Symposium on Accelerator Physics

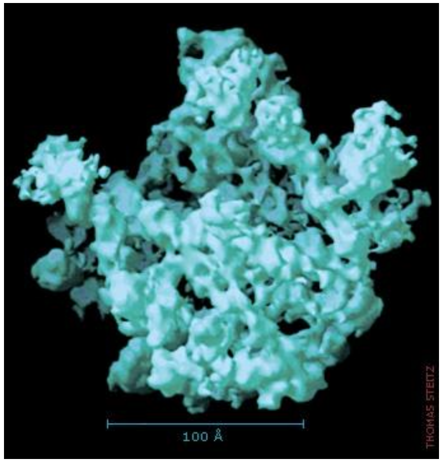
Accelerator based ultrafast electron diffraction and microscopy

Dao Xiang, for MeV UED/UEM group
Shanghai Jiao Tong University

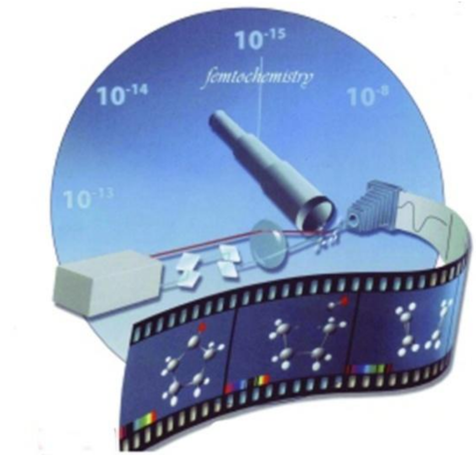
2014. 08. 13

上海交通大學 SHANGHAI JIAO TONG UNIVERSITY
北京大學 PEKING UNIVERSITY
清華大學 Tsinghua University

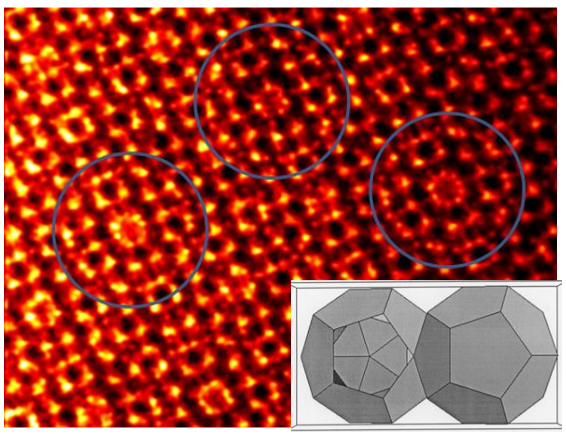
Capture the ultrafast OR probe the ultrasmall



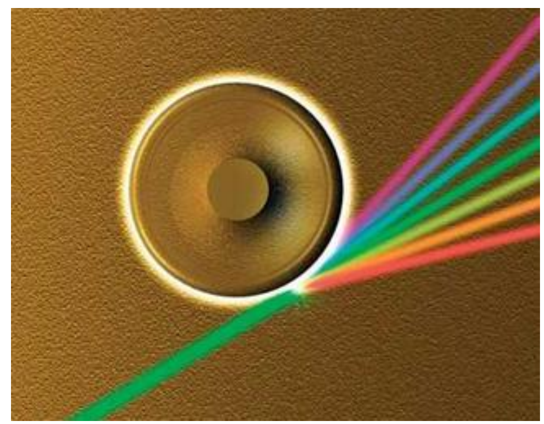
Structure of Ribosome, 2009
Nobel Prize in Chemistry



Femtosecond spectroscopy, 1999
Nobel Prize in Chemistry



Quasicrystal, 2011 Nobel Prize in Chemistry



Frequency comb, 2005 Nobel Prize in Physics

Spatial resolution

Temporal resolution

Capture the ultrafast **AND** probe the ultrasmall

"Making the Leap from Observation Science to Control Science"

This grand challenge requires new instruments with both high temporal and spatial resolution

World-wide interest in ultrafast-ultrasmall

NSF

Office of Basic Energy Sciences — Serving the Present, Shaping the Future

NSFC
National Natural Science Foundation of China

Department of Energy — United States of America

Japan Society for the Promotion of Science — Founded 1932

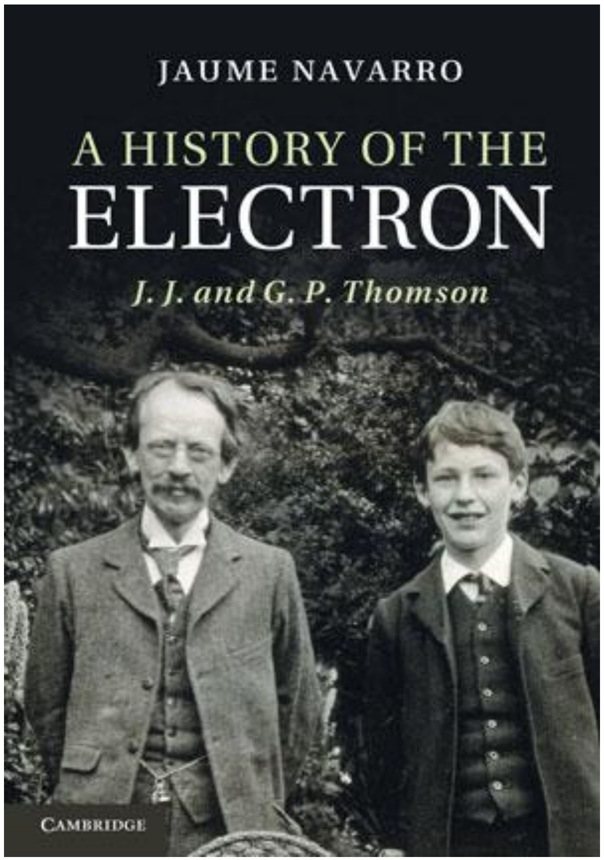
National Institutes of Health

DARPA

Electron's wave-particle duality

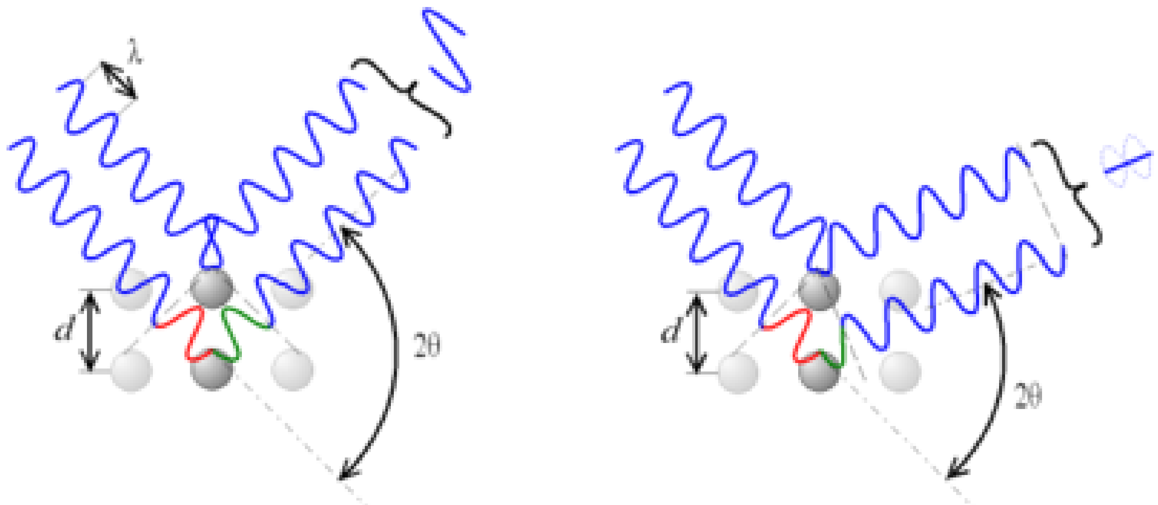
J.J. Thomson: 1906 Nobel prize; electrons are particles

G.P. Thomson: 1937 Nobel prize; electrons are NOT particles



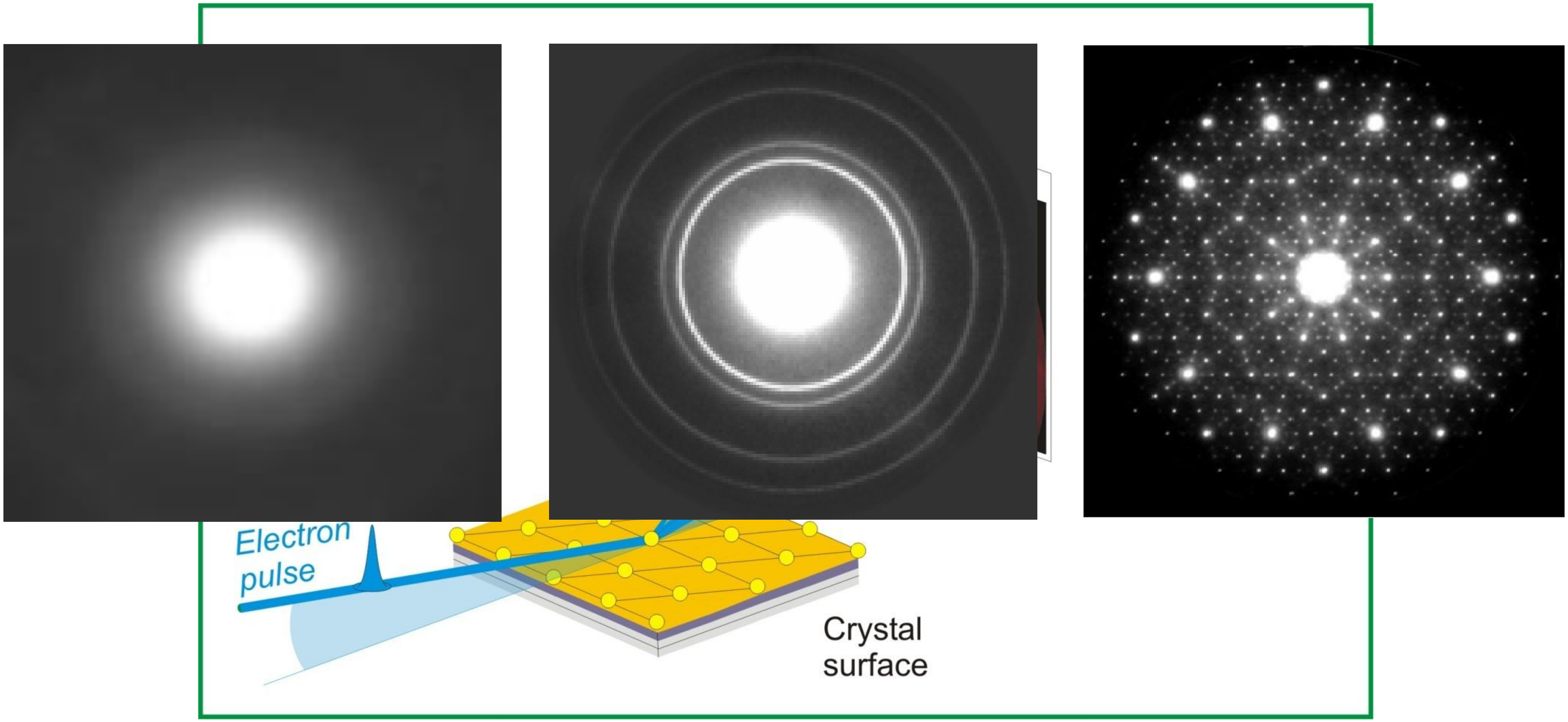
$$\lambda = h / p$$

$$\sin(\theta) = \frac{\lambda}{2d}$$



Ultrafast electron diffraction

Structure information encoded in the diffraction pattern

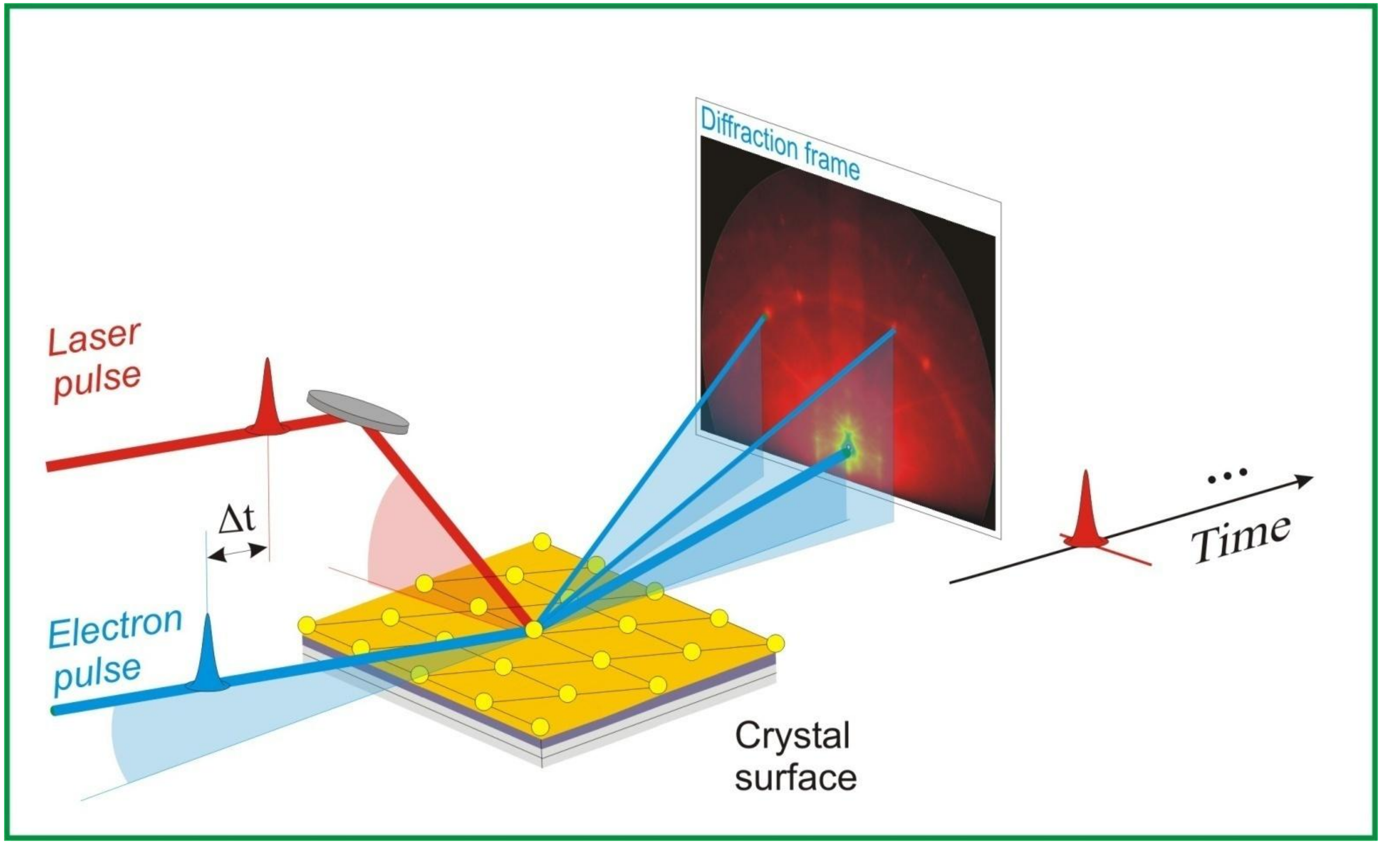


Pump-probe technique

Ultrafast electron diffraction

Structure information encoded in the diffraction pattern

Dynamics initiated by an ultrafast laser



Pump-probe technique

Ultrafast electron diffraction

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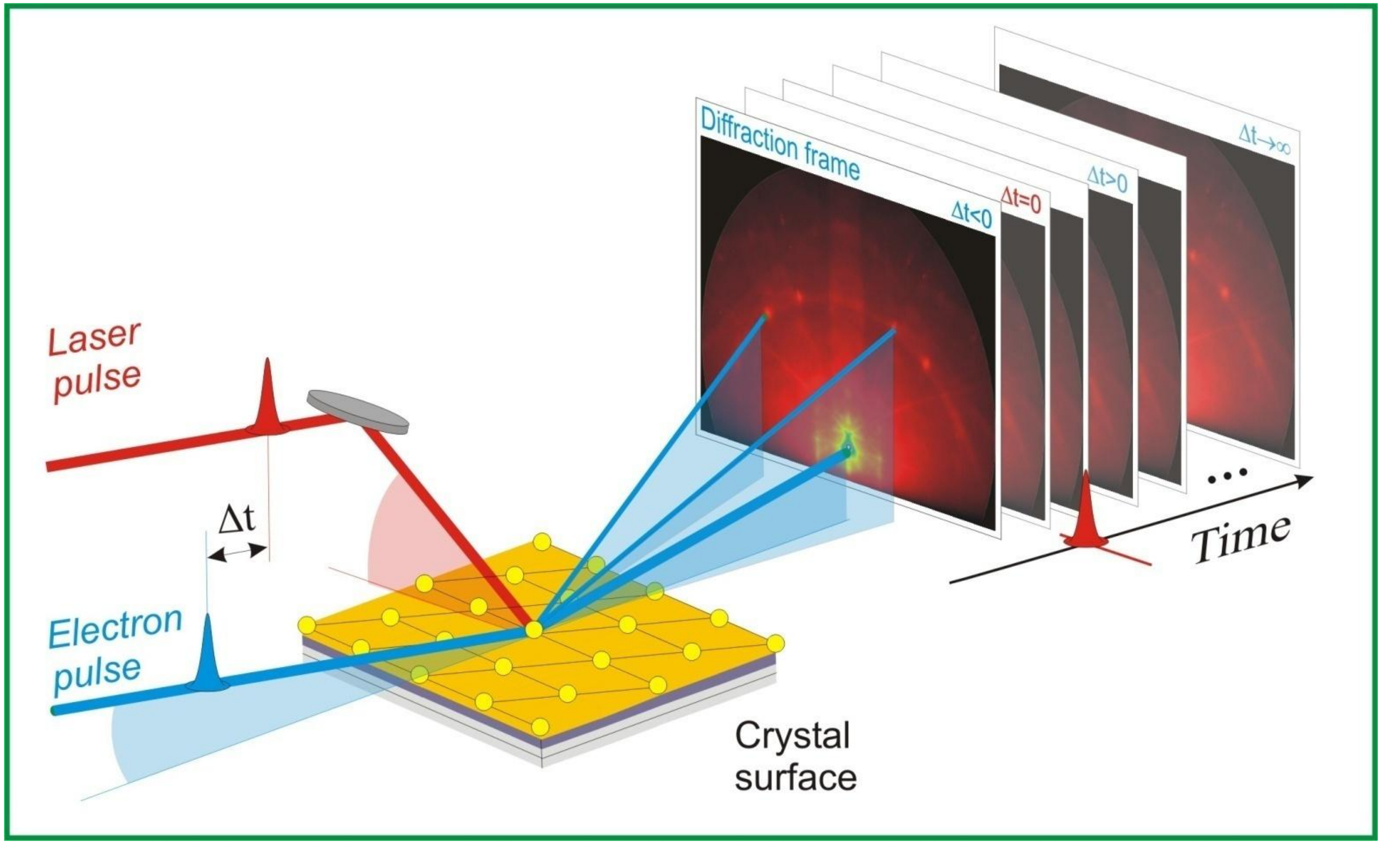
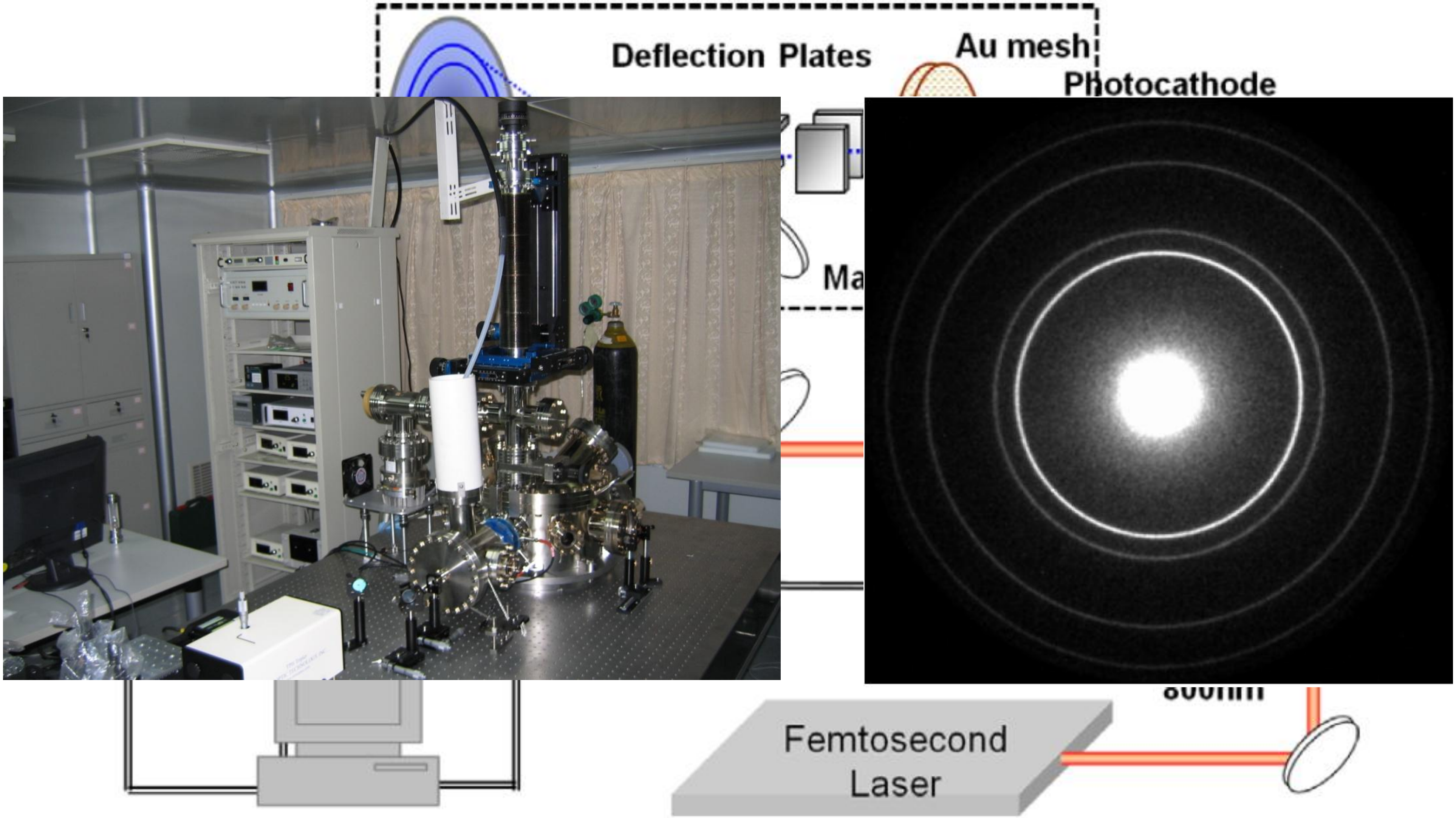
Dynamics initiated by an ultrafast laser



Pump-probe technique

Ultrafast electron diffraction facility



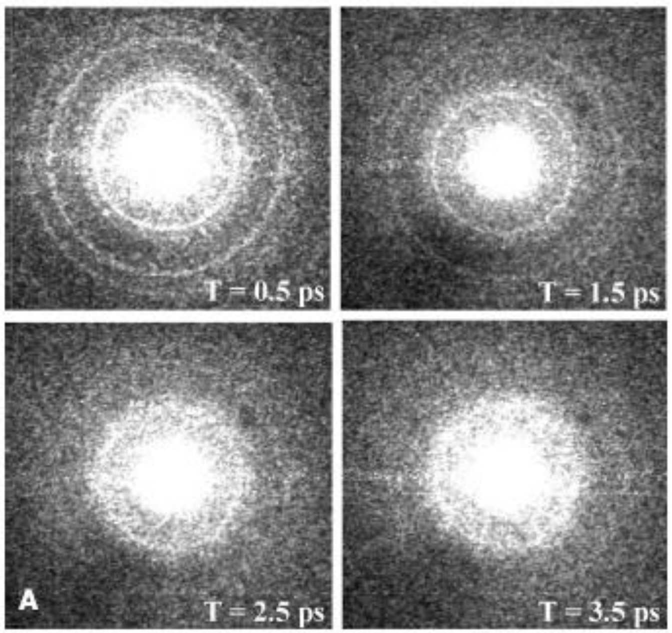
60 keV UED @ Shanghai Jiao Tong University

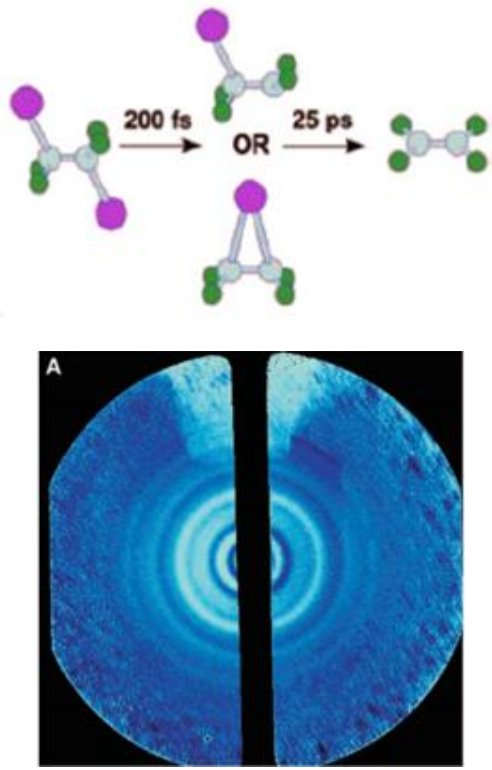
Applications of ultrafast electron diffraction

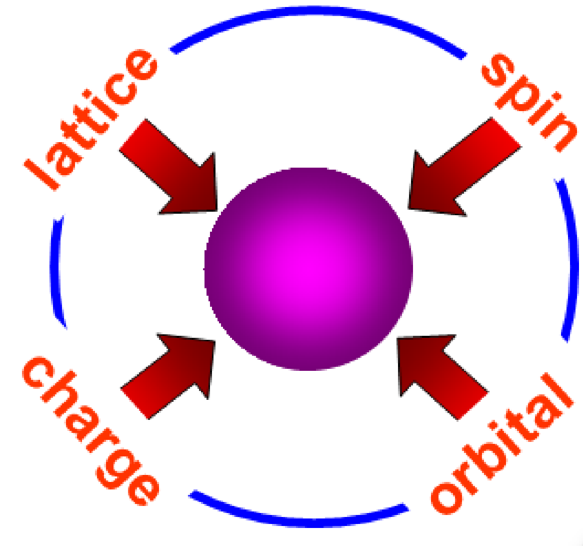
Atomic view of phase transitions

Making molecular movie

Understanding high Tc superconductor







Melting of Aluminium

Science (2003)

Photodissociation

Science (2001)

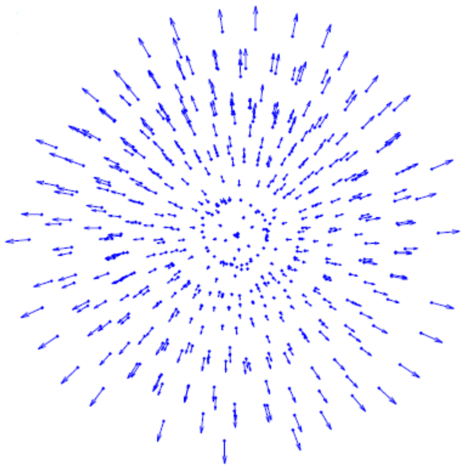
Disentangle freedom

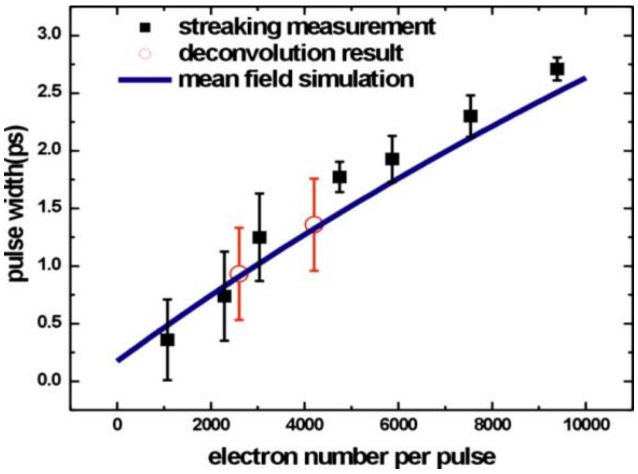
PNAS (2010)

Limitations of keV UED

Single-shot capability or high temporal resolution

Space charge force increases e-beam pulse width





Limitations of keV UED

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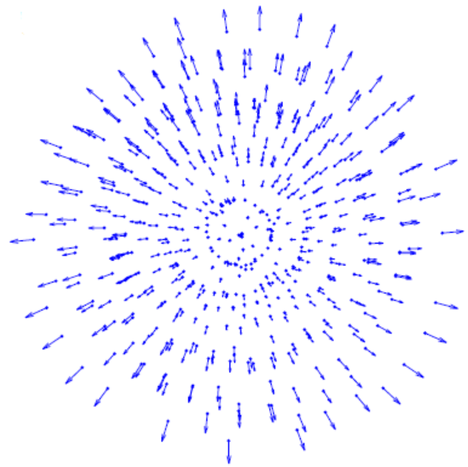
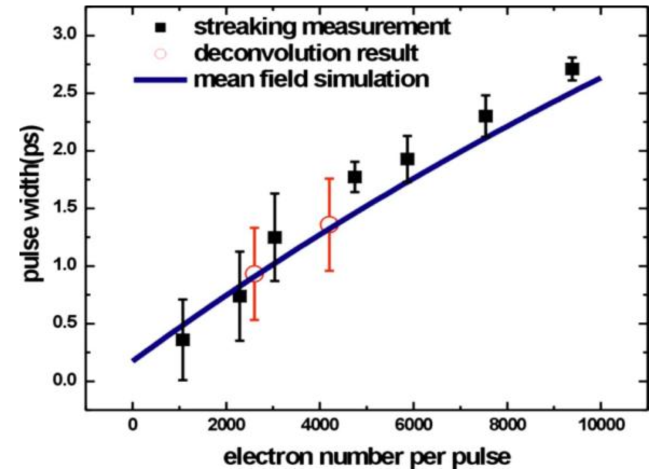
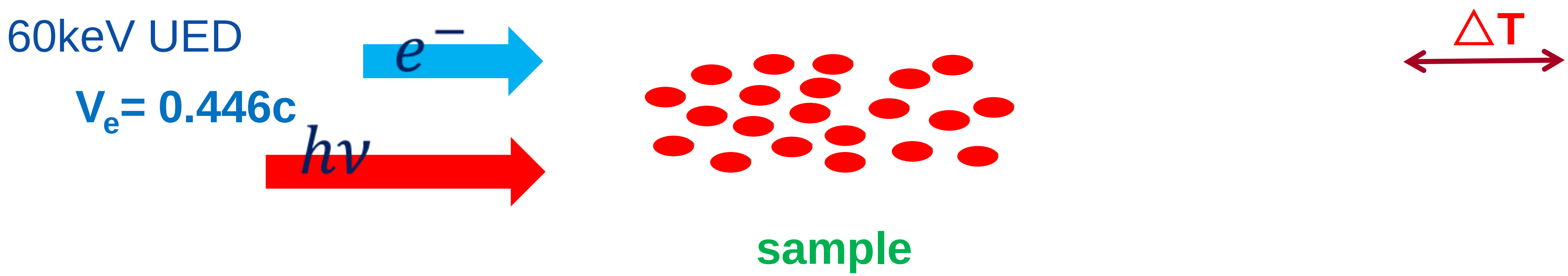






Velocity mismatch limits the temporal resolution of keV UED (in gas sample) to >1 ps

UED: poor man's FEL

Femtosecond Chemistry

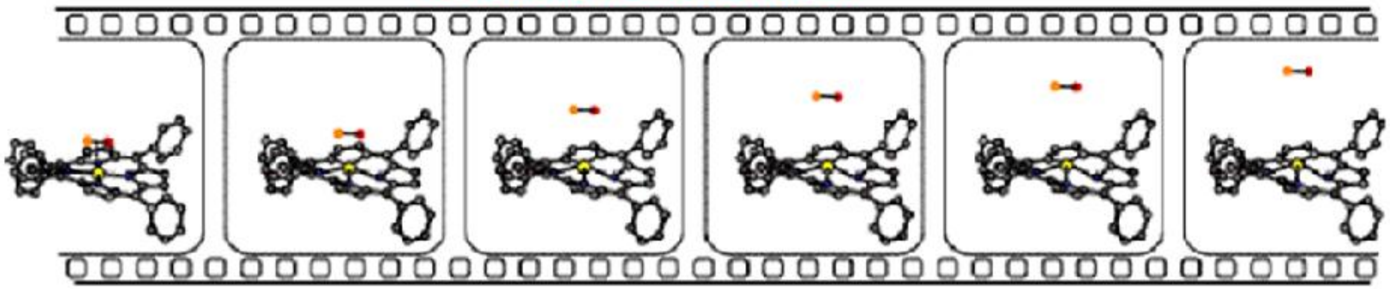
LCLS

- Forefront area in chemistry

  So far the domain of fast laser spectroscopy with a few fs resolution
- Chemical dynamics happens in fs - ps range

  Lasers probe charge dynamics
- Electron Diffraction limited to ps range

Chemistry is about Motion



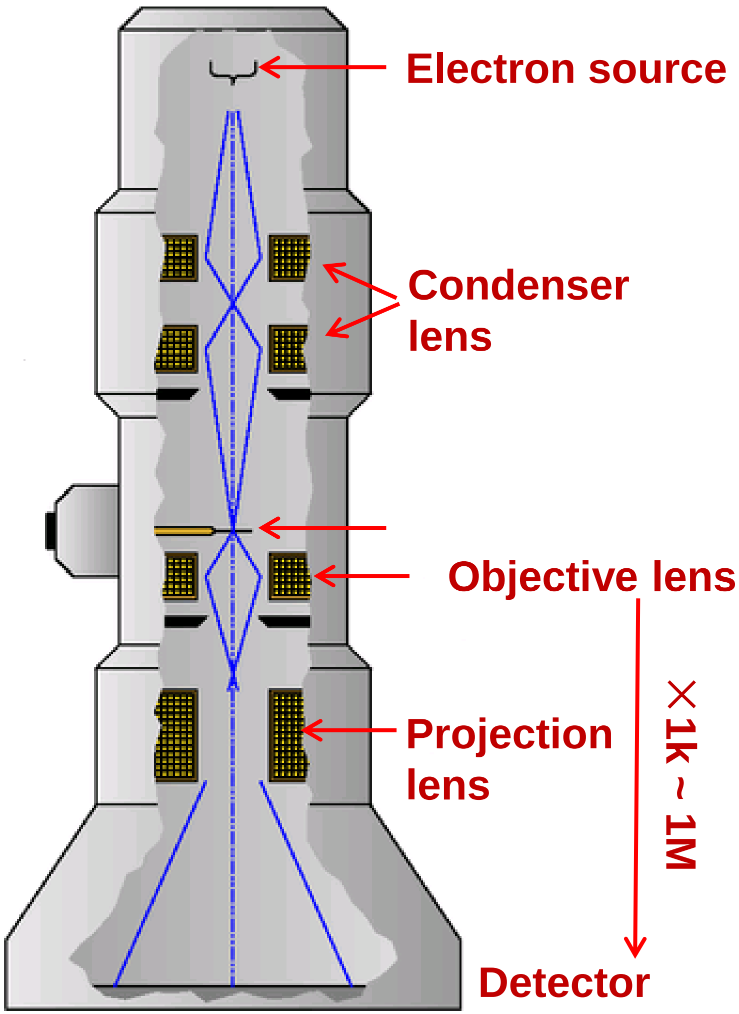
$H_2O \rightarrow OH + H$ about 10 fs — time depends on mass → $CH_2I_2 \rightarrow CH_2I + I$ about 100 fs

FEL: Gun → Accelerator → Undulator → User's stations

UED/UEM: Gun → User's stations

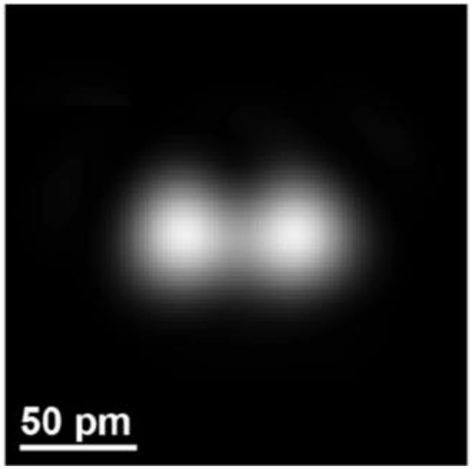
Ultrafast electron microscope

Transmission electron microscope



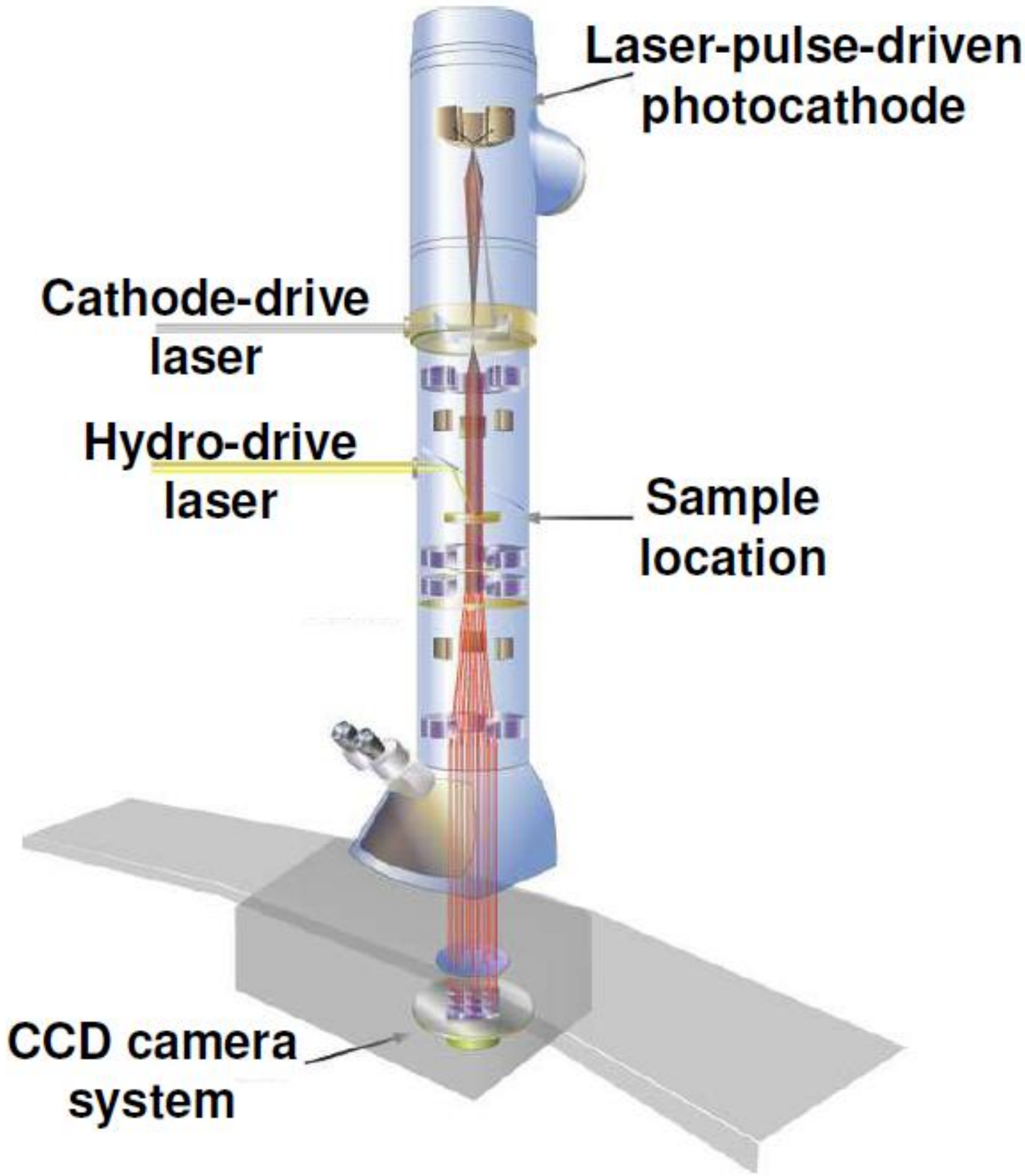
Schematic of a transmission electron microscope

- ✓ Gun: thermionic or field emission
- ✓ Acceleration with DC field
- ✓ Voltage: <200 kV (routine); 200 ~ 500 kV (medium energy); 500 kV ~ 3 MV (high voltage)
- ✓ Spatial resolution: down to 50 pm



5^{th} order aberration corrected TEM (2009)

Ultrafast electron microscope



LLNL's Dynamic TEM

- **Laser triggered photocathode DC gun**
- **~ 10^8 electrons per pulse (single shot)**
- **Temporal resolution: ~10 ns**
- **Spatial resolution: ~10 nm**
- **Applies to irreversible process**
- **Resolution limited by space charge**

How to improve UEM temporal resolution?

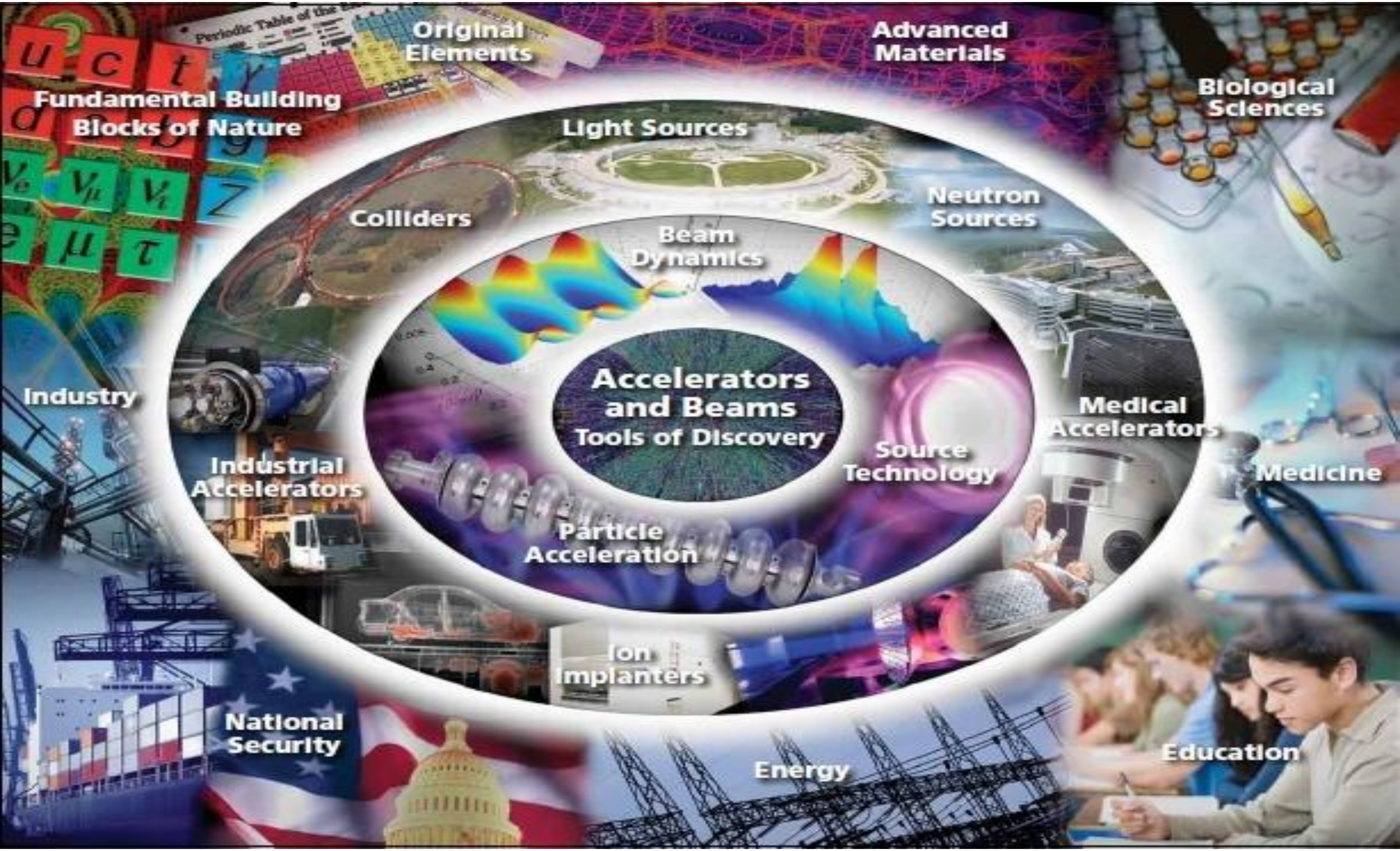
Increasing beam energy causes more problems than it solves

- **Size**
- **Cost**
- **Stability**
- **Magnets**
- **Radiation**
- **…….**

1 MV TEM @ Beijing costs 0.05% of the GDP at 1971

3 MV TEM @ Osaka U

Accelerator as the ultimate solution



Accelerator based UED/UEM - Why

Higher beam energy mitigates space charge effect

Space charge force is proportional to $1/\gamma^2$

Higher beam energy mitigates velocity mismatch effect (v≈c)

Higher accelerating gradient gives higher beam brightness

$$B_e = \frac{N_e}{(2\pi)^3 \varepsilon_{nx} \varepsilon_{ny} \varepsilon_{ns}}$$

- **Produce a beam with smaller thermal emittance**
- **Reduces emittance growth**

Higher gradient reduces the size of a MeV TEM

- **World's highest voltage TEM with 3 MeV beam stands 13 m high and weighs 140 tons**
- **S-band photocathode rf gun: ~15 cm**

Feasibility of MeV UED

First systematic study of MeV UED

Journal of the Korean Physical Society, Vol. 48, No. 3, March 2006, pp. 390∼396

Potential of Femtosecond Electron Diffraction Using Near-Relativistic Electrons from a Photocathode RF Electron Gun

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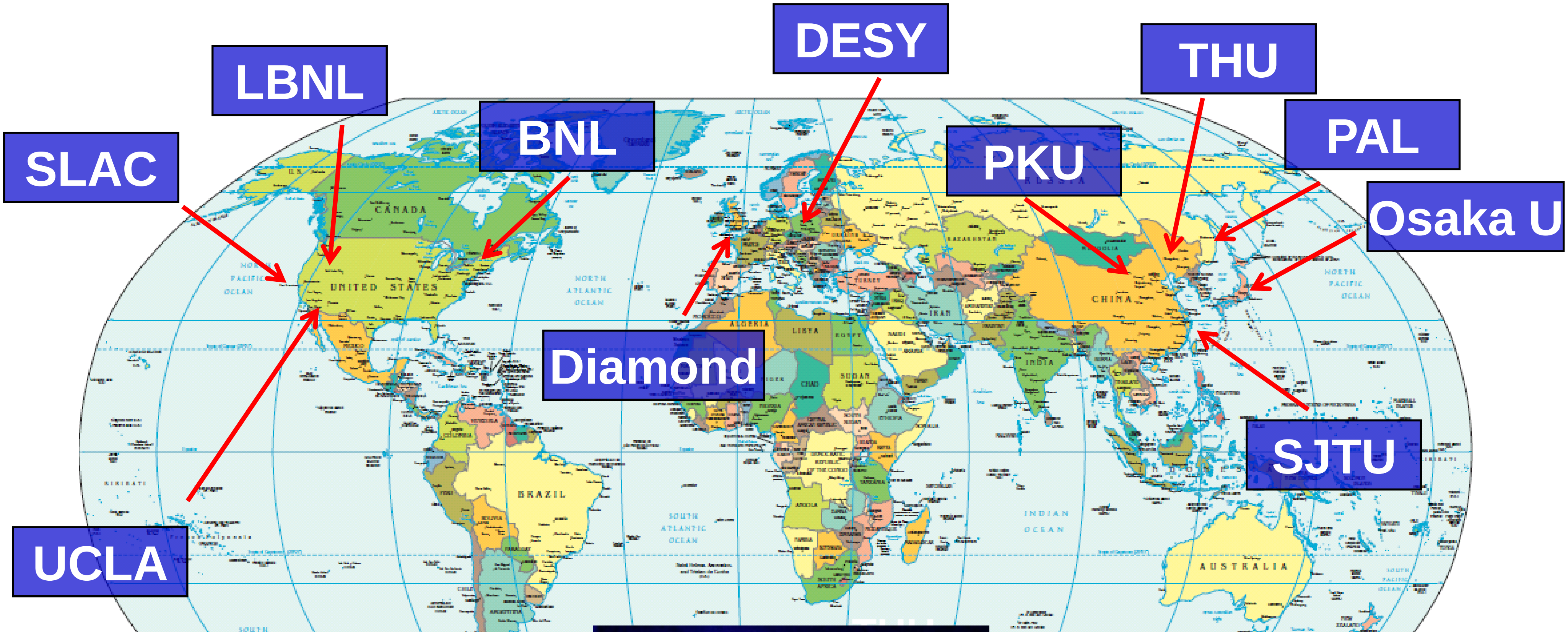
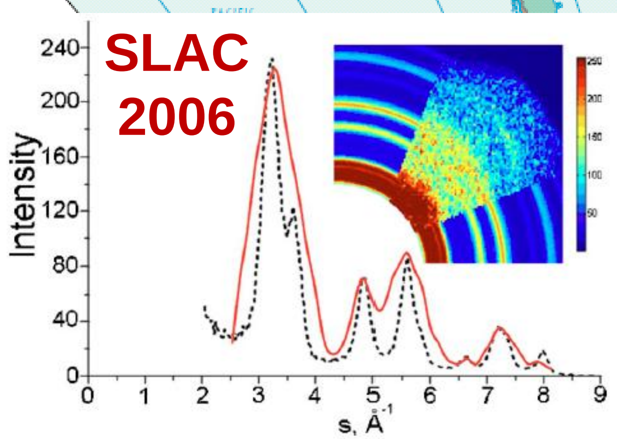
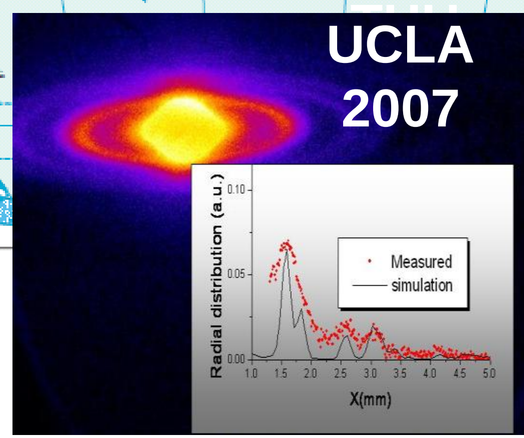
(Received 20 December 2005)

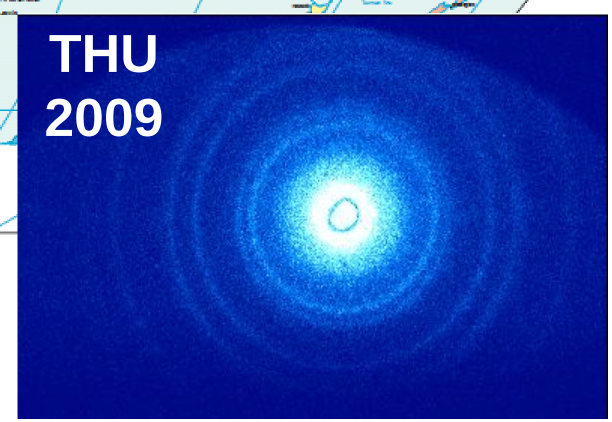
Wang, BNL LDRD, 2000; Wang et al., PAC03; Xiang et al., PAC05; Wang et al., 2006

MeV UED (world-wide interest)









Accelerator based UEM – feasibility

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journal homepage: www.elsevier.com/locate/nima

Accelerator-based single-shot ultrafast transmission electron microscope with picosecond temporal resolution and nanometer spatial resolution

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ABSTRACT

We present feasibility study of an accelerator-based ultrafast transmission electron microscope (u-TEM) capable of producing a full field image in a single-shot with simultaneous picosecond temporal resolution and nanometer spatial resolution. We study key physics related to performance of u-TEMs and discuss major challenges as well as possible solutions for practical realization of u-TEMs. The feasibility of u-TEMs is confirmed through simulations using realistic electron beam parameters. We anticipate that u-TEMs with a product of temporal and spatial resolution beyond 10^{-19} ms will open up new opportunities in probing matter at ultrafast temporal and ultrasmall spatial scales.

Accelerator based UEM – feasibility

PHYSICAL REVIEW APPLIED **2,** 024003 (2014)

Single-Shot MeV Transmission Electron Microscopy with Picosecond Temporal Resolution

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Department of Physics and Astronomy, UCLA, Los Angeles, California 90095, USA

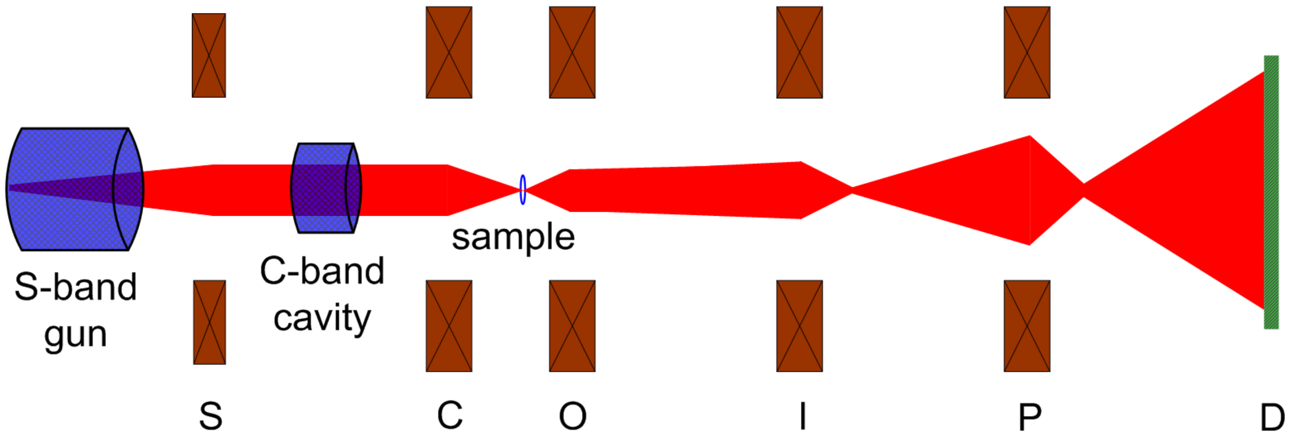
(Received 13 May 2014; published 5 August 2014)

Pushing the limits in temporal resolution for transmission electron microscopy (TEM) requires a revolutionary change in the electron source technology. In this paper, we study the possibility of employing a radio-frequency photoinjector as the electron source for a time-resolved TEM. By raising the beam energy to the relativistic regime, we minimize the space-charge effects which otherwise limit the spatiotemporal resolution of the instrument. Analysis and optimization of the system taking into account the achievable beam brightness, electron flux on the sample, chromatic and spherical aberration of the electron optic system, and space-charge effects in image formation are presented and supported by detailed numerical modeling. The results demonstrate the feasibility of 10-nm–10-ps spatiotemporal resolution single-shot MeV TEM.

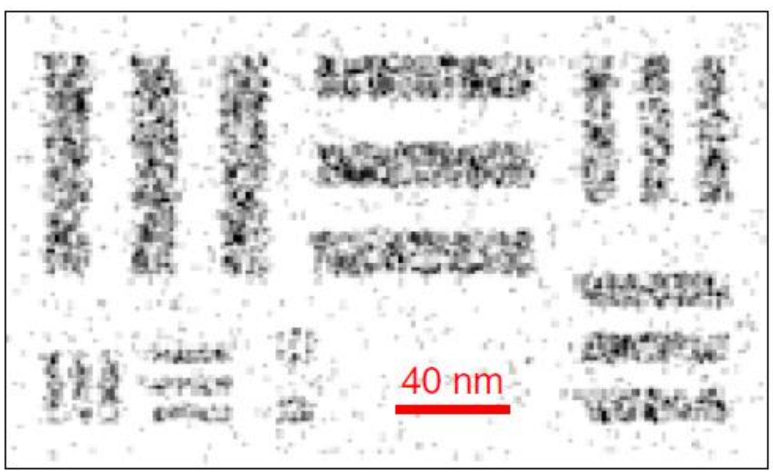
DOI: 10.1103/PhysRevApplied.2.024003

Accelerator based UEM – feasibility

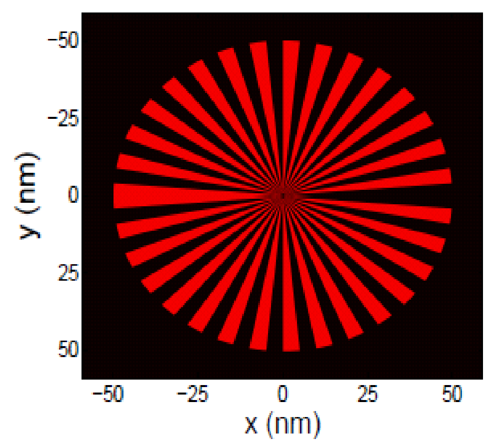
A representative design (10 ps & 10 nm)



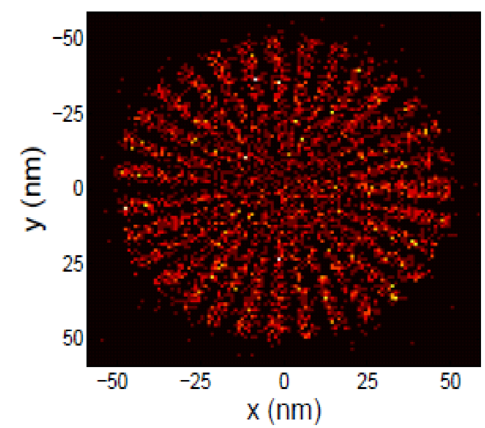
- **S: solenoid**
- **C: condenser lens**
- **O: objective lens**
- **I: intermediate lens**
- **P: projection lens**
- **D: detector**



$$\frac{50\,e}{(10\text{ nm})^2}$$



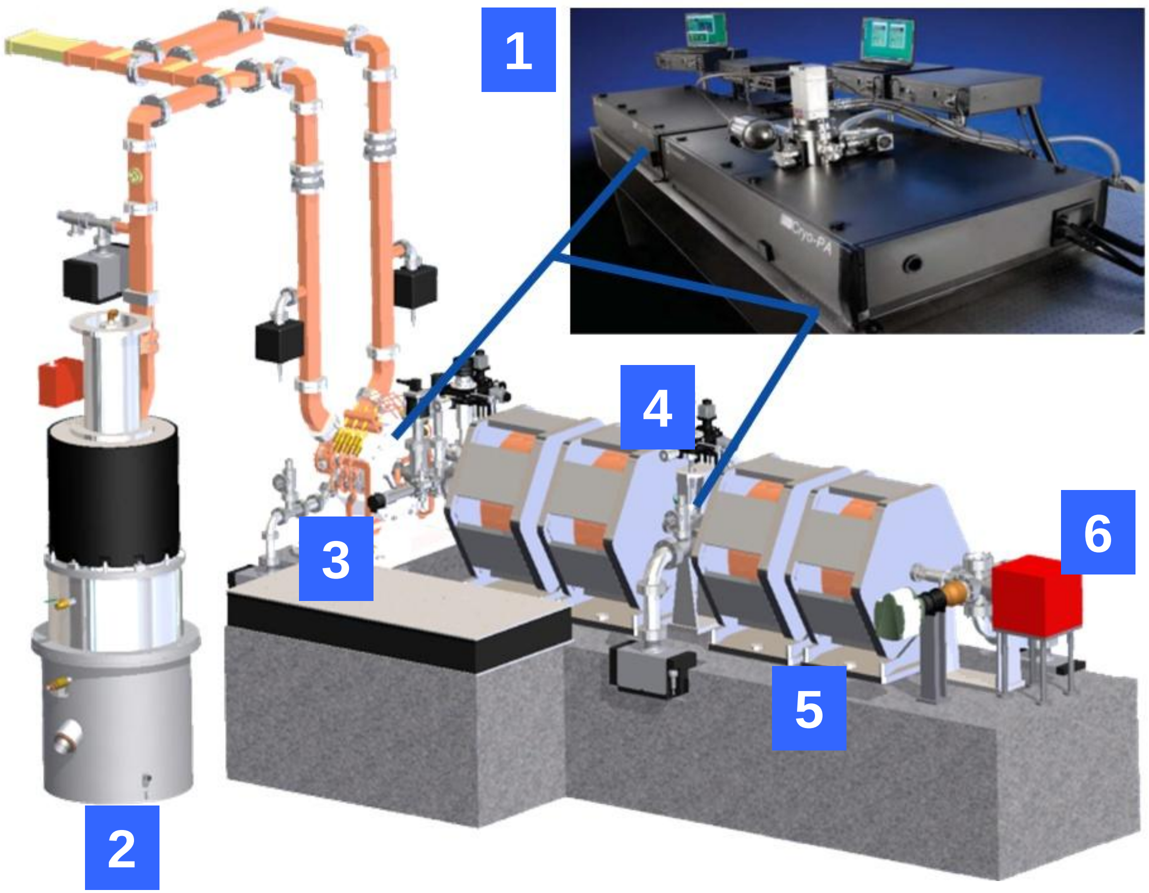
sample



image

Xiang et al., NIM A (2014); Li and Musumeci, PRA (2014)

兆伏特超快电子衍射与成像系统



1. 飞秒激光
2. 高重频高稳定度功率源
3. 高亮度电子束
4. 多功能样品室
5. 超导螺线管磁铁
6. 高灵敏电子探测

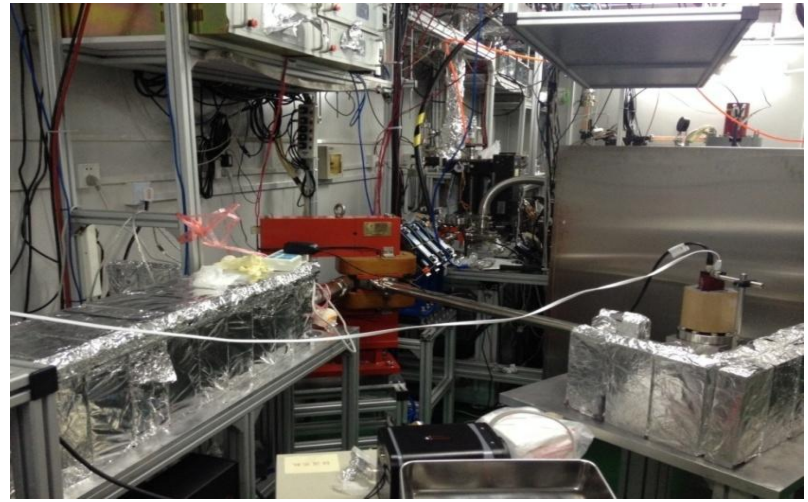
模式	衍射	透镜	重频
目前水平	~500 fs	10 ns 10 nm	~10
项目目标	50 fs	10 ps 10 nm	~1000

本系统预期达到的工作参数与相应世界最好水平相比，均有量级的提高，可满足原子尺度物质结构动力学研究的需求

超快电子衍射与显微中心

加速器物理@上海交通大学

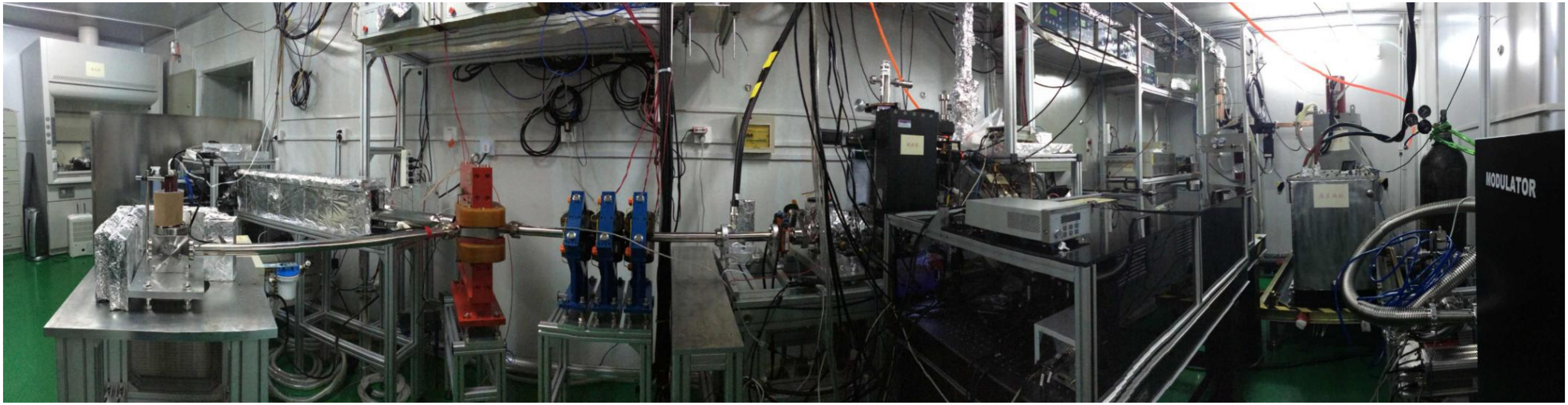
激光等离子体教育部重点实验室



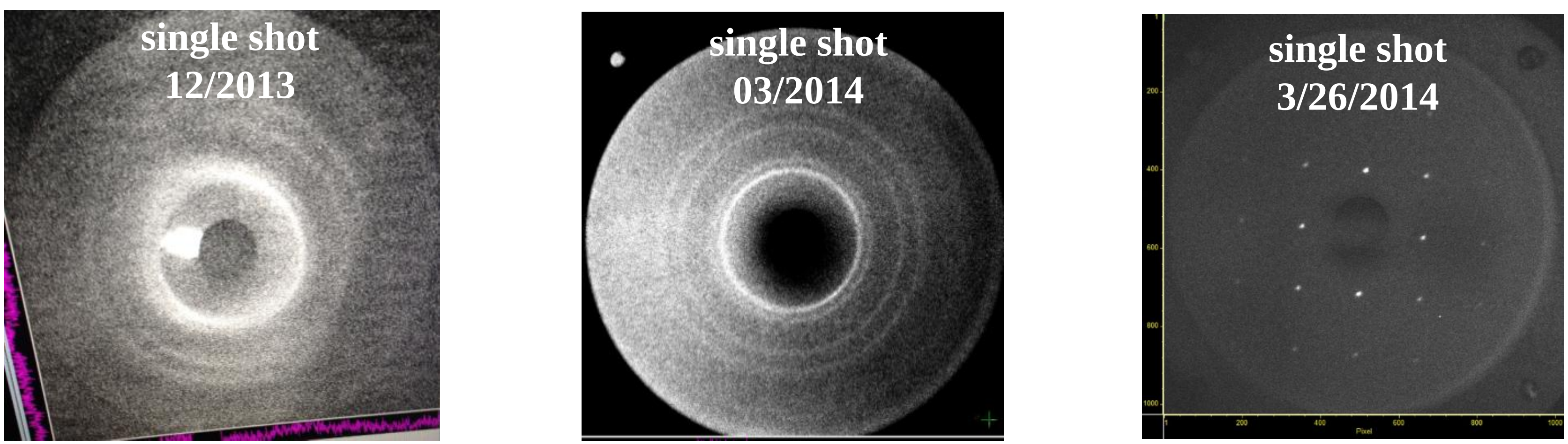
基于光阴极微波电子枪的加速器

200 TW 强激光系统及作用靶室

兆伏特超快电子衍射进展

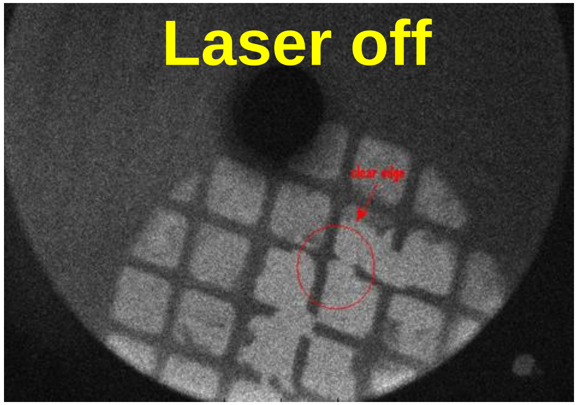


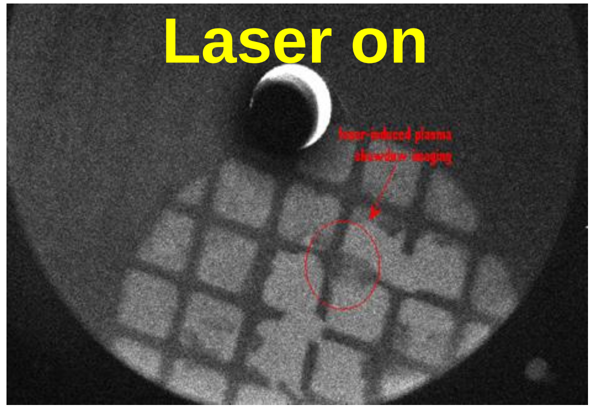
基于光阴极微波电子枪的原型机

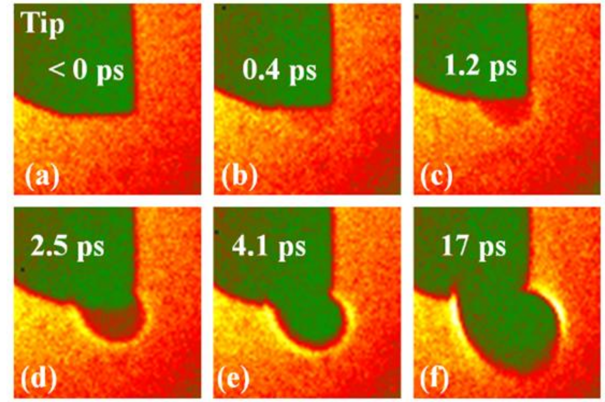


多晶铝和单晶金的衍射样斑 (*Fu et al., Rev. Sci. Instru. 2014*)

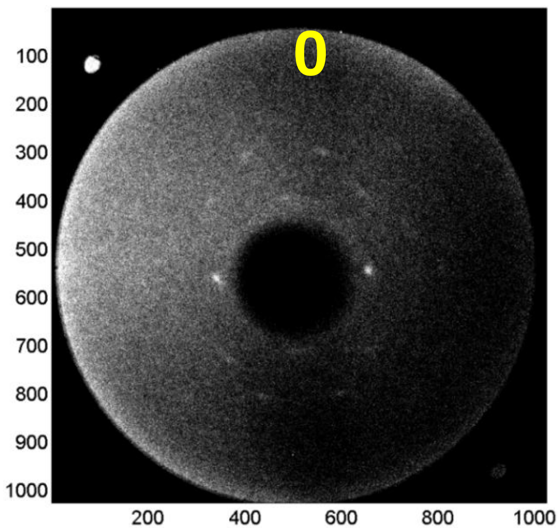
兆伏特超快电子衍射进展

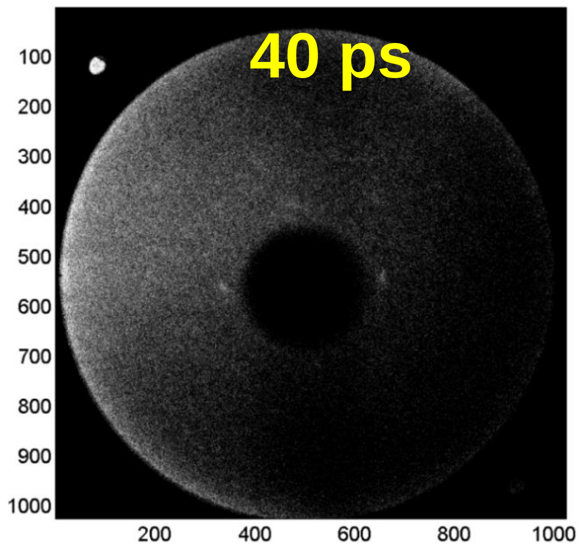


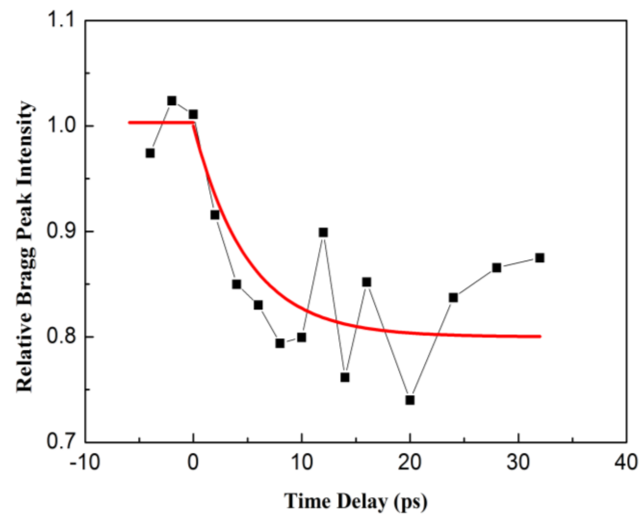




利用等离子体对电子束的扰动确定激光/电子的相对时间







兆伏特超快电子衍射泵浦-探测动态实验 (*Zhu et al., CPL, 2014*)

超快电子衍射与成像总体规划

2014

2015

2016

2017

2018

1 kHz激光订购 | OPA订购 | 过渡实验室 | 原型机实验

1 kHz电子枪概念设计 | 原型机电子束参数测量 | 高温超导螺线管磁铁订购

1 kHz电子枪工程设计 | 1 kHz激光安装 | 原型机实现200 fs分辨率 | 色差校正研究

1 kHz电子枪加工 | 1 kHz调制器订购 | CDI算法研究 | 阴极研究

高重频泵浦源验收 | 高温超导螺线管磁铁测试 | 原型机实现100 fs分辨率

中能电镜CDI初步实验研究 | 谐波腔加工 | 1 kHz电子枪热测

高重频高亮度电子束验收 | 发展测量时间抖动新方法

超快电子衍射验收 | 订购高温超导螺线管磁铁或调整技术路线

订购混凝土平台 | 谐波腔运行

电子束参数达到超快电子透镜要求

超快电子无透镜成像验收 | 超快电子透镜集成

超快电子透镜调试

超快电子透镜单发成像验收

开展超快电子衍射科学应用

开展CDI科学应用

总结

1. 机遇

率先成功建设基于加速器的超快电子衍射与成像用户装置；体现科研需求，推动原始创新；加速器的新应用。

2. 挑战

多项技术均为国际上首次大胆尝试，如1000 Hz电子枪，10^{-4}能散及能量稳定度，高温超导螺线管磁铁等。

3. 责任

“在仪器领域，国外对中国采取的策略是，对你不能制造的精密仪器，它会要高价，甚至不卖给你；当你有能力制造时，它以低价销售给你，打垮你，不让你发展。”

---- 姚骏恩 院士