The 13th Symposium on Accelerator Physics

Electron diffraction and imaging at Tsinghua

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2017.08.29

清華大學

Tsinghua University

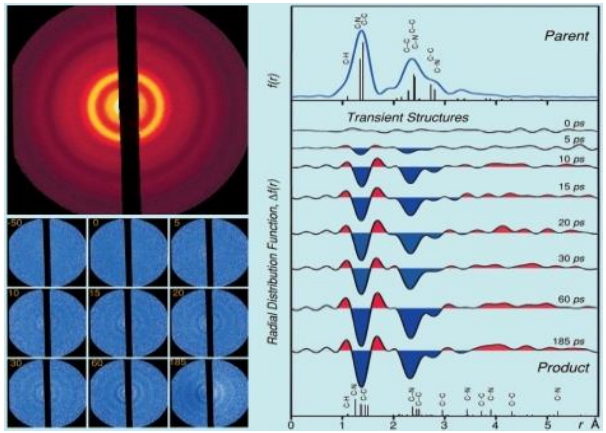
Outline

I. MeV Ultrafast electron Diffraction(UED)

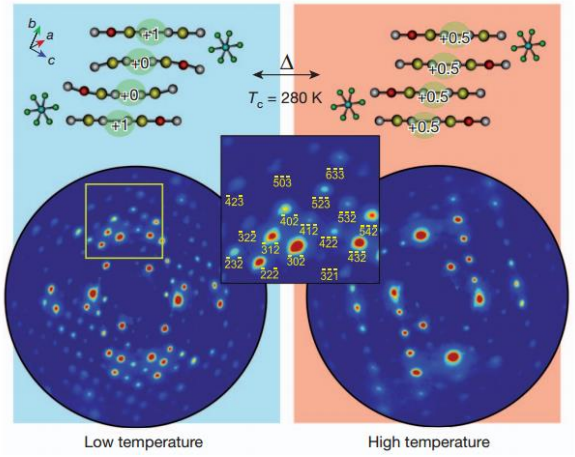
II. High energy electron imaging

III. Summary and outlook

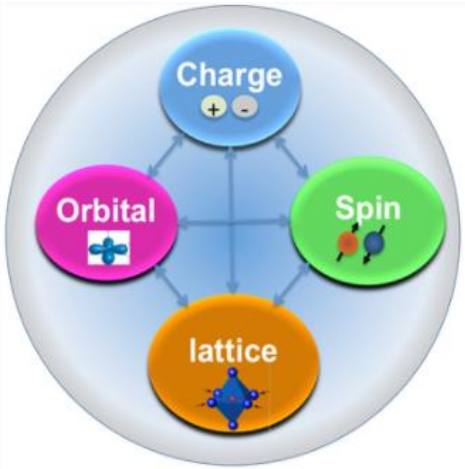
Motivations



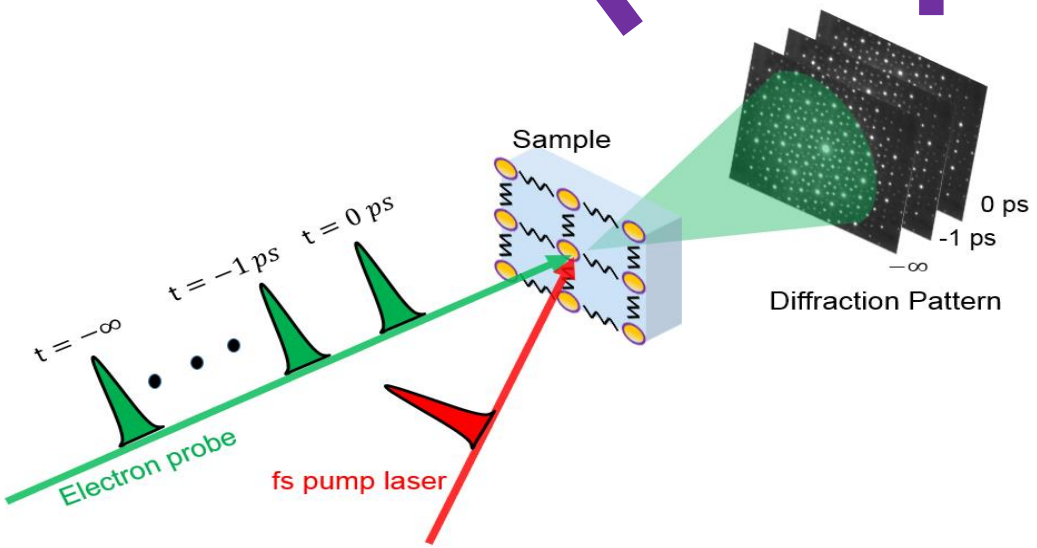
Structure Dynamics



Phase Transformation



Strongly Coupled System



- Mainly for Ultrafast sciences;
- Dream probe:

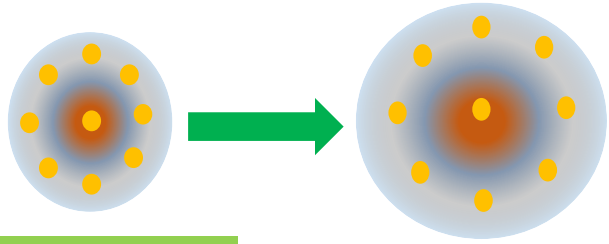
100fs time resolution

sub-angstrom space resolution

UED Instrument

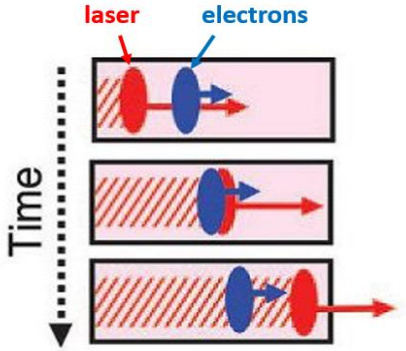
Time resolution limited to ~1ps in keV UED

- Space charge effect

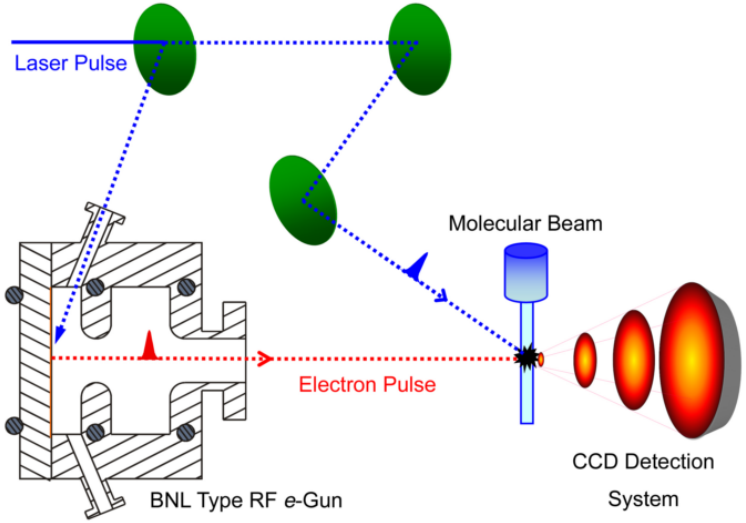


Electron bunch

- Velocity mismatch



MeV UED based on photocathode rf gun



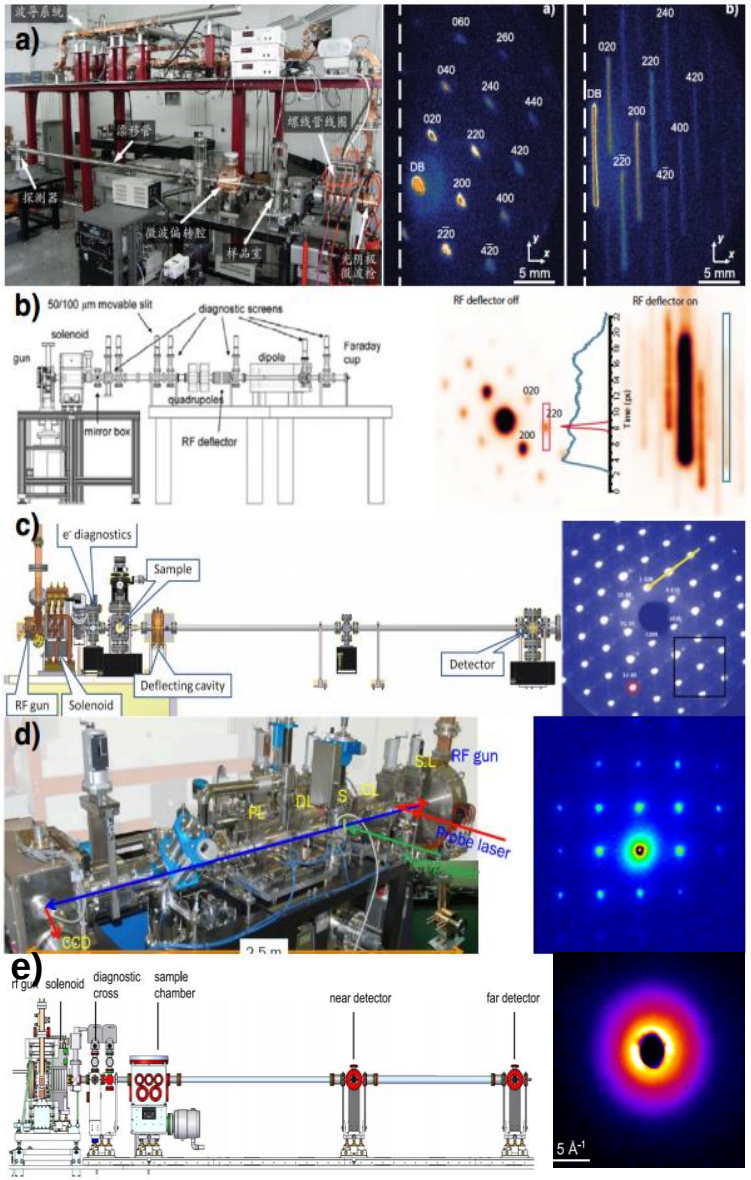
- Space charge effect scales with γ^{-3}
- Velocity mismatch negligible

$$\gamma = 10 \Rightarrow v = 0.995c$$

Wang X J, Xiang D, Kim T K, et al. JOURNAL-KOREAN PHYSICAL SOCIETY, 2006, 48(3): 390.

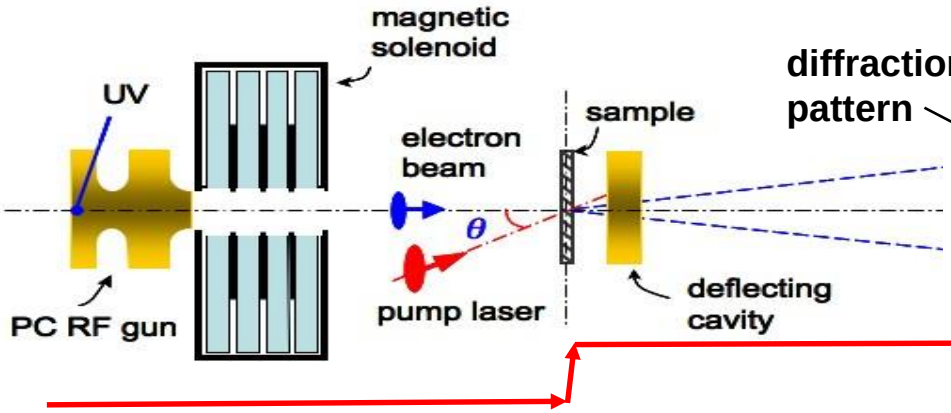
MeV UED Instrument

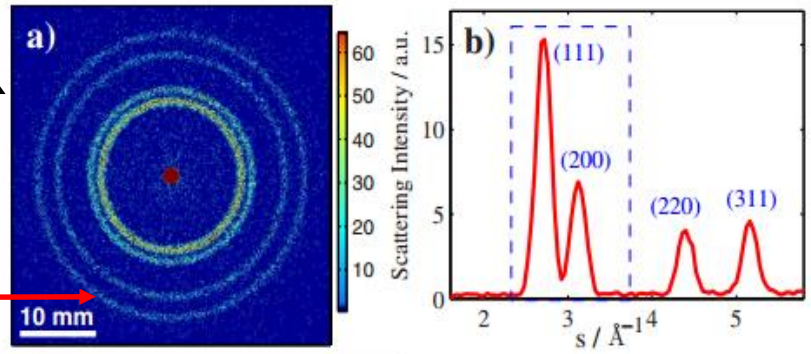
- Worldwide interest in MeV UED
  a) Tsinghua University
  b) UCLA
  c) BNL & Shanghai Jiao Tong University
  d) Osaka University
  e) SLAC
  f) DESY REGAE
- Intensive efforts devoted
  - Machine performance
    - beam optimization
    - stability & high repetition rate
  - Methodology
    - continuously-time resolved mode
    - advanced pump technology
  - Scientific applications
    - Gas phase molecular dynamics
    - complex materials



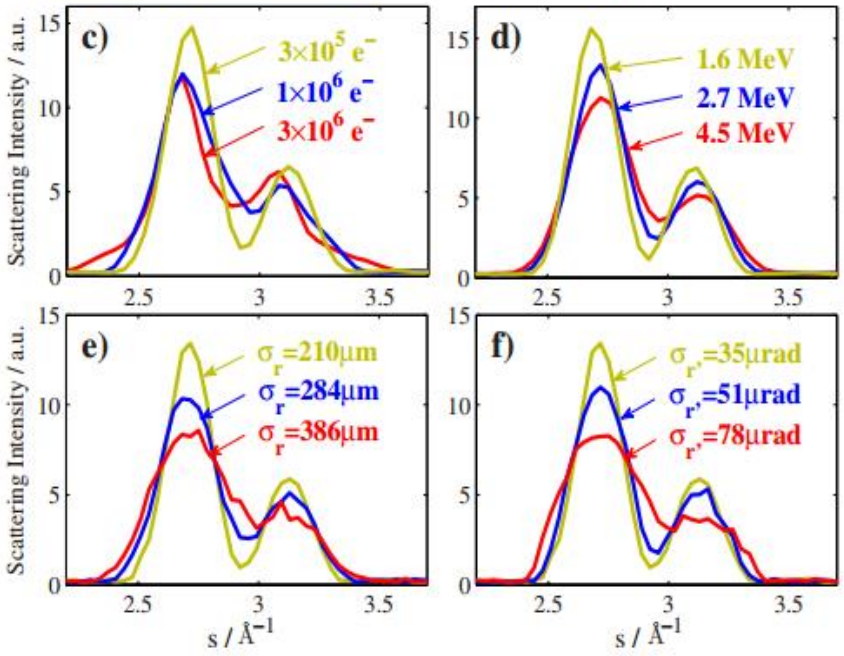
MeV UED at THU

Simulation and optimization





Start-to-end simulation



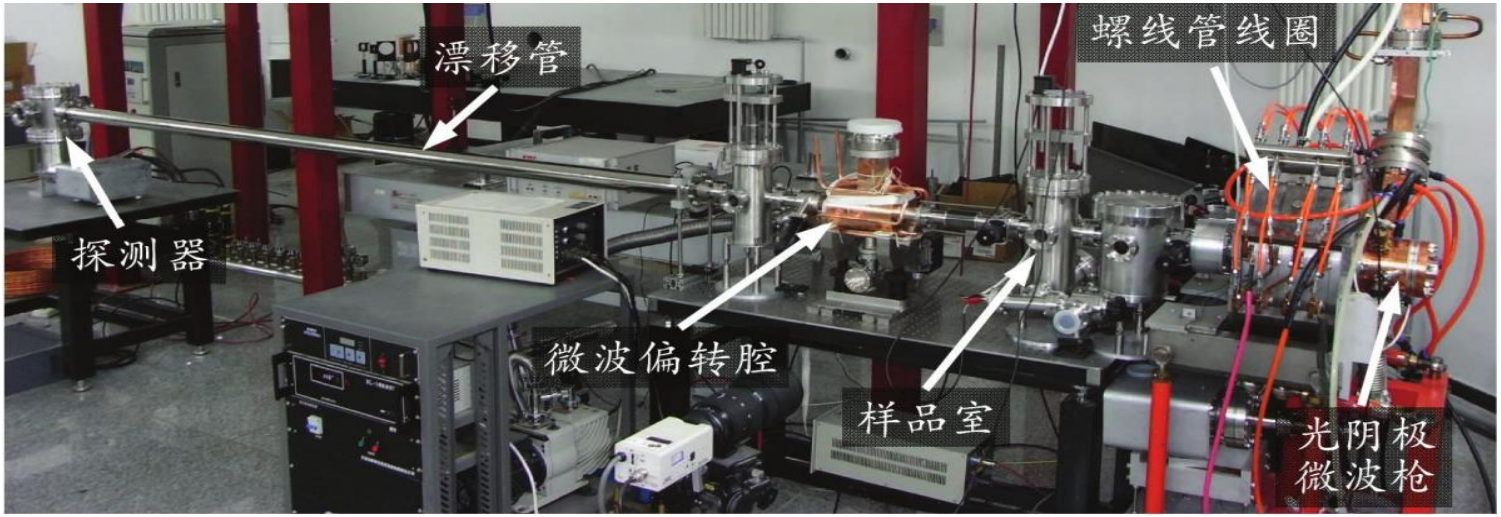
Goal: To improve DP quality

- bunch charge
- energy
- spot-size
- divergence

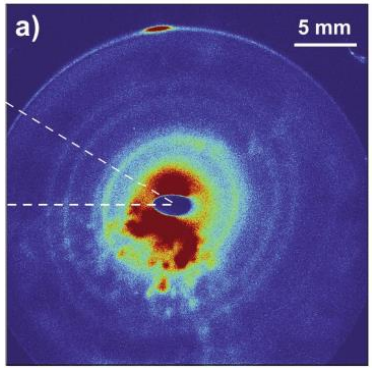
Rev. Sci. Instrum. 80, 083303 (2009)

MeV UED at THU(cont.)

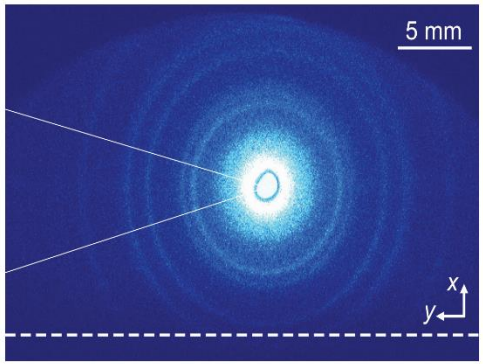
- Photocathode gun based MeV UED prototype



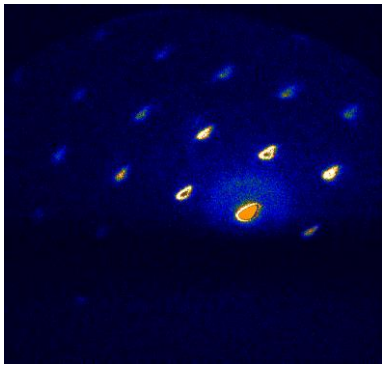
- High quality static diffraction pattern



Poly. Al, accumulated



Poly. Al, **single-shot !**



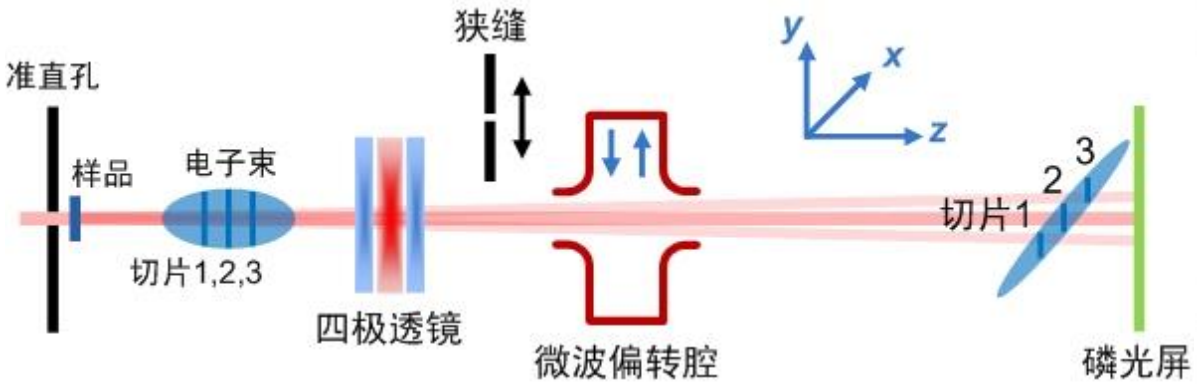
Au, **single-shot**

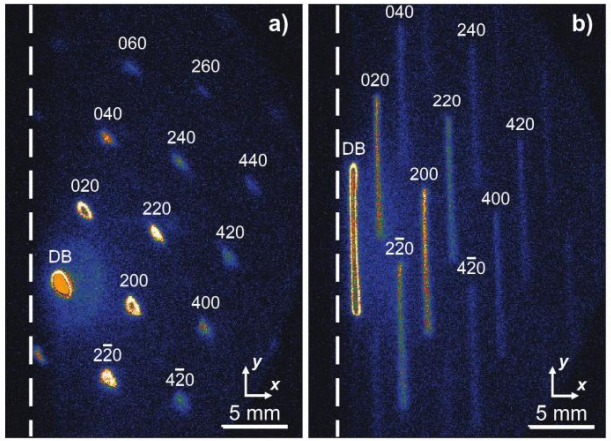
Li R.K., Ph.D. thesis.

MeV UED at THU(cont.)

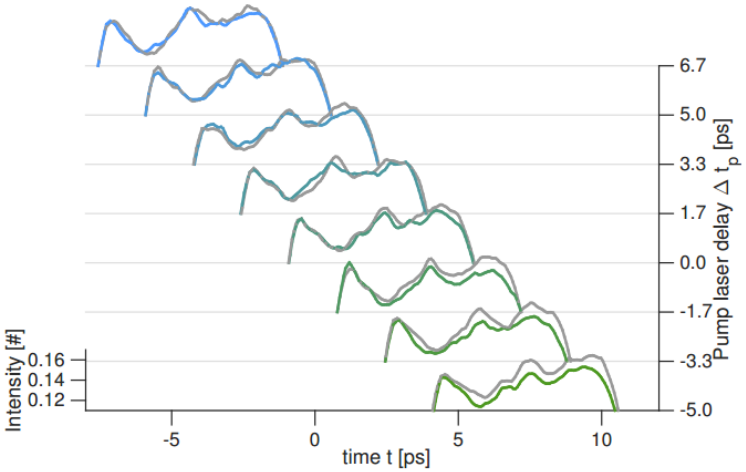
- Continuously-time resolved mode UED

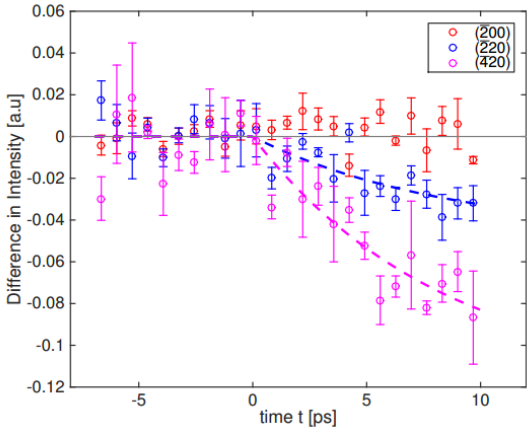
Li R.K., Ph.D. thesis.





- pump-probe experiment





"Movie" mode

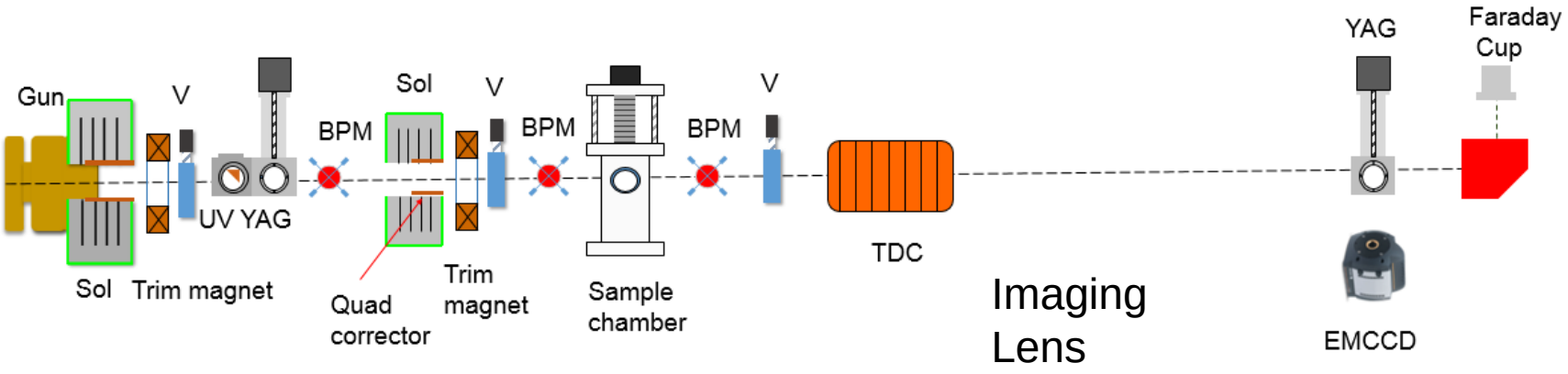
Single-shot

Sub-ps resolution

Lu X.H., Ph.D. thesis.

UED user facility

- high quality facility for **user experiment**

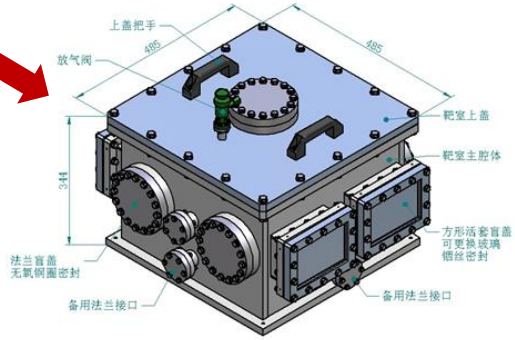


- significant improvement over prototype

- New Modulator: peak-to-peak 0.1% Voltage jitter

Rf amplitude jitter: 0.1% (p2p)
Rf phase jitter: 0.1 deg (p2p)

- Multi-functional sample chamber: solid, gas phase



- More magnets to take full control of the beams
- Systematic beam diagnostics

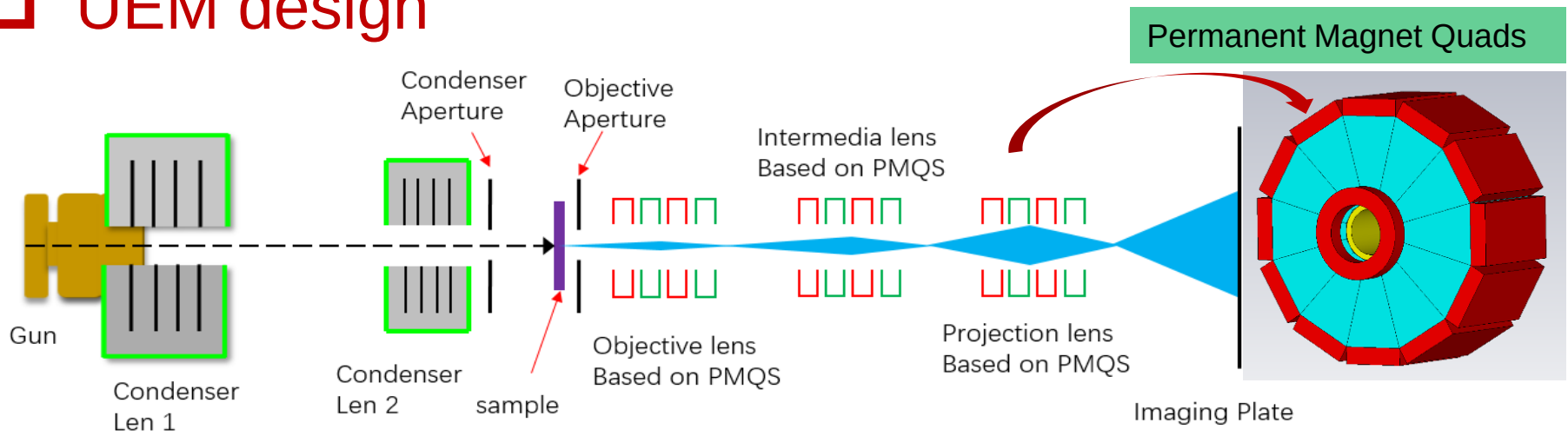
To offer high quality machine performance with ~100 fs time resolution for users.

Diffraction to Imaging

From reciprocal space to real space

- No space resolution in UED: Diffraction info is not sufficient for clarifying the structural dynamic process of a single atom or molecule;
- Electron imaging, such as Ultrafast Transmission Electron Microscope (UEM), can elucidate such process with ultrahigh space and time resolution.

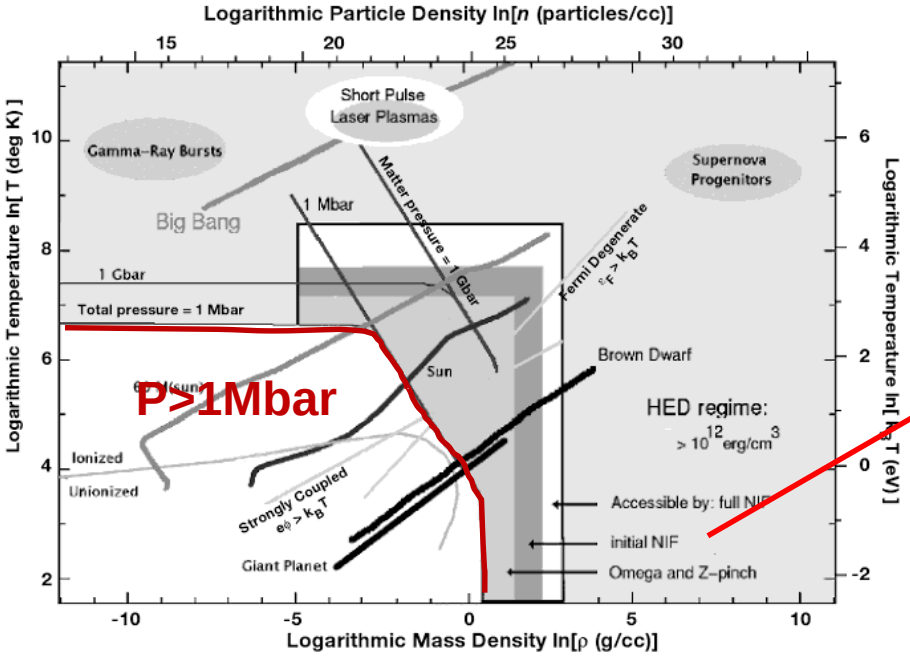
UEM design

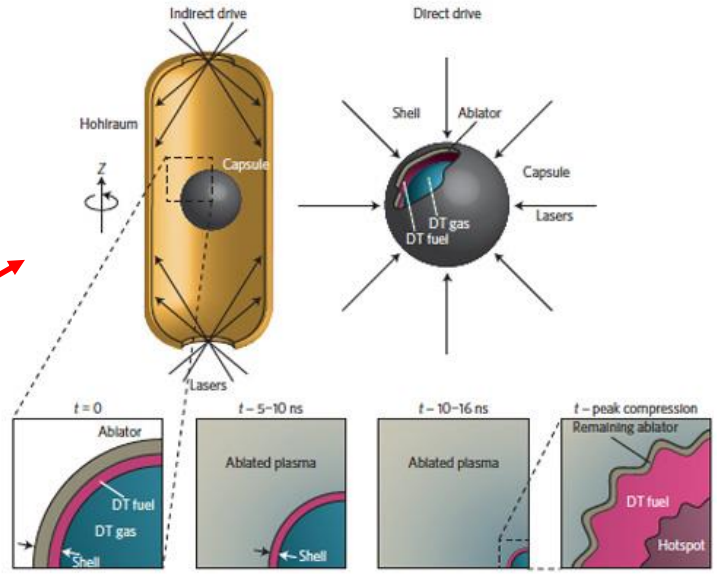


- PMQs based imaging lens are strong and compact, suitable for UEM facility;
- Imaging column has been designed, and cascade imaging is possible;
- Prototype of single imaging unit has been constructed, and will be demonstrated soon on TTX.

High energy electron imaging

Motivations





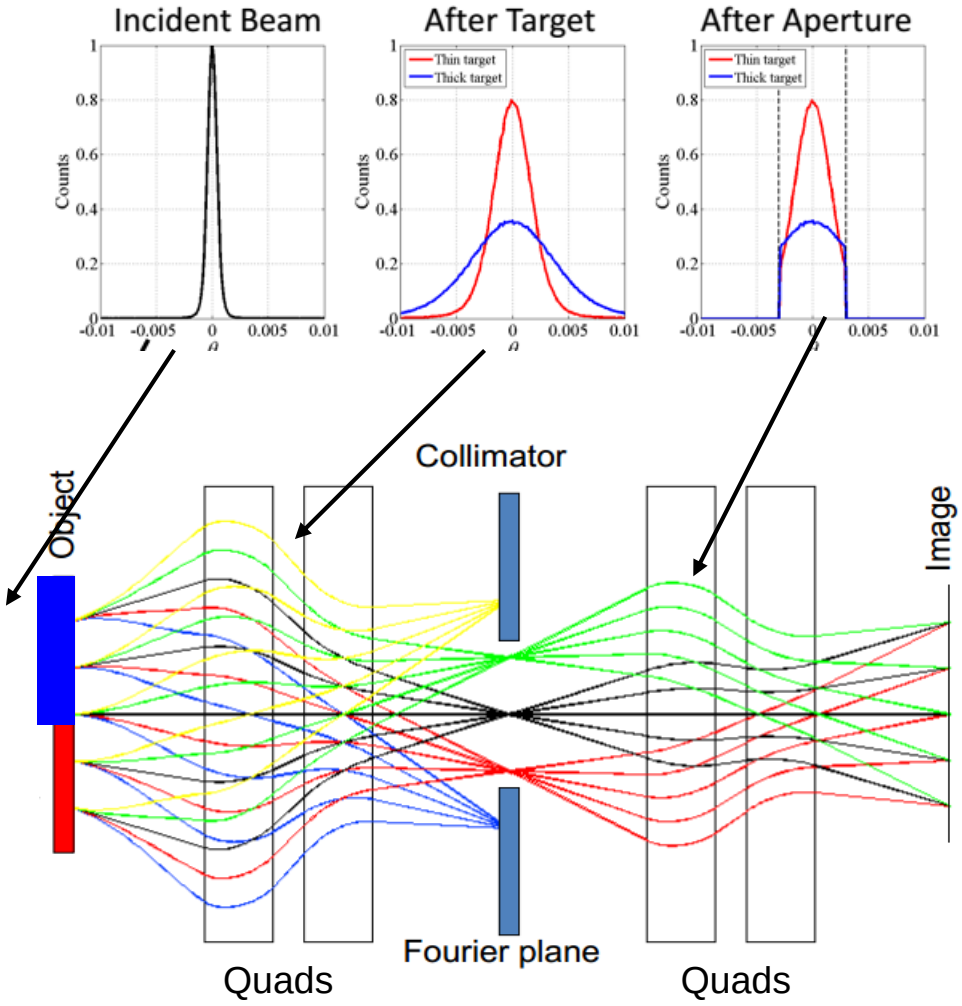
High Energy Density Physics (HEDP)

Inertial Confinement Fusion (ICF)

- Character: pressure exceeds 1Mbar;
- Hydrodynamic response : high expansion velocity in the range of km/s (um/ns);
- Diagnostic requirement: a) high time resolution (<ns);
  b) high space resolution (um);
  c) large dynamic range: um~mm, ns-ms;
  d) areal density (thickness) resolution.

Principle of electron imaging

- Imaging condition : **point-to-point**



First order transfer matrix

$$\begin{pmatrix} x_i \\ x_i' \end{pmatrix} = \begin{pmatrix} R_{11} & 0 \\ R_{21} & R_{22} \end{pmatrix} \begin{pmatrix} x_o \\ x_o' \end{pmatrix}$$

Second order transfer matrix

$$x_i = R_{11}x_o + T_{116}x_o\delta + T_{126}x_i'\delta$$

Matching: $$x'_{object} = -\frac{T_{116}}{T_{126}} x_{object}$$

Chromatic blur resolution:

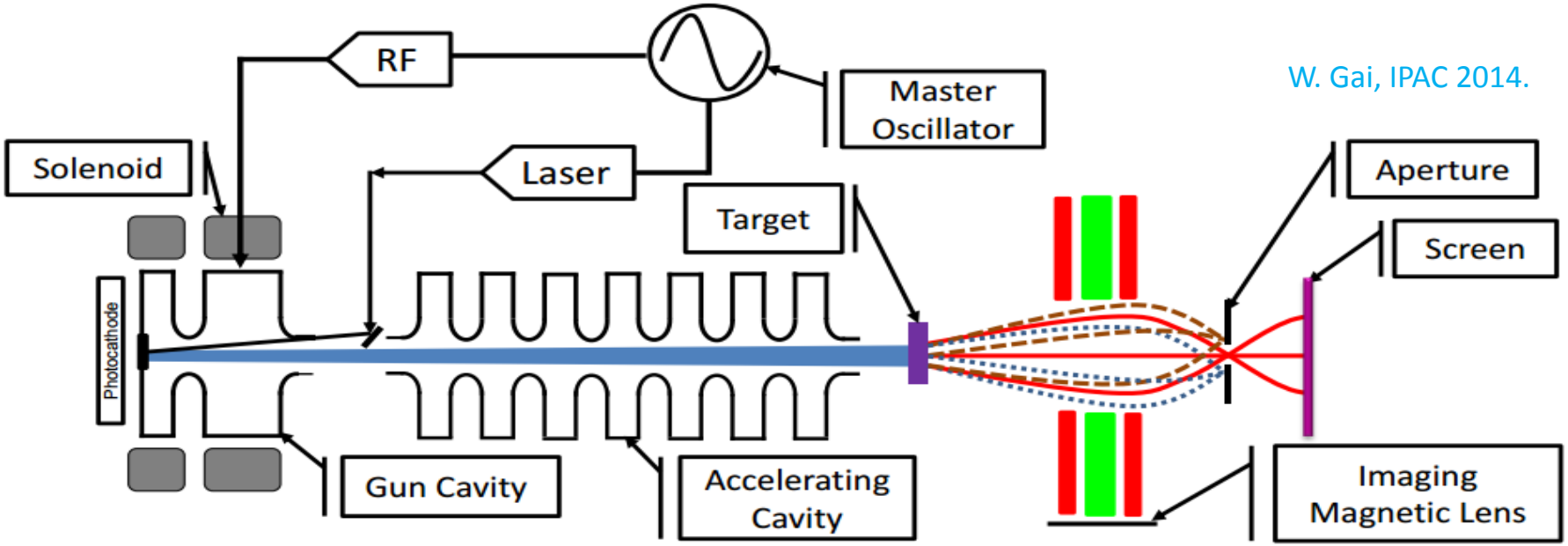
$$\Delta x = \frac{T_{126}\varepsilon\delta}{M}$$

ε: *Aperture collecting angle*

W. Gai, IPAC 2014.

Imaging system

S-band photo-injector based imaging system



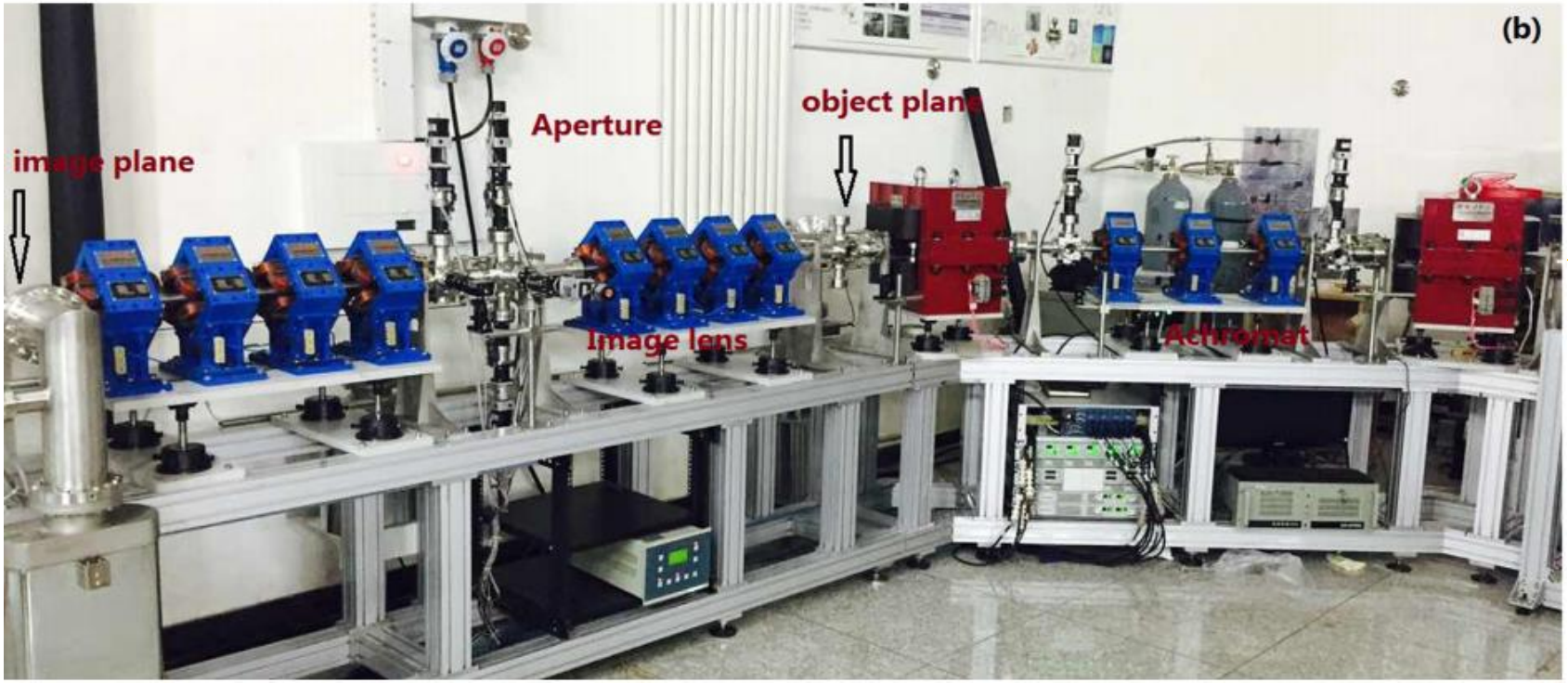
W. Gai, IPAC 2014.

Take Tsinghua Thomson scattering X-ray source for example

- Bunch charge: pC-nC; Emittance: <1um@500pC; beam energy: ~50MeV; Rms energy spread: 0.1% , Bunch length: 10ps without compression.
- Suitable for high spatial resolution studies;
- 3-D imaging with pump-probe technique: ps time resolution can be achieved.

Imaging experiment

- High energy electron radiography system

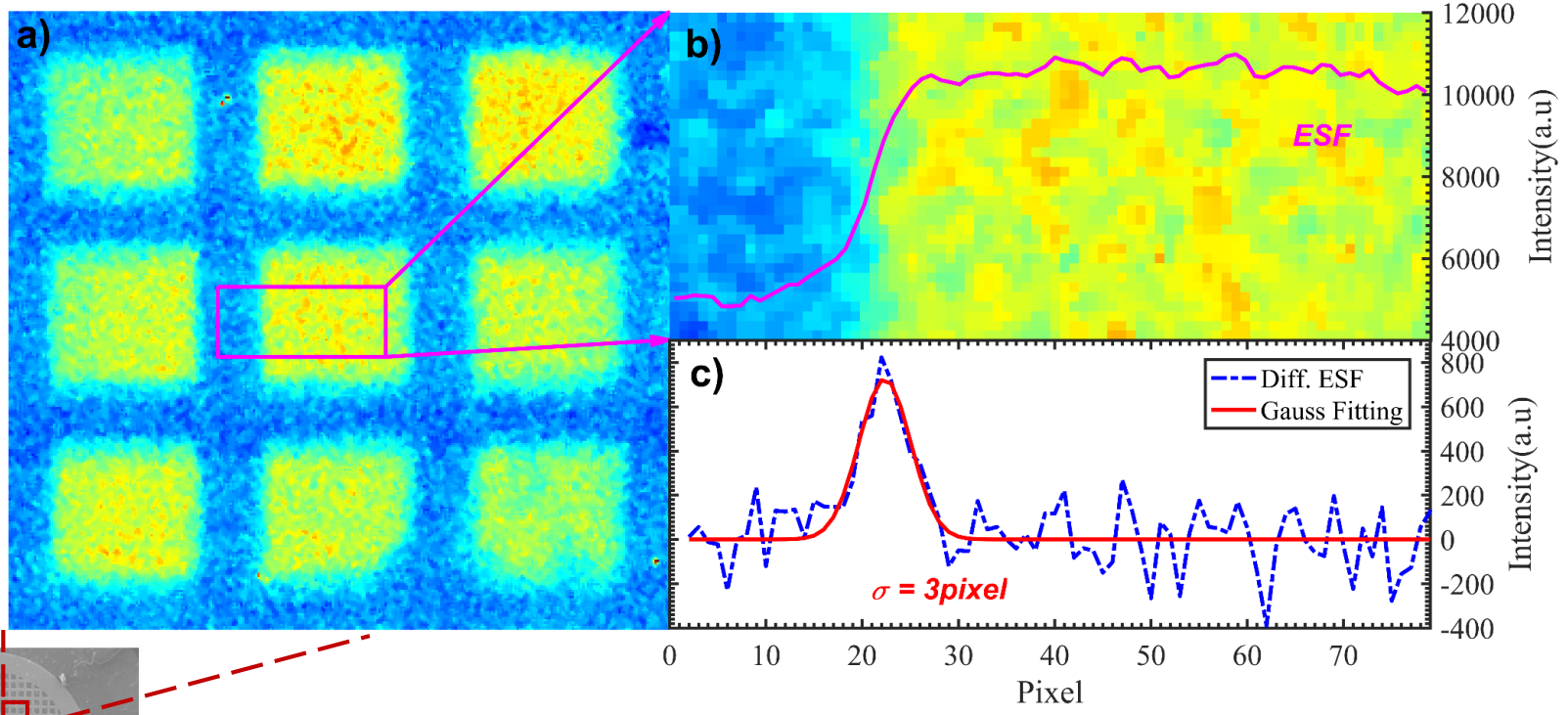


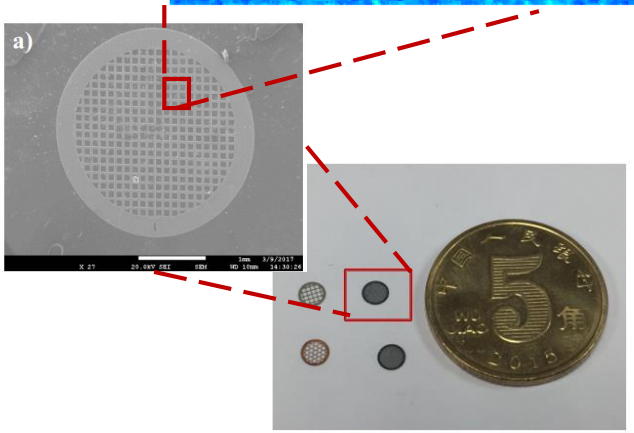
- Based on TTX beamline
- In collaboration with Institute of Modern Physics

Work supported by NSFC Grants No. 11435015. (清华大学，中科院近代物理研究所)

Imaging experiment results(1)

- High spatial resolution studies





TEM Grid :

200 lines/inch Mo $\phi = 3.05\text{mm}$

Pitch Width : 125 um

Hole Width : 90um

Bar Width : 35um

- Spatial resolution: $\Delta x_o \sim 4\mu m$
- Single-shot

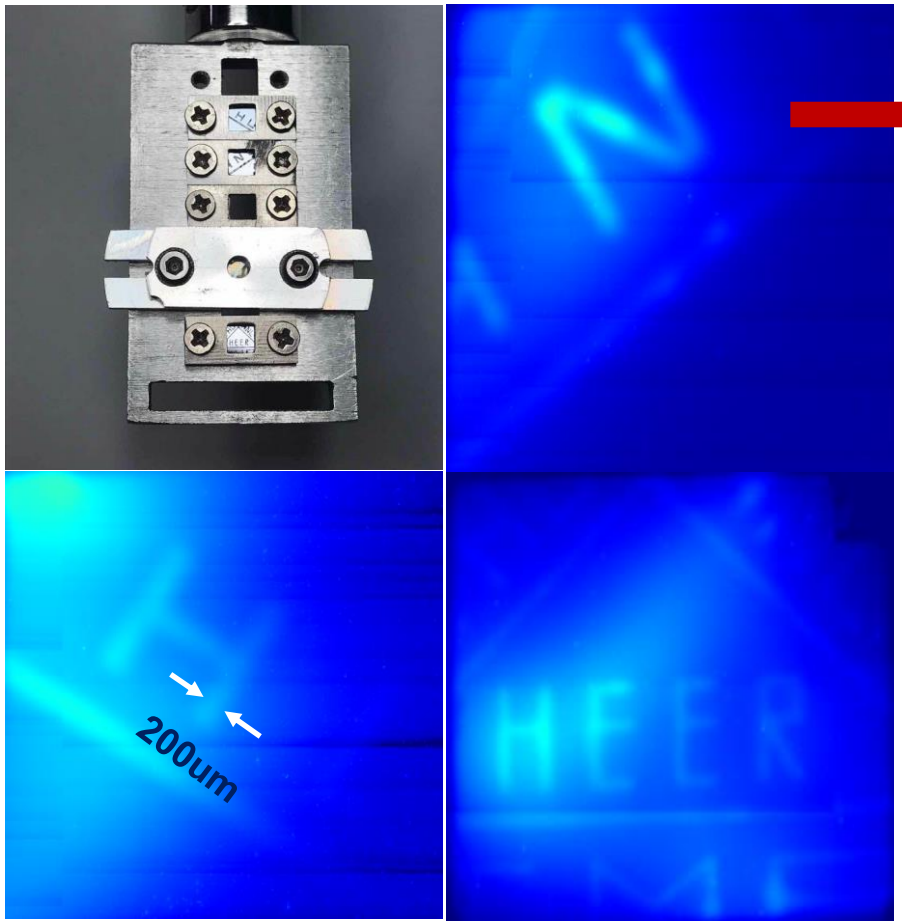
arXiv:1705.09810, submitted to P.R.L

Imaging experiment results(2)

- thickness resolution studies

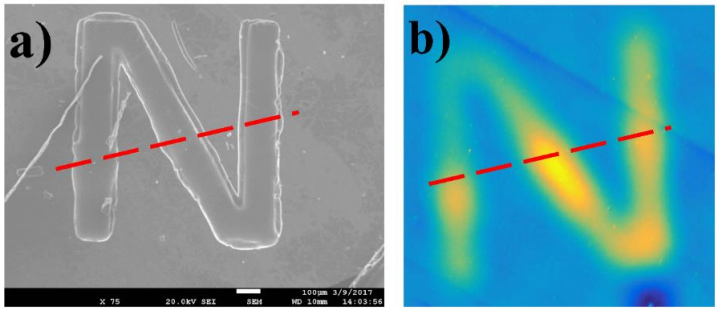
Thick Silicon Target

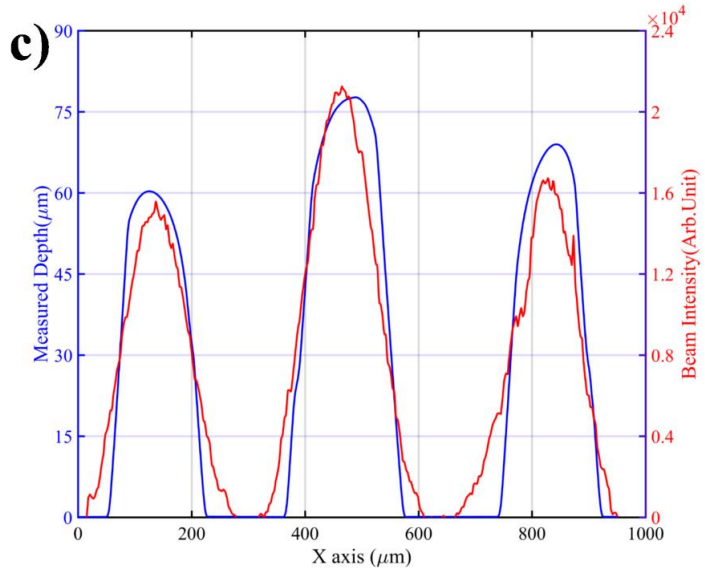
ANL logo



THU logo

HEER logo





~10um resolution of 300um thick target

arXiv:1705.09810, submitted to P.R.L

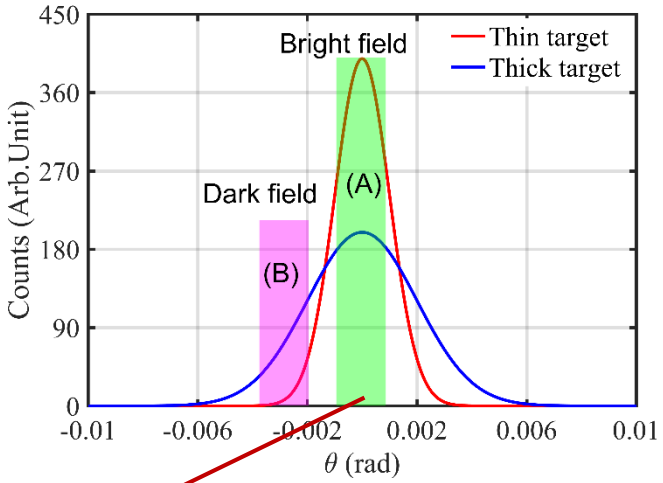
Imaging experiment results(3)

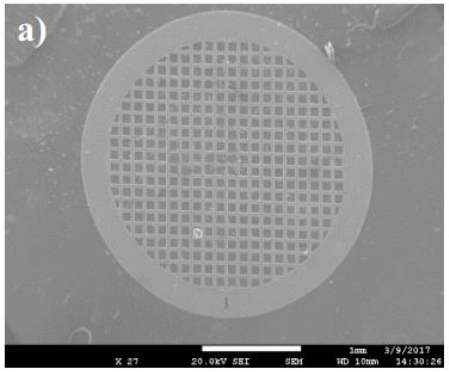
Dark field imaging

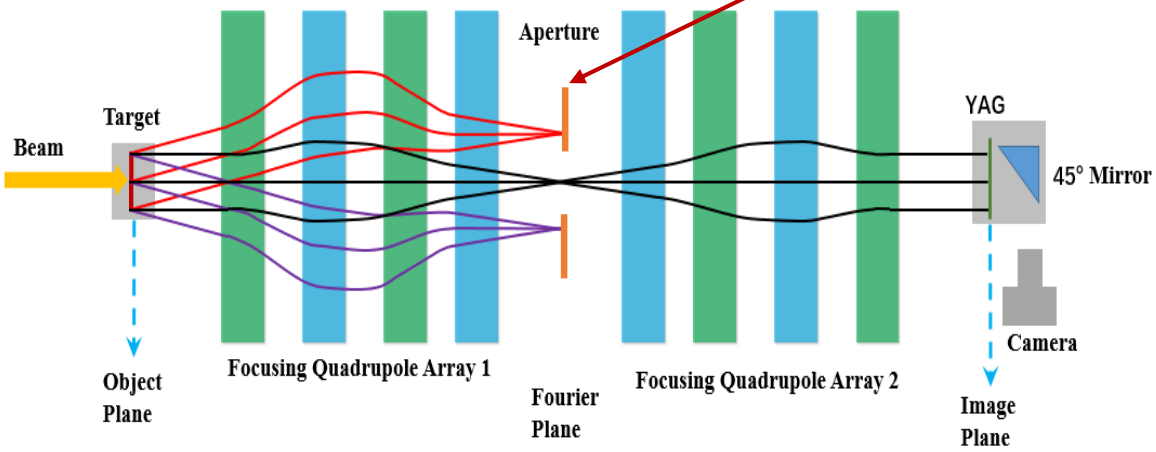
Scattering angle distribution:

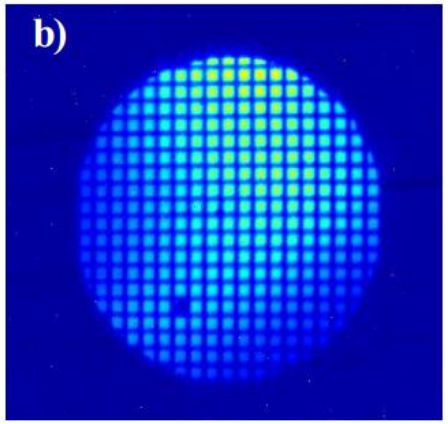
$$\frac{N(t,\phi)}{N_0} = \frac{1}{\phi_0(t)\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{\phi}{\phi_0(t)}\right)^2}$$

$$\phi_0(t) = \frac{13.6MeV}{\beta cp}\sqrt{t}\left(1 + 0.038ln(t)\right)$$









Bright field or “on-axis” imaging

arXiv:1705.09810, submitted to P.R.L

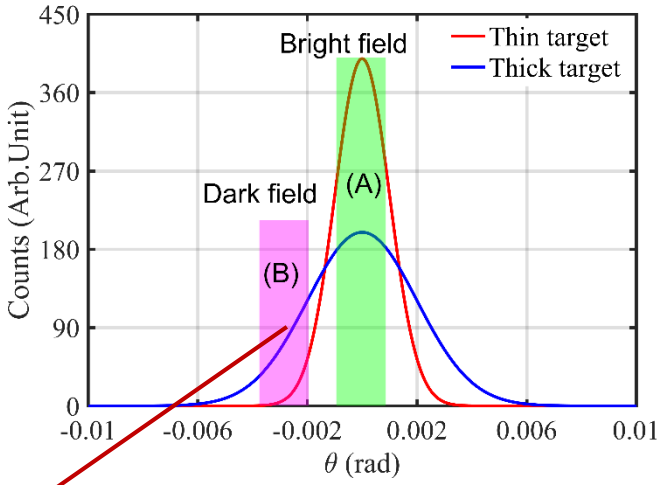
Imaging experiment results(4)

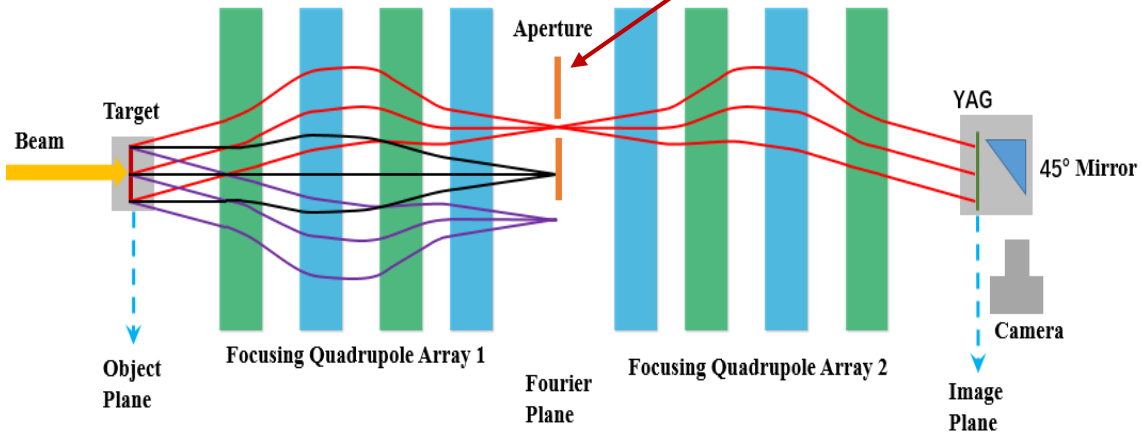
Dark field imaging

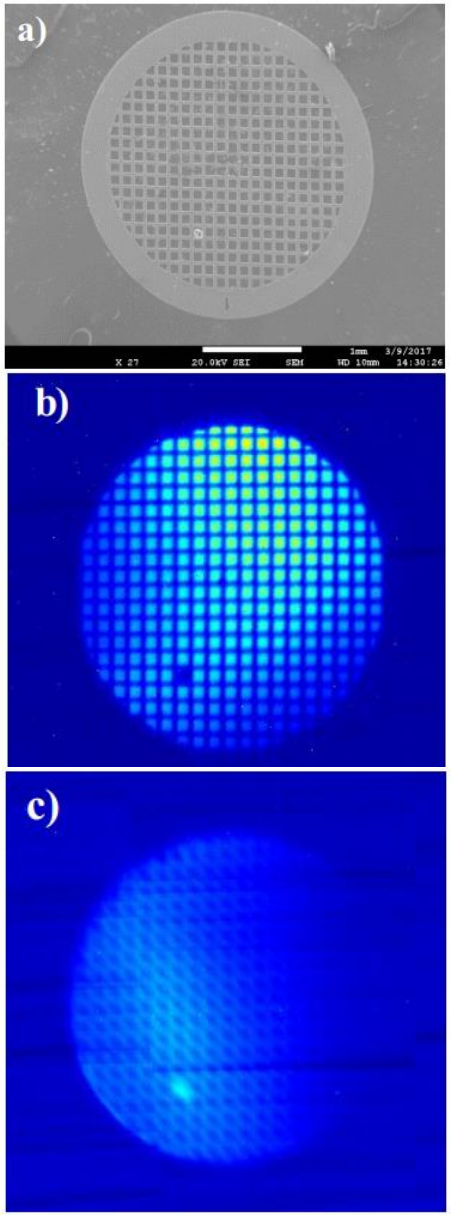
Scattering angle distribution:

$$\frac{N(t,\phi)}{N_0} = \frac{1}{\phi_0(t)\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{\phi}{\phi_0(t)}\right)^2}$$

$$\phi_0(t) = \frac{13.6MeV}{\beta cp}\sqrt{t}\left(1 + 0.038ln(t)\right)$$







Dark field or “off-axis” imaging

arXiv:1705.09810, submitted to P.R.L

Summary and outlook

Urgent need

Remarkable results of ultrafast dynamics have been achieved based on MeV UED facilities, and there is a strong need for high quality platform to explore the frontiers of the ultrafast sciences.

Solid foundations

We have over ten years of successful experiences in MeV UED, and Ultrafast transmission Electron Microscope is in proceeding. Rich accumulations in RF structures, beam generating and diagnostics and experimental technologies have laid solid foundations for the future advanced experiments based on high energy electron diffraction and electron imaging.

Users are warmly welcome

Everyone is welcome to our lab. We hope we can offer help for studies of ultrafast science, complex materials and so on.

Thank you