Ultra-fast electrons in imaging of microscopic structural changes

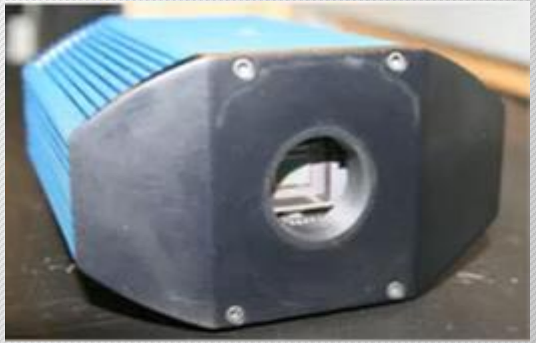
Zahra Rezaei

Detectors:

- Single point detector:

Imaging: ADC
Photon → Electron → Voltage → Digital number

- Multiple point detector (cameras)



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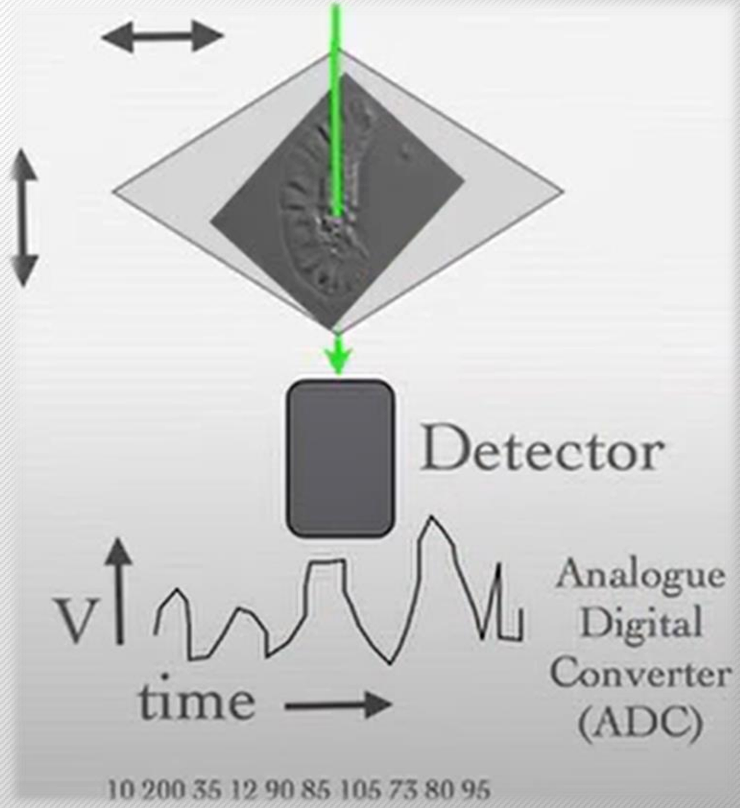

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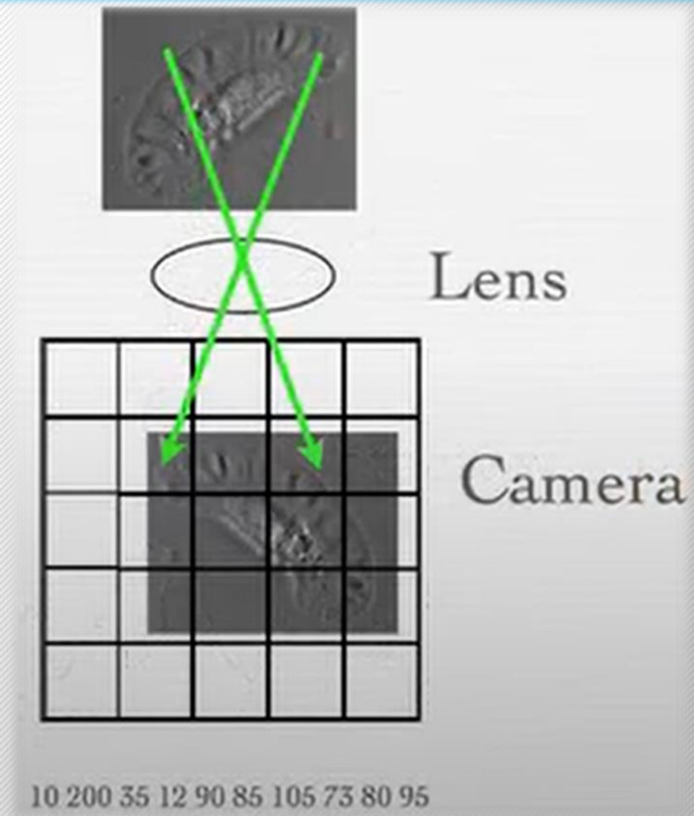
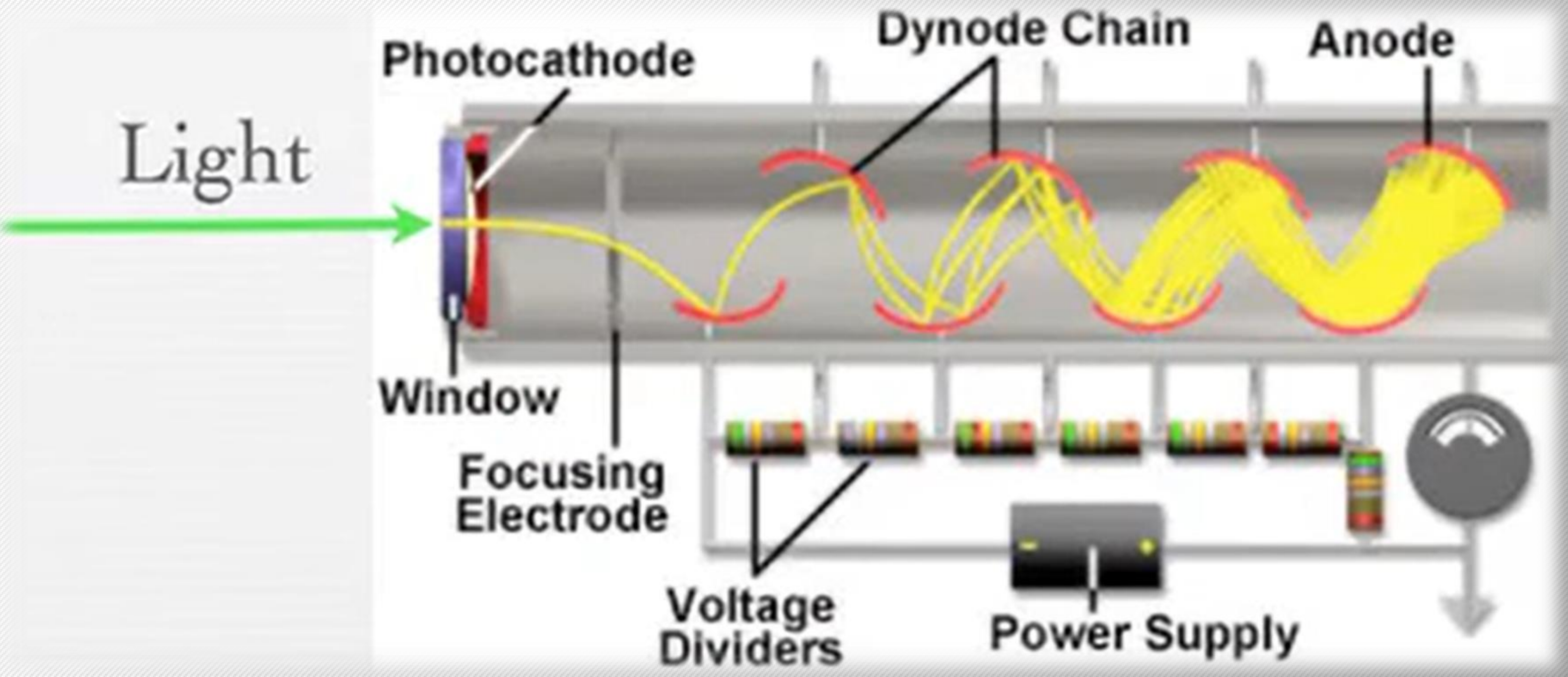


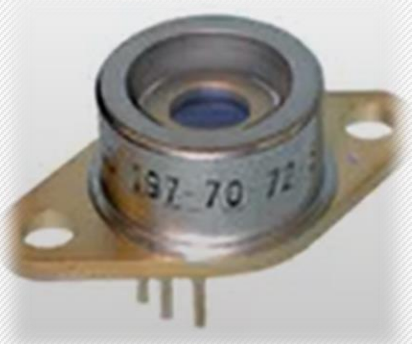
Single point detector example: Photo-Tube (PMT)

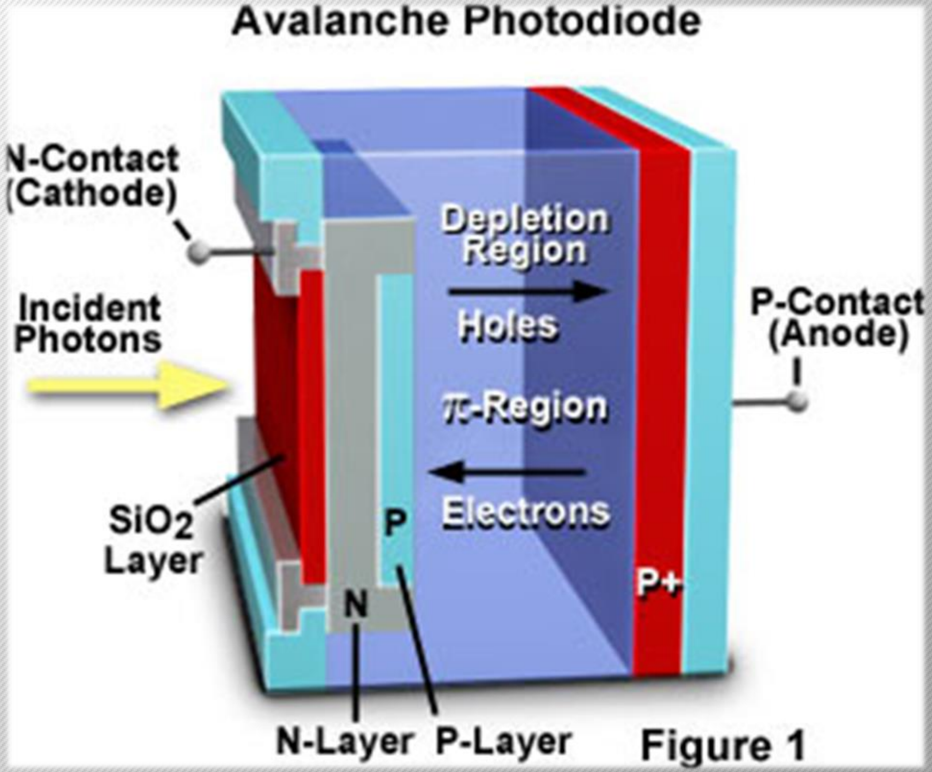
- Very fast & linear
- Very high gain
- Fast response
- Poor quantum efficiency (%25)



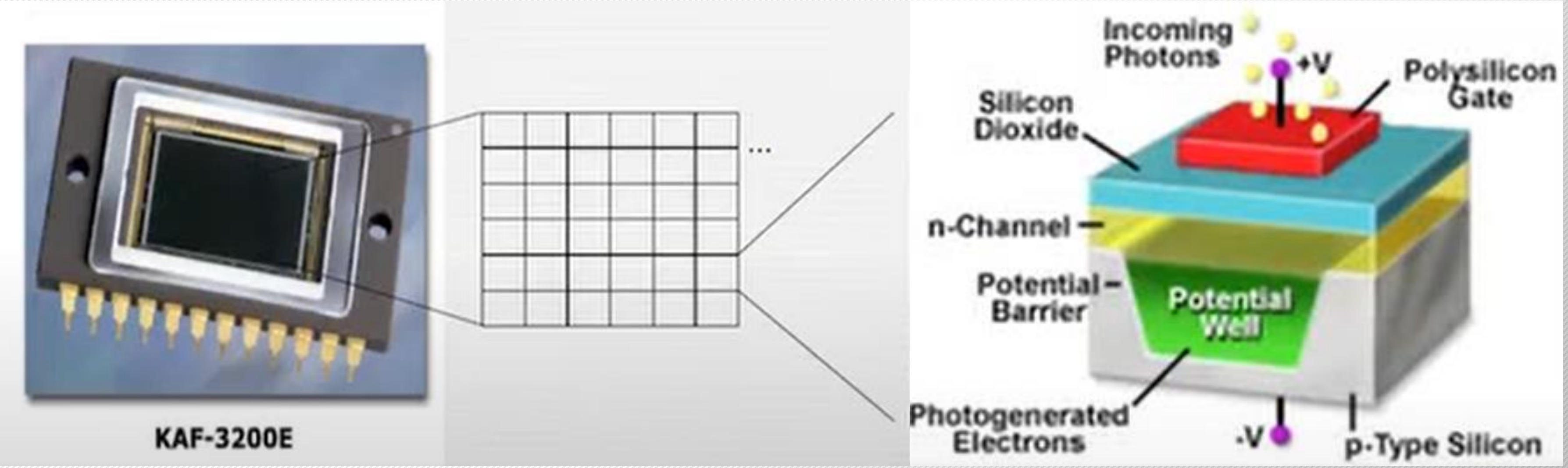
Single point detector example: Avalanche Photodiodes (APD)

- Absorbed photons -> electron
- Electrons amplified by high voltage & impact ionization
- High quantum efficiency (%90)
- Photon-counting ability
- Overheat if runs too fast

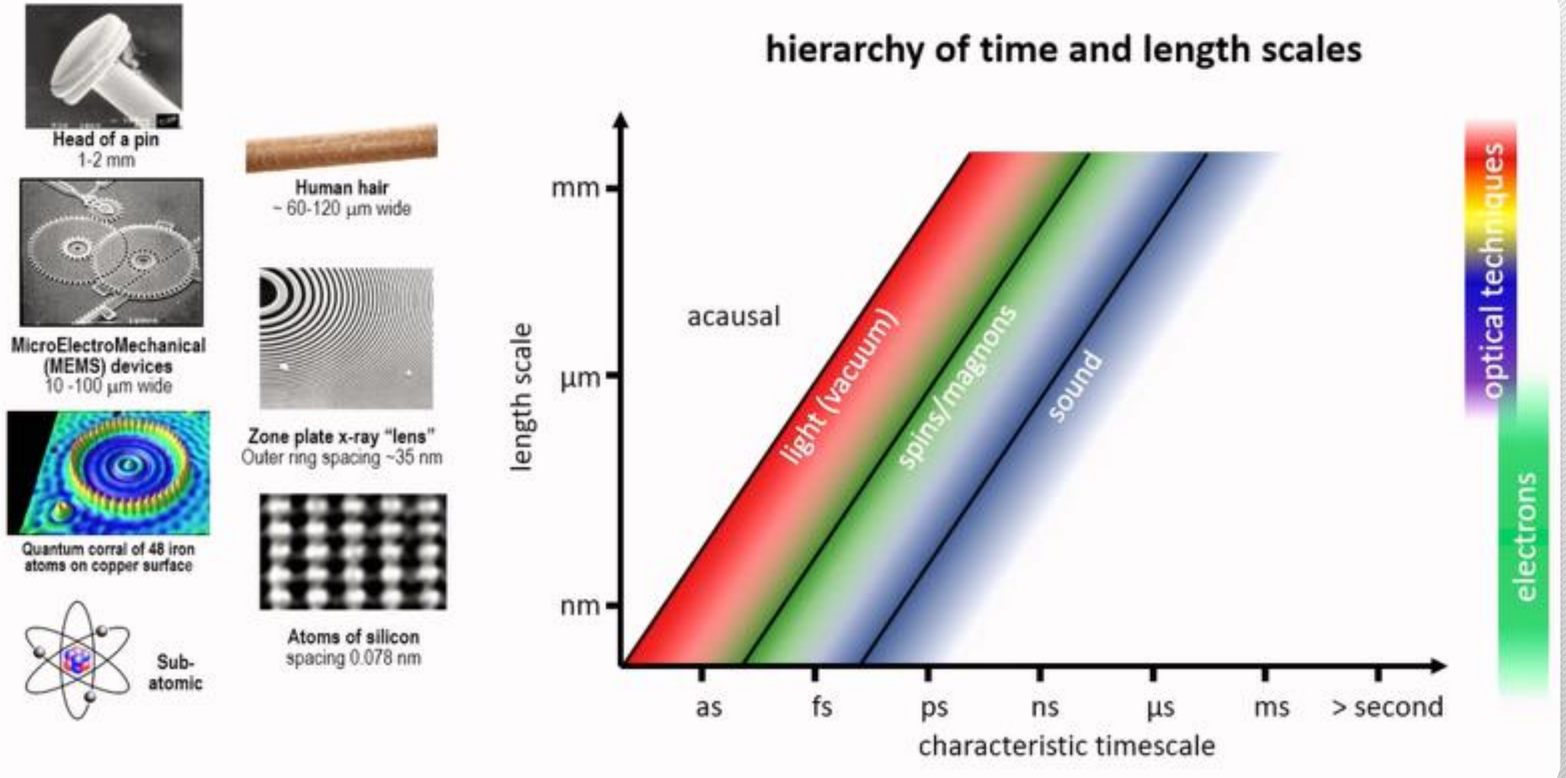




Cameras in Microscopy:



Microscopes:
Small Time and length scales

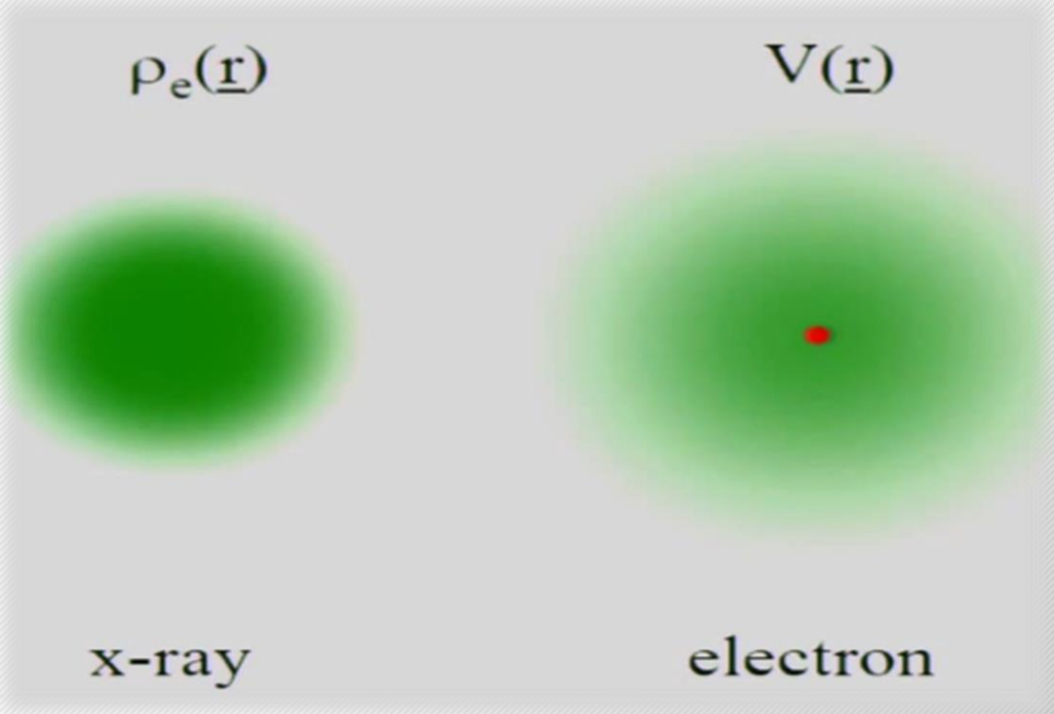


Office of Basic Energy Sciences, Office of Science, U.S. DOE (https://science.energy.gov/bes/community-resources/scale-of-things-chart/)

Temporal changes in atomic and molecular structures can be directly measured with **diffraction techniques** that utilize:

- short-wavelength X-rays ——→ XFEL
- electrons

diffraction techniques:



Electrostatic Potential

Larger interaction cross- section

Single point detector:
Ultrafast Electron Diffraction

UED اکنون به وضوح زمانی 100 فمتوثانیه می رسد که تنها چند برابر دوره ی ارتعاشی اتم ها، و وضوح فضایی $0.01\hat{A}$ است که تنها کسری از فاصله بین اتمی است. ترکیبی از چنین جزئیات زمانی و مکانی در سطح اتمی، این پتانسیل را دارد که مکانیسم‌های فیزیکی و همبستگی‌های بین ساختارماده-عملکرد آن را بتوان آشکار نمود. چنین کاری قبلا و با روش های قدیمی امکان پذیر نبوده است.

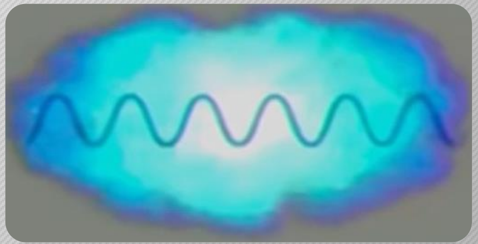
Electrons as an ultra-fast probe: Diffraction

Mass: $9.10938291(40)\times10^{-31}$ kg
0.510998928 MeV/c^2
Electric charge:
$-1.602176565(35)\times10^{-19}$ C

$$r_e = \frac{1}{4\pi\varepsilon_0}\frac{e^2}{m_e c^2} = 2.8179403267(27)\times10^{-15}\ \text{m}$$

Single point detector

- Diffraction refers to the phenomena that a wave deviates from its original propagating direction due to interference caused by obstacles, apertures, and so on. It is mostly pronounced when the wavelength is comparable to the dimension of the scattering elements.
- Particularly, electron diffraction has been widely used for material characterization, in which electrons are usually accelerated to very high energy (1 keV to 100 keV) so that their de Broglie wavelengths become a few percent of typical inter-atomic distance ensuring the resolution of atomic-level details.

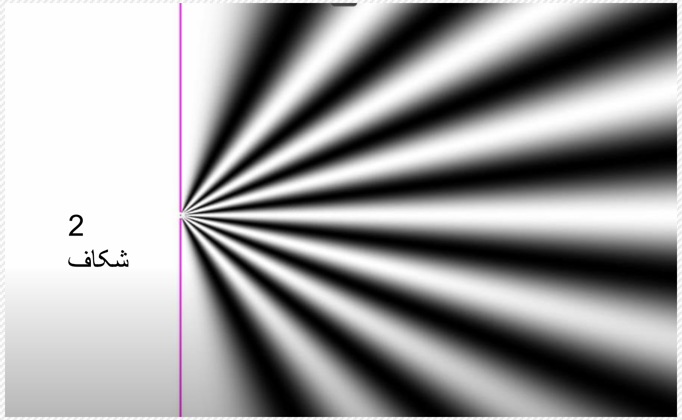


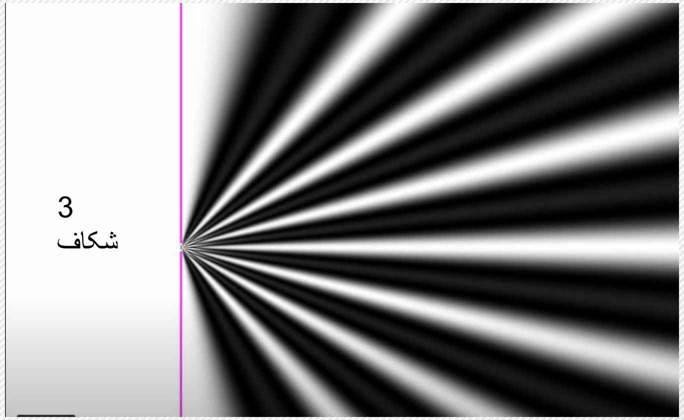
V_{acc} / kV	Relativistic wavelength / pm	Mass x m_0	Velocity x 10^8 m/s
100	3.70	1.20	1.64
200	2.51	1.39	2.09
300	1.97	1.59	2.33
400	1.64	1.78	2.48
1000	0.87	2.96	2.82

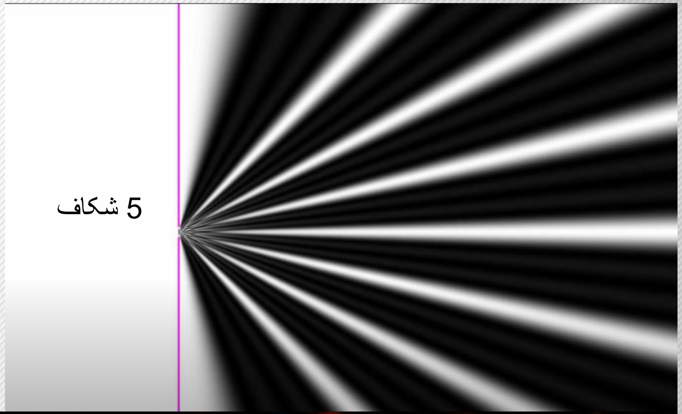
$$\lambda = h / (2m_0eV)^{1/2}\ (\approx 1.22 / V^{1/2}\ \text{nm})$$

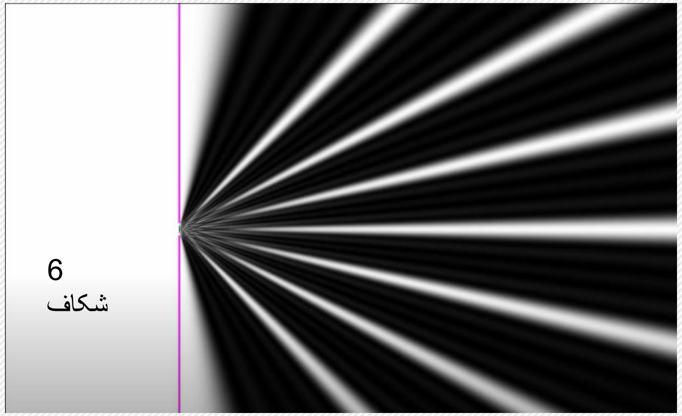
Electrons as an ultra-fast probe: Diffraction

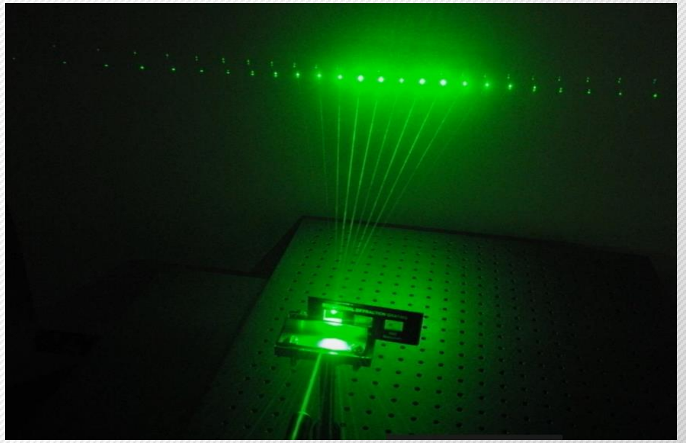
Single point detector

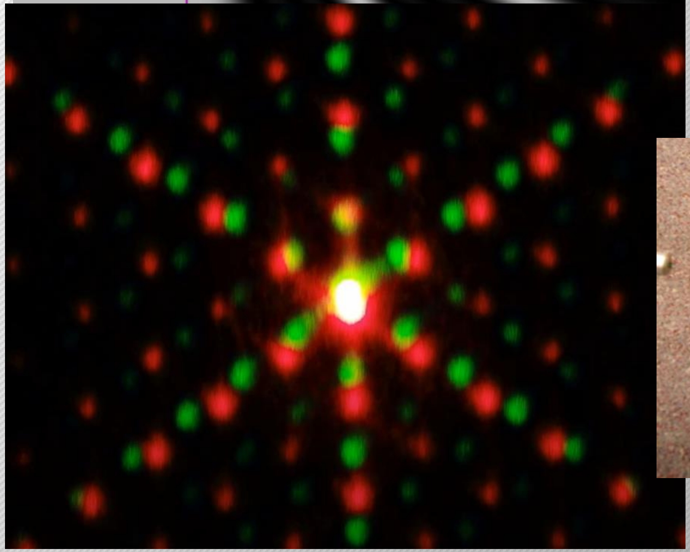


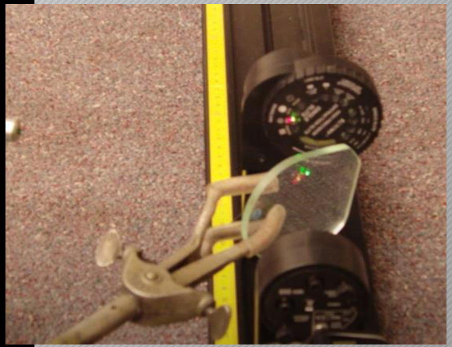






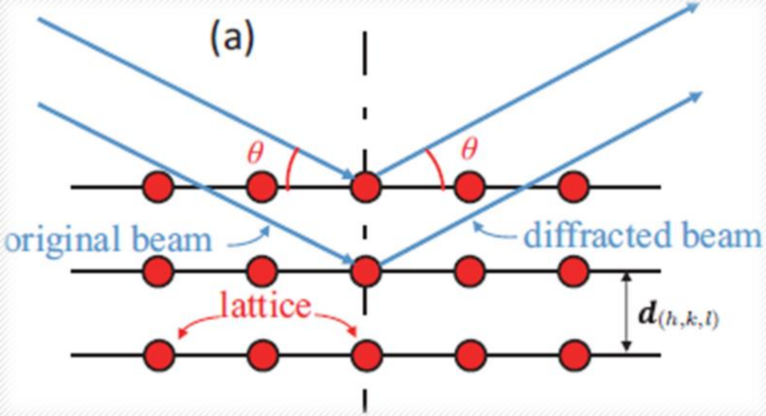




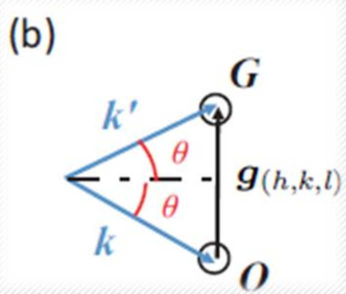


Electrons as an ultra-fast probe: Diffraction

For elastic scattering and by considering the superpositions of the reflections from adjacent parallel lattice planes, the criterion of constructive interference (or formation of diffraction peaks) is described by Bragg's law:



$$2d_{(h,k,l)}\sin(\theta) = \lambda,$$



$$k' - k = g$$

reciprocal lattice space

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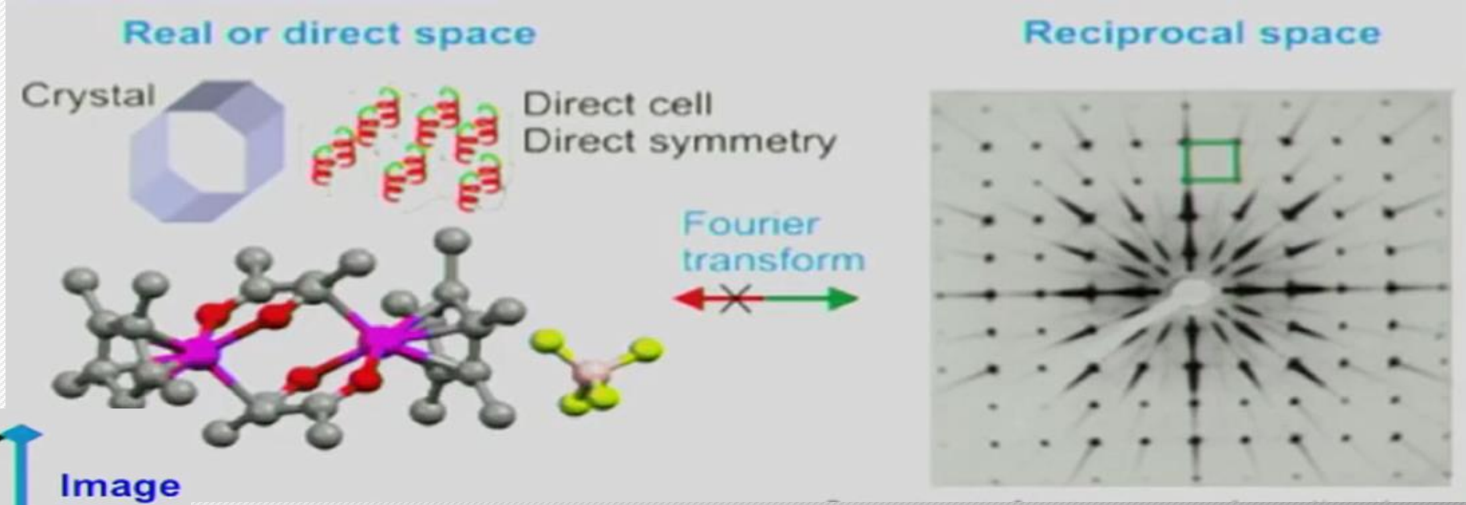
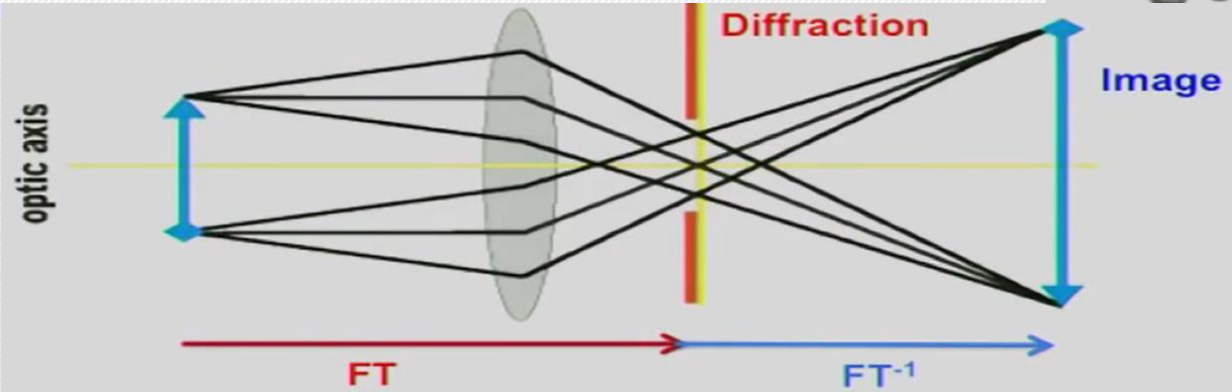




Why Electron-probe based techniques ––→ UED and UEM ??

- X-ray diffraction
- Electron diffraction … structures, particularly in the gas phase

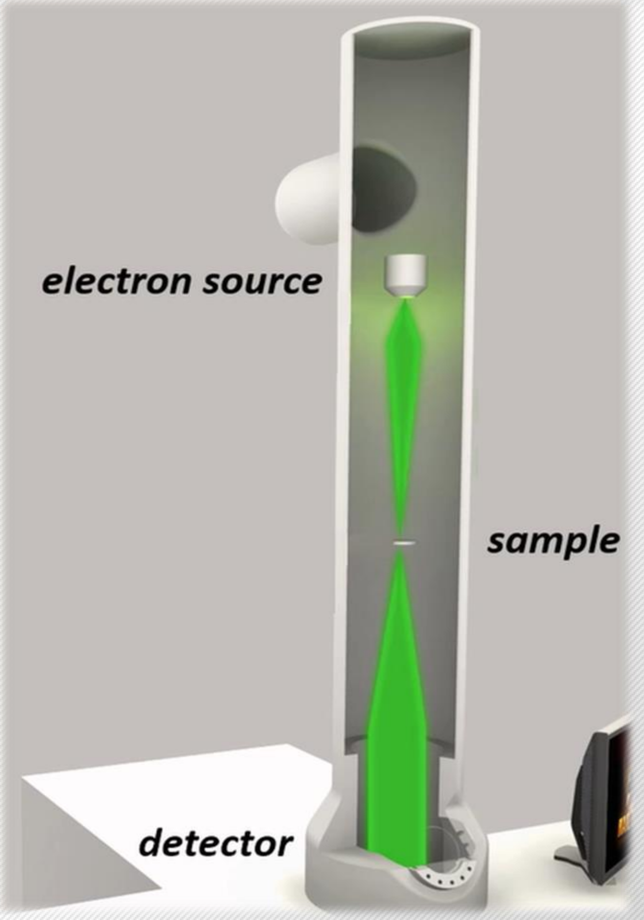
… and UEM are entering this field,

… sensitivities with only lab-scale instrumentation.

Electron microscopes:
Transmission Electron Microscopy (TEM)
scanning electron microscope (SEM)
reflection electron microscope (REM)

- Continues electron beam
- Fast Camera : $100\ ms\ - s\ scales$

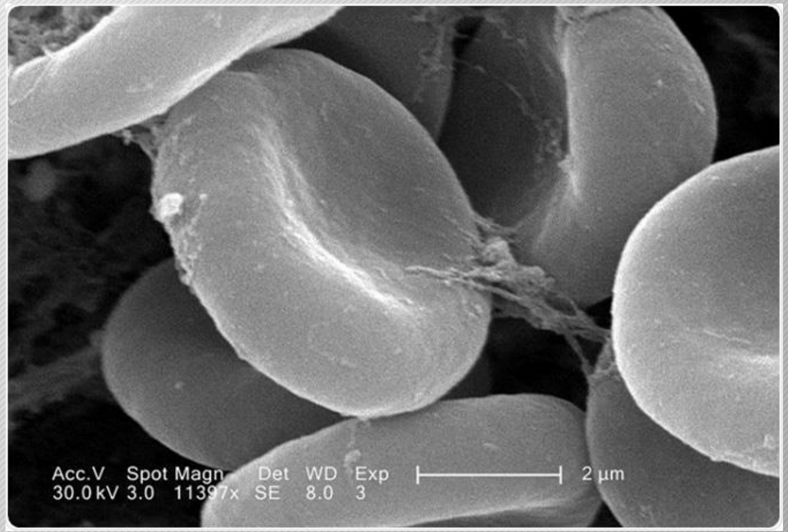
the cross section of a capillary with a red blood cell present, taken using a TEM



$100\ - 300\ KeV$

- Magnification: more than 50 million times
- very thin specimen samples, usually less than $100\ nm$

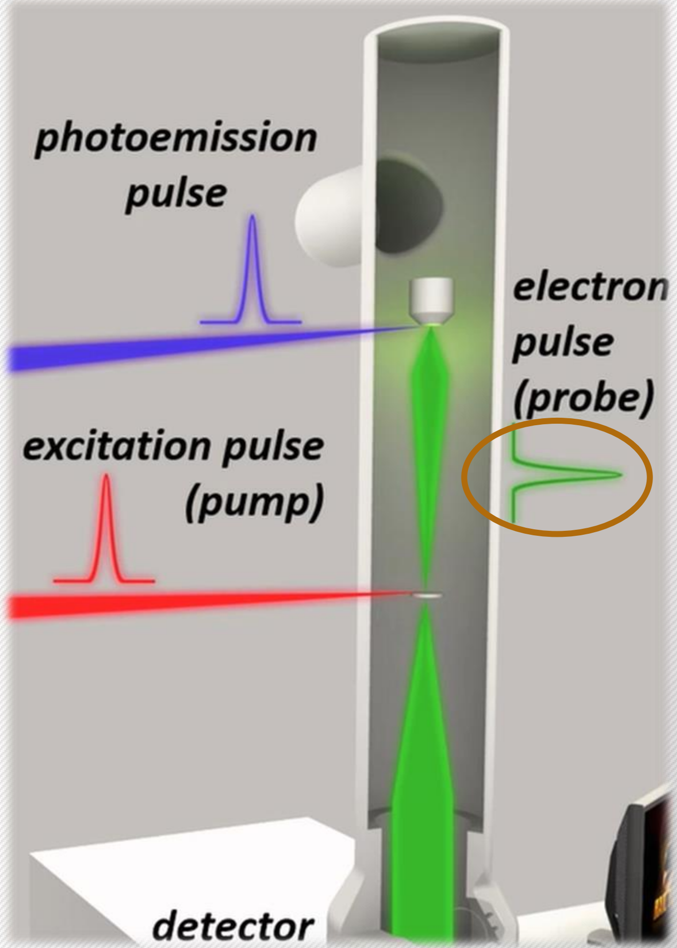
SEM resolution: ~0.5 nm,
TEM spatial resolution: < 50 pm



The image shows red blood cells, taken using a SEM

Ultrafast Transmission Electron Microscopy

- a stroboscopic imaging technique, in which induced changes in physical, chemical, electrical properties of an investigated sample are triggered by short (typically optical) excitation pulses. At well-defined delay times after excitation, the evolving state of the sample is probed by an ultrashort electron pulse



- Pump-Probe Technique: to increase the temporal resolution
- Very high temporal-resolution + Very high spatial-resolution

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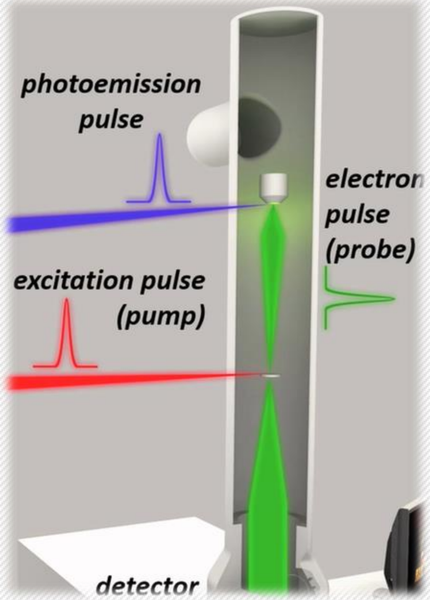

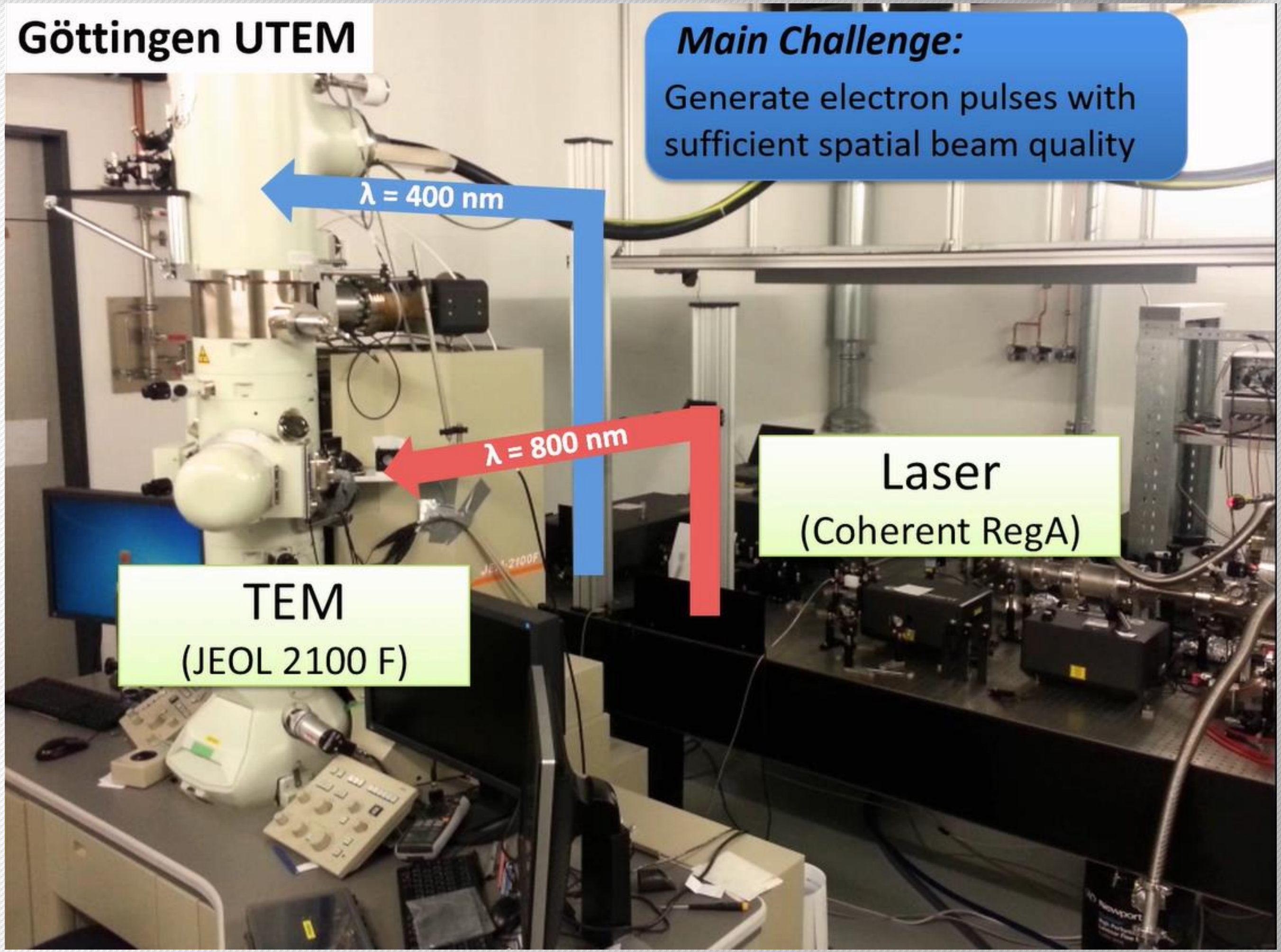

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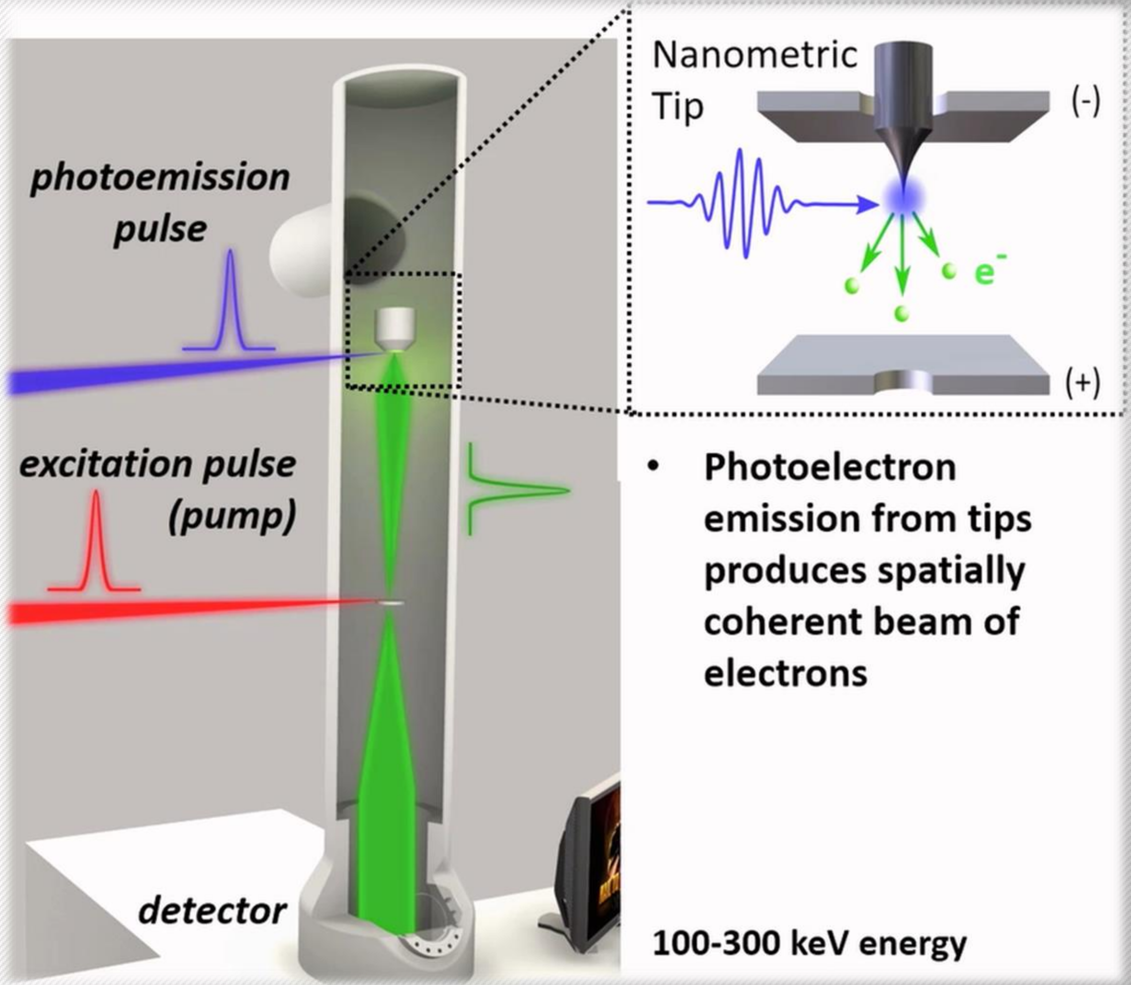
- Localized source −−> better beam quality

- **Stroboscopic approach** (Not flash photography):
For every laser pulse (photoemission pulse), just few electrons will be emitted.
  - Repetition rate at least: $several\ 10s\ of\ 1000\ of\ times/s$

- Slow detector
  - Delay time between probe and pump



- Sensitive to reversible changes (dynamic) in sample

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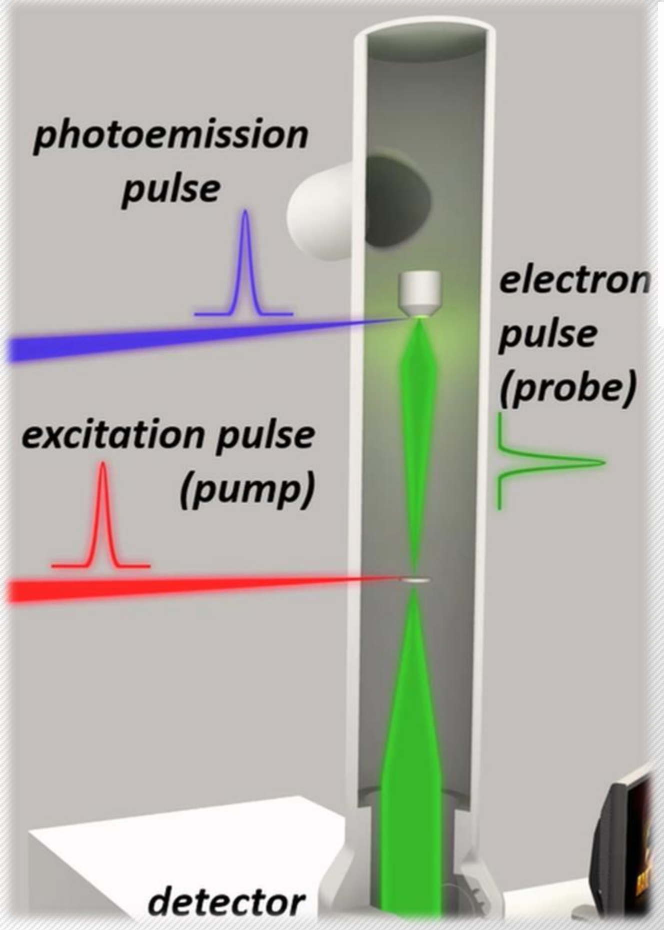

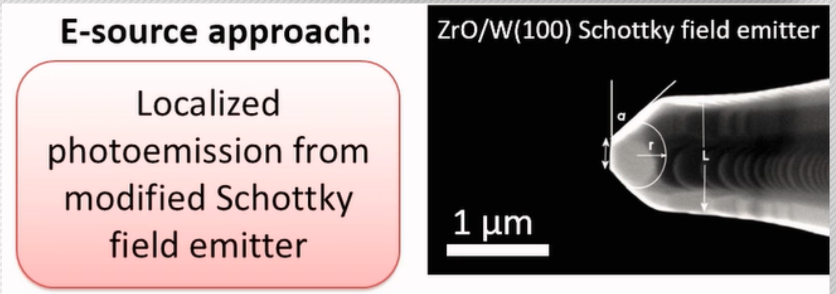

Liu et al., J. Vac. Sci Tech. (2010).

- The ZrOW(100) Schottky cathode
  - Cathode lifetimes > 10,000 h, if vacuum requirements are maintained and high voltage arcing is eliminated
- It has been found that a reversible, field dependent change in the equilibrium work function and shape of the cathode end occurs at the typical operating temperature of 1800 K .
- work function of facet < work function of side

Ultrafast Transmission Electron Microscopy

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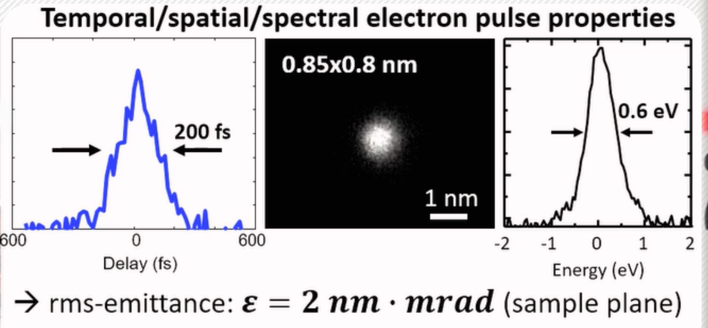
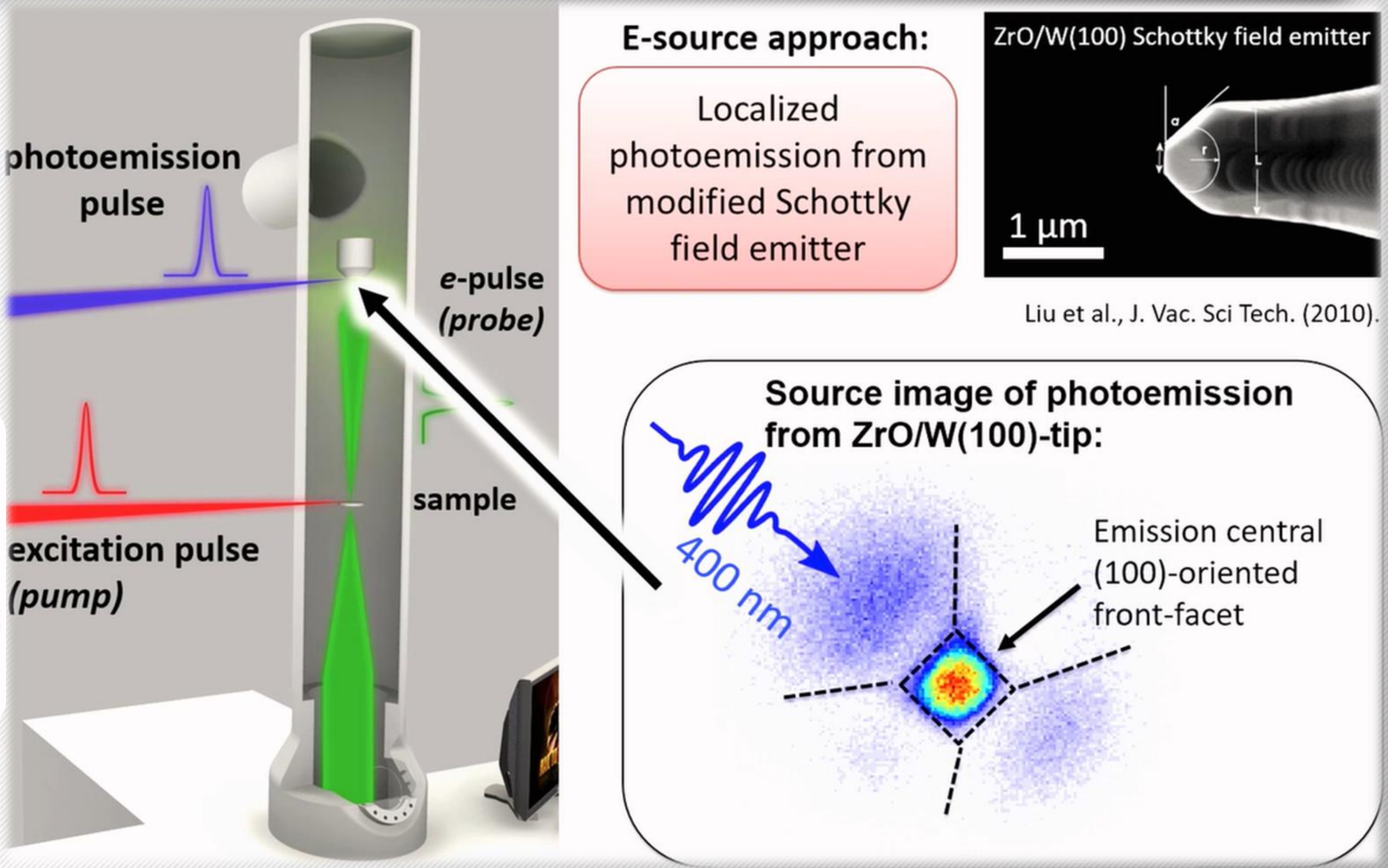


A. Feist et al., Nature 521, 200 (2015)



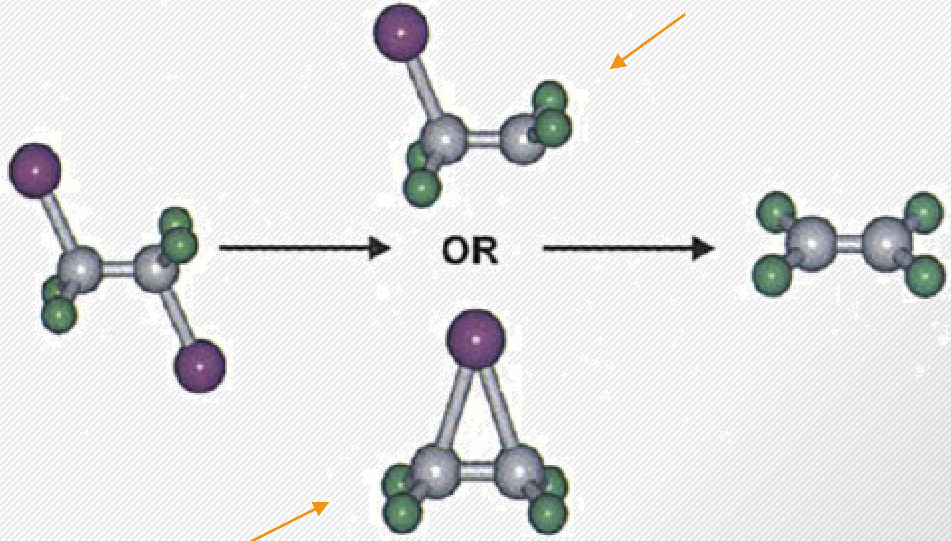
Liu et al., J. Vac. Sci Tech. (2010).

Some Applications:
——→ UED

$C_2F_4I_2 \rightarrow C_2F_4I + I$

$C_2F_4I \rightarrow C_2F_4 + I$

" classical" structure: the primary halide (I) resides predominantly on one -CF, moiety



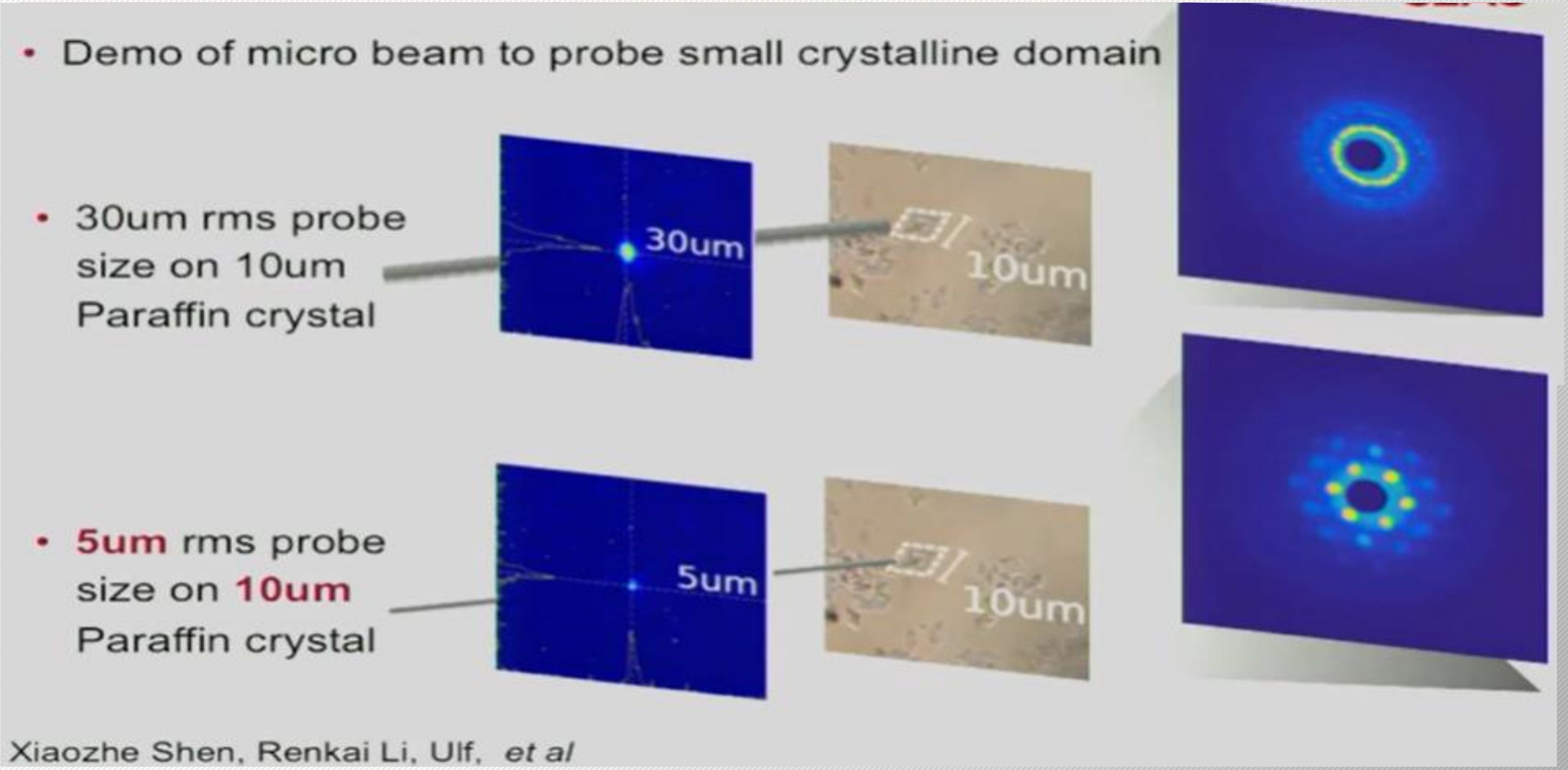
"bridged" structure: primary halide is shared equally between the two -CF, moieties

Table 1. Structural parameters of the classical C_2F_4I radical intermediate.

Distances	Angles
r(C-I) = 2.153 ± 0.013 Å	∠(CCI) = 115.0° ± 3.1°
r(C-F) = 1.340 ± 0.037 Å	∠(CCF) = 108.6° ± 6.0°
r(C-C) = 1.478 ± 0.049 Å	∠(CCF′) = 117.9° ± 3.1°
r(C-F′) = 1.277 ± 0.027 Å	∠(FCF/2) = 54.0° ± 5.6°
	∠(F′CF′/2) = 59.9° ± 3.9°

Direct Imaging of Transient Molecular Structures with Ultrafast Diffraction
19 JANUARY 2001 VOL 291 SCIENCE www.sciencemag.org

Some Applications:



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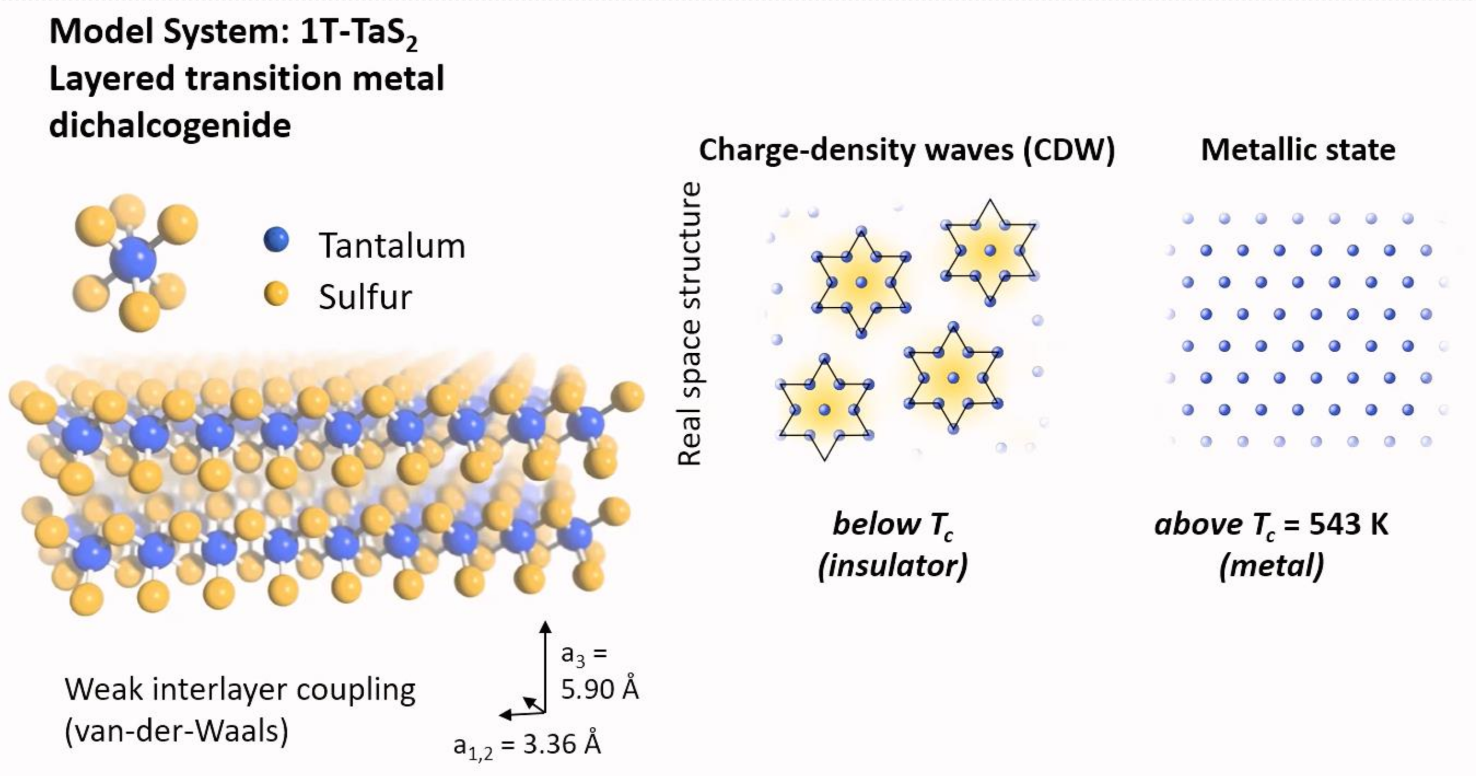

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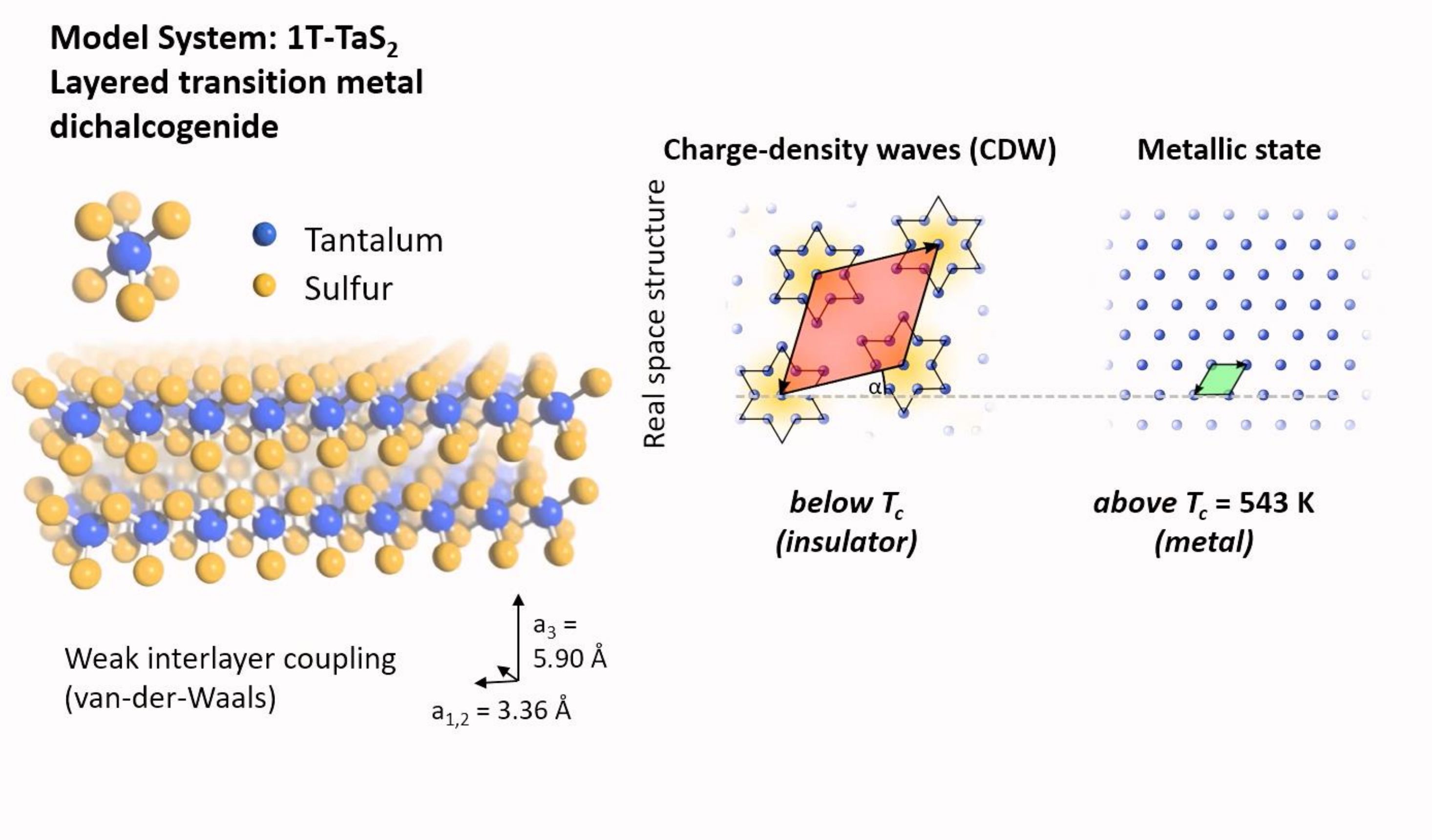

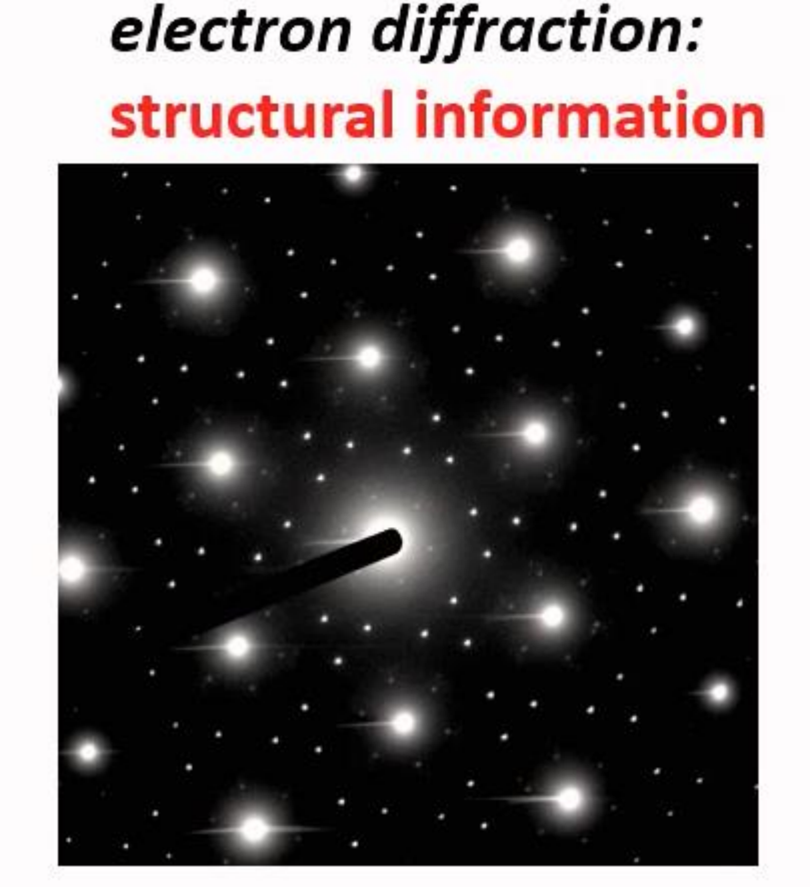

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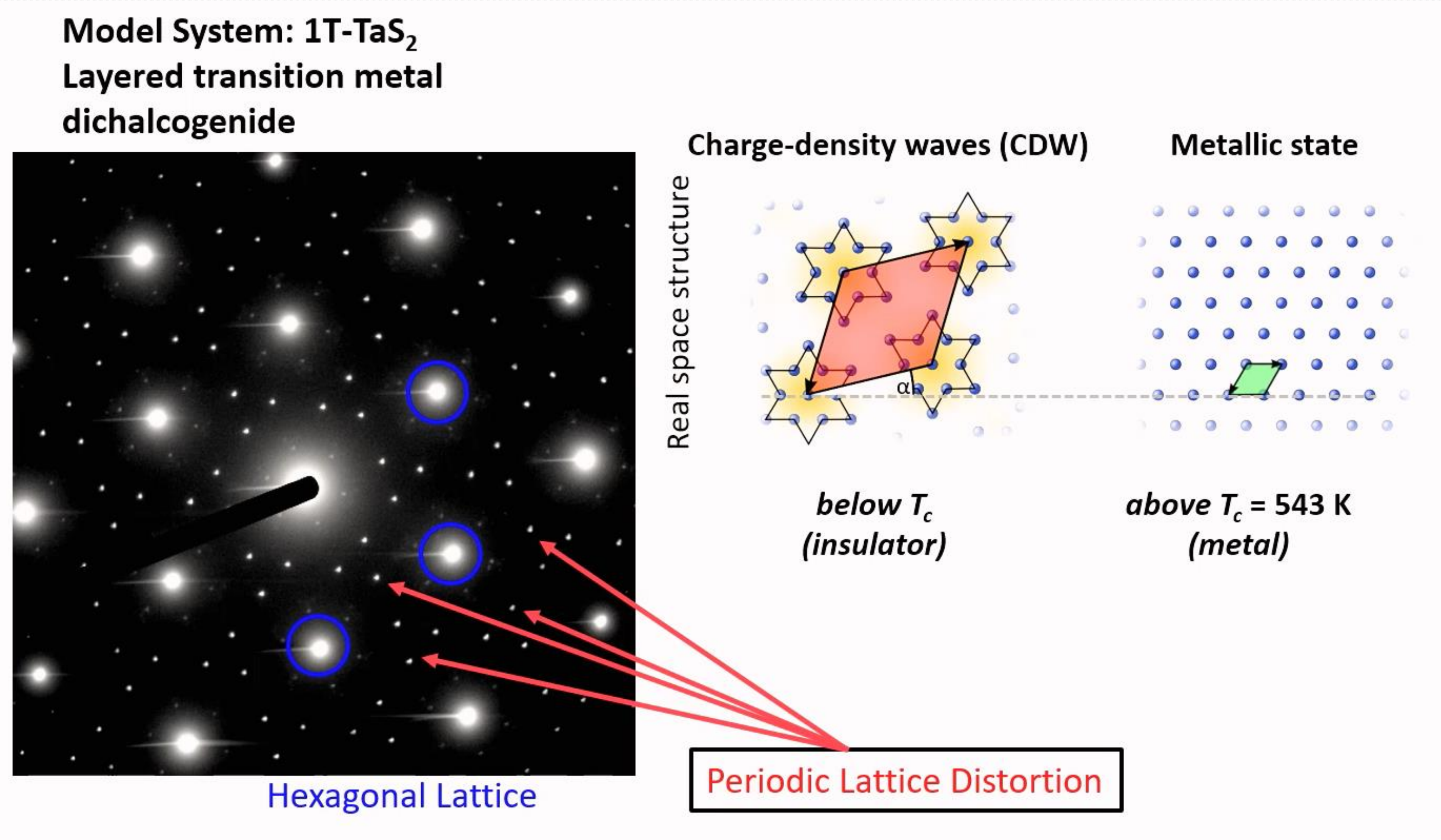
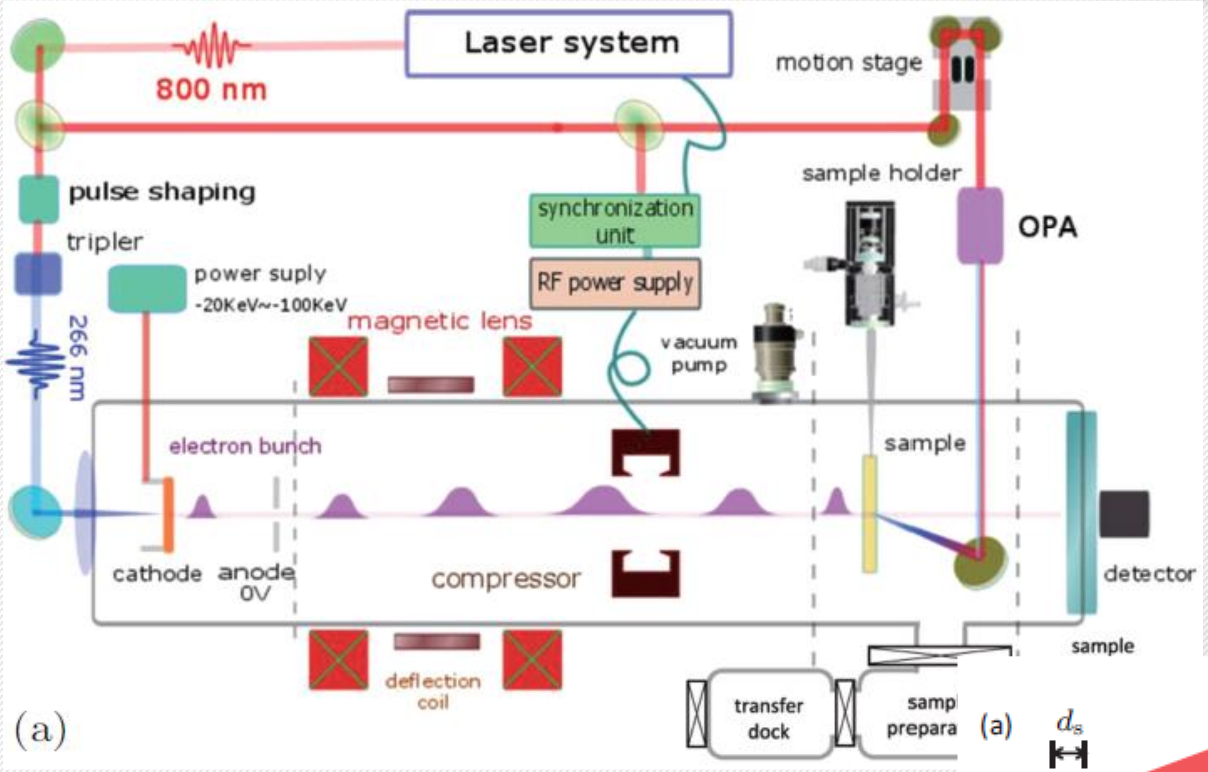
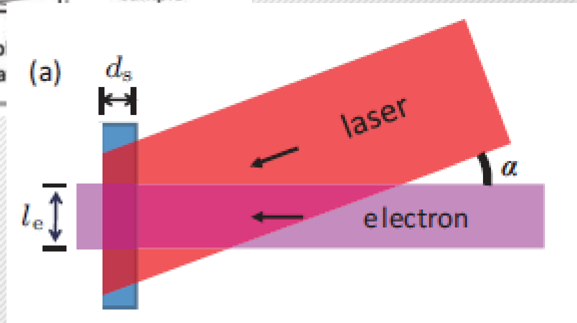


UED station in SECUF (Synergetic Extreme Condition User Facility (in China))

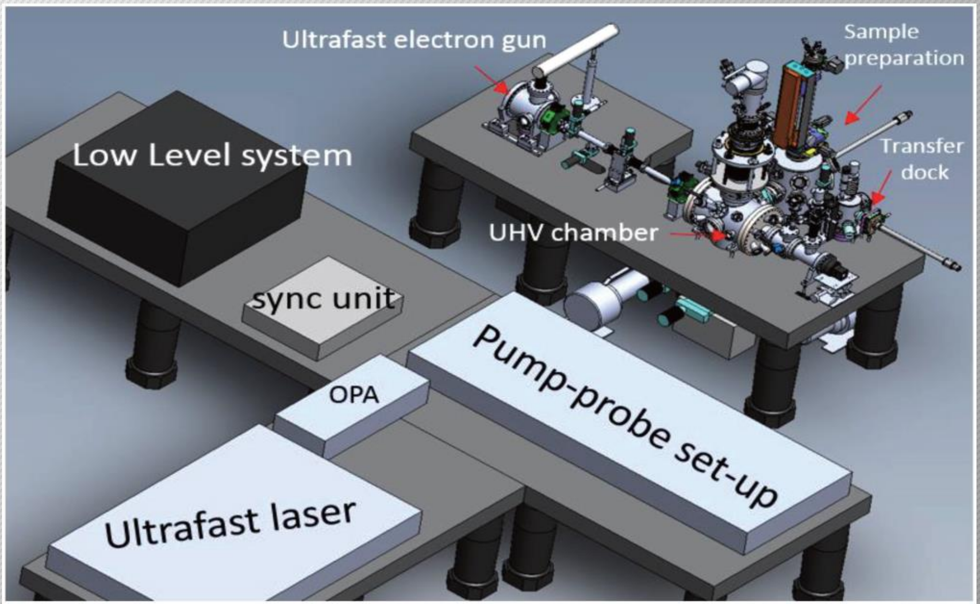




fast-decay (0.11 s) P47 phoshor screen coated by
100 nm aluminum foil in front to block the scattering light
from the pump.

Table 1. Figures of merit.

Parameter	Value
Spacial sensitivity	$\lesssim 0.01$ Å
Temporal resolution	$\lesssim 500$ fs
Electron fluence	$\gtrsim 10^9$ cm^{-2}
Transverse beam size	~ 100 μm
Coherent length	$\gtrsim 2$ nm



To be Continued…

Thanks Foe Your Attention