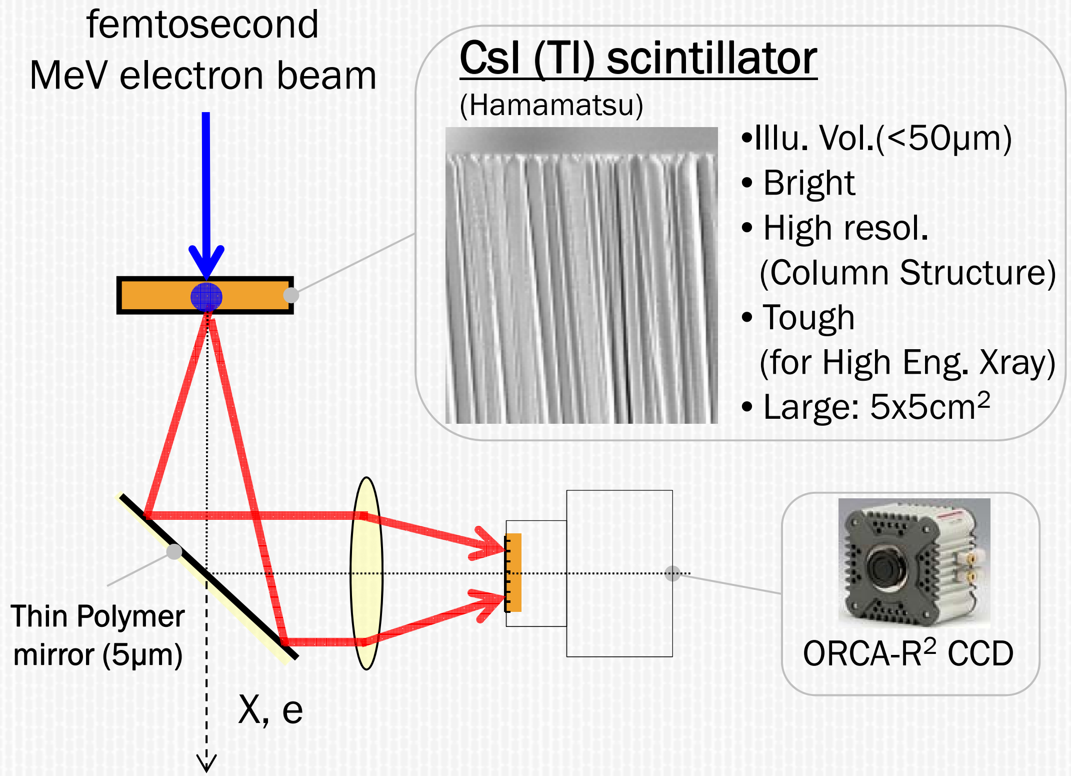
f = 5 mm for 2MeV e^-
C_s (C_c) ~ 4 mm

70 cm (D) x 35 cm (H)

Detection of MeV electron images

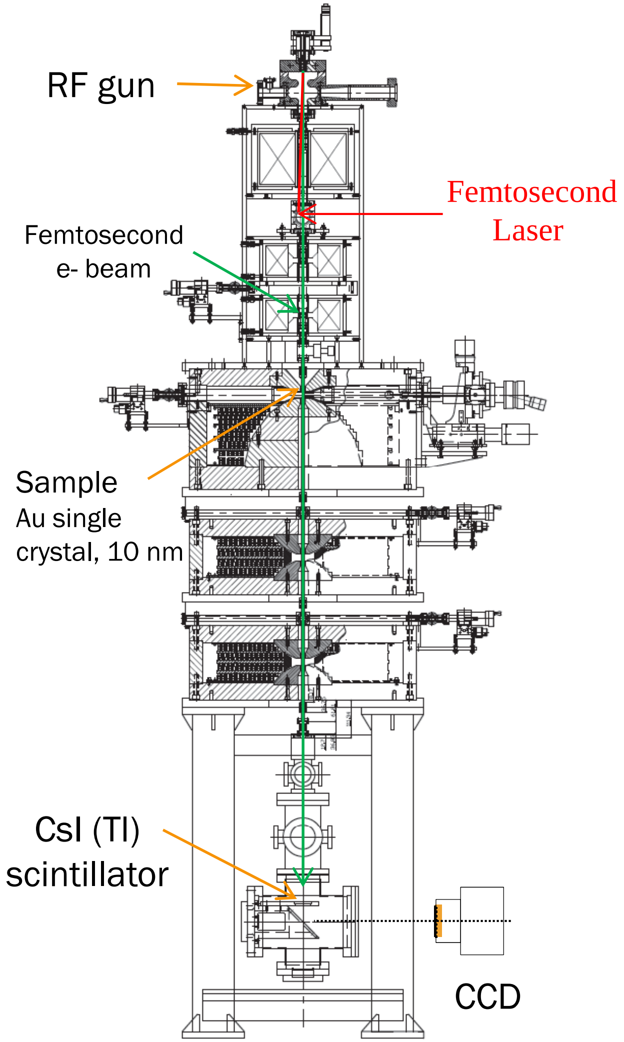
Problems in MeV e^- image detection

- Very low current,
  i.e. ~pA (10^7~10^8 e-'s/pulse)
- Strong X-ray emission,
  i.e. Background, pixel defect
- Damage by MeV electrons,
  i.e. scintillator, fiber
- Image to be shifted.



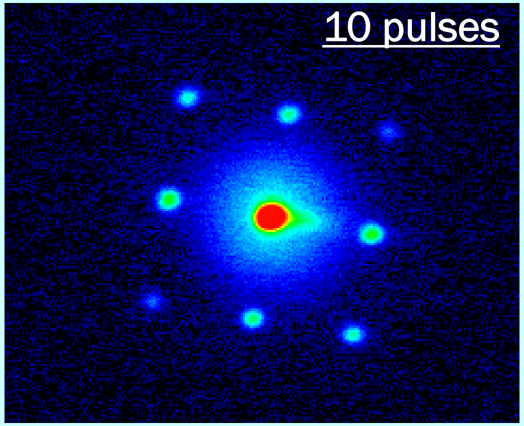
The detection system was successfully used in UED measurement.
(single-shot measurement with 10^5 e^-s/pulse)

Demonstrations of MeV ED/TEM imaging



Prototype of MeV UEM in Osaka Univ.

MeV electron diffraction

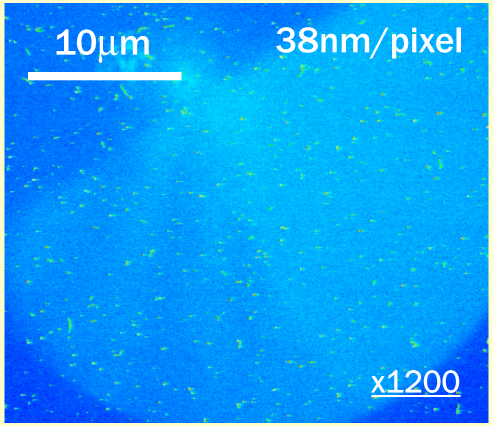


Sample: Au single-crystal film (10nm)

Electron energy: ~ MeV
Electron number: 10^5 e-'s/pulse)

A good-quality MeV ED was observed at 10^6 e-'s/image!

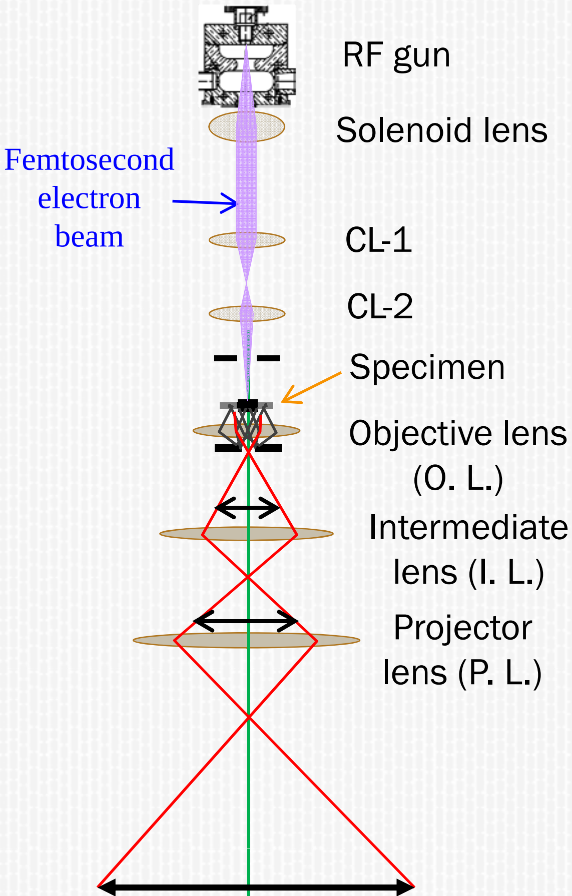
Relativistic-energy TEM image



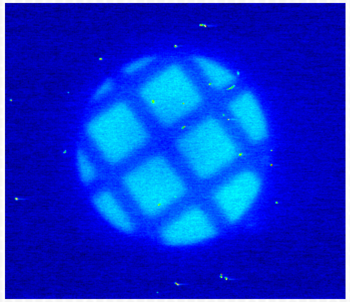
Electron charge at scint.:
~10 fC/pulse
(10^5 e-'s/pulse)
Measurement time:
~10 min

~10^8 e-'s/image

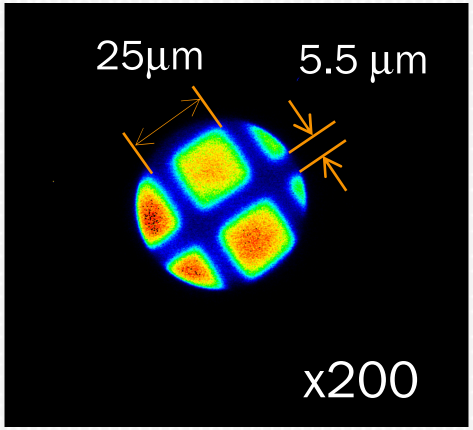
Magnifications & resolutions



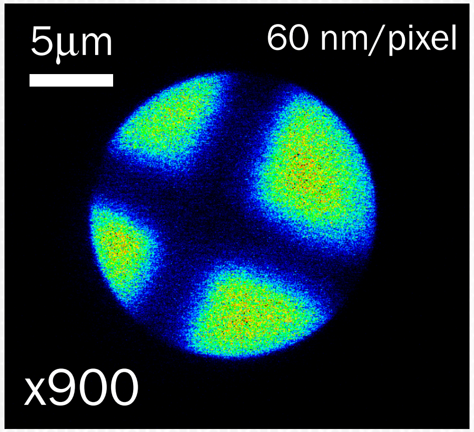
Sample:
Standard Cu grid(1000mesh)



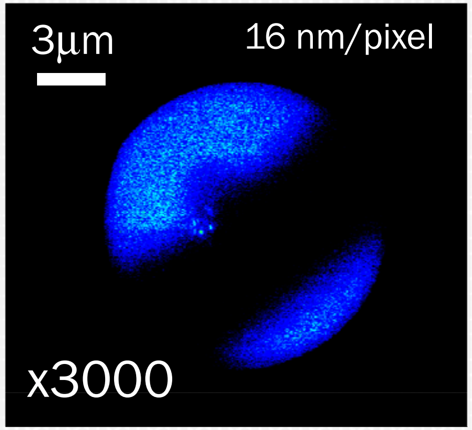
e^- energy: ~ MeV
e^- number: ~10^7/pulse



Using Obj. lens only



Using O.L. and I. L.



Using O.L., I. L. and P. L.

<u>Spatial resolution</u>

10nm (next step)
x10,000

~1nm (in future)

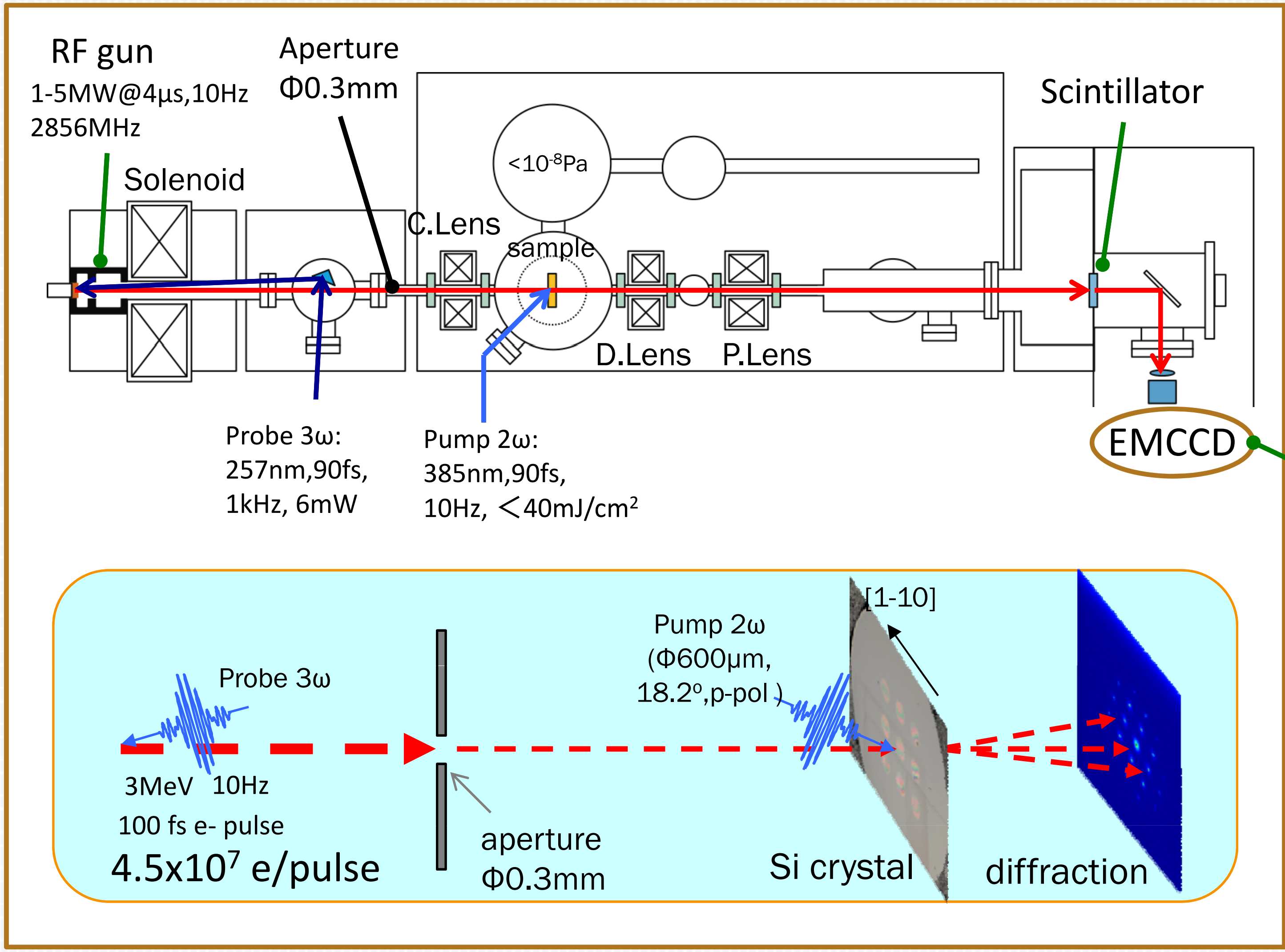
RF gun based UED

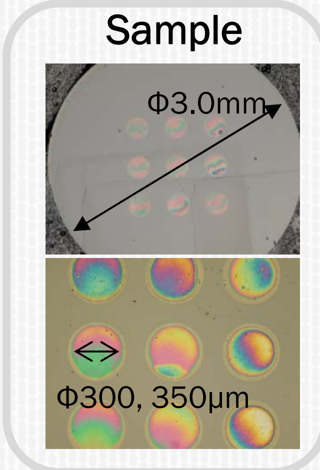
at Osaka University

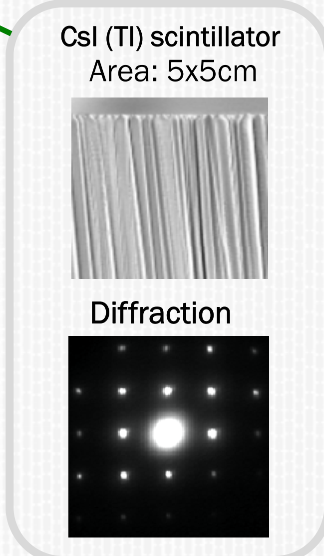
Electron energy:	1～3 MeV
Time resolution:	100 fs

RF gun based MeV UED at Osaka Univ.

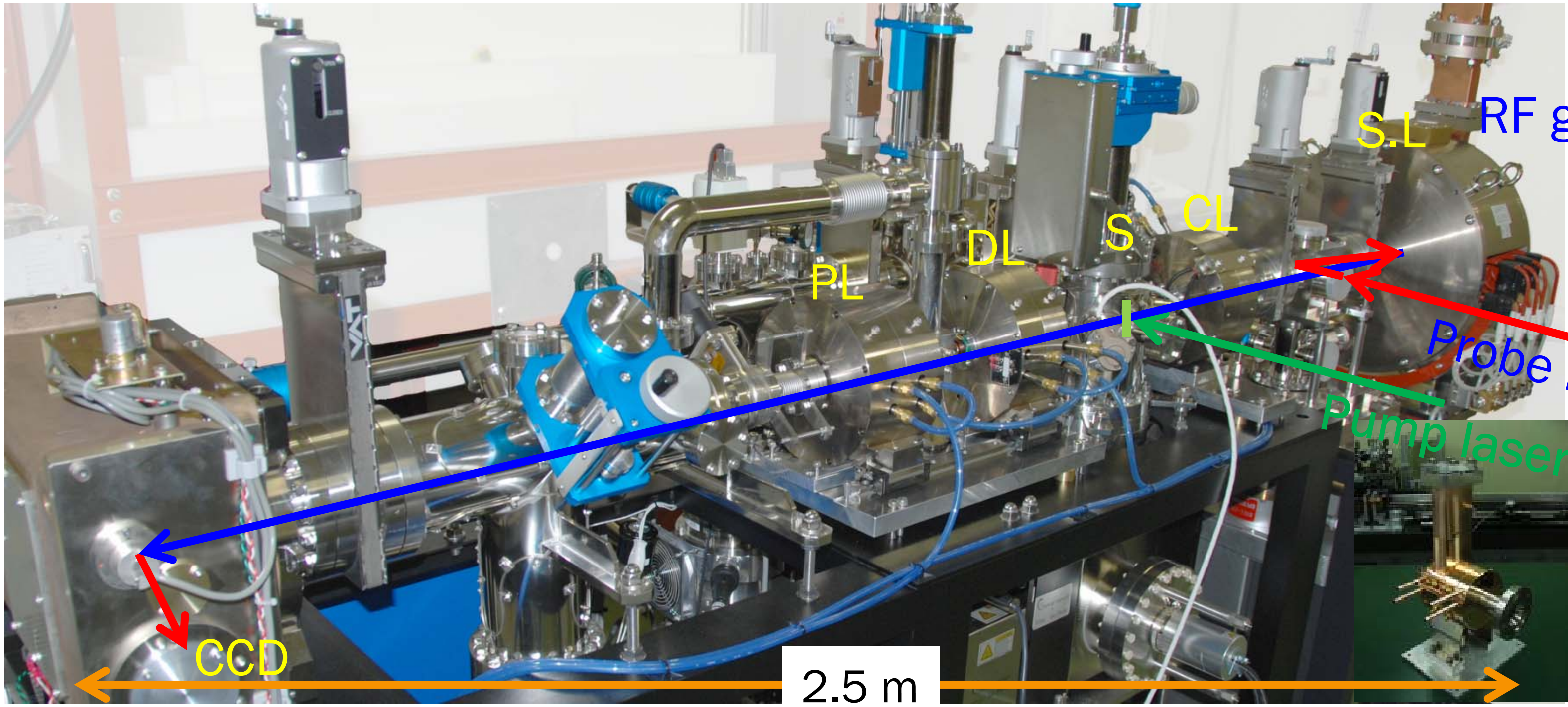
use of electron optical lenses as like in electron microscopy







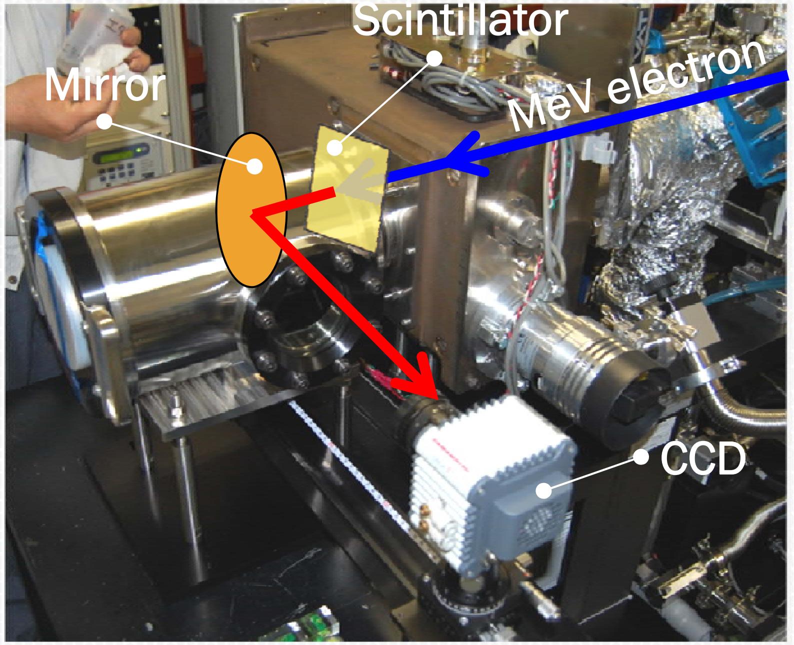
Picture of UED system at Osaka Univ.

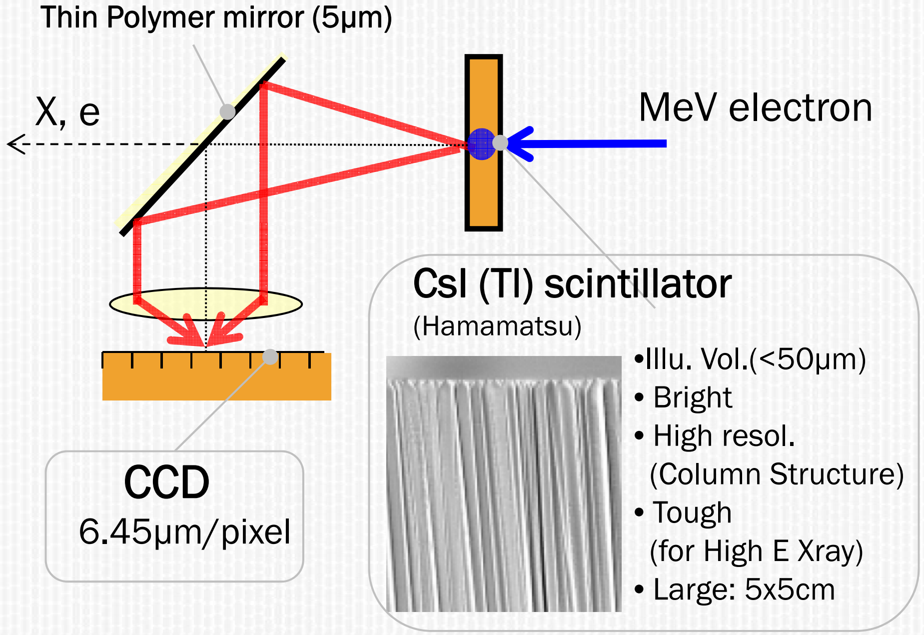


use of electron optical lenses, therefore, compact.

Detection of MeV electron diffraction

Requirements of MeV electron 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

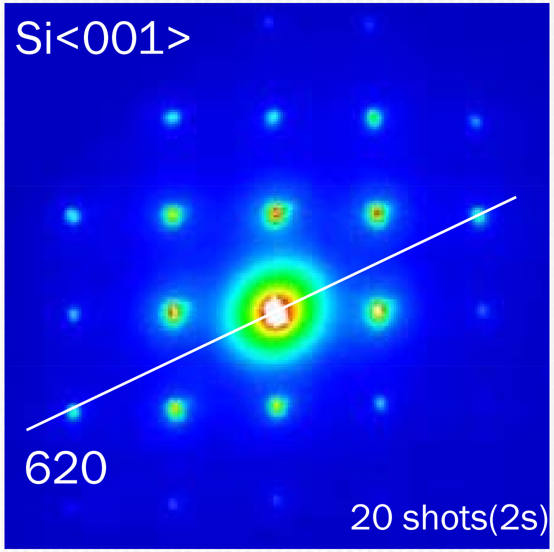
Solution

- 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

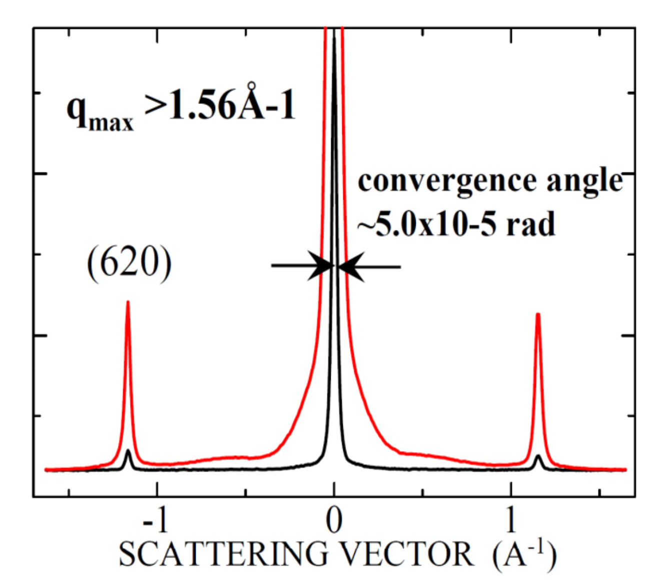
Electron beam: 3 MeV, $8.9\times10^{7}\, e/cm^{2}/pulse$

Sample: 180nm-thick single crystal Si



A high-quality MeV ED was observed!

Intensity profile of 620 pattern



- Beam convergence angle: 0.05 mrad
- Maximum scattering vector : q_{max} >1.56Å^{-1}
- Requirement of the e^- number: 10^{6-7}

- Bragg law

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

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

Y. Murooka, et al., Appl. Phys. Lett. 98, 251903 (2011)

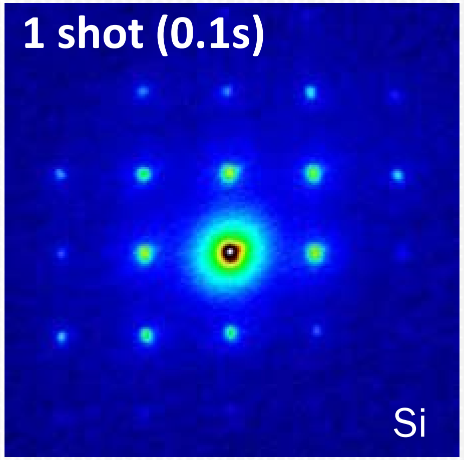
Power of the technique: static diffractions

- Single-shot measurement

Si
single crystal
Thickness: 180nm

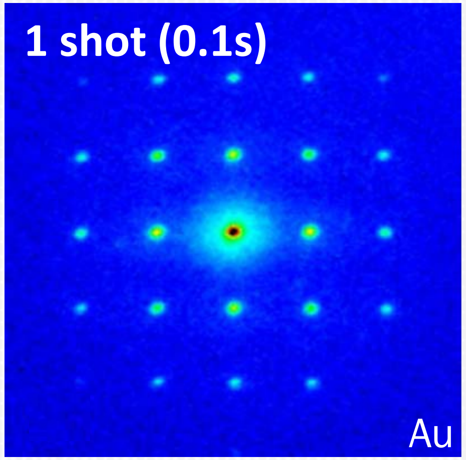
e- energy: 3MeV

Y. Murooka, et al.,
Appl. Phys. Lett.
98, 251903 (2011)

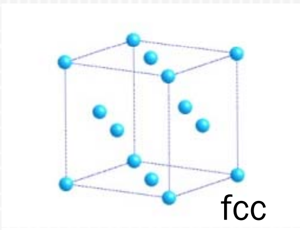


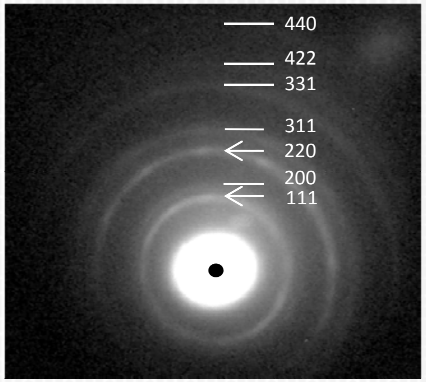
Au
single crystal
Thickness: 10nm

e- energy: 3MeV
No. of e⁻'s: 10^5/pulse



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

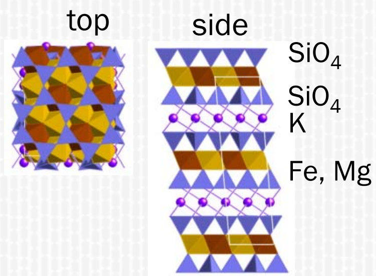


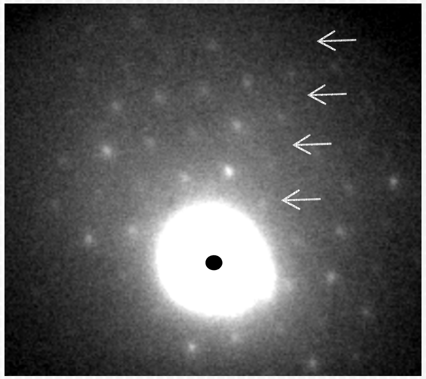


Large scattering vector
q_{max}

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

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



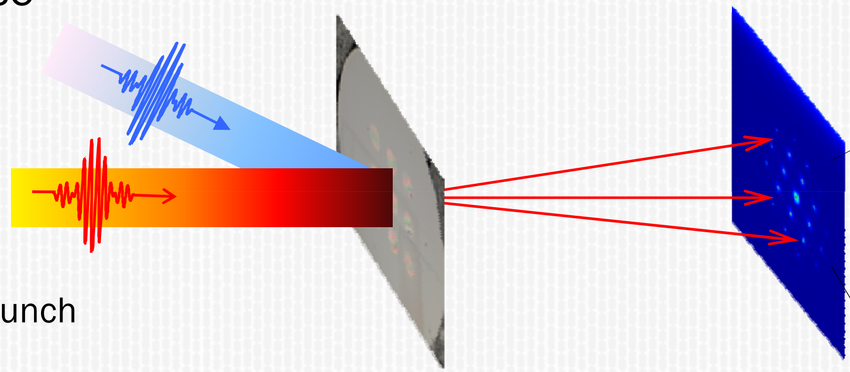


No charging effect
(Difficult at Low Voltage)

UED：Phase transformation on single-crystal Au

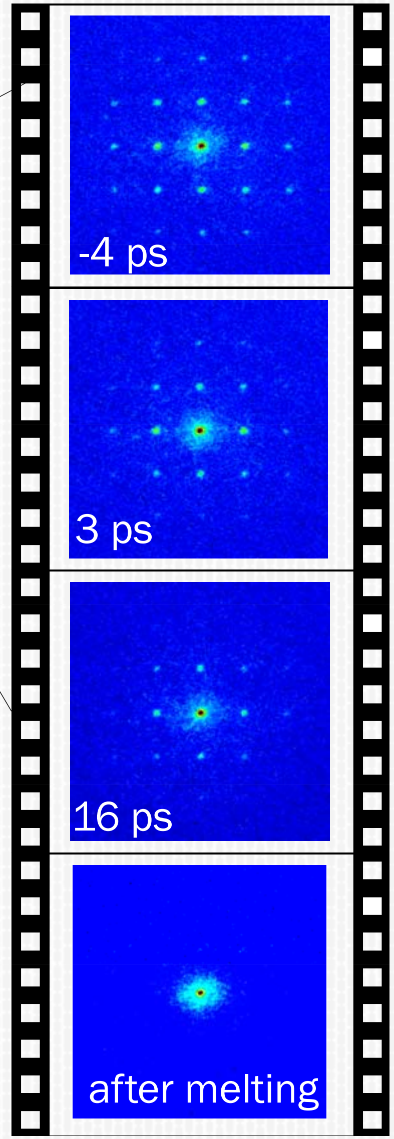
Pump laser pulse
385nm,90fs

Single crystal Au
~10 nm

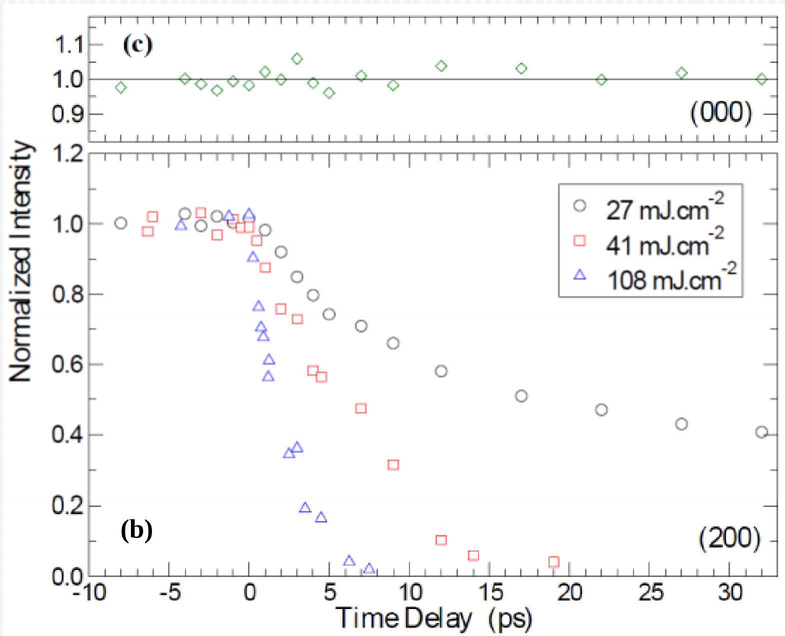


Electron pulse
3 MeV, 90fs, $10^5 e^-$/bunch

Movie of melting



Ultrafast laser heating on single crystal gold (as function of intensity of pump laser)



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Conclusion and remarks

✓Both RF gun based UED and UEM systems have been constructed at Osaka University.

✓In UED, single-shot and time-resolved measurements have been succeeded. The time resolution was achieved to be 100 fs.

✓In UEM, the demonstrations of MeV electron diffraction and imaging were carried out.

✓Both experiments suggest that RF gun is very useful for ultrafast MeV electron diffraction and is also expected to be used in ultrafast electron microscopy.

However, great efforts and many challenges are required:

- reduce further the emittance (<0.1 μm) and energy spread (10^{-5} or less),
- increase the beam brightness,
- improve the stabilities on the charge and energy,
- develop a detection of very electron with MeV energy, and so on.