2022 고려대 가속기 여름학교

Ultrafast Electron Beam,
A Tool to Explore the Nanoscopic World of Materials

WCI
WORLD CLASS INSTITUTE

Young Uk JEONG (정 영 욱, 鄭 永 旭) 2022. 7. 13

COLLECTIVE INTELLIGENCE
Radiation Center for Ultrafast Science
circus

KAERI 한국원자력연구원 Korea Atomic Energy Research Institute

“Scientific advance is more often driven by the development of a new tool than a new concept”

Freeman Dyson

***In a review of a biography of the mathematician* George Green**

Contents

목 차

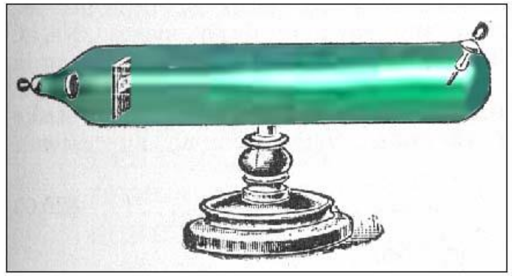
1. Free Electrons

Electron

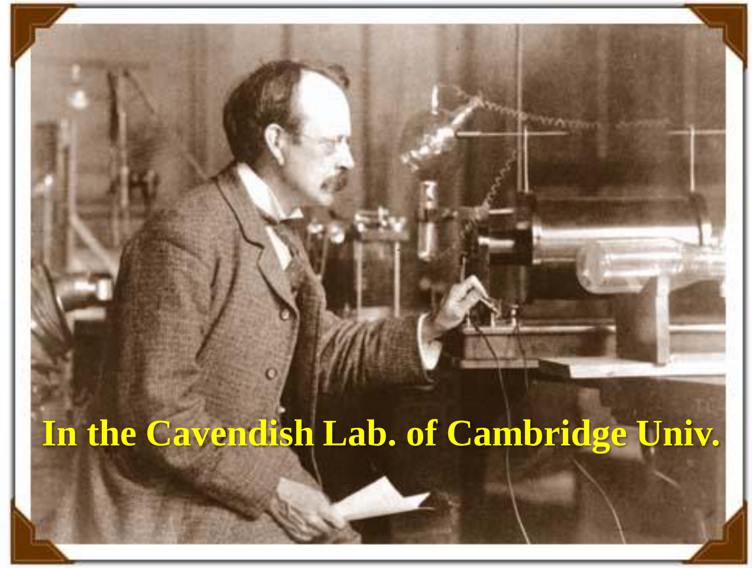
1897, (자유) 전자의 발견

Sir Joseph J. Thomson
(1856.12.18 ~ 1940.8.30)

The Novel Prize in Physics 1906

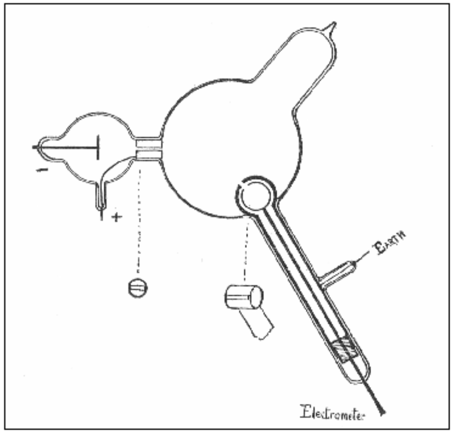


Mysterious rays

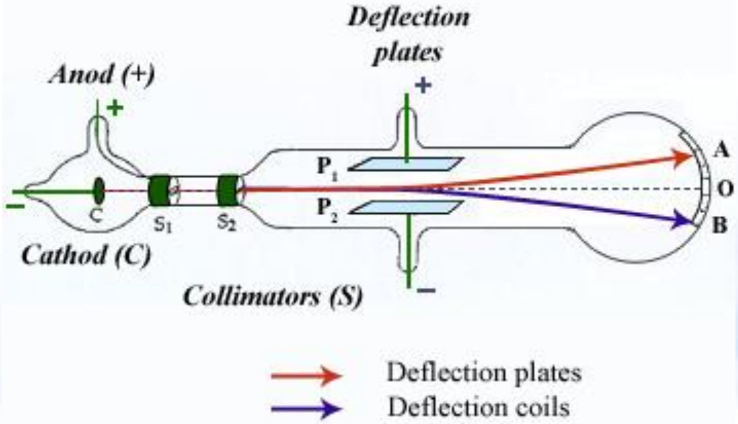


In the Cavendish Lab. of Cambridge Univ.

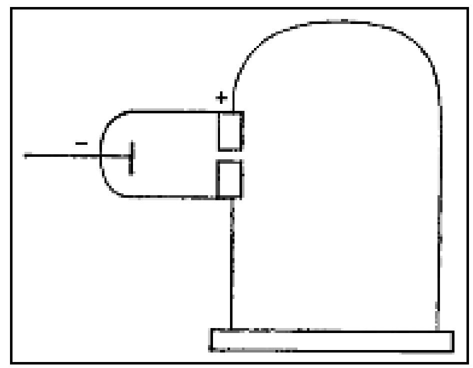
1st Exp.
Cathode rays : negative charge



2nd Exp.
Cathode rays : deflected by E-field



3rd Exp.
Cathode rays m/e : < 1/1000 of H^+



Electron to me 나에게 전자는?

- Stable subatomic particle with a negative charge
  Mean lifetime : > 6.6 x 10^{28} yr

- e^- : -1.602 x 10^{-19} C
  m_e : 9.10938 x 10^{-31} kg, 1/1836 the mass of a proton
  Spin or intrinsic angular momentum : $\frac{1}{2}\hbar$
  Radius : < 10^{-22} m

- Elecktron : the ancient Greek word for amber
  Electron : first suggested by G. J. Stoney in 1891

Electron?

전자의 크기와 모양은?

"The size and shape of the electron", *Arthur H. Compton*, Phys. Rev. 14, 20 – Published 1 July 1919

THE SIZE AND SHAPE OF THE ELECTRON.[1]

By Arthur H. Compton.

Synopsis.—Attention is called to two outstanding differences between experiment and the theory of scattering of high frequency radiation based upon the hypothesis of a sensibly point charge electron. In the first place, according to this theory the mass scattering coefficient should never fall below about .2, whereas the observed scattering coefficient for very hard X-rays and γ-rays falls as low as one fourth of this value. In the second place, if the electron is small compared with the wave-length of the incident rays, when a beam of γ-rays is passed through a thin plate of matter the intensity of the scattered rays on the two sides of the plate should be the same, whereas it is well known that the scattered radiation on the emergent side of the plate is more intense than that on the incident side.

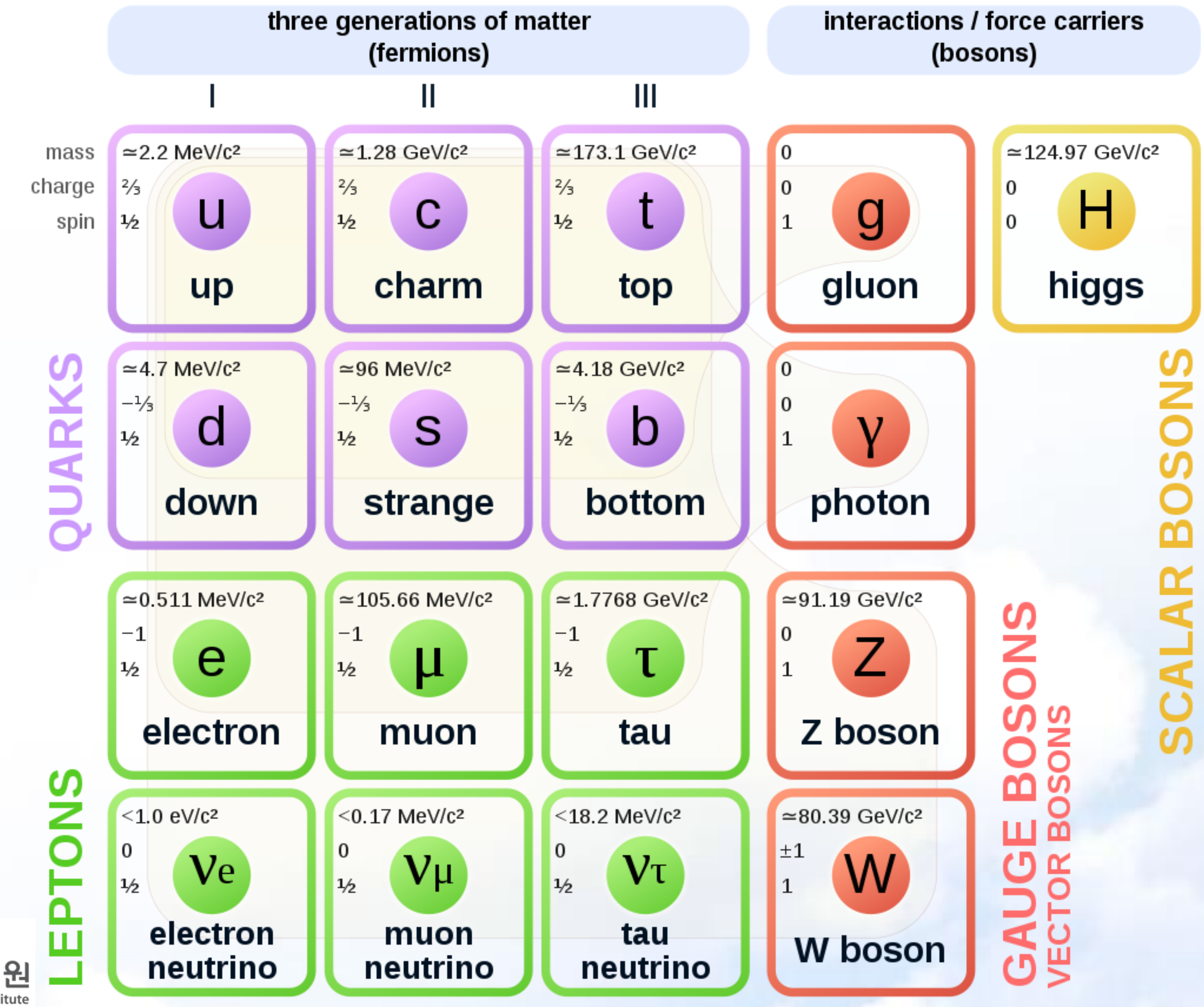
It is pointed out that the hypothesis that the electron has a diameter comparable with the wave-length of the hard γ-rays will account qualitatively for these differences, in virtue of the phase difference between rays scattered by different parts of the electron. The scattering coefficient for different wave-lengths is calculated on the basis of three types of electron: (1) A rigid spherical shell of electricity, incapable of rotation; (2) a flexible spherical shell of electricity; (3) a thin flexible ring of electricity. All three types are found to account satisfactorily for the meager available data on the magnitude of the scattering coefficient for various wave-lengths. The rigid spherical electron is incapable of accounting for the difference between the emergent and the incident scattered radiation, while the flexible ring electron accounts more accurately for this difference than does the flexible spherical shell electron.

It is concluded that the diameter of the electron is comparable in magnitude with the wave-length of the shortest γ-rays. Using the best available values for the wave-length and the scattering by matter of hard X-rays and γ-rays, the radius of the electron is estimated as about 2×10^{-10} cm. Evidence is also found that the radius of the electron is the same in the different elements. In order to explain the fact that the incident scattered radiation is less intense than the emergent radiation, the electron must be subject to rotations as well as translations.

한국원자력연구원
KAERI Korea Atomic Energy Research Institute

Electron to them 그들에게 전자는?

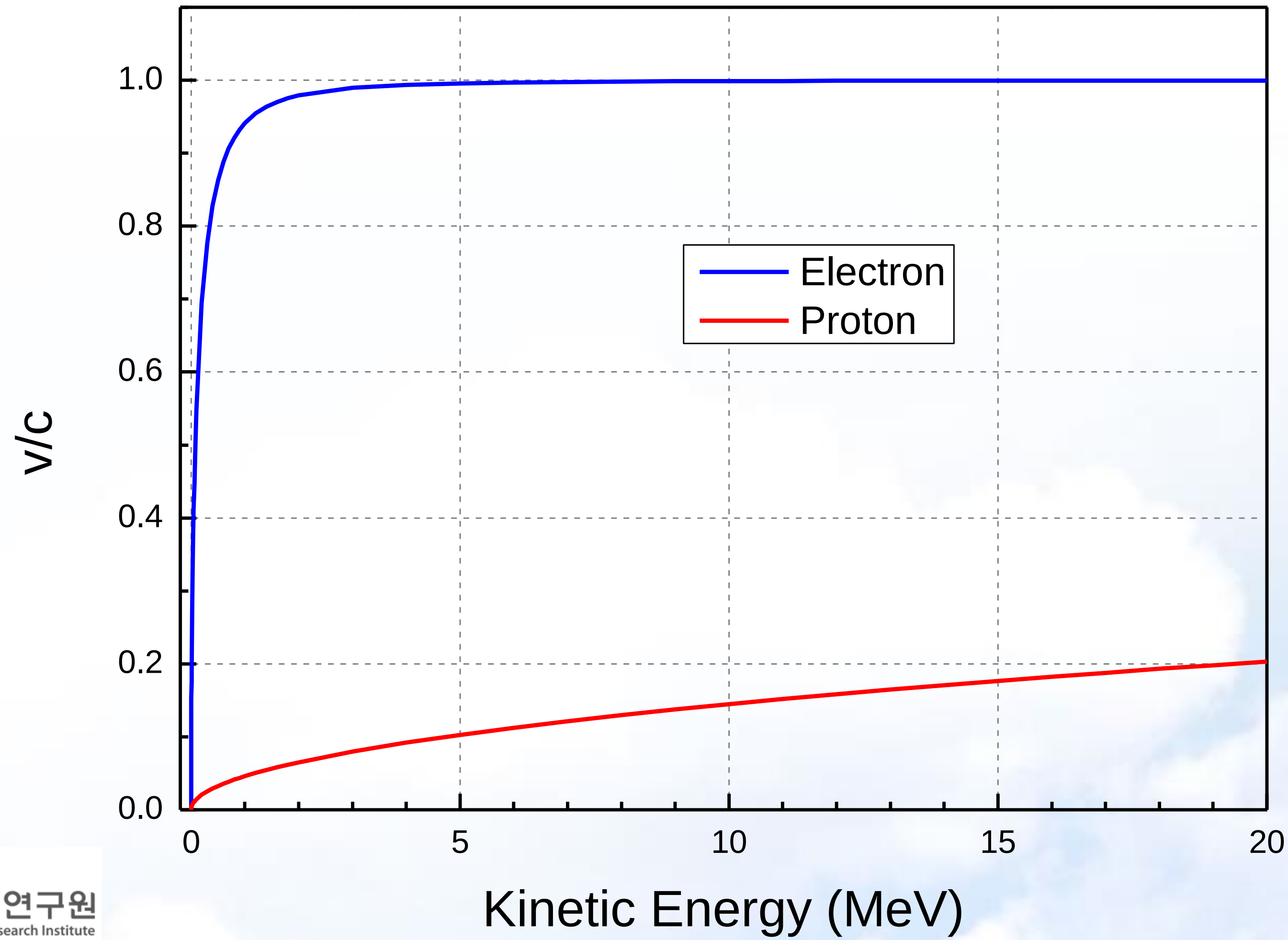
Standard Model of Elementary Particles



한국원자력연구원 Korea Atomic Energy Research Institute

Electron 전자는?

- **The most suitable particle to accelerate**



Acceleration 가속원리

Charles-Augustin de Coulomb
(1736. 6. 14 – 1806. 8. 23)

$$\vec{\mathbf{F}} = q\vec{\mathbf{E}}$$

Hendrik Antoon Lorentz
(1853. 7. 18 – 1928. 2. 4)

$$\vec{\mathbf{F}} = q\vec{\mathbf{E}} = m_q\vec{\mathbf{a}}$$ (non-relativistic v << c)

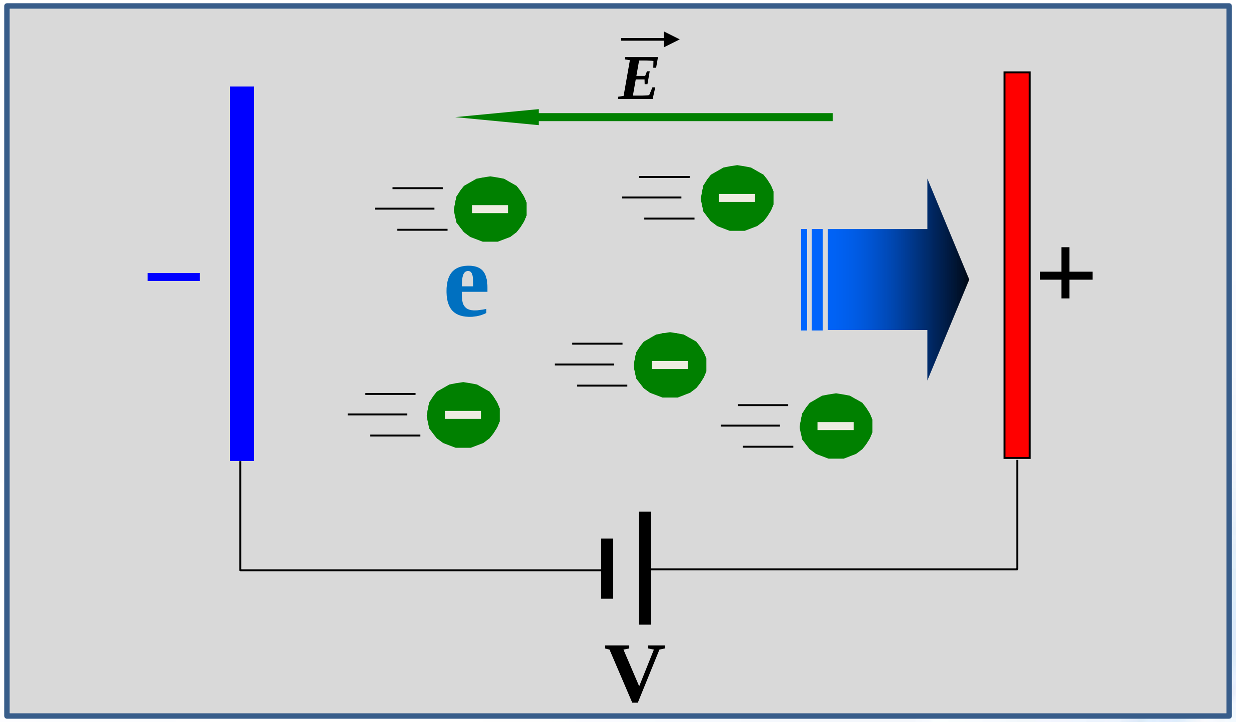
(relativistic case v ~ c) $= \frac{d}{dt}(\vec{\mathbf{P}}) = m_q\frac{d}{dt}(\gamma\vec{\mathbf{v}})$

Lorentz factor : $\gamma = \frac{1}{\sqrt{1-\left(\frac{v}{c}\right)^2}}$

Electron Energy 전자 에너지

$E = qV = eV$

(1 eV = 1 electron volt = 1.6×10^{-19} J)



Lorentz factor : $\gamma = (1 - v^2/c^2)^{-1/2} = 1 + \dfrac{E}{m_e c^2} = 1 + \dfrac{E\ [\mathrm{MeV}]}{0.511\ [\mathrm{MeV}]}$

Accelerators 가속기의 종류

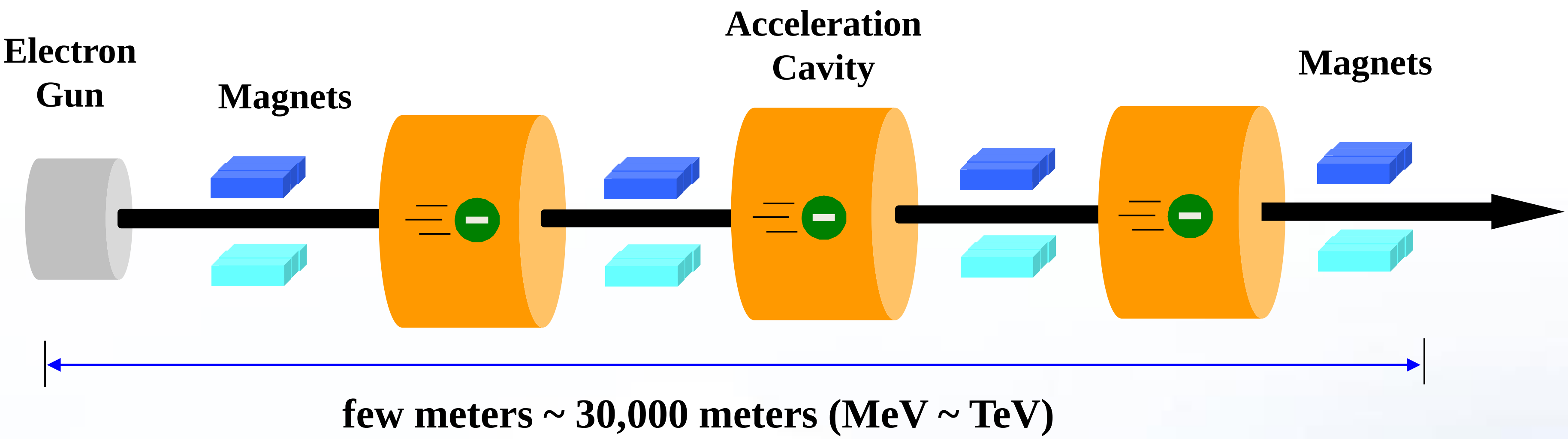
- **Particles :** electron, proton, ion (heavy ion, hadron)

- **Acceleration method :**
  - 정전 가속기 (Electrostatic Accelerator)
  - 고주파 가속기 (Radio-Frequency/RF Accelerator)
  - 자기유도 가속기 (Induction Accelerator)
  - 플라즈마 가속기 (Plasma Accelerator)

- **Depending on shape :**
  - 선형 가속기 (Linear Accelerator, Linac)
  - 원형 가속기 (Circular/Cyclic Accelerator)

- **Depending on usage :**
  - 방사광 가속기 (Synchrotron Accelerator)
  - 의료용 가속기 (Medical Accelerator)
  - 산업용 가속기 (Industrial Accelerator)

Electron Accelerator 전자 가속기

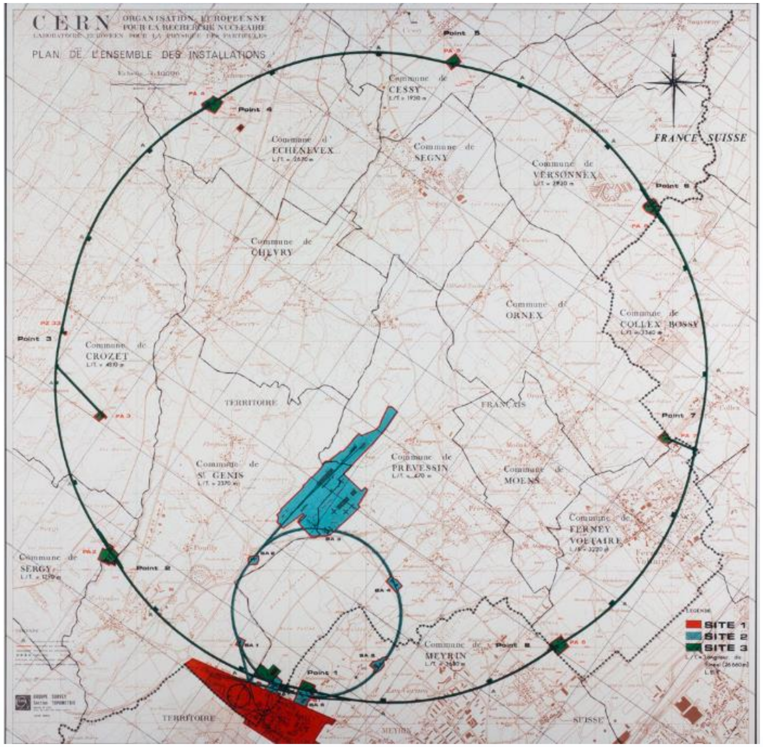


- Electron guns : thermionic, field emission, & photo-electron guns
- Electron optics : bending magnets, quadrupole magnets …
- Acceleration cavity : normal conducting or superconducting

Biggest Electron Accelerator

가장 큰 전자 가속기는?

- **The Large Electron-Positron Collider (LEP, 1989-2000), CERN**
  - Energy : 209 GeV, circumference : 27 km



c.f. Linear Collider Program : electron/positron 500 GeV, 1 TeV
Large Hadron Collider (LHC) : 7 TeV proton beam

Synchrotron

방사광 가속기

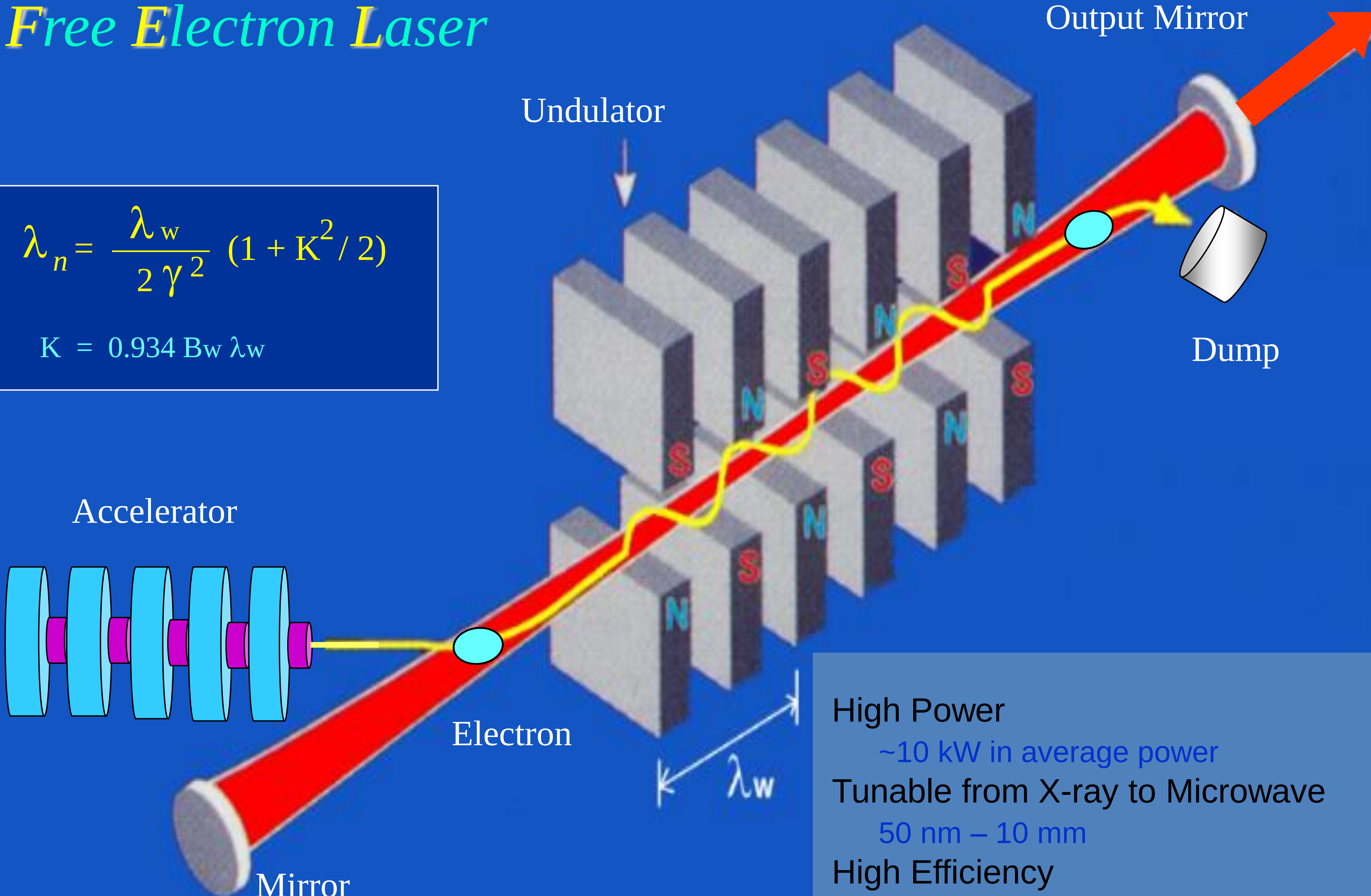
- 1944 : Theoretical prediction (D. Iwanenko, I. Pomeranchuk)
  1947 : First observation (GE Lab.)
  1956 : Spectroscopy with UV (Cornell Univ.)

- 1G (-70s): Study for high-energy physics
  2G (70s-): Radiation from dipole magnet, userfacility
  3G (90s-): Radiation from insertion devices (wiggler, undulator)
  4G (00s-): X-ray free-electron laser, ultimate ring

Free Electron Laser

$$\lambda_n = \frac{\lambda_w}{2\gamma^2}\left(1 + K^2/2\right)$$

$$K = 0.934\, B_w \lambda_w$$



High Power

~10 kW in average power

Tunable from X-ray to Microwave

50 nm – 10 mm

High Efficiency

II. Spatial Confinement of Free Electrons

지수와 SI 접두어

인 자	접두어	인 자	접두어
10^{24}	요타(Y)	10^{-1}	데시(d)
10^{21}	제타(Z)	10^{-2}	센티(c)
10^{18}	엑사(E)	10^{-3}	밀리(m)
10^{15}	페타(P)	10^{-6}	마이크로(m)
10^{12}	테라(T)	10^{-9}	나노(n)
10^{9}	기가(G)	10^{-12}	피코(p)
10^{6}	메가(M)	10^{-15}	펨토(f)
10^{3}	킬로(k)	10^{-18}	아토(a)
10^{2}	헥토(h)	10^{-21}	젭토(z)
10^{1}	데카(da)	10^{-24}	욕토(y)

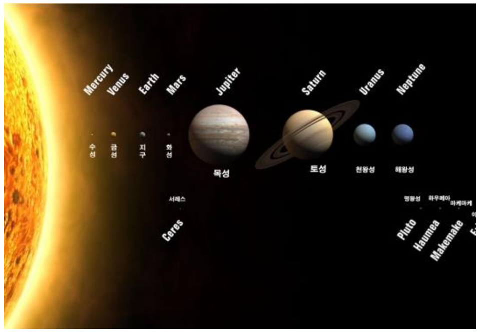
사용빈도

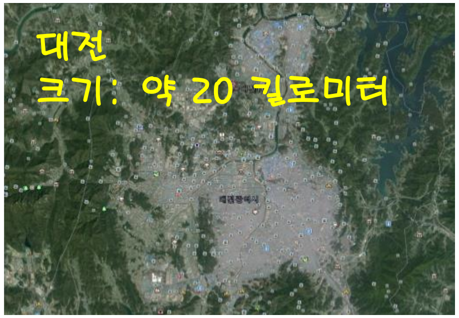
- 자주
- 가끔
- 글쎄
- 전혀

우리가 보는 세상

우 주
크기: 약 160 억 광년
(10^{26} 미터 = 100 요타미터)

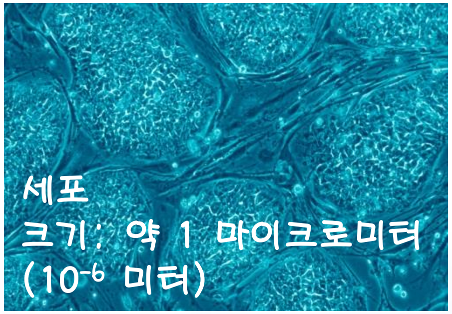
은하계
크기: 약 10 만 광년
(10^{21} 미터 = 1 제타미터)



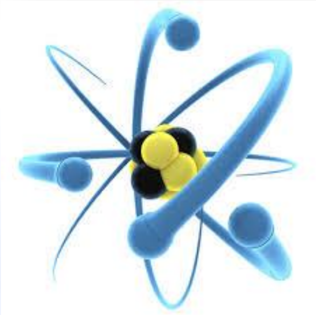


대전
크기: 약 20 킬로미터

사람
크기: 약 2 미터



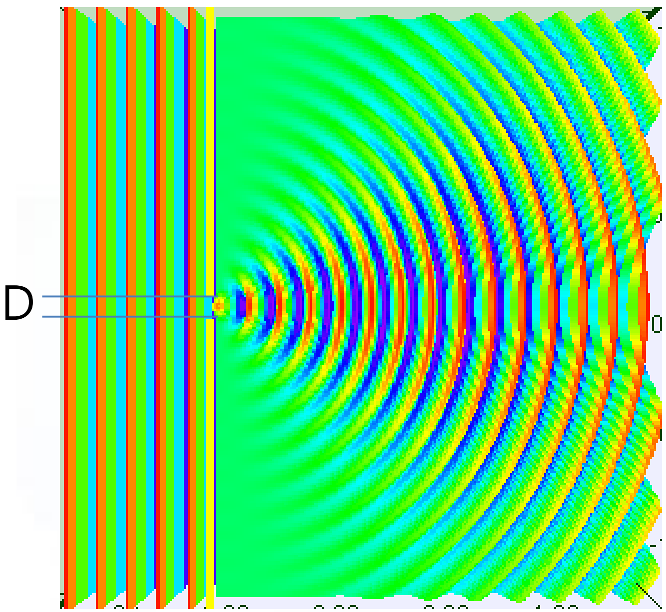
세포
크기: 약 1 마이크로미터
(10^{-6} 미터)

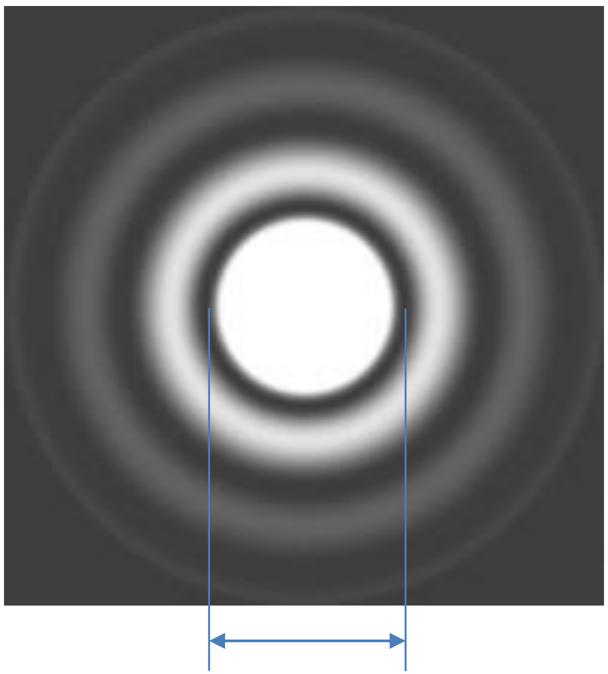


원자
크기: 약 0.1 나노미터
(10^{-10} 미터)

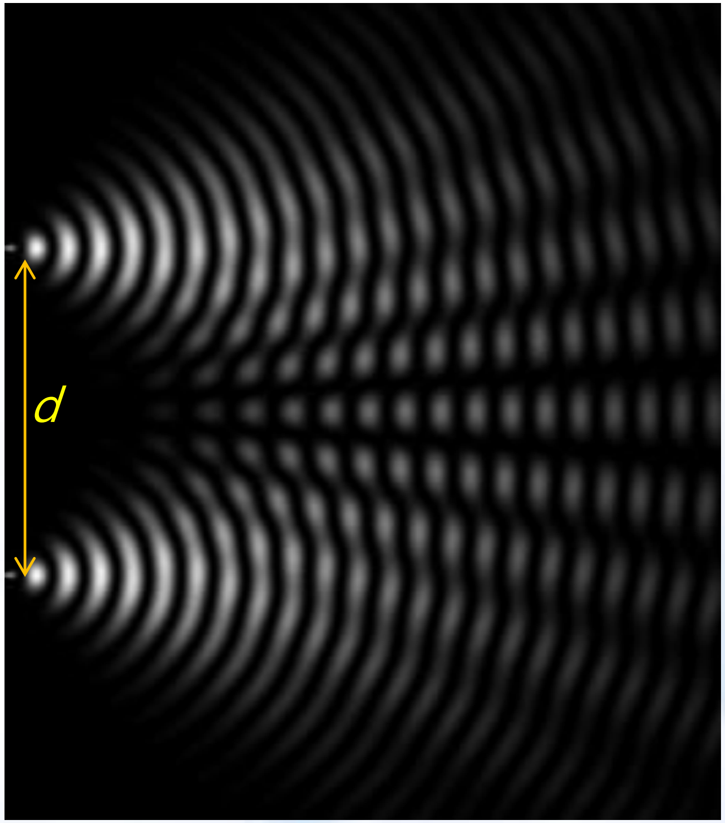
Diffraction & Interference

Diffraction by single hole





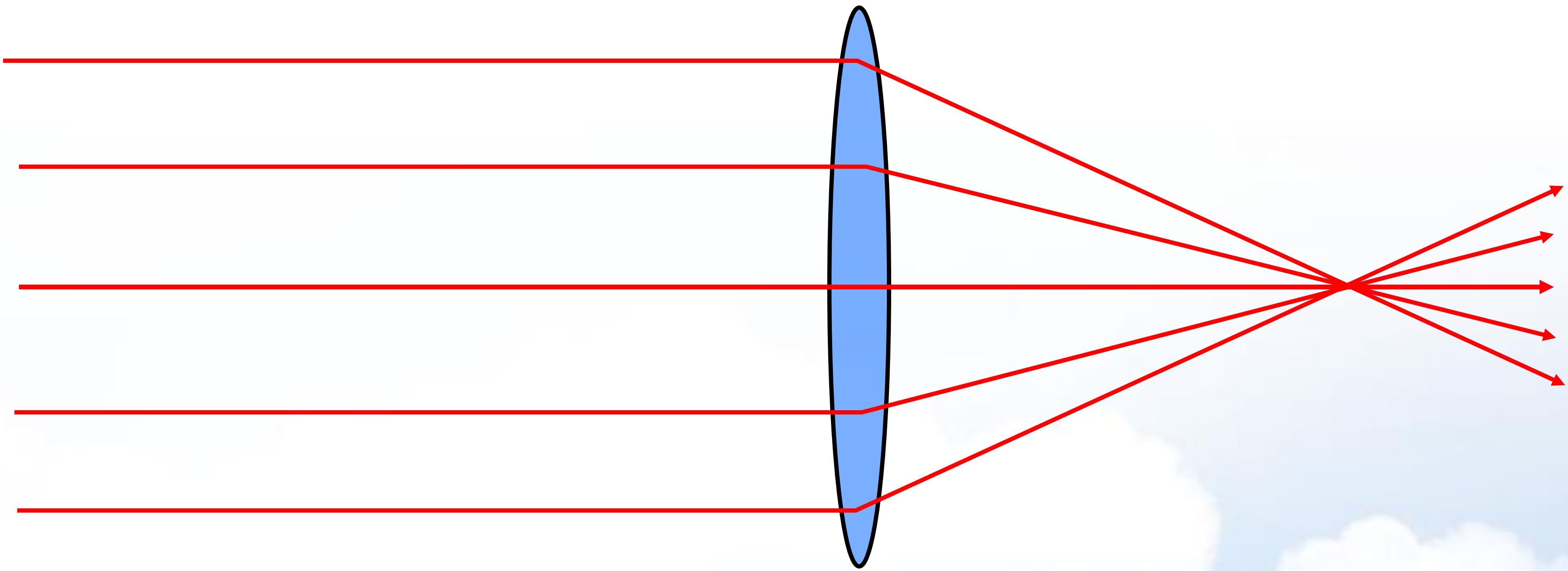
Airy Disk ~ 2.44 λ/D



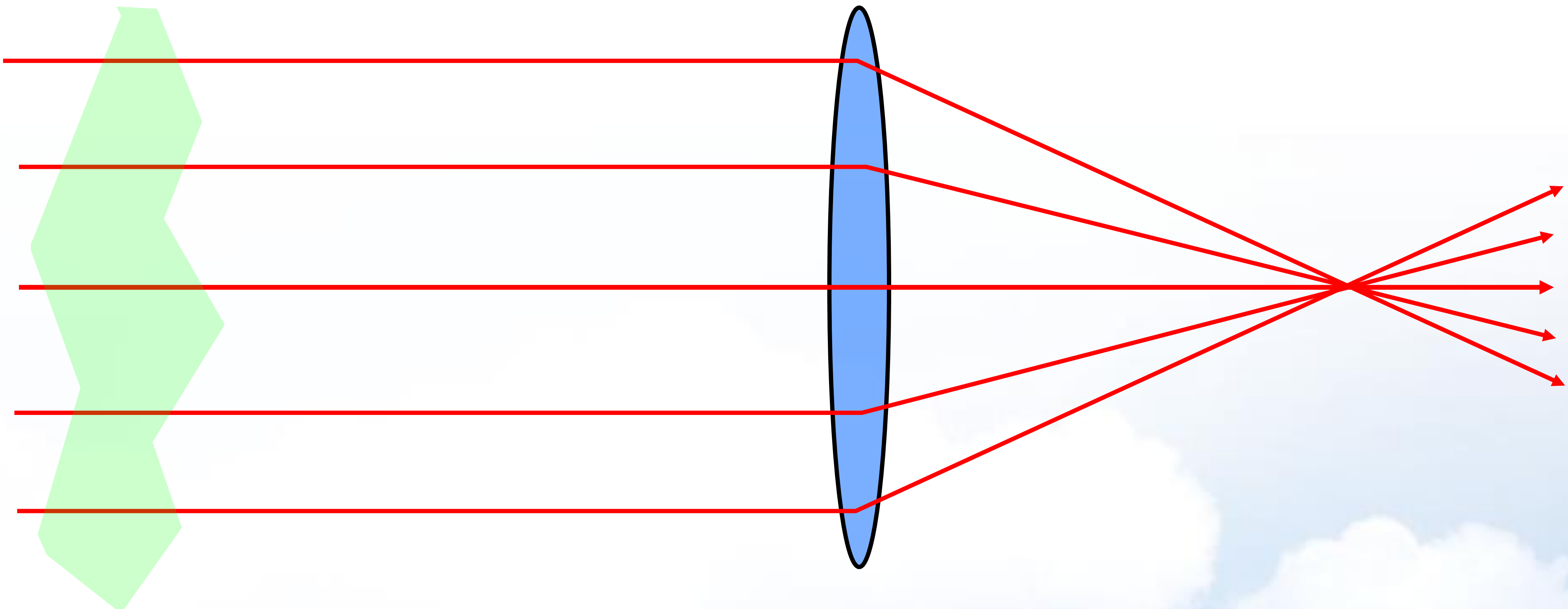
Interference by diffracted waves by two holes

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

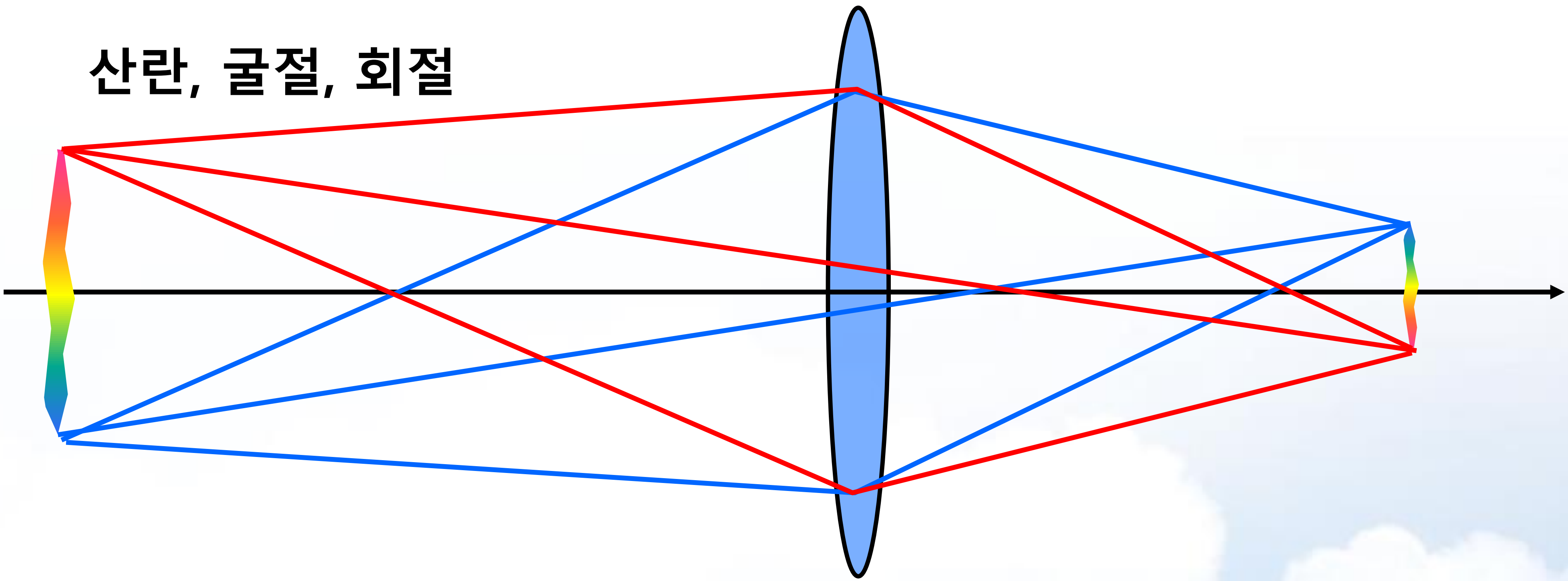
How are we able to see objects



How are we able to see objects



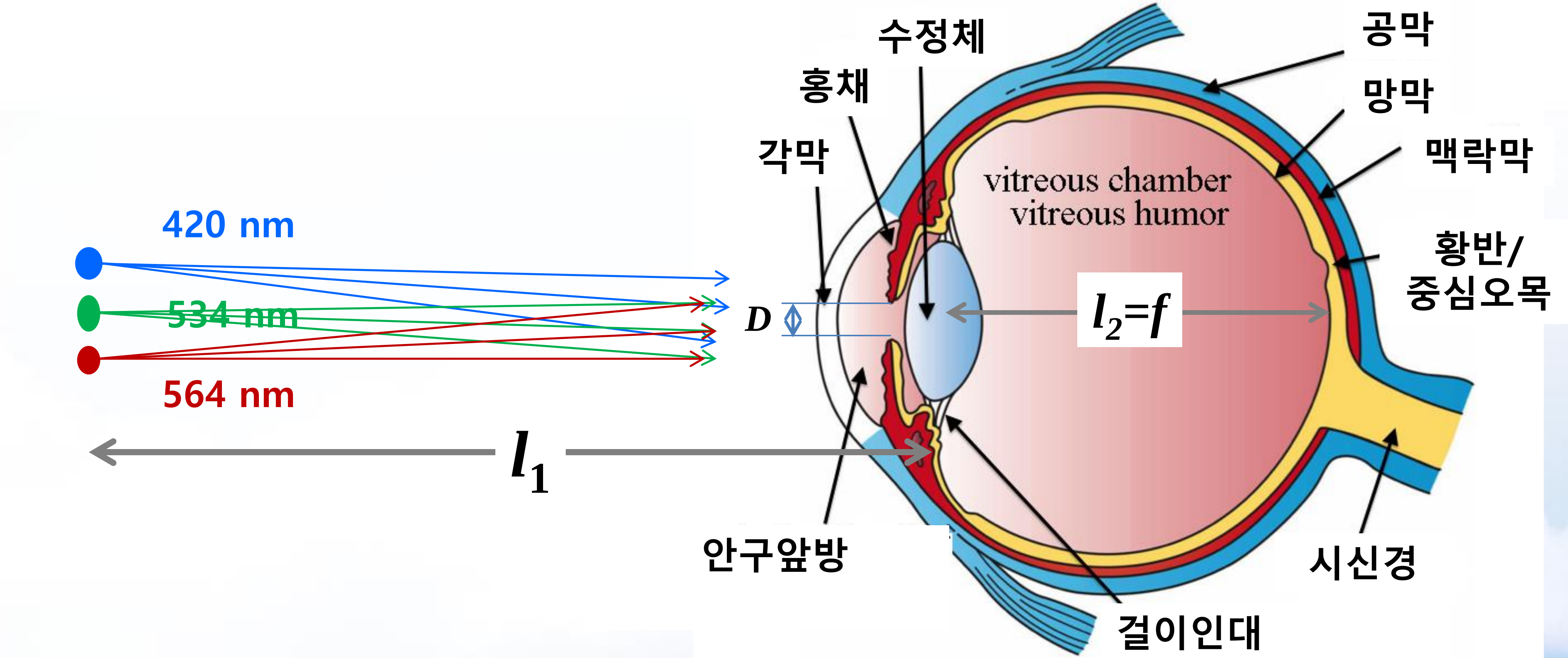
How are we able to see objects



How are we able to see objects

f/2~f/8

f/# = f/D



배율 = $M = l_2/l_1$

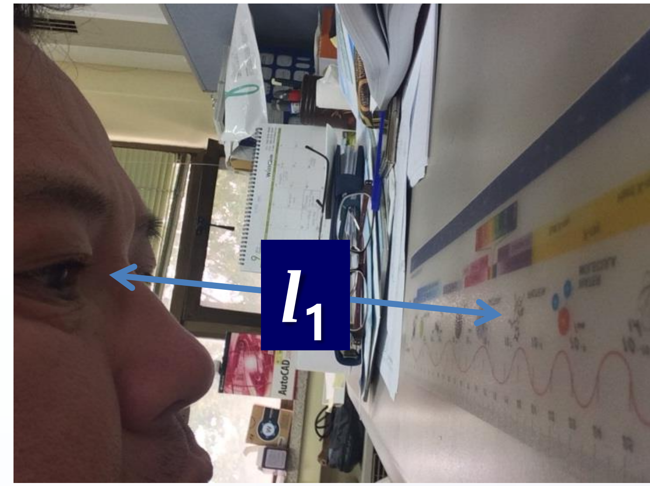
Spatial Resolution 공간분해능

나의 눈

l_1=100 mm, l_2=f=20 mm

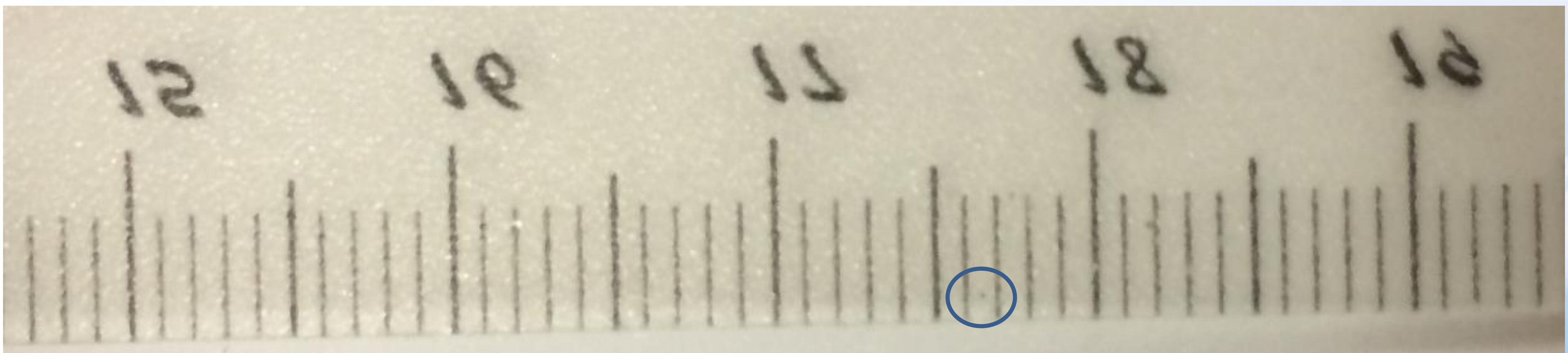
망막에서의 분해능 $\Delta l = 1.22 f \dfrac{\lambda}{D} \approx 3\ \mu m$

사물의 분해능 $= \Delta l \times \dfrac{l_1}{l_2} = 15\ \mu m$



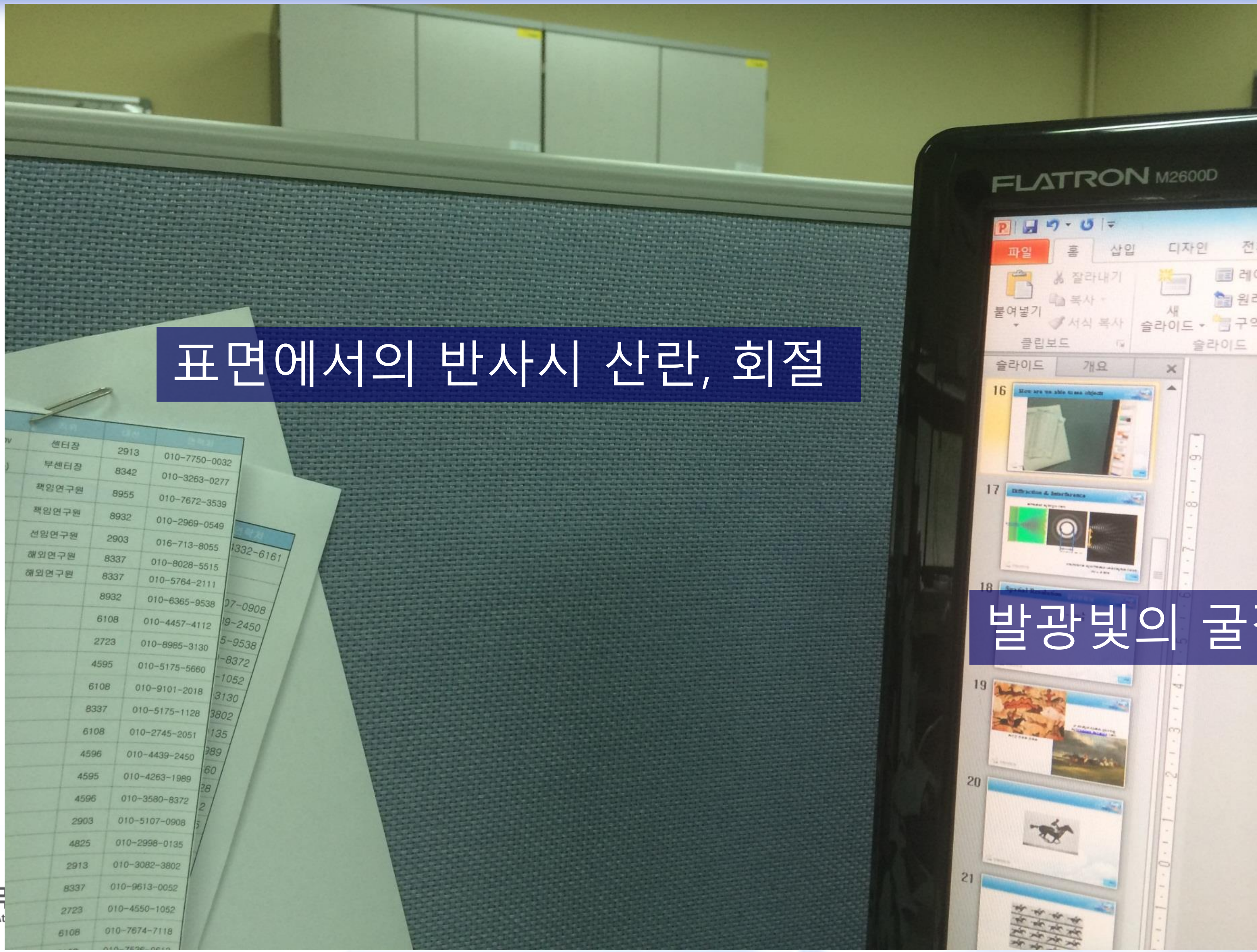
iPhone5S

iPhone 5S, 4.8X3.6 mm^2, l_1=100 mm, l_2 < 6 mm



See, Optics 4th Edition, Eugene Hecht, p473

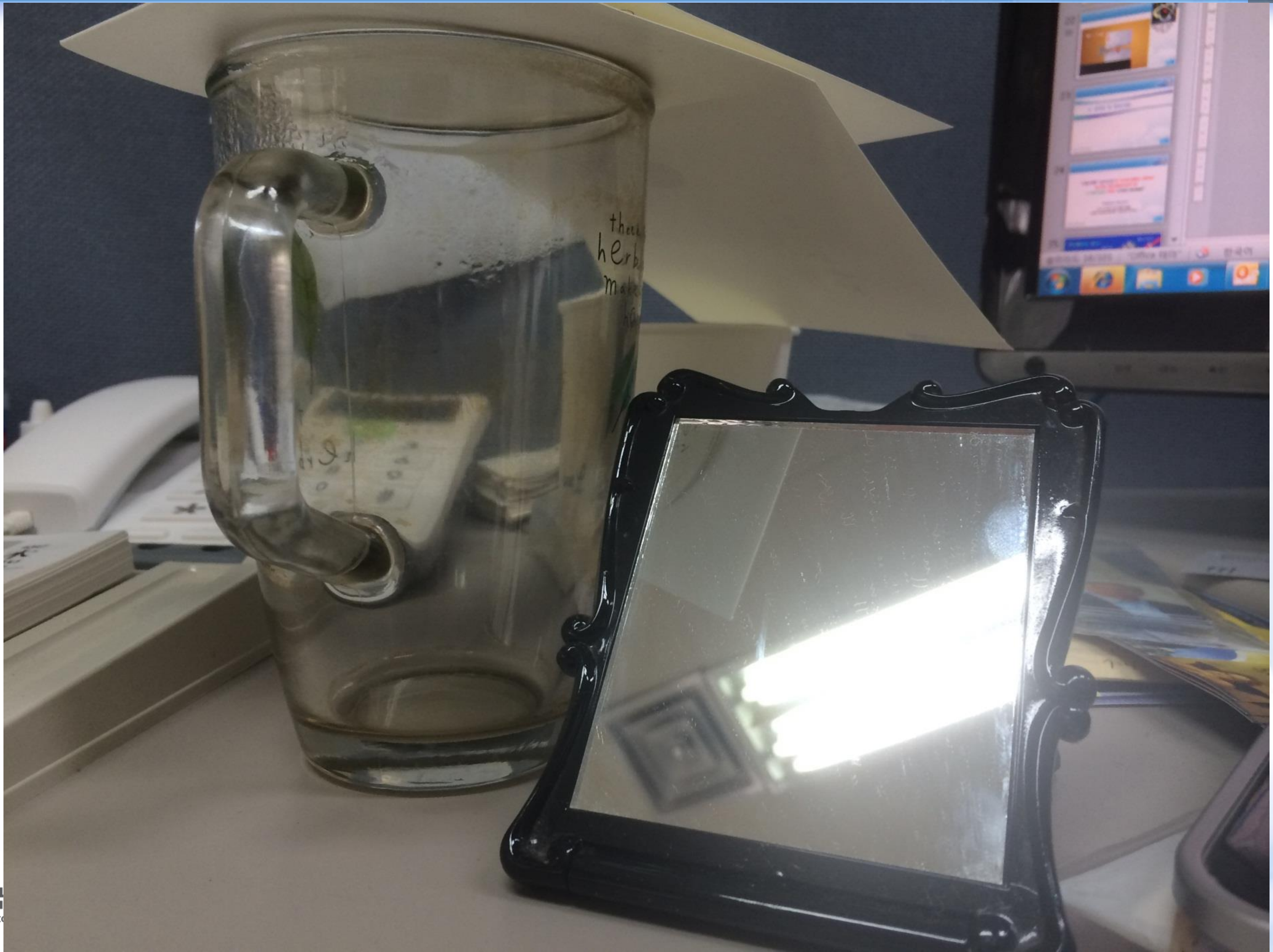
How are we able to see objects



표면에서의 반사시 산란, 회절

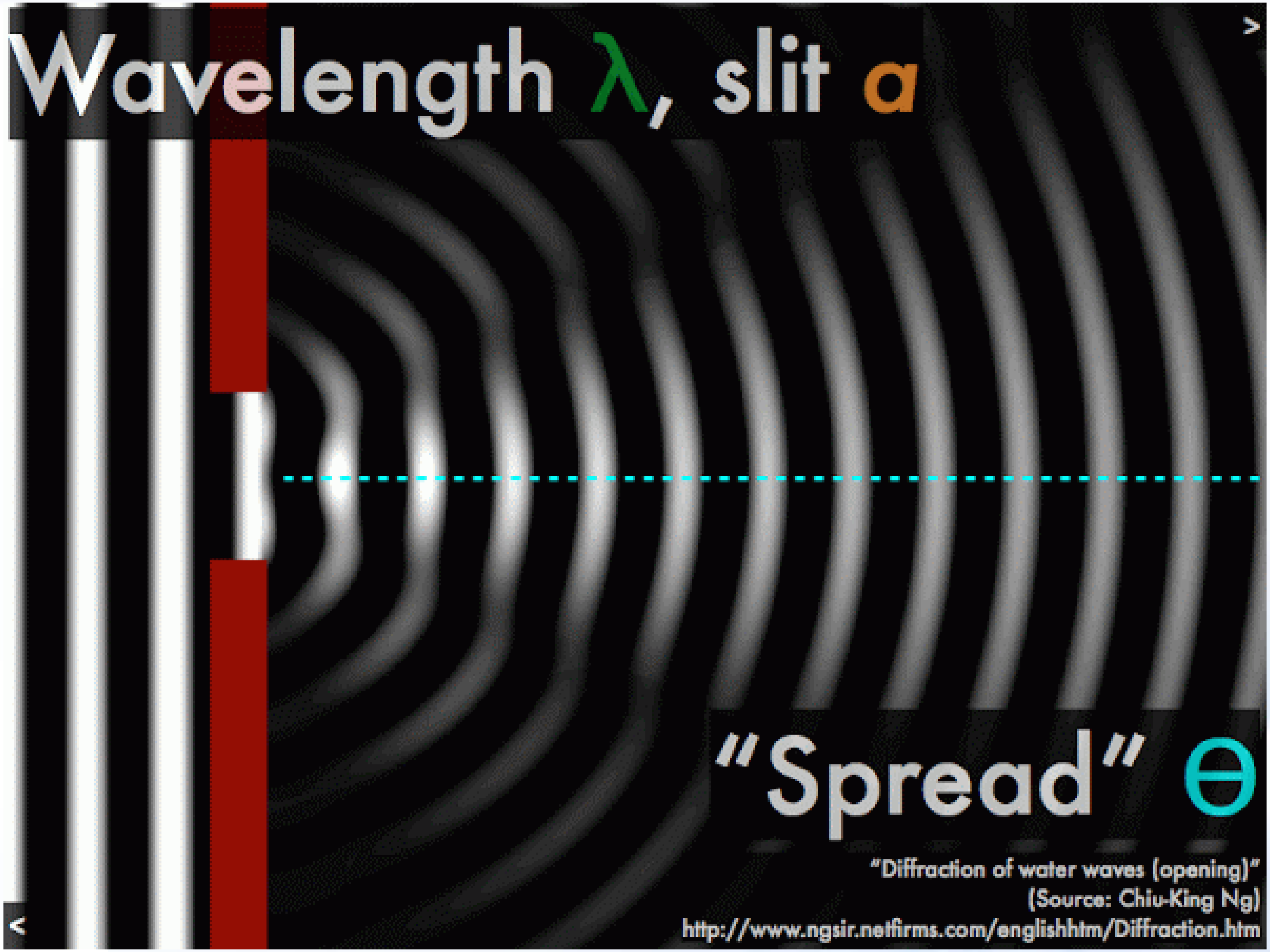
발광빛의 굴절, 회절

How are we able to see objects

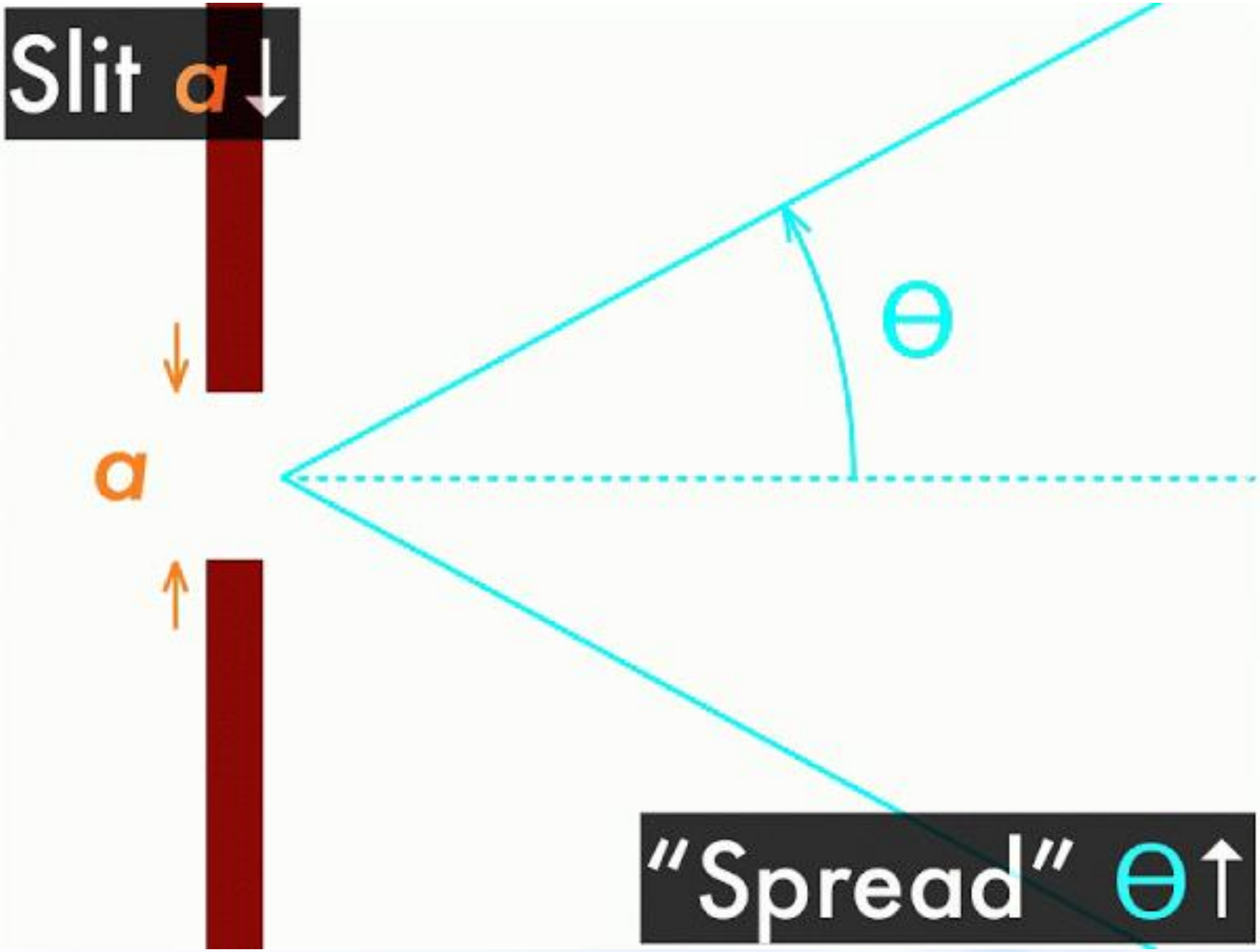


KAERI 한국
Korea At

Diffraction 회절

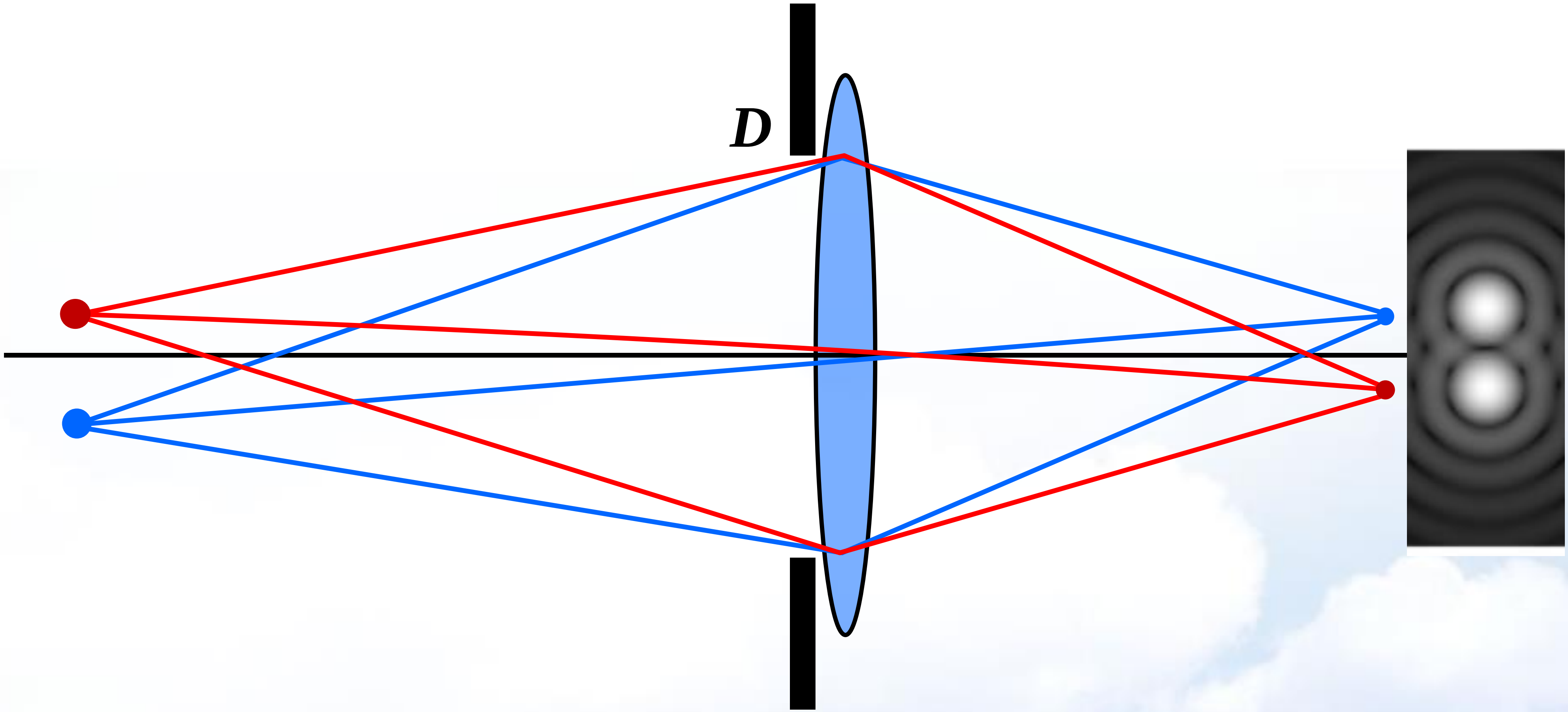


Diffraction 회절



Diffraction

회절

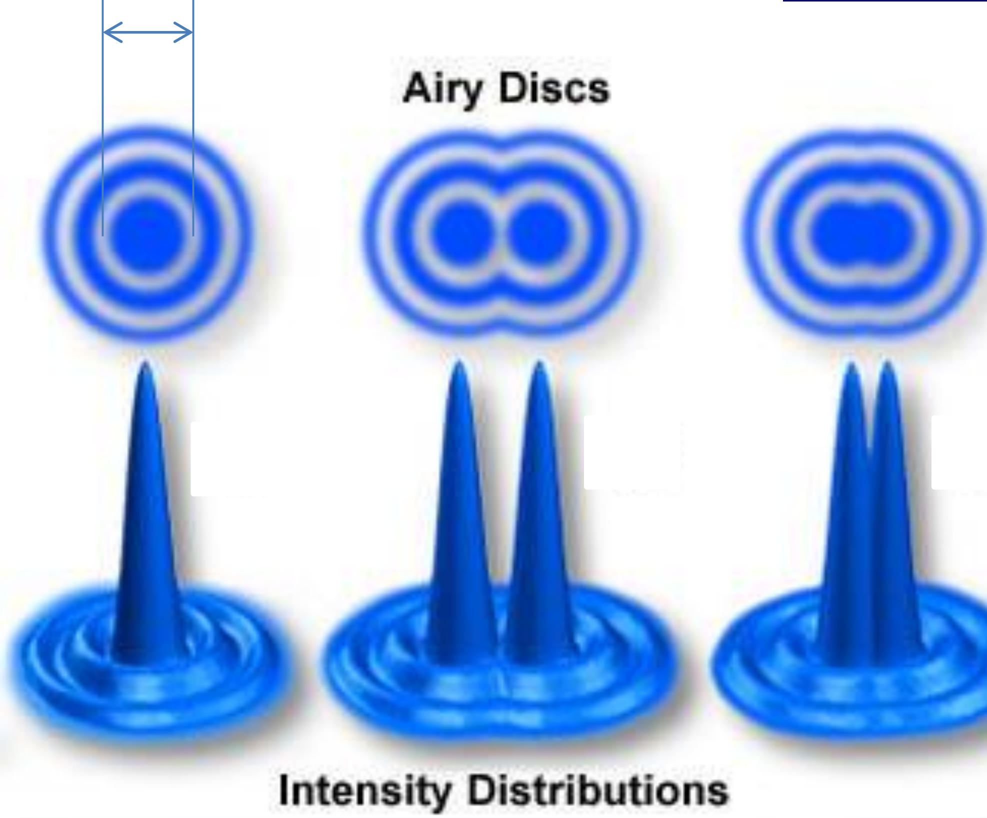


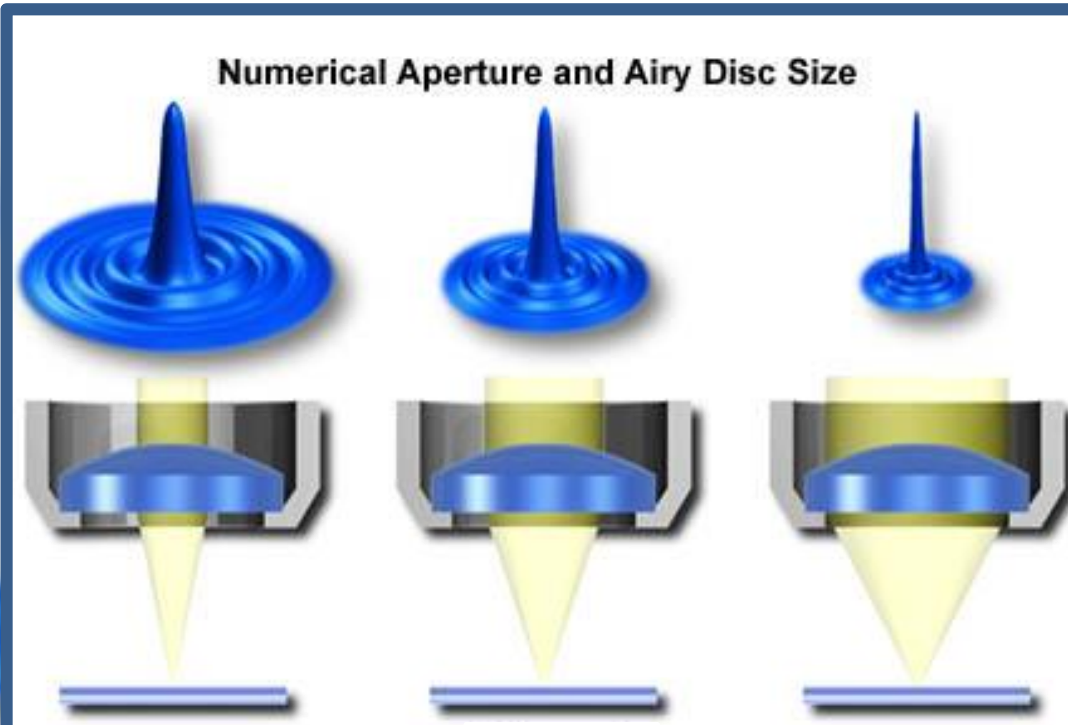
Resolving Power

분해능

$$\Delta l = 1.22 f \frac{\lambda}{D}$$

$2\Delta l$





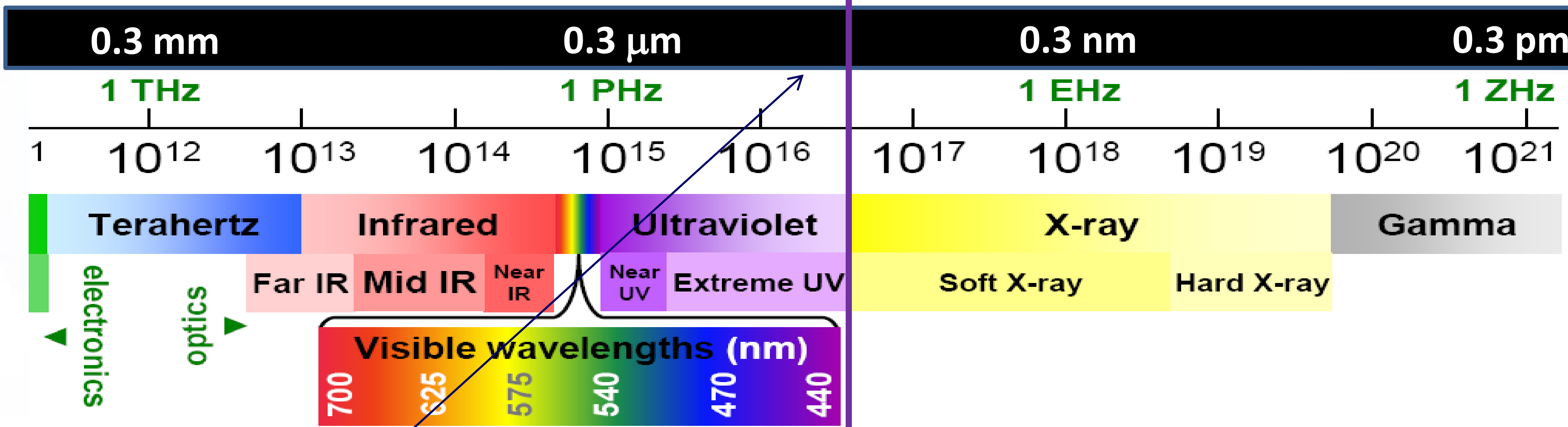
$\Delta l \approx \lambda$

Resolving Power

분해능

$\Delta l \approx \lambda$

Size of molecules : 0.1 ~ 100 nm



EUV for lithography : 13.5 nm

Resolving Power

분해능

Louis de Broglie (1892~1987)
Y1929 Novel laureate

$$\Delta l \approx \lambda$$

Matter Wave, Wavelength $\lambda = \frac{h}{p}$

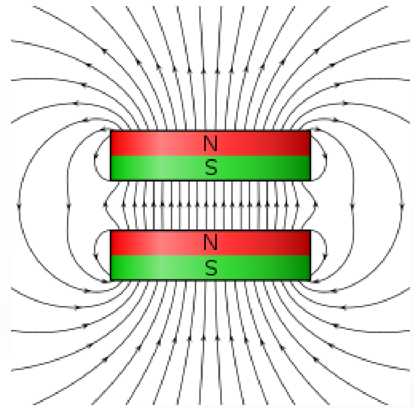
h : Plank constant
p : Momentum

Electron Kinetic Energy [MeV]	0.1	0.3	1	3	10
λ	3.7 pm	1.97 pm	0.872 pm	0.357 pm	0.118 pm

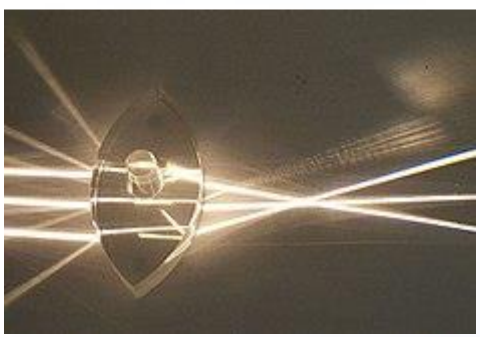
Size of molecules : 0.1 ~ 100 nm

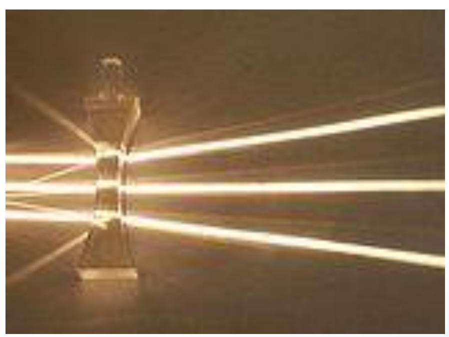
Electron Optics 전자광학

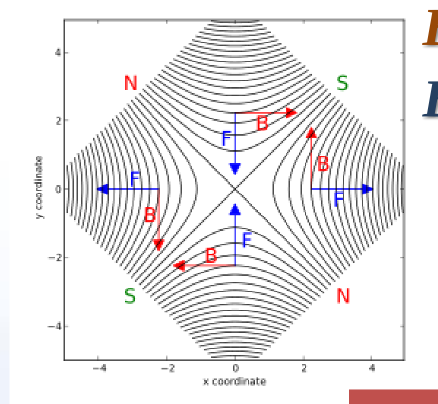
$$\vec{F} = q(\vec{E} + \vec{v} \times \vec{B})$$



Dipole magnet

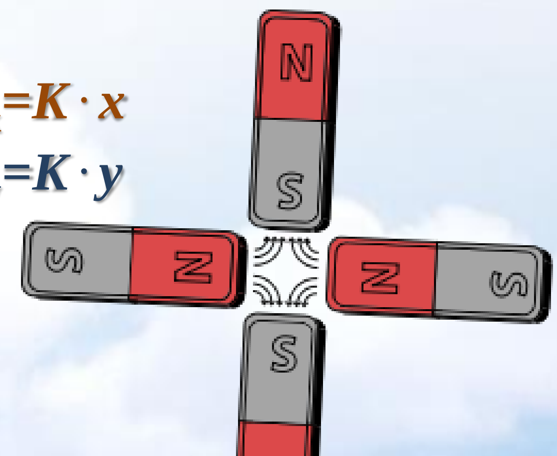






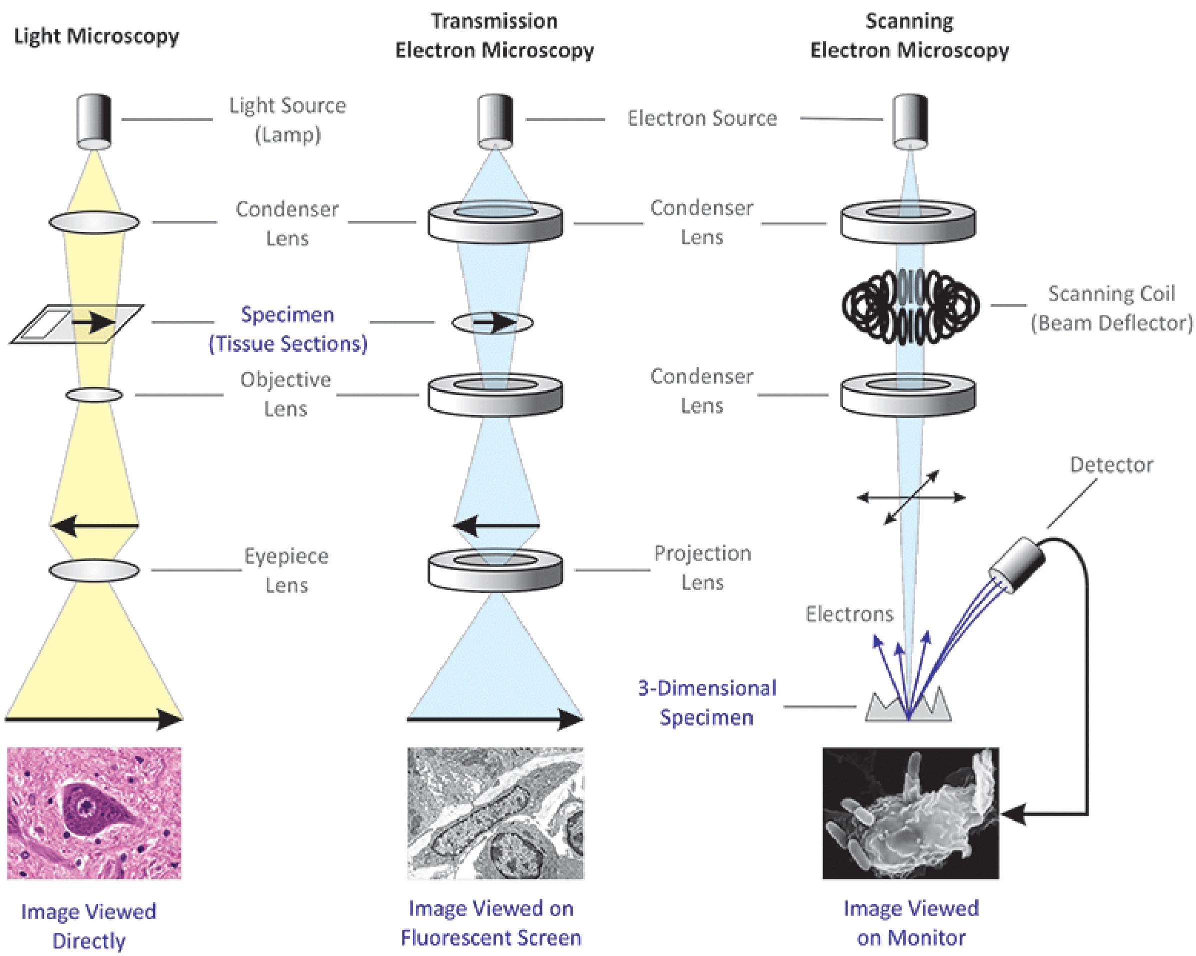
$B_x = K \cdot x$

$B_y = K \cdot y$



Quadrupole magnet

Microscopes 광학현미경과 전자현미경



500X~1500X

100,000X~300,000X

출처 : microbiologyinfo.com

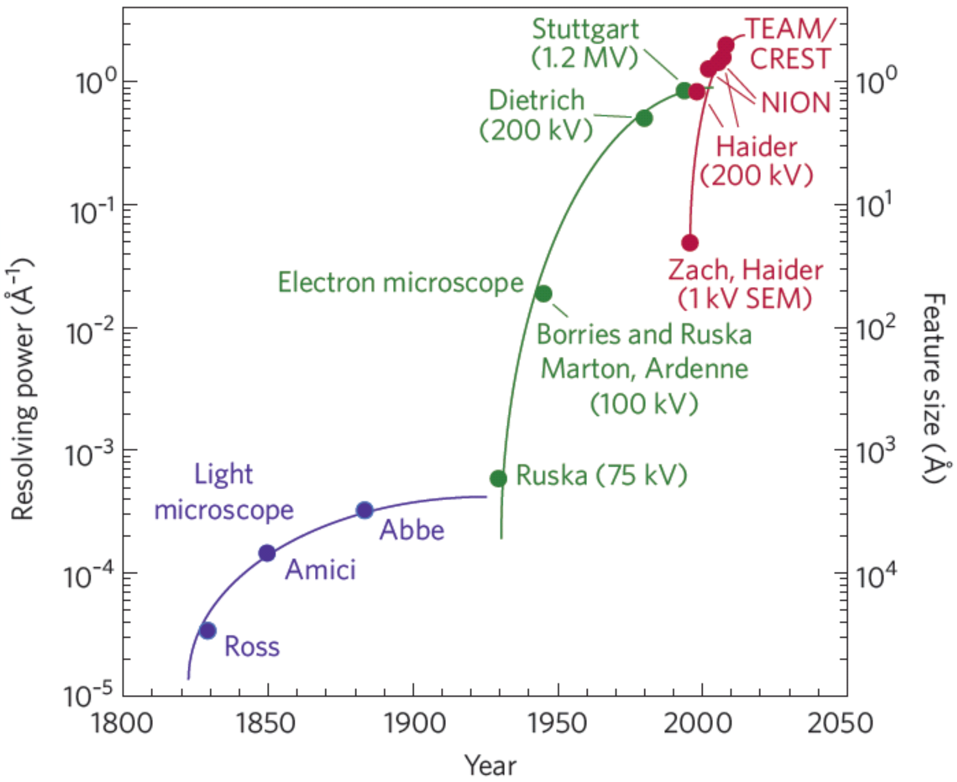
Resolving Power of Microscopes

현미경 공간분해능

Early Ross Compound Microscope (circa 1831)

Amici Achromatic Microscope (circa 1850)

Abbe-Zeiss Microscope (circa 1879)



D. A. Muller, *Nat. Mater.* **8**, 263 (2009).

Resolving Power of Microscopes

현미경 공간분해능

Spatial Resolution of 40.5 pm with a STEM

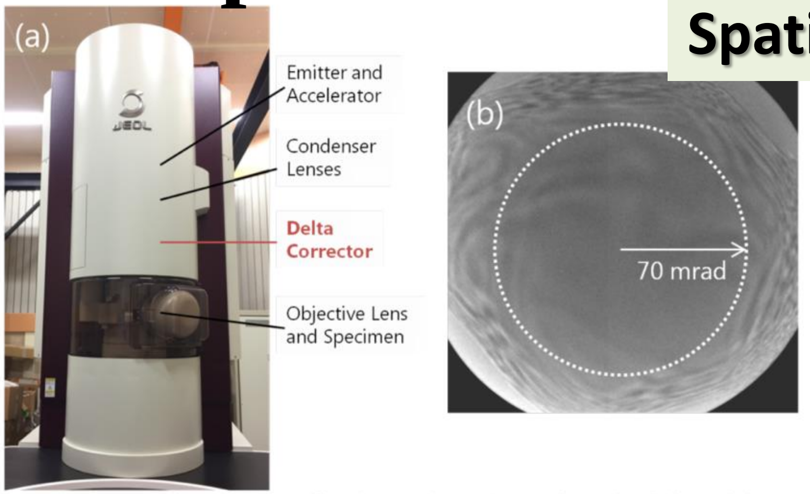


Figure 1. (a) 300 kV electron microscope (GRAND ARM) equipped with a delta corrector and a cold field emission gun for STEM. (b) Ronchigram at 300 kV after aberration correction with delta type corrector for probe forming system.

$$\Delta l = 1.22 f \frac{\lambda}{D} = 0.61 \frac{\lambda}{\alpha}$$

30.5 pm

$$\alpha = \frac{D}{2f}$$

Convergence angle (Numerical Aperture)

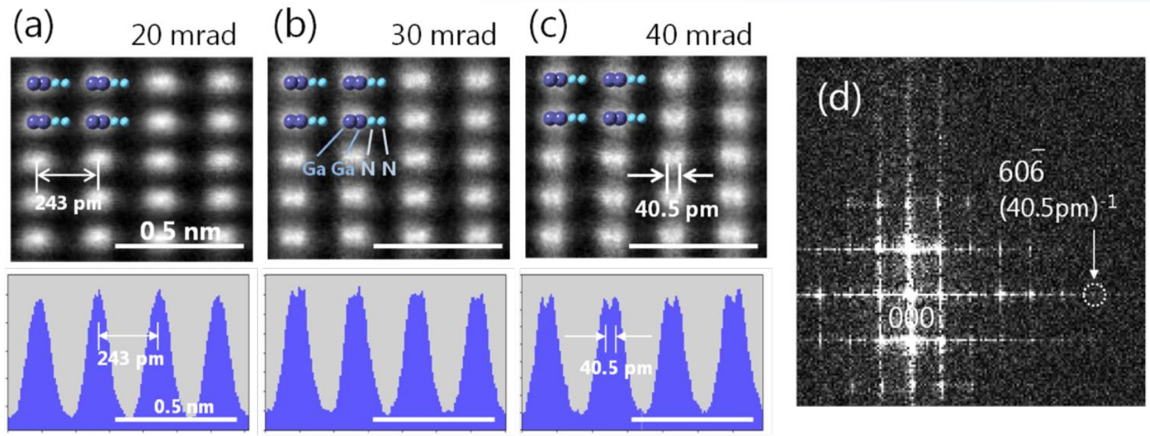


Figure 2. ADF STEM images of GaN [212] with convergence semi-angles of (a) 20 mard, (b) 30 mrad and (c) 40 mrad. Intensity profiles of these images are also shown below. (d) Modulus of the Fourier transform from the image obtained with the 40 mrad convergence angle.

Shigeyuki Morishita, *et. al.*, '**Resolution Achievement of 40.5 pm in Scanning Transmission Electron Microscopy using 300 kV Microscope with Delta Corrector**', Microsc. Microanal. 24 (Suppl 1), (2018).

Brightness 전자빔 밝기

Ernst Ruska,
1986 Nobel Prize
for the invention
of the electron microscope

$$B = \frac{I}{S\Omega}$$

Current (I)

Beam cross-section (S)

Beam solid angle (Ω)

$B_{microscope} \sim 10^{13}$ A/m²/sr

$$B = \eta \frac{I}{\epsilon_x \epsilon_y}$$

Transverse emittances ($\epsilon_x \epsilon_y$)

Coherence Length 결맞음 길이

$$l_{longitudinal\ coherence} \propto \frac{1}{\Delta E}$$

ΔE : Energy spread of e-beam

$$l_{transverse\ coherence} \propto \frac{1}{R_{source}}$$

R_{source} : Electron beam radius at the source

Emittance 에미턴스

Electrons moving through z-axis

$$\sigma_x = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(x_i - \langle x\rangle)^2} \qquad \sigma'_x = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(x'_i - \langle x'\rangle)^2} \qquad x' = \frac{dx}{dz}$$

$$\sigma_y = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(y_i - \langle y\rangle)^2} \qquad \sigma'_y = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(y'_i - \langle y'\rangle)^2} \qquad y' = \frac{dy}{dz}$$

Deviation of electron's position

Deviation of electron's angle

$$\epsilon_x = 4\sigma_x\sigma'_x$$

$$\epsilon_y = 4\sigma_y\sigma'_y$$

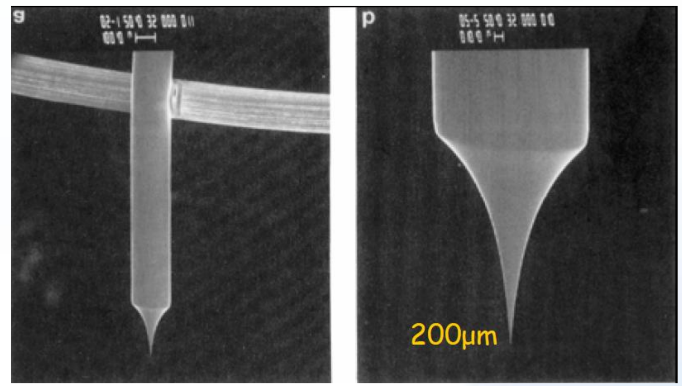
Conserved with linear optics (Liouville's theorem)

Electron Sources

전자총

- **Thermionic gun**

- **Field emission gun**



- **Photoelectron gun**

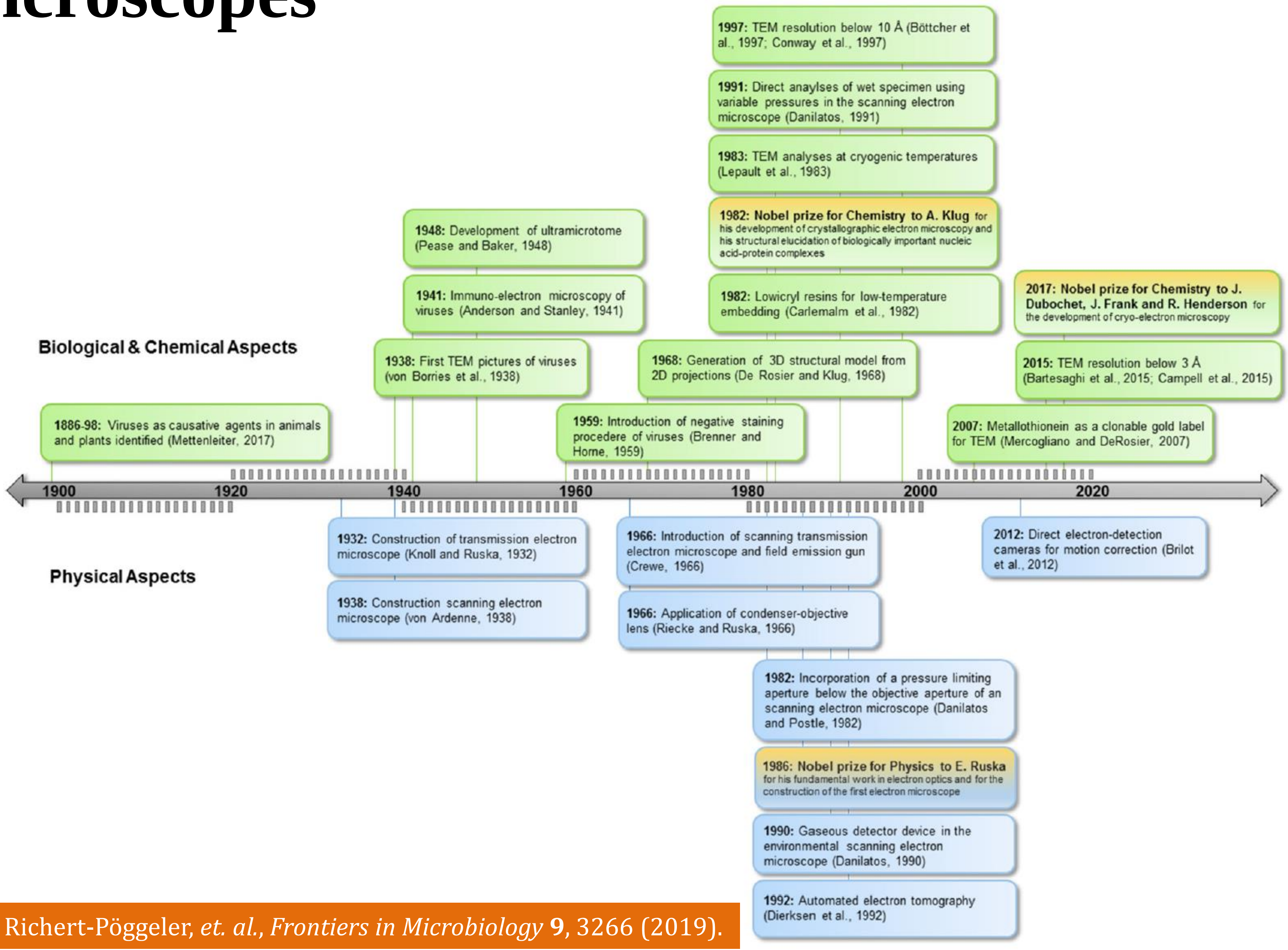
Electron Sources

Characteristics of the 3 principal sources operating 100 kV

	Tungsten	LaB_6	Field Emission
Operating temp. (K)	2700	2000	300
Current density (A/cm^2)	5	100	10^6
Crossover size (μm)	50	10	< 0.01
Brightness ($A/m^2/sr$)	10^9	5×10^{10}	10^{13}
Energy spread (eV)	3	1.5	0.3
Vacuum (Pa)	10^{-2}	10^{-4}	10^{-8}
Lifetime (hr)	100	500	> 1000
Emission current stability (%/hr)	< 1	< 1	5

History of Electron Microscopes

전자현미경의 역사



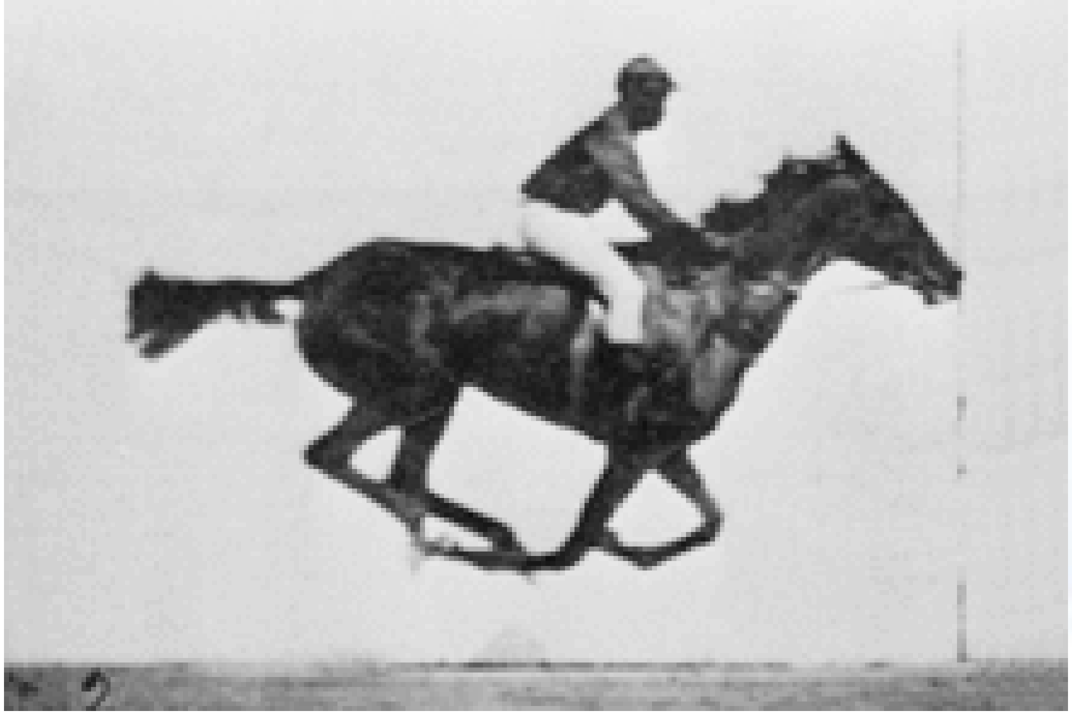
Katja R. Richert-Pöggeler, *et. al., Frontiers in Microbiology* **9**, 3266 (2019).

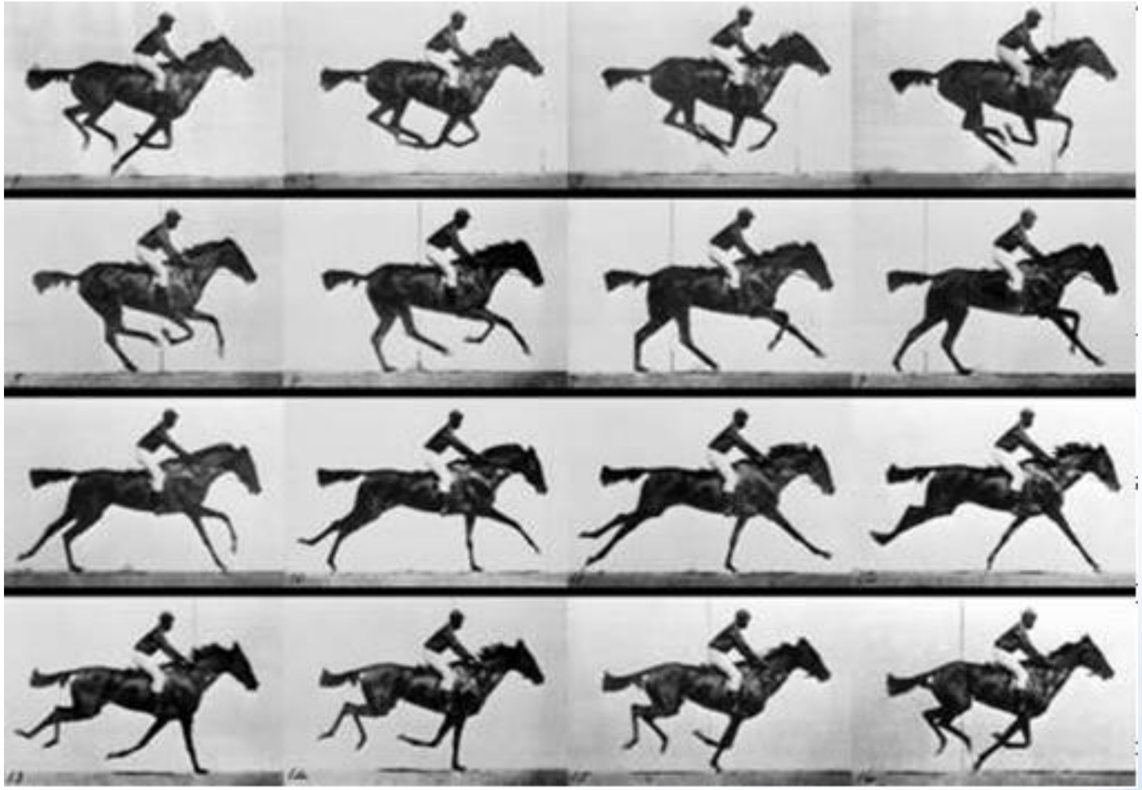
III. Temporal Confinement of Free Electrons

고구려 무용총 수렵도

Le derby d'Epsom, painting
by Théodore Géricault, 1821

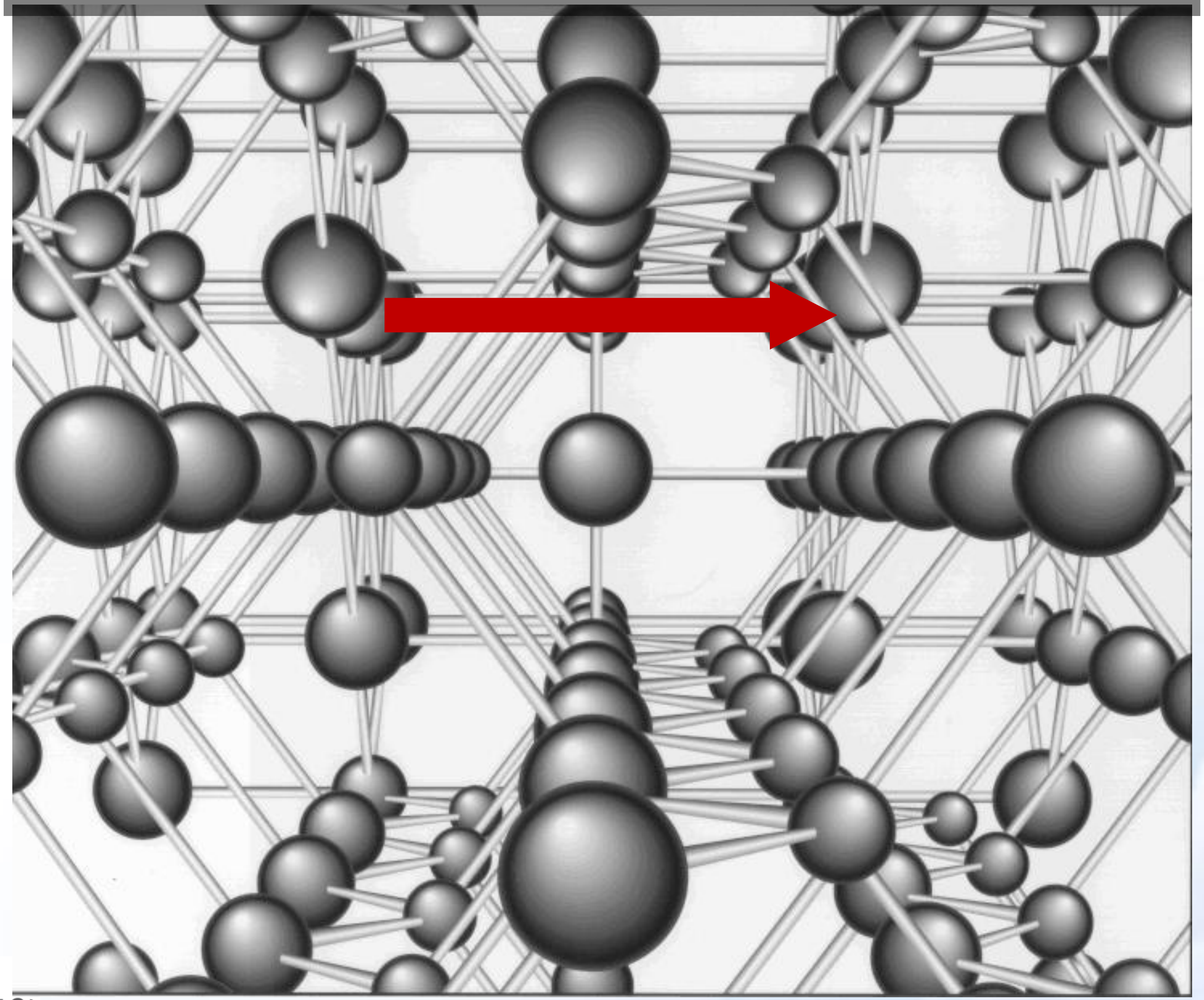
한국원자력연구원
Korea Atomic Energy Research Institute





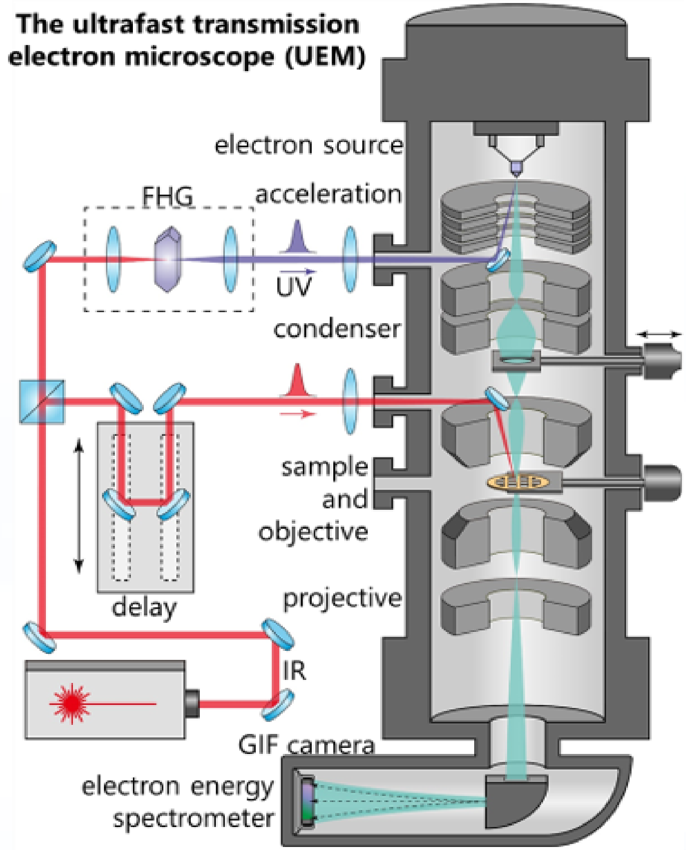
Eadweard Muybridge (1830. 4. 9 ~ 1904. 5. 8)

Time for sonic wave passing through a molecule 10~1000 fs

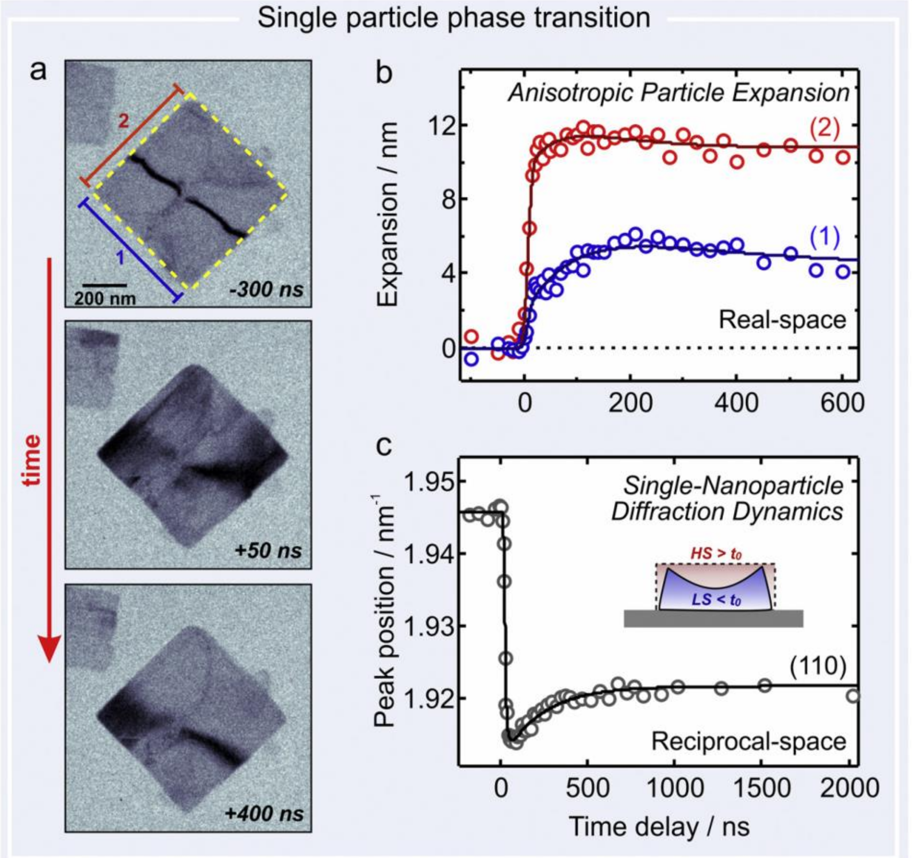


한국원자력연구원
Korea Atomic Energy Research Institute

Time-resolved TEM (UEM or UED)



Referred from website of Kaminer group @ TECHNION

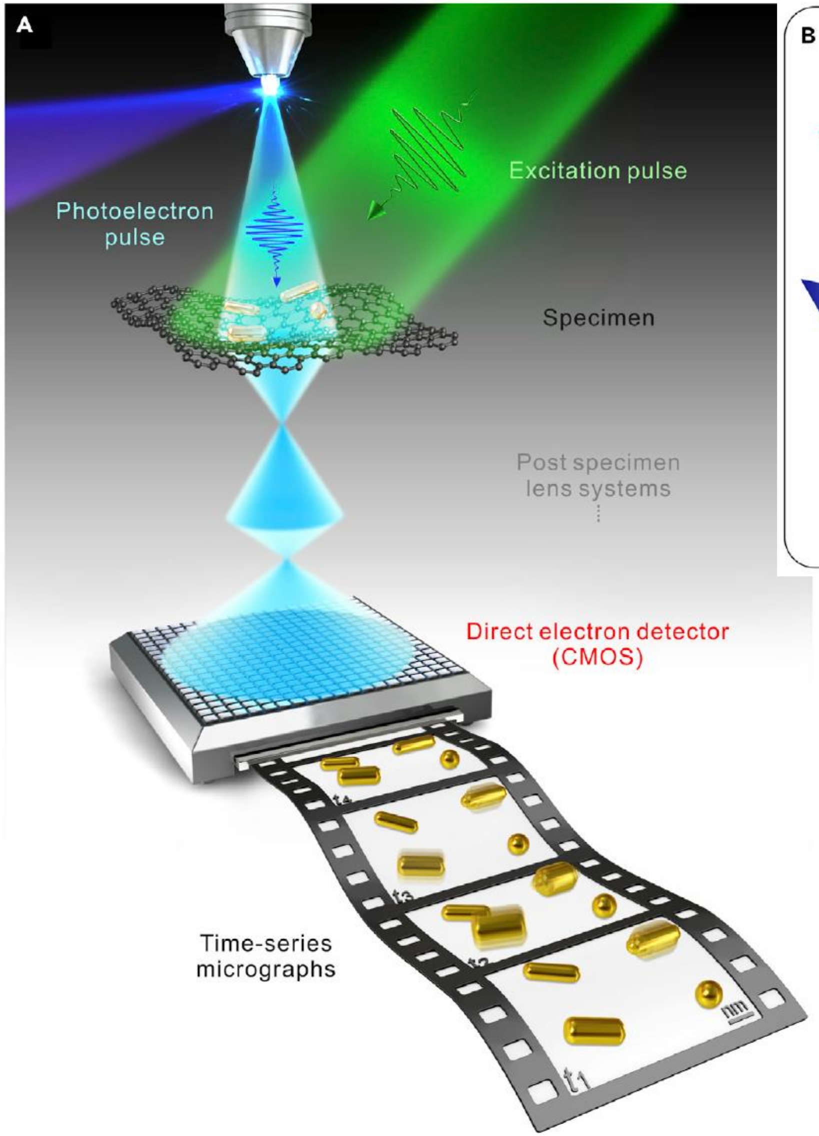


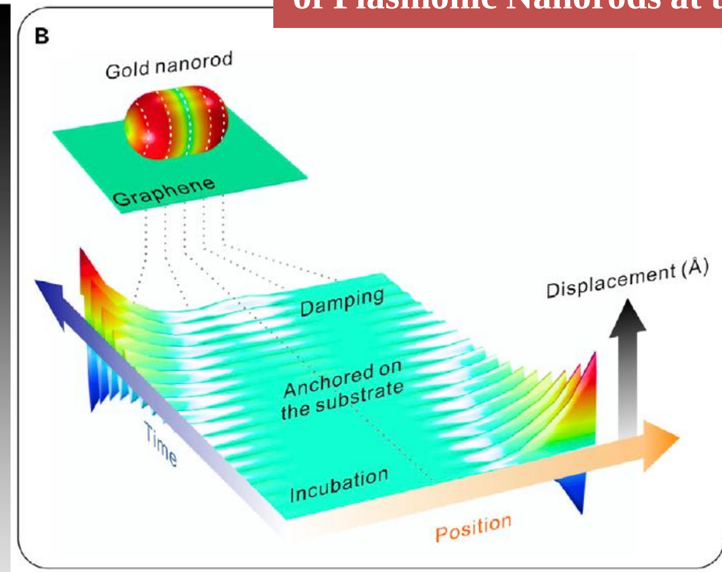
R.M. van der Veen *et al., Nat. Chem.* **5**, 395-402 (2013).

시분해 전자현미경

Time-resolved TEM (UEM)

Ultrafast Electron Microscopy Visualizes Acoustic Vibrations of Plasmonic Nanorods at the Interfaces, Matter 1, 481, 2019

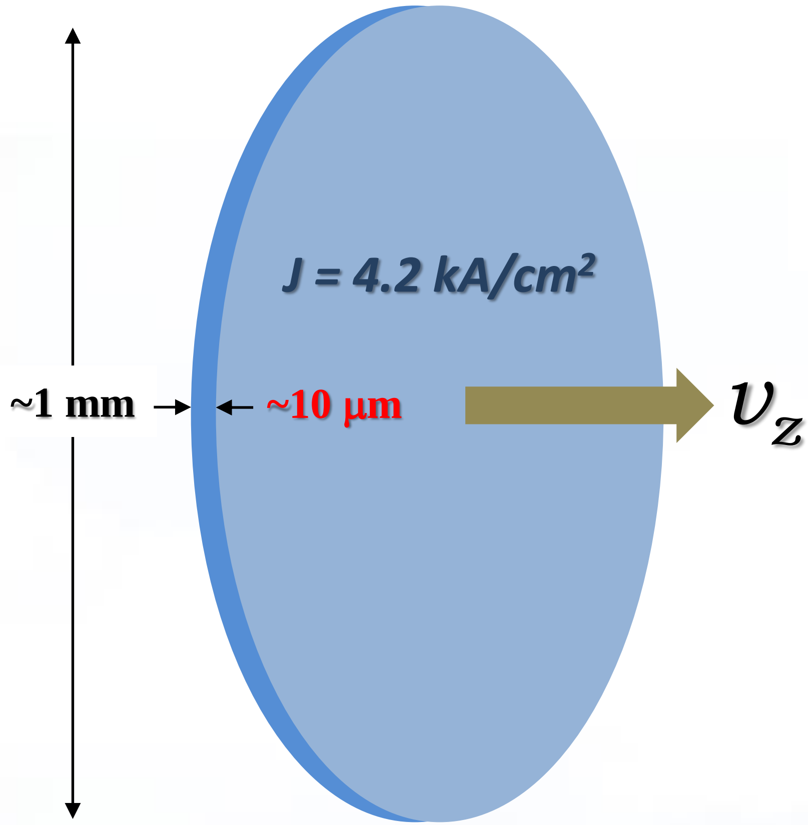


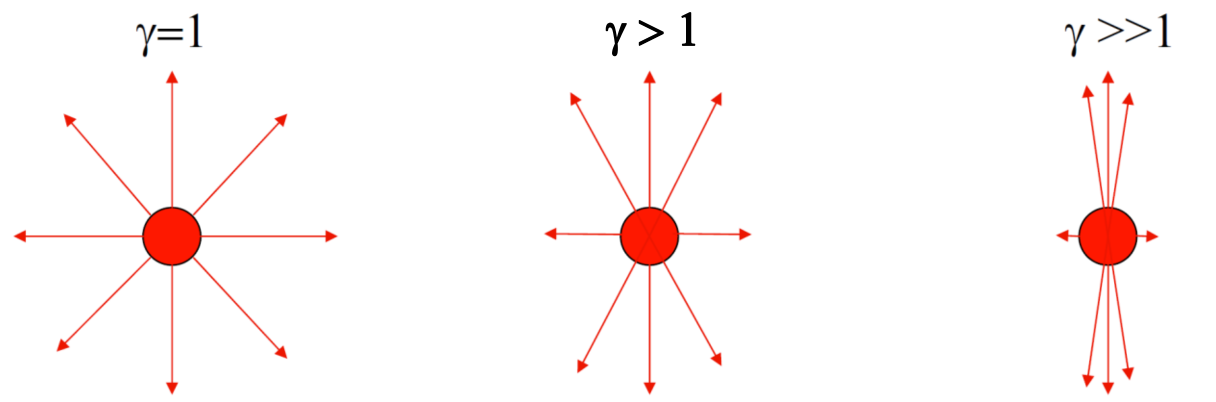


Electron Flash

초고속 전자빔

Compressed electron beam of
30 fs bunch duration
and 1 pC bunch charge





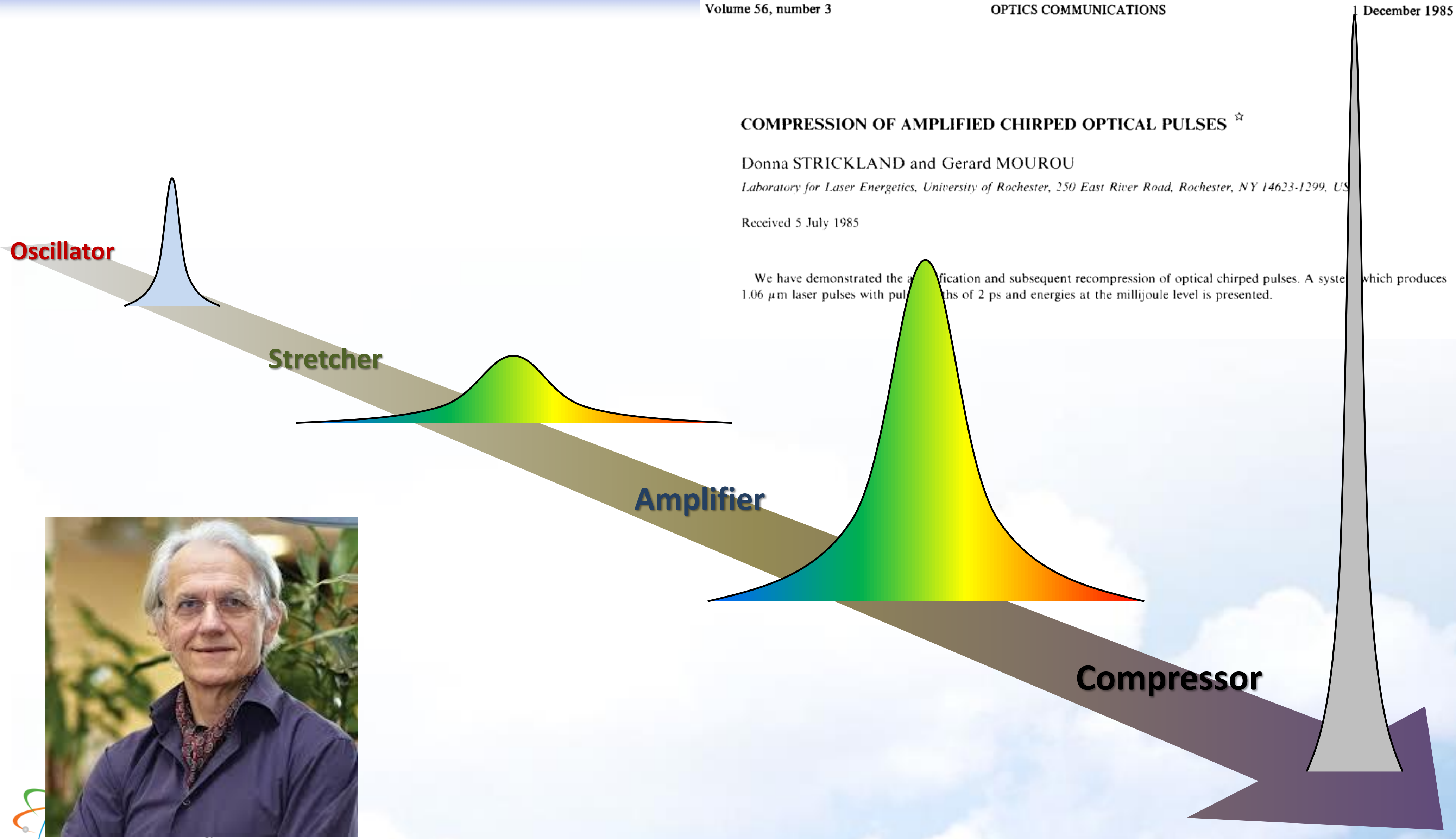
$$E_r(z=0) = \frac{q}{4\pi\varepsilon_0}\frac{\gamma}{r^2},$$

$$B_\varphi(z=0) = \frac{q\beta}{4\pi\varepsilon_0 c}\frac{\gamma}{r^2},$$

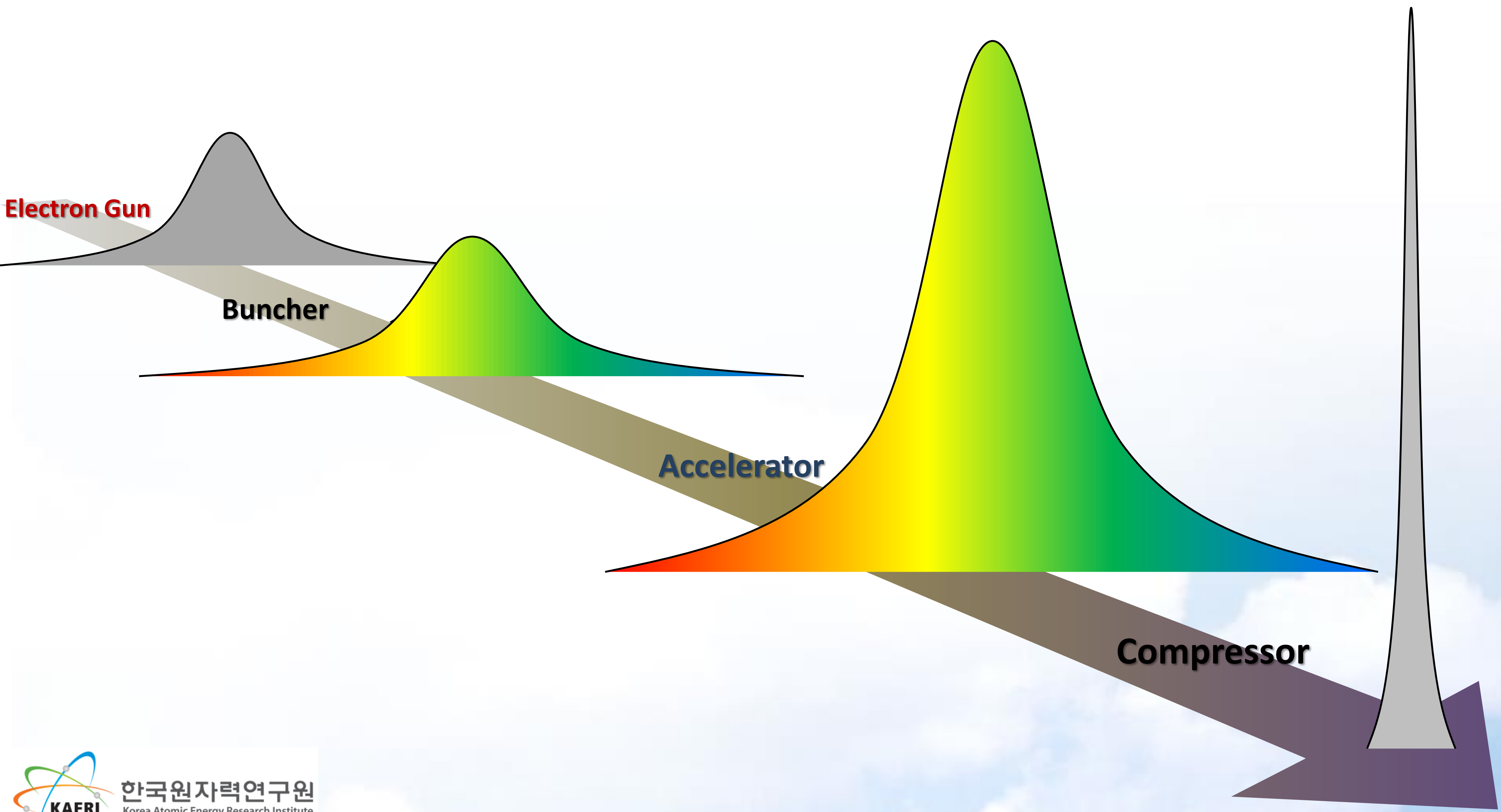
$$E_z(r=0) = \frac{q}{4\pi\varepsilon_0}\frac{1}{\gamma^2 z^2}$$

$$F_r = q\left(E_r - \beta c B_\varphi\right) = \frac{qq\gamma}{4\pi\varepsilon_0 r^2}\left(1-\beta^2\right) = \frac{q^2}{4\pi\varepsilon_0\gamma}\frac{1}{r^2}$$

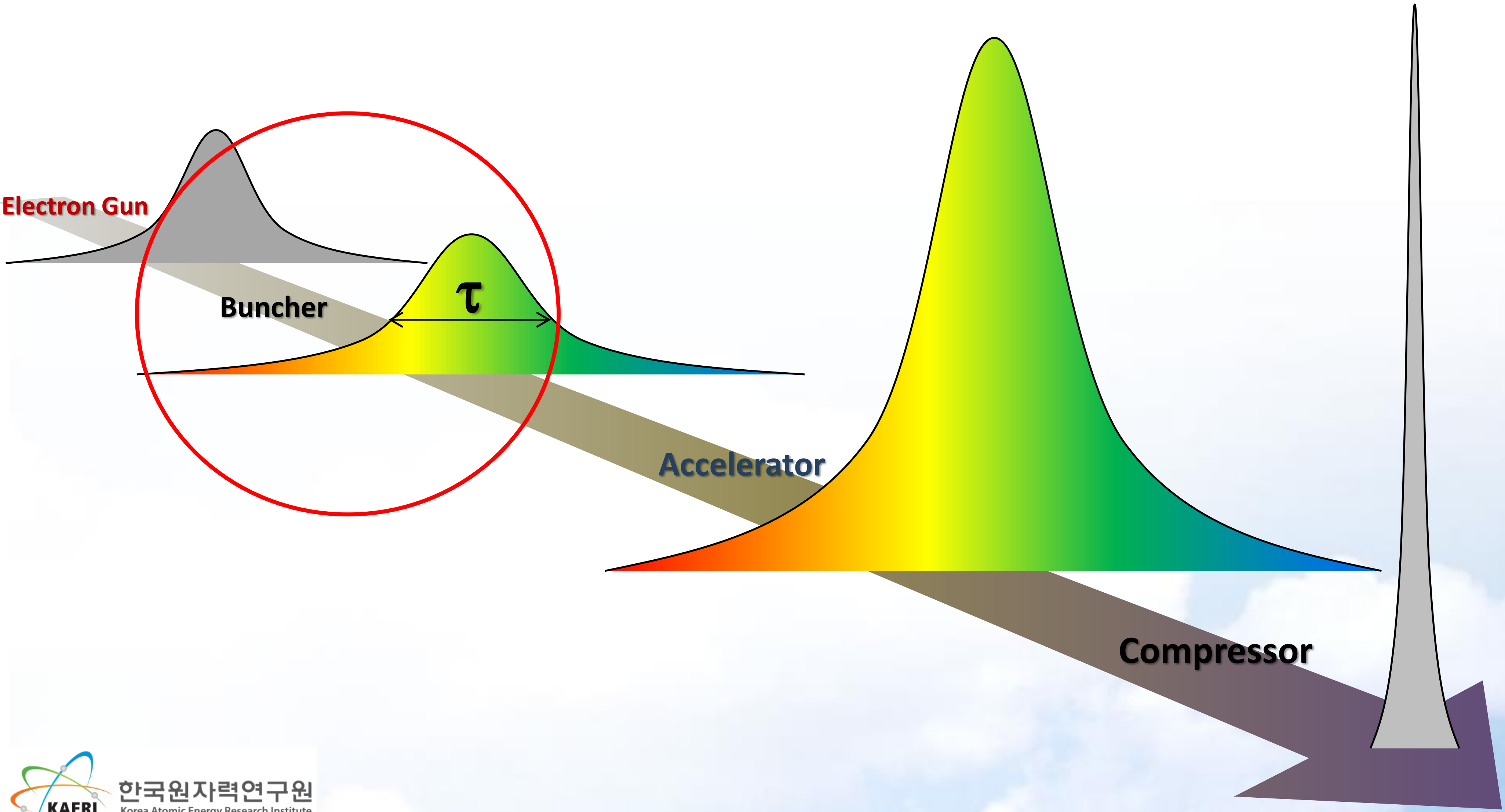
Chirped Pulse Amplification



Electron Bunch Compression

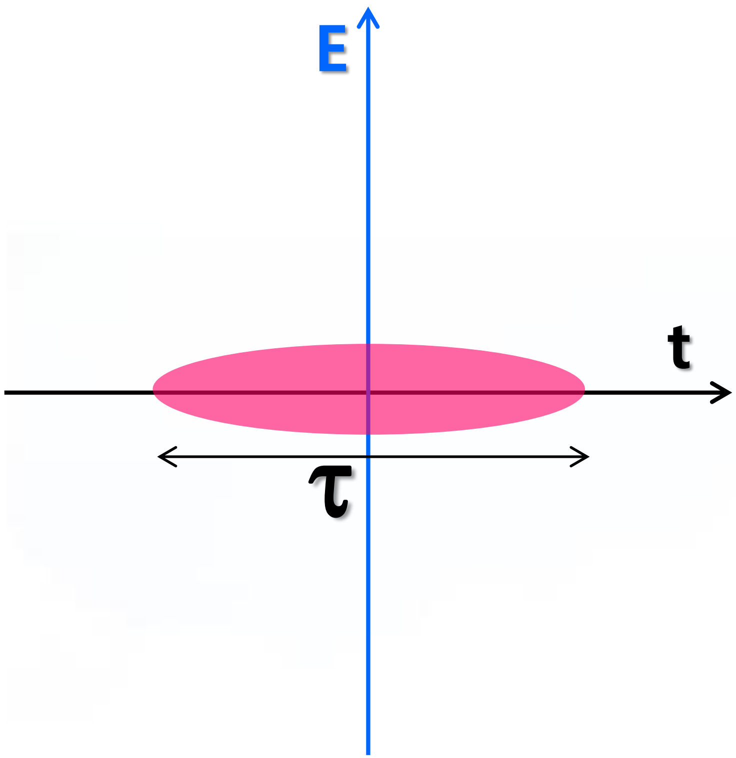


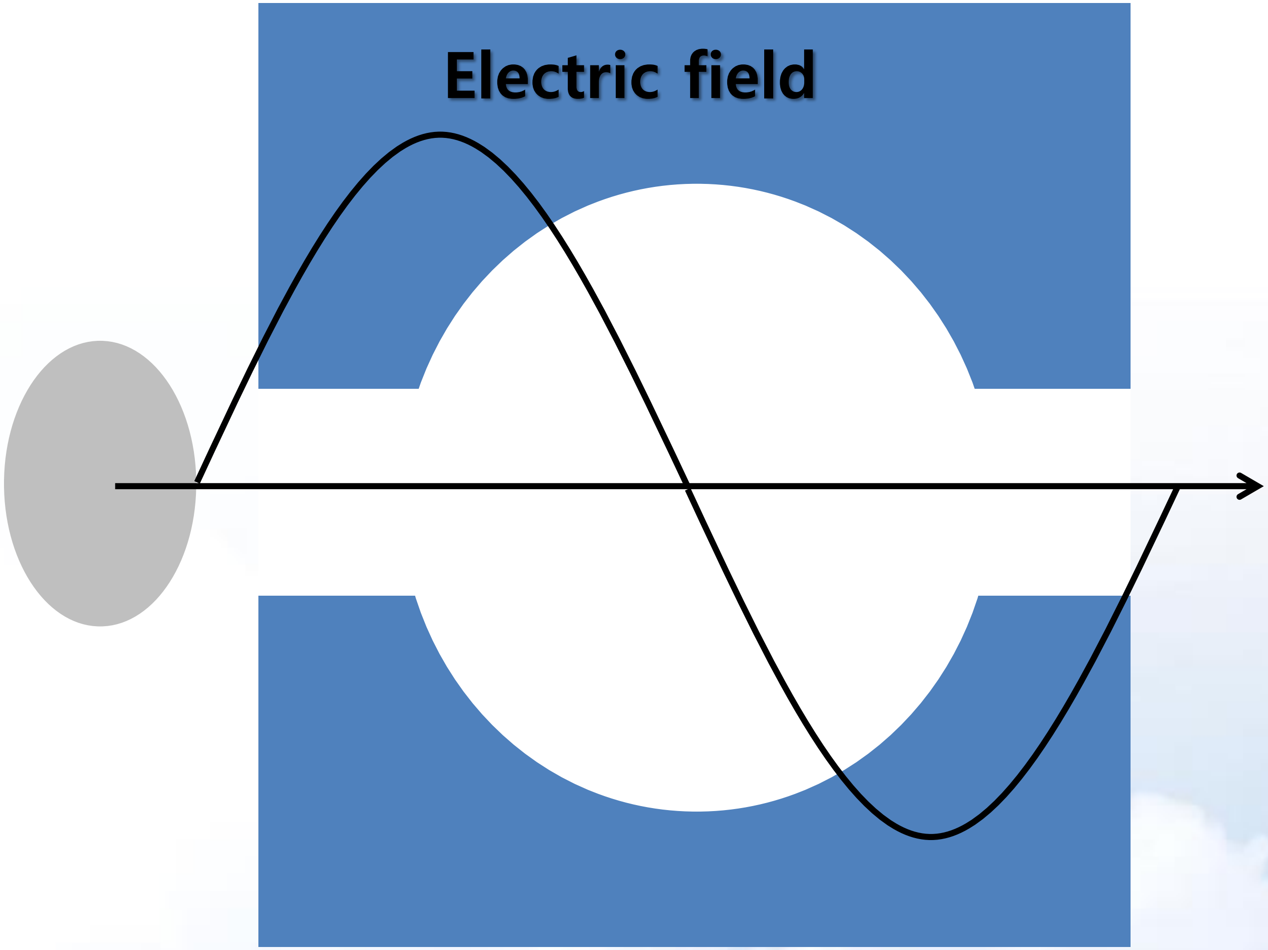
Electron Bunch Compression



KAERI 한국원자력연구원 Korea Atomic Energy Research Institute

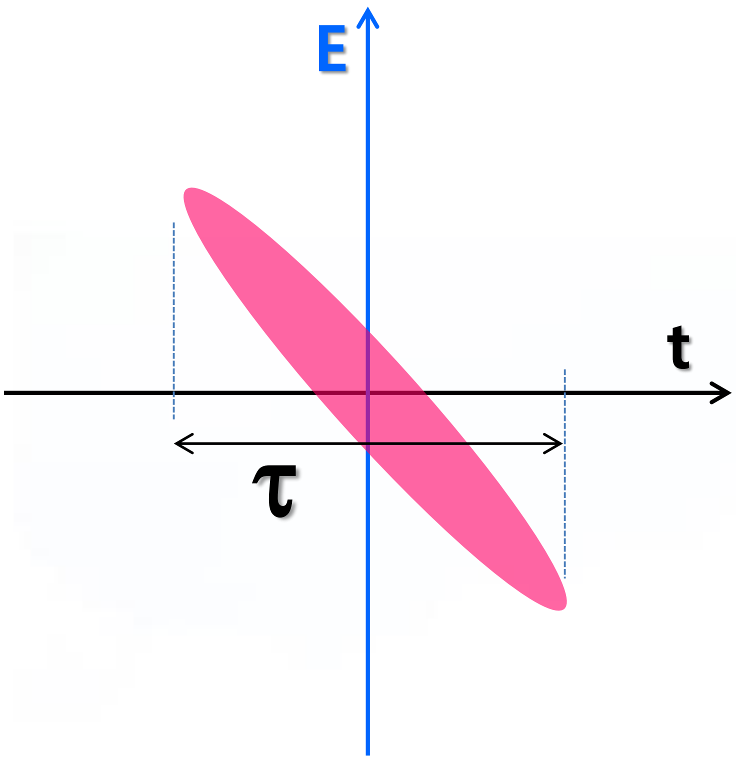
Electron Bunch Compression

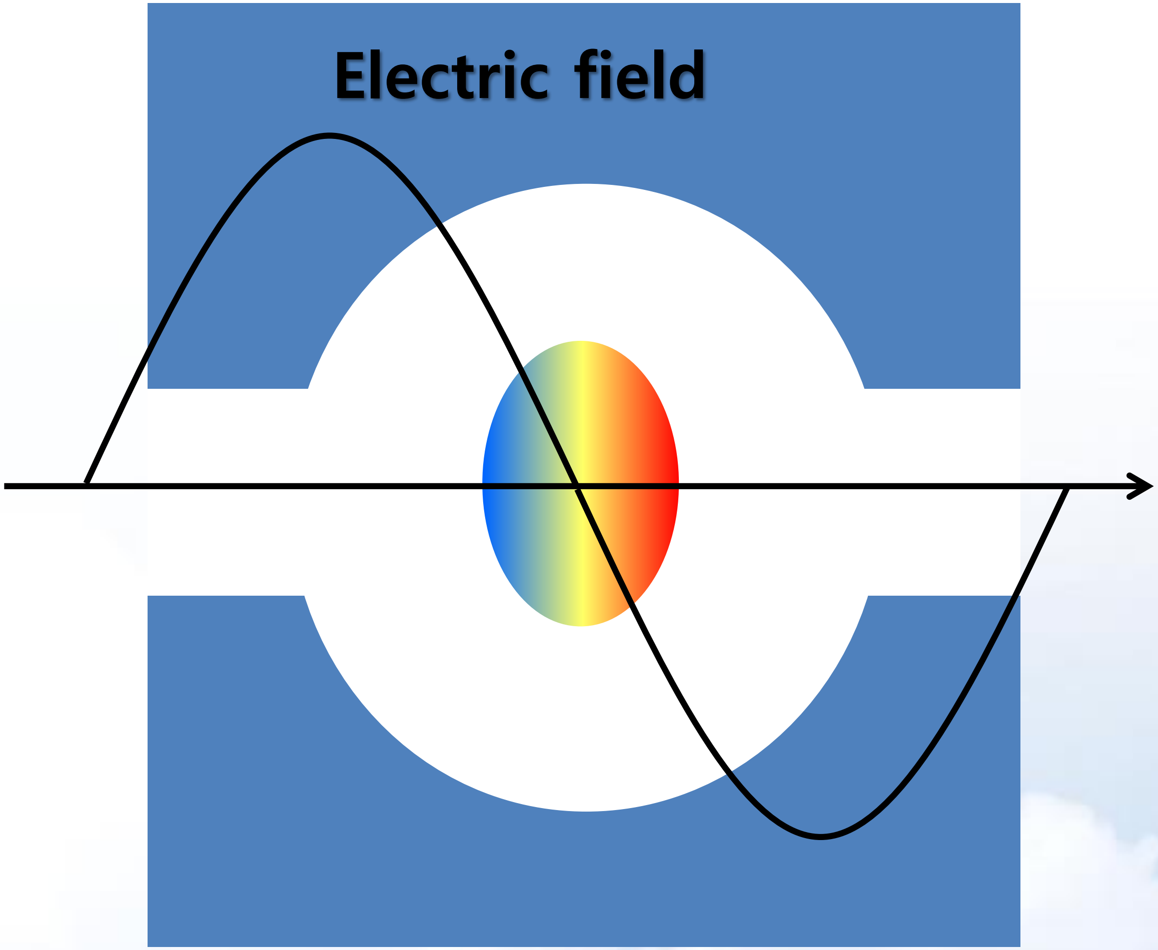




Buncher Cavity

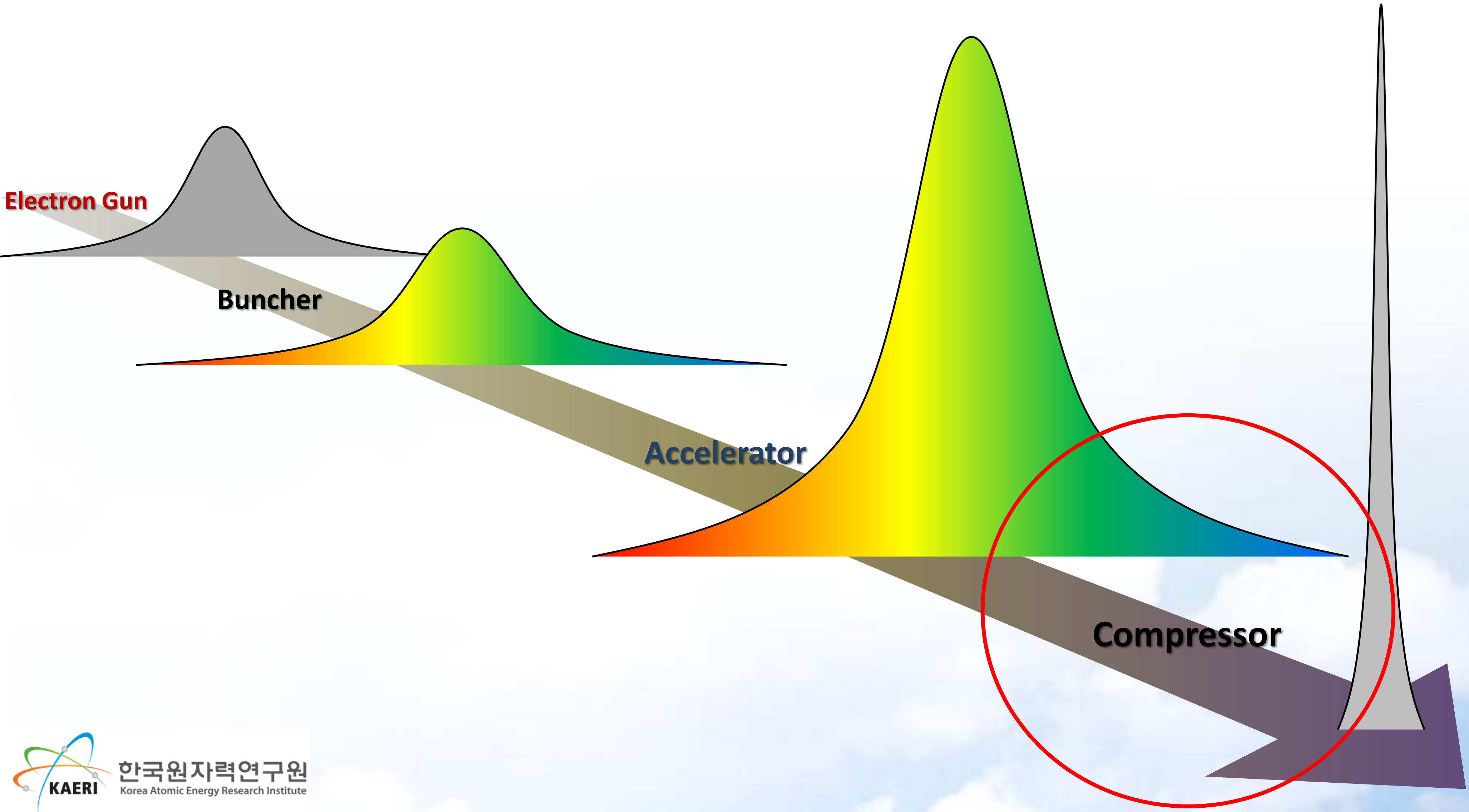
Electron Bunch Compression



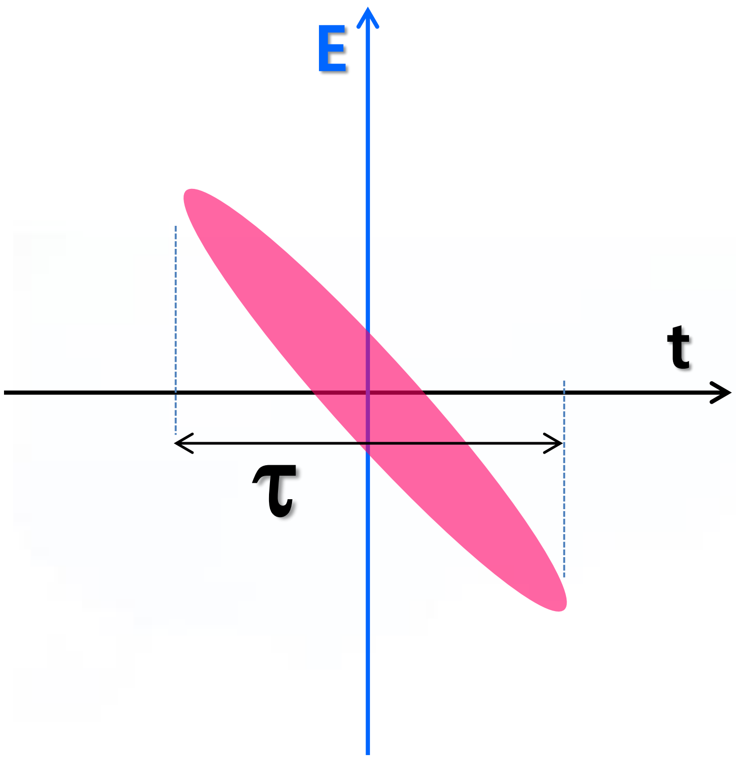


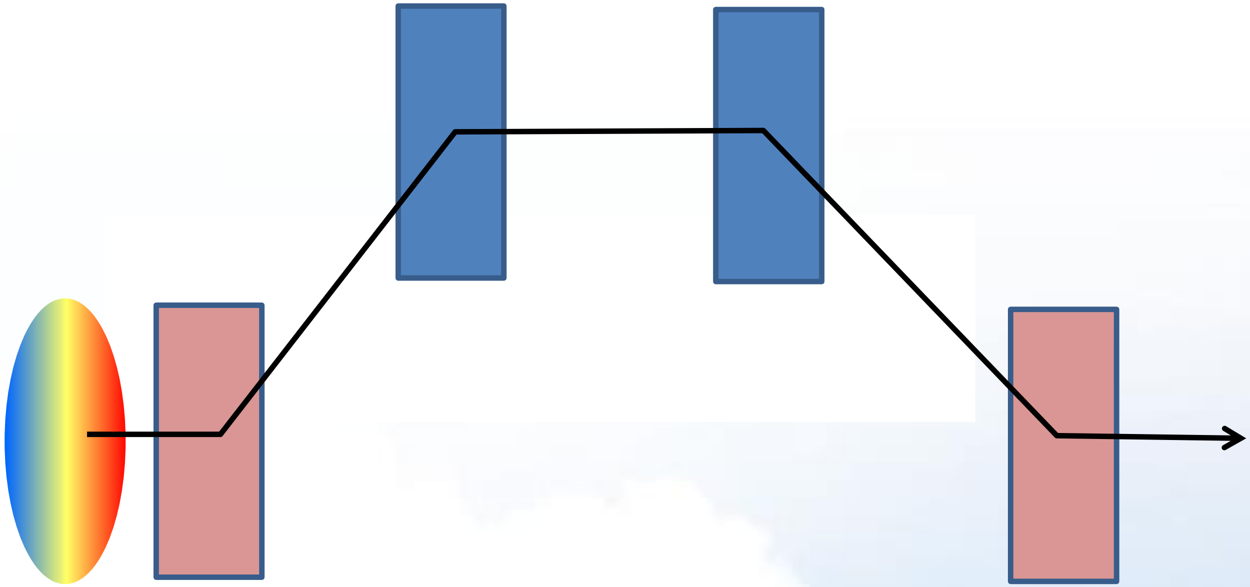
Buncher Cavity

Electron Bunch Compression



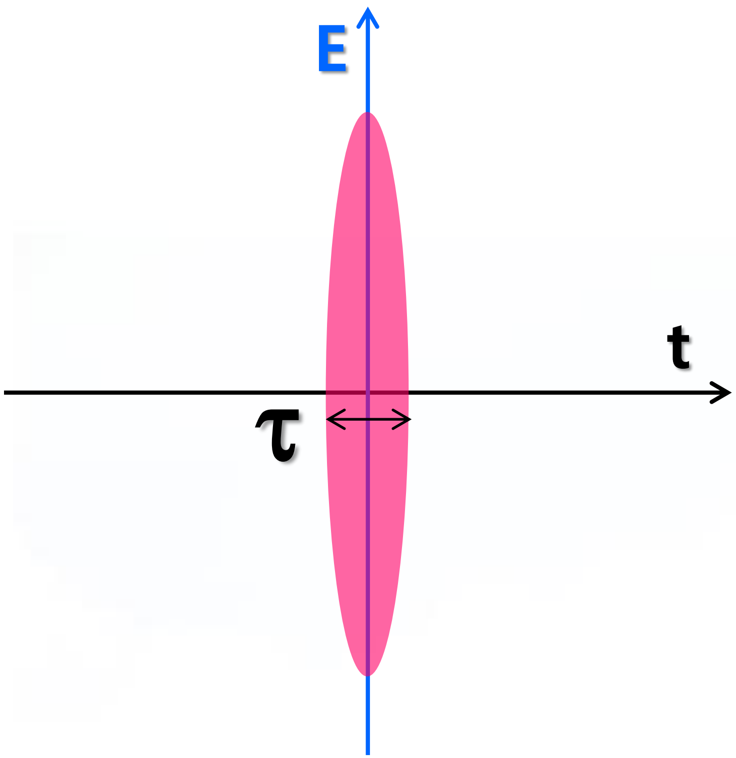
Electron Bunch Compression

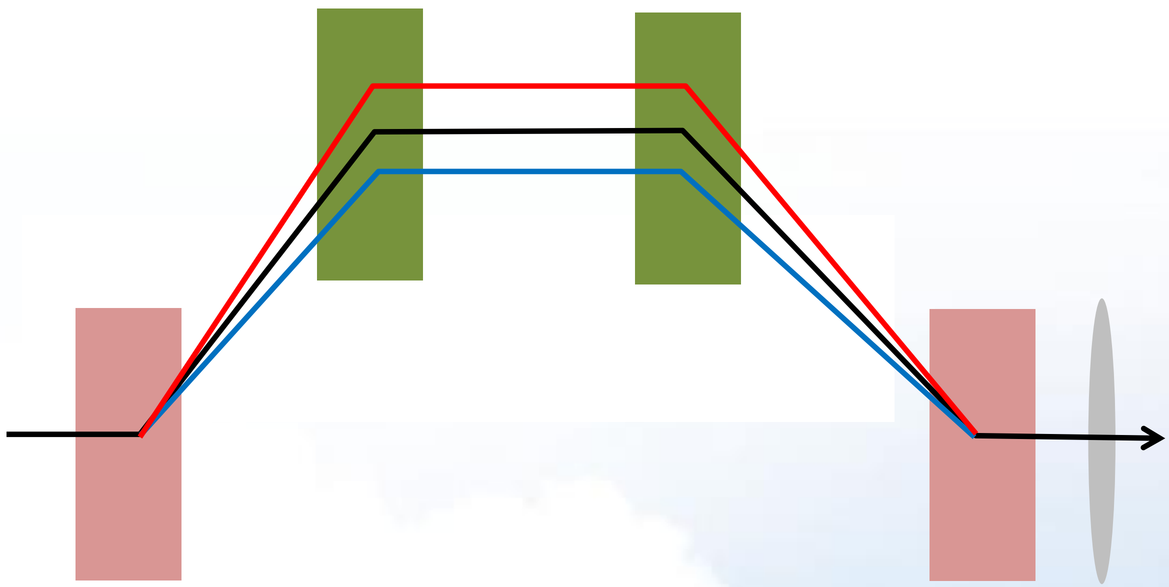




Chicane Compressor

Electron Bunch Compression





Chicane Compressor

IV. Ultrafast Electron Diffraction

한국원자력연구원
Korea Atomic Energy Research Institute

Tools for Exploring Dynamics of Molecules

Nano structure (< 1 nm)

- EM wave : X-ray선 (λ < 1 nm)
- Matter wave : electron (E > 10 keV)

&

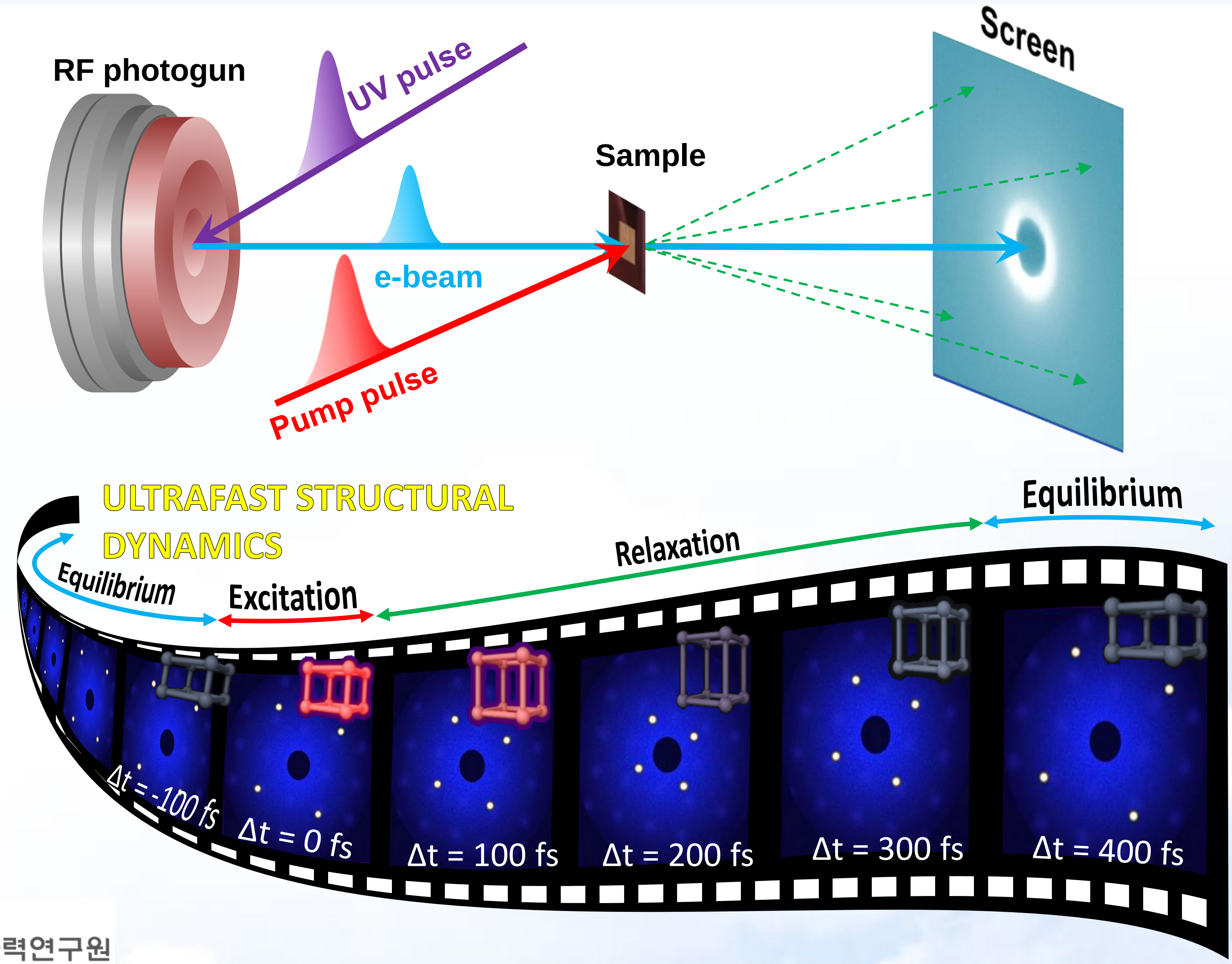
Ultrafast dynamics (< 1 ps)

- EM wave : X-선 자유전자레이저 (X-ray Free Electron Laser)
- Matter wave : 초고속전자회절장치 (Ultrafast Electron Diffraction)

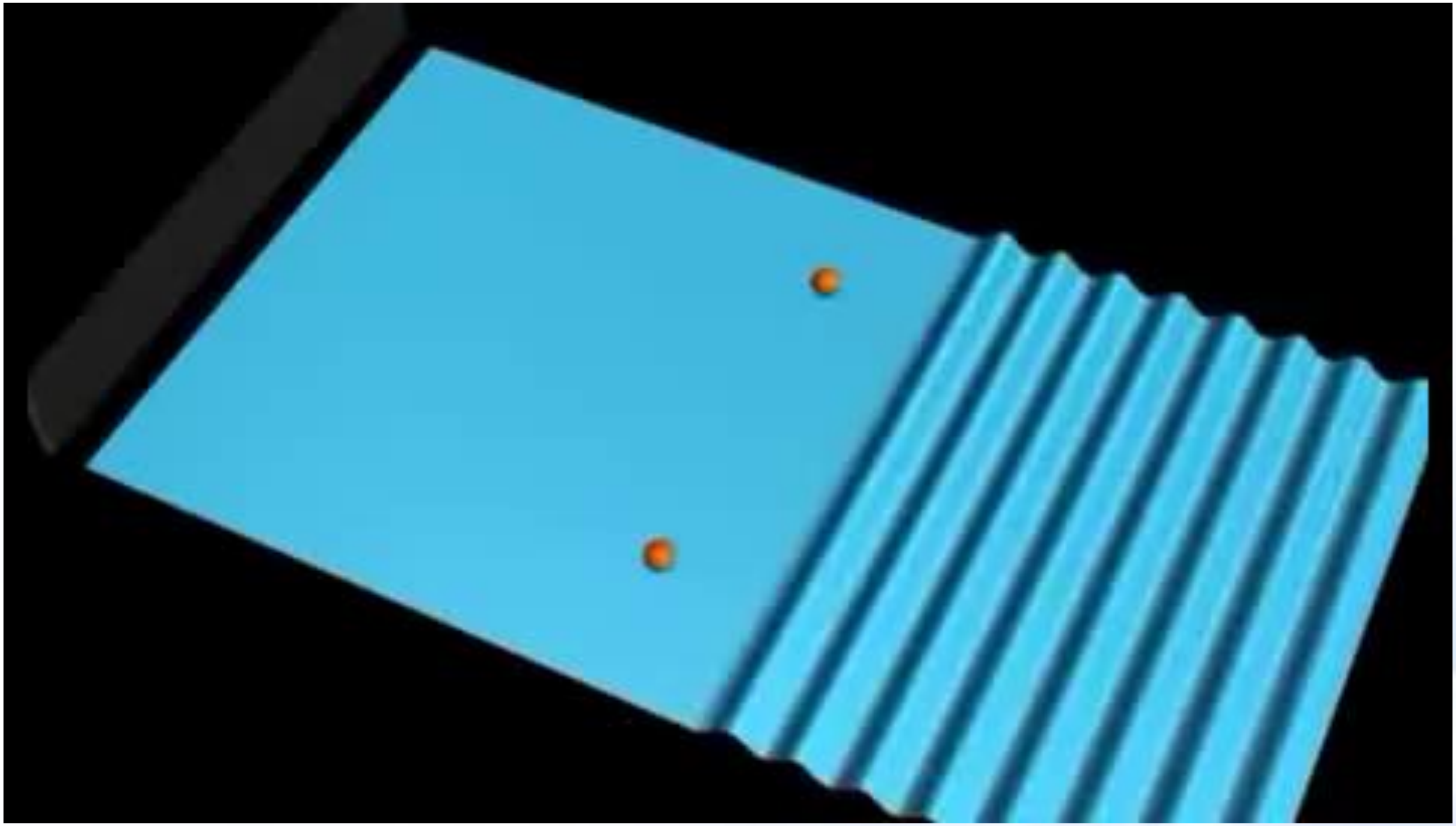
X-FEL v.s. UED 엑스선과 전자 비교

	X-FEL	UED
Source	X-ray	Electron
Wavelength	10-0.1 nm	0.1-0.001 nm
Interaction with	Electrons	Nuclei & Electrons
Scattering Power	Low	High
Penetration Depth	High	Low
Minimum Photon/Particle Numbers for Single-shot Measurement	10^{12} photons	10^{6} electrons
Facility Size	Huge (~ km)	Compact (~ m)
Coherence Length	A few mm	A few nm

Ultrafast Electron Diffraction (UED)

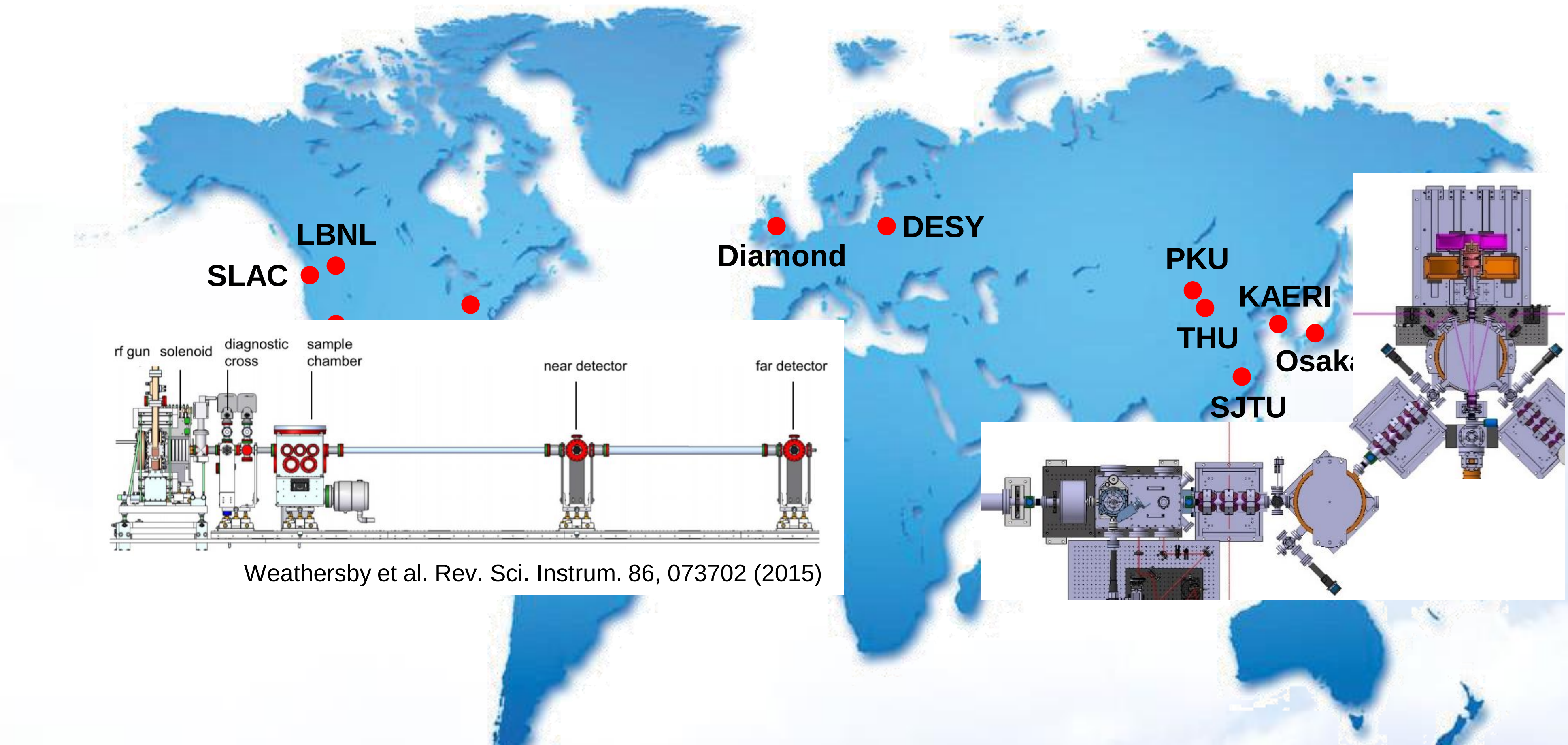


Interference by Diffraction 회절/간섭



$$\Delta l \approx \lambda L/d$$

World-wide efforts for MeV UED

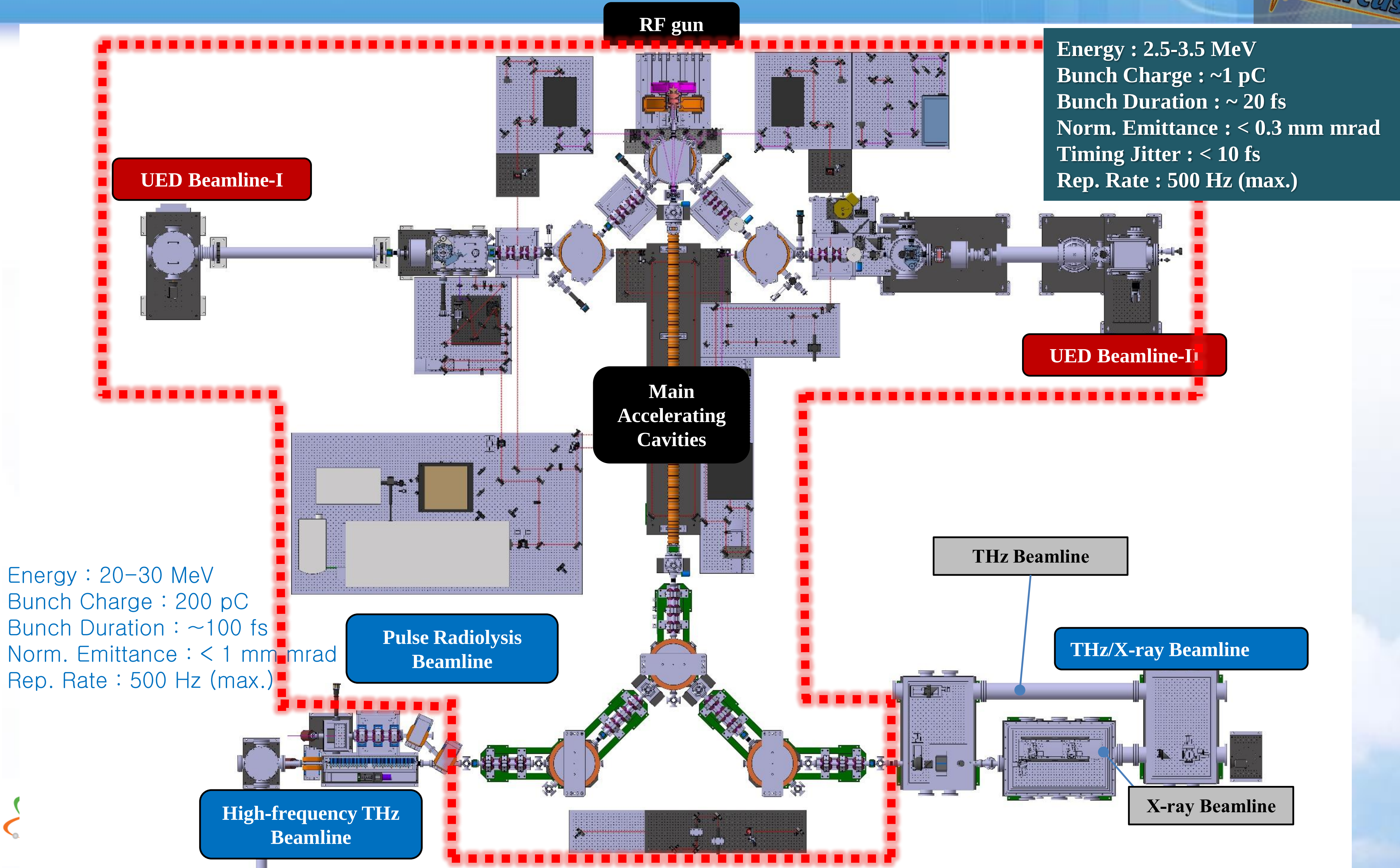


Weathersby et al. Rev. Sci. Instrum. 86, 073702 (2015)

Instrumental temporal resolution of UEDs is still limited >100 fs.

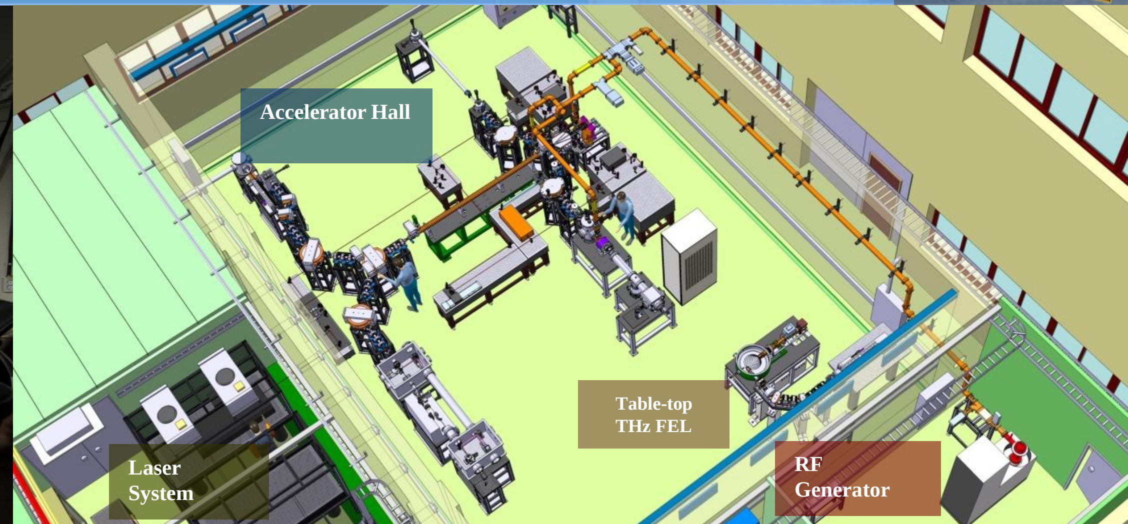
Facility Bird-eye View

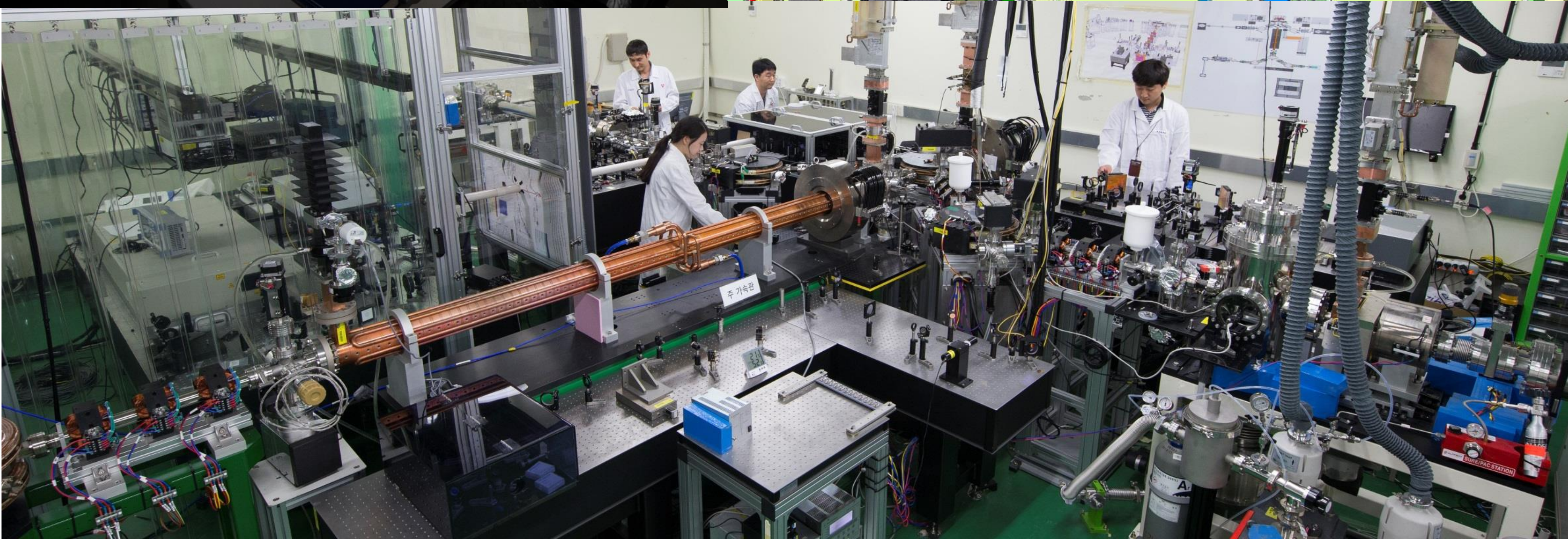
시설 개관



Facility Appearance

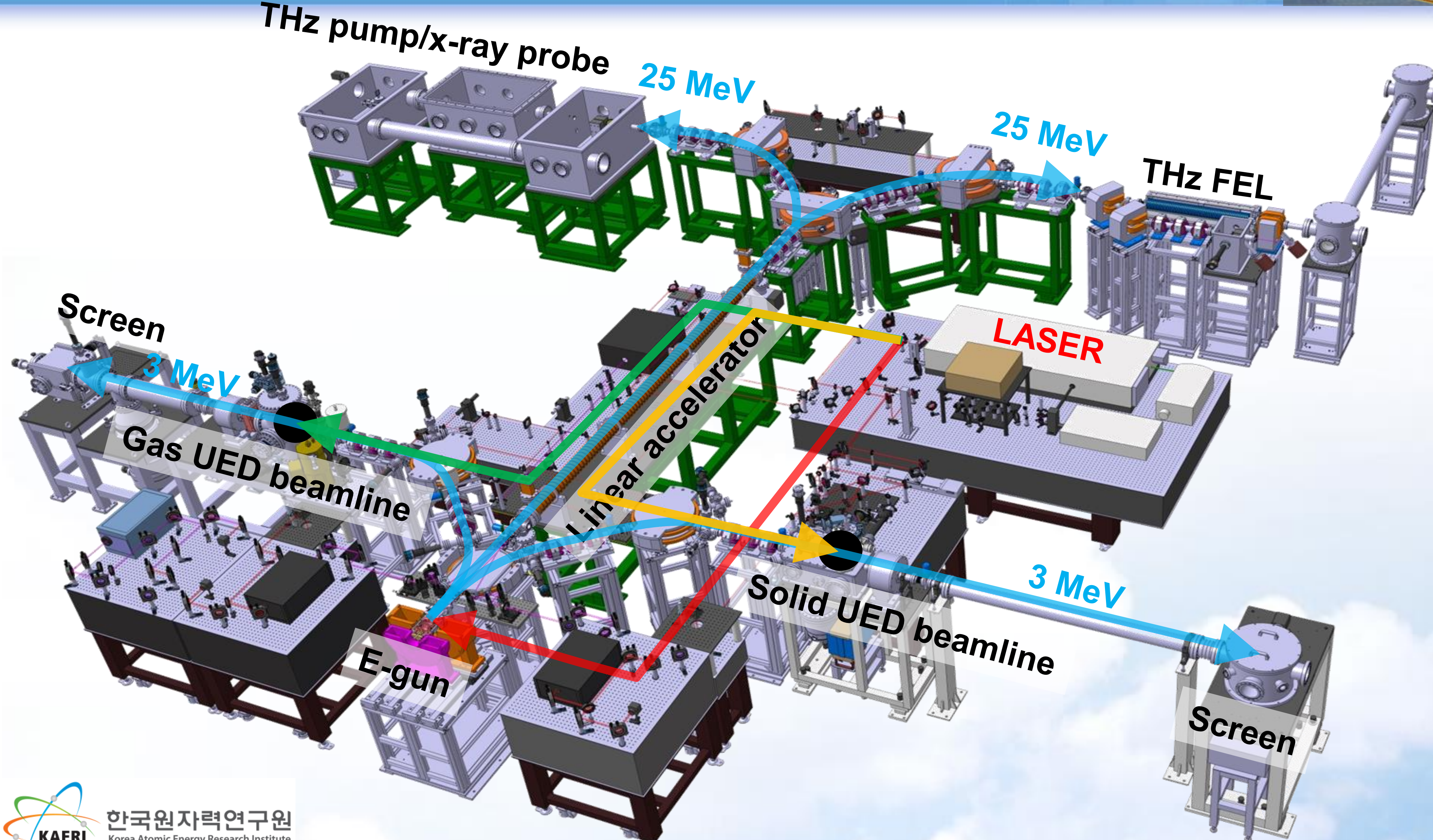
시설 개관





Facility Overview

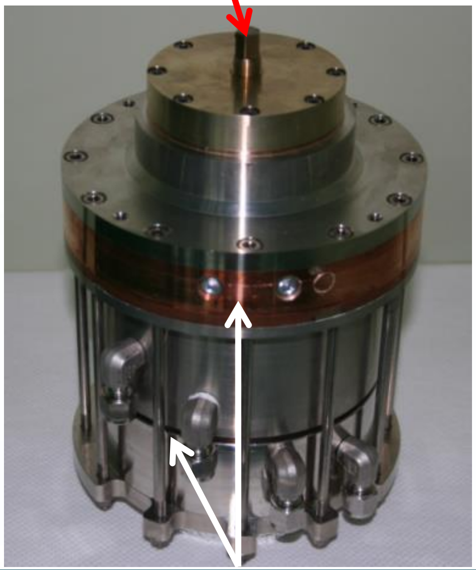
시설 개관



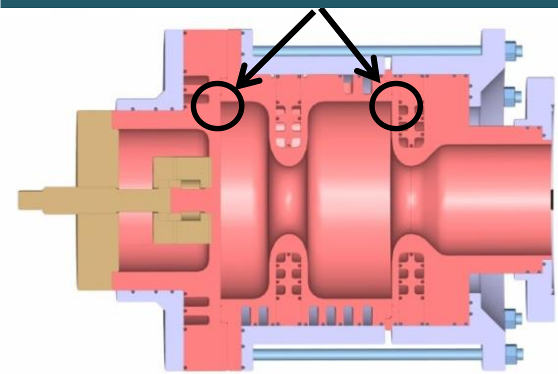
한국원자력연구원
KAERI
Korea Atomic Energy Research Institute

Coaxial-type Indium-sealed RF Photogun

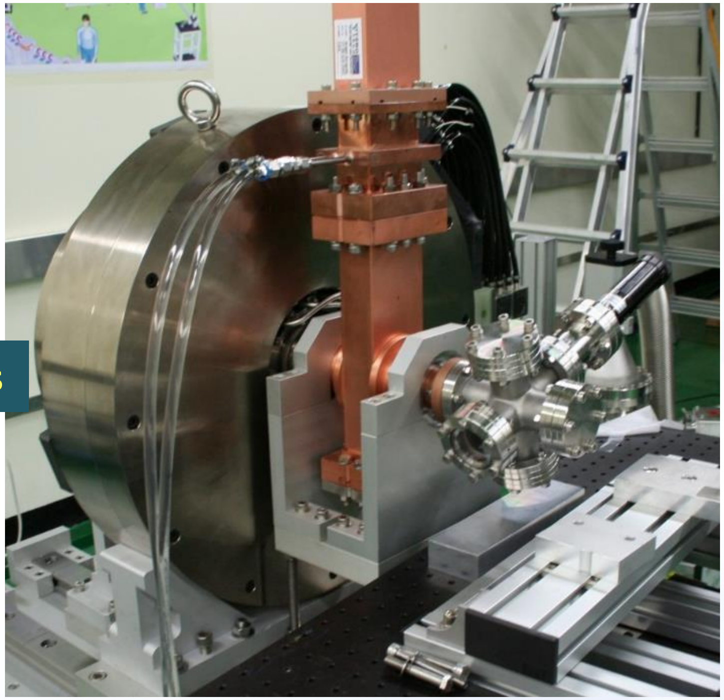
Frequency Tuning Mechanics

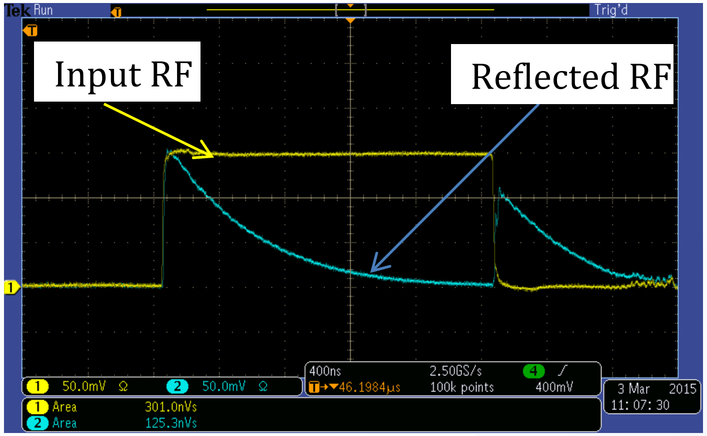


Vacuum sealed with Indium wires

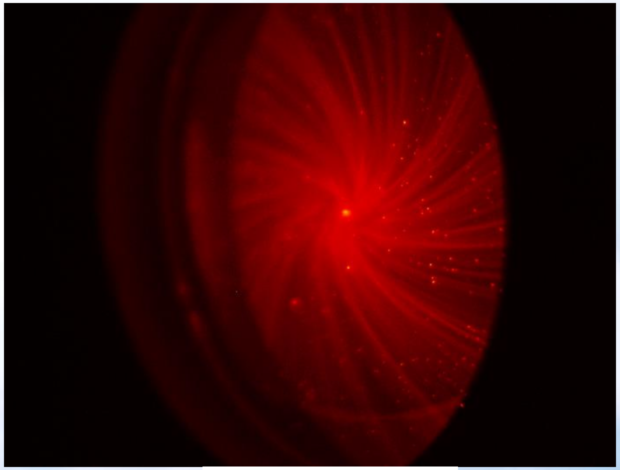


Frequency : 2.856 GHz
Repetition Rate : 1-500 Hz
Axial Symmetry with a Coaxial Coupler





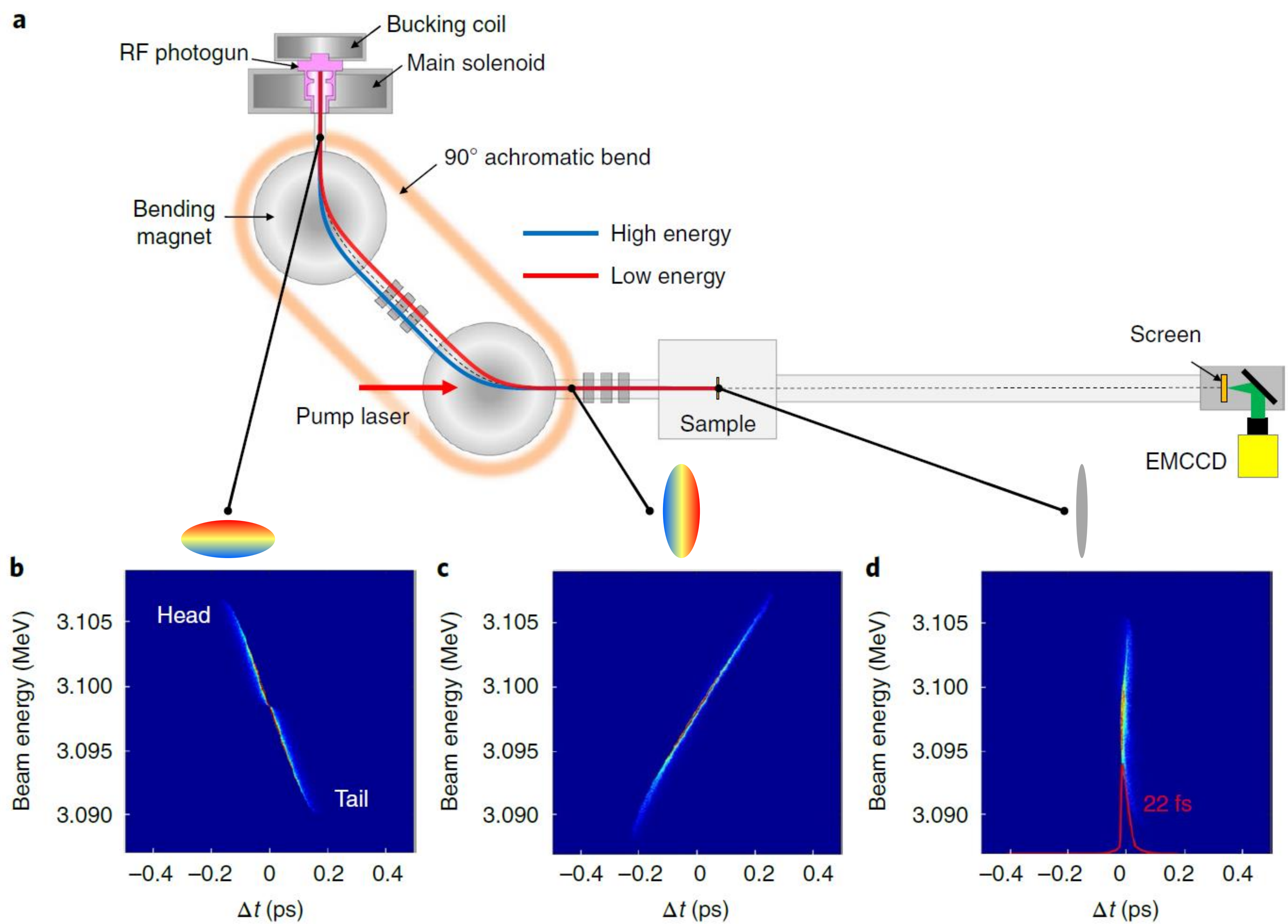
High power test



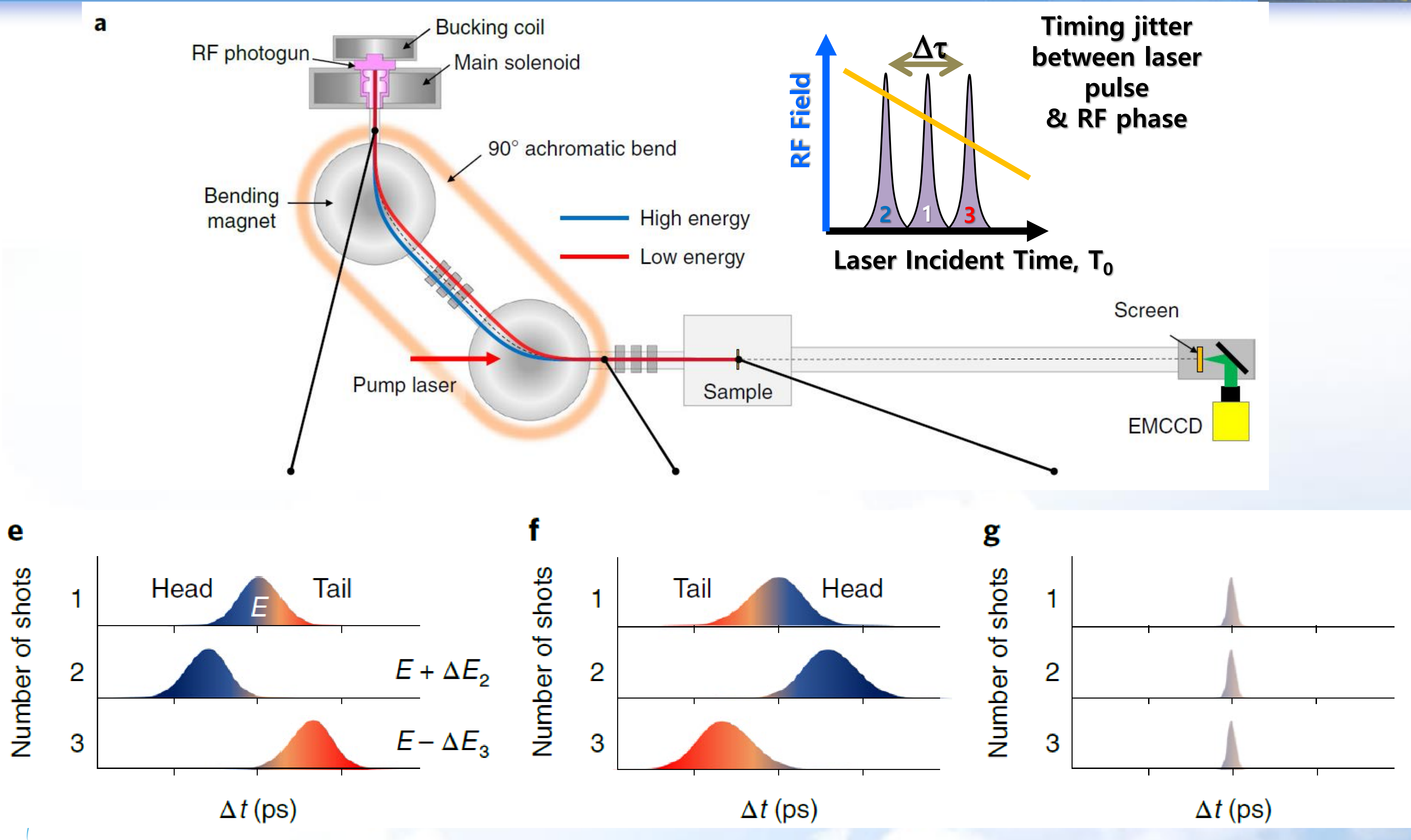
Dark current

H. W. Kim et al., J. Kor. Phys. Soc., 74, 24 (2019)

KAERI UED: Bunch Compression

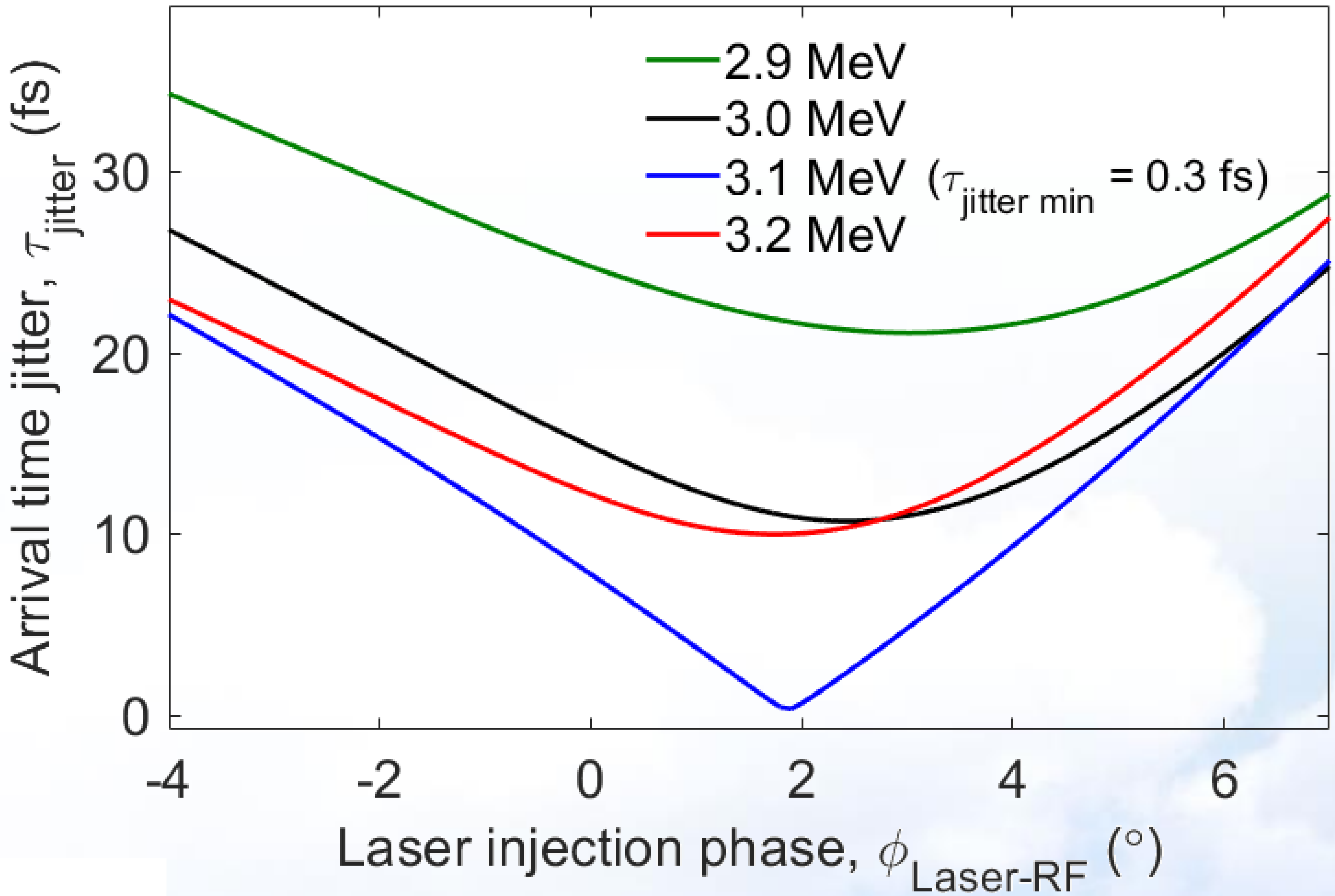


KAERI UED: Jitter Compression



Arrival time jitter due to RF amplitude & phase

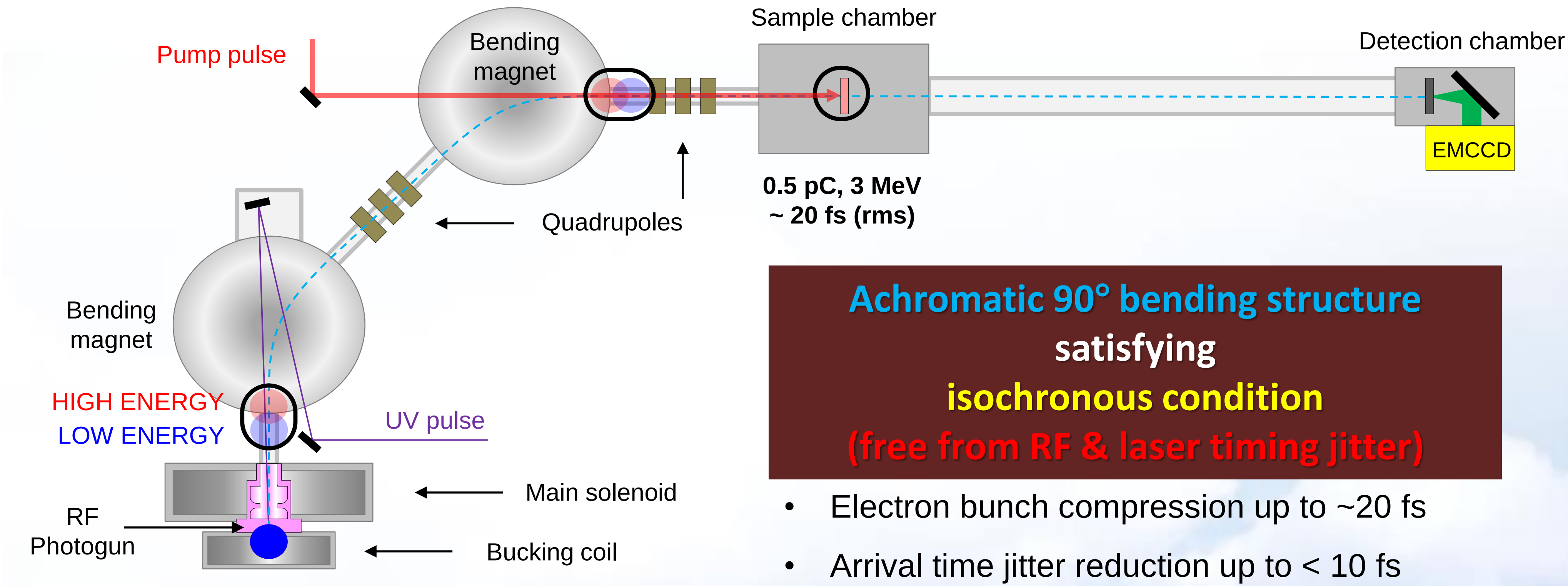
$\Delta E/E$ = 0.07%
$\Delta\Phi_{Laser\text{-}RF}$ = 40 fs



한국원자력연구원
KAERI
Korea Atomic Energy Research Institute

Toward the fastest Electron Camera

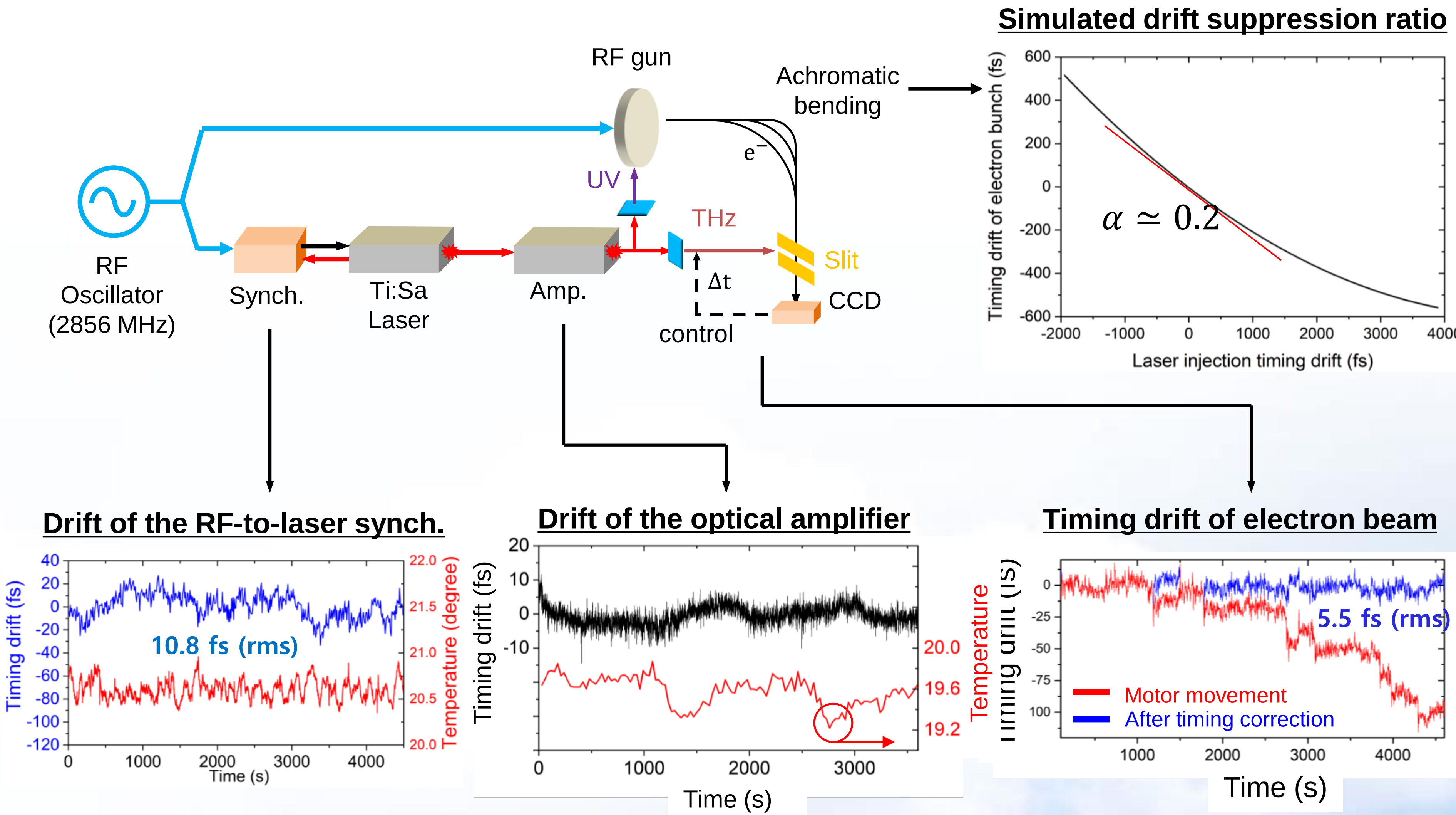
$$\tau_{Inst.res.} = \sqrt{\tau^2_{pump\ laser} + \tau^2_{e-bunch} + \tau^2_{jitter} + \tau^2_{velocity-mismatching}}$$



Achromatic 90° bending structure
satisfying
isochronous condition
(free from RF & laser timing jitter)

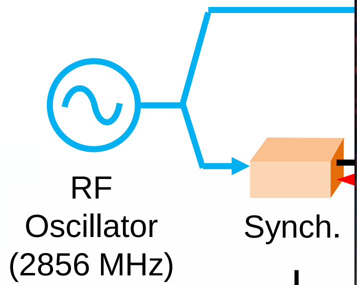
- Electron bunch compression up to ~20 fs
- Arrival time jitter reduction up to < 10 fs
- Velocity mismatching-free scheme
- Multiple beamlines

Timing Stabilization between Laser & RF



J. Shin et al., Laser Photon. Rev. 15, 200326 (2021).

Timing Sta




Vol. 15 | February 2021

www.lpr-journal.org

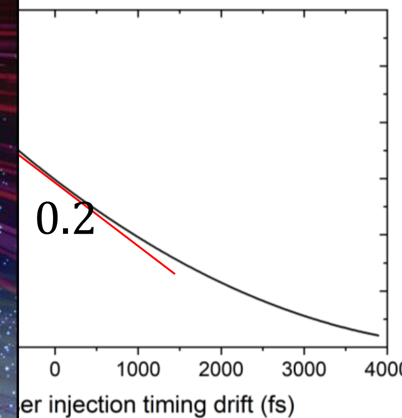
LASER & PHOTONICS REVIEWS

Sub-10-fs Timing for Ultrafast Electron Diffraction with THz-Driven Streak Camera

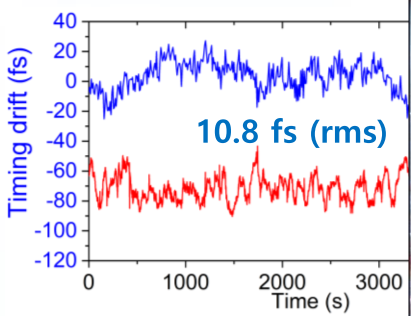
Junho Shin, Hyun Woo Kim, In Hyung Baek, Sunjeong Park, Hyeon Sang Bark, Key Young Oang, Kyu-Ha Jang, Kitae Lee, Fabian Rotermund, Young Uk Jeong, and Jungwon Kim

WILEY-VCH

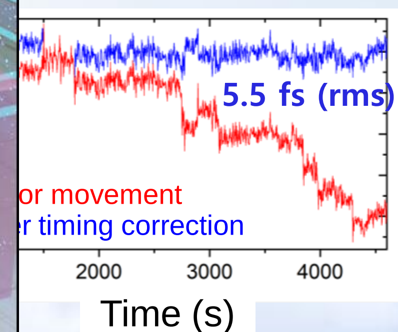
rift suppression ratio



Drift of the RF-to-las



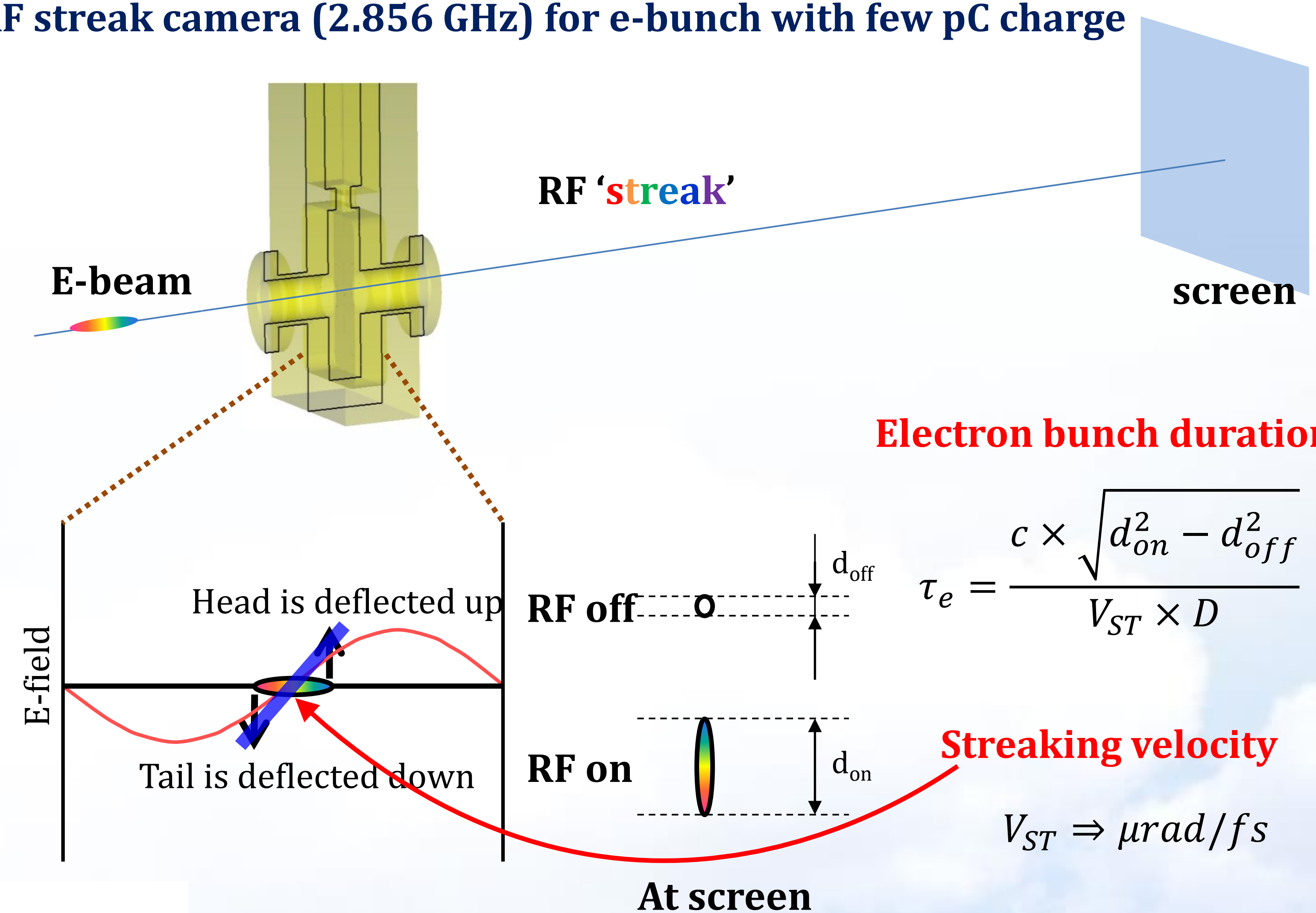
rift of electron beam



KAERI 한국원자력연구원 Korea Atomic Energy Research Institute

Conventional Characterization of Electron Bunch

RF streak camera (2.856 GHz) for e-bunch with few pC charge



Electron bunch duration

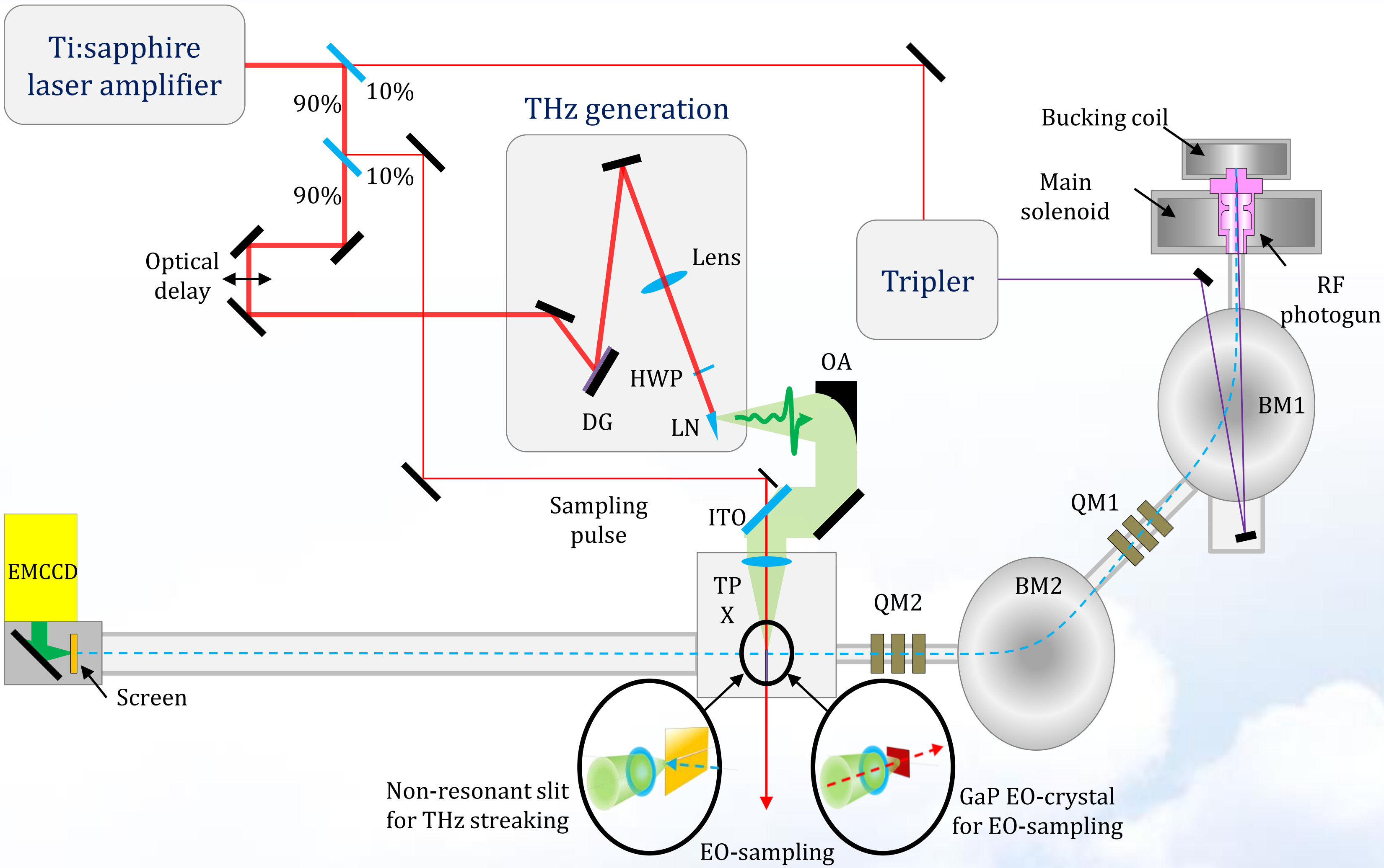
$$\tau_e = \frac{c \times \sqrt{d_{on}^2 - d_{off}^2}}{V_{ST} \times D}$$

Streaking velocity

$$V_{ST} \Rightarrow \mu rad/fs$$

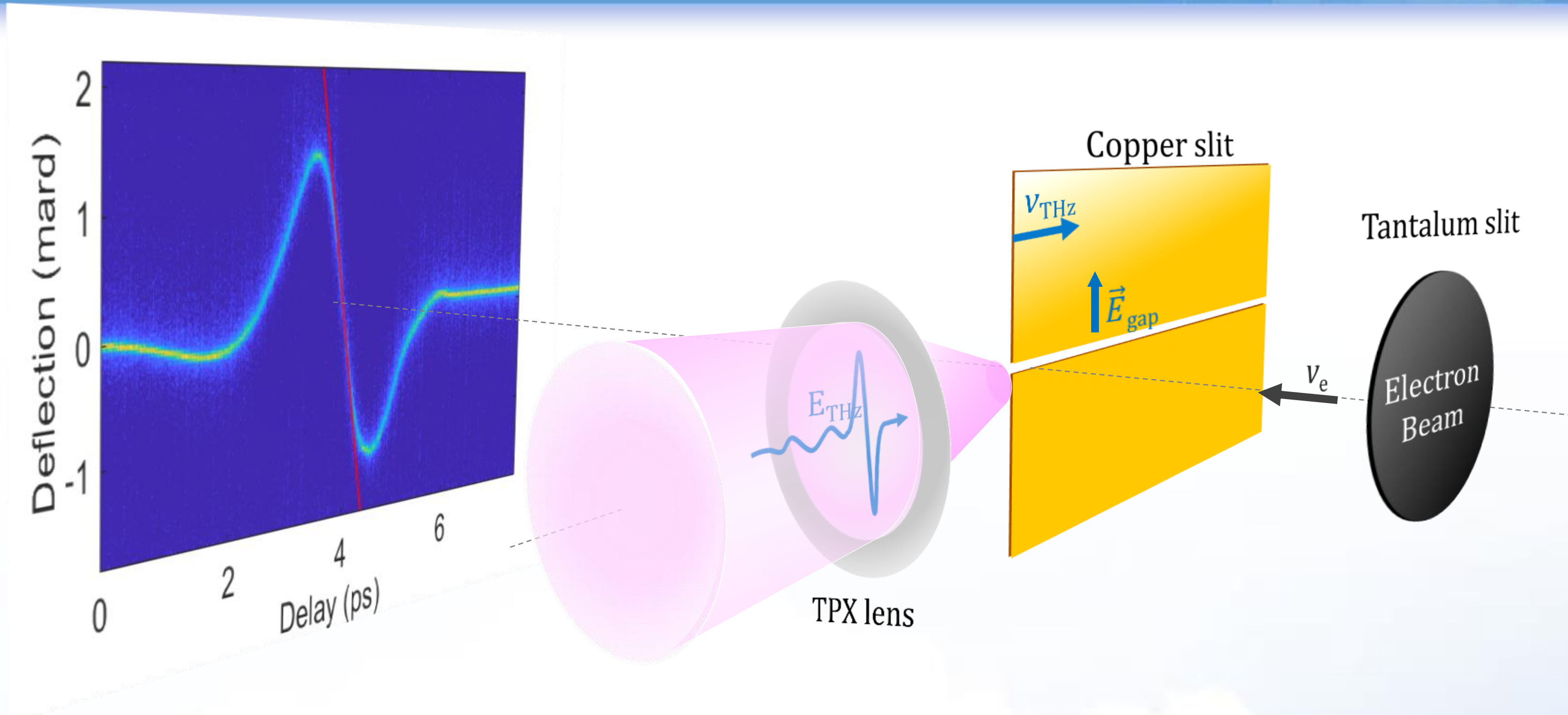
KAERI 한국원자력연구원 Korea Atomic Energy Research Institute

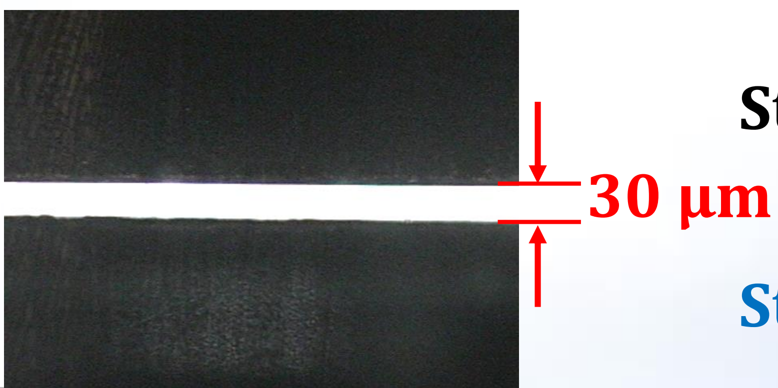
Setup of Terahertz (THz) Streak Camera



Kim et al., Nat. Photon. **14**, 245-249 (2020).

THz Streak Camera with Non-resonant Slit

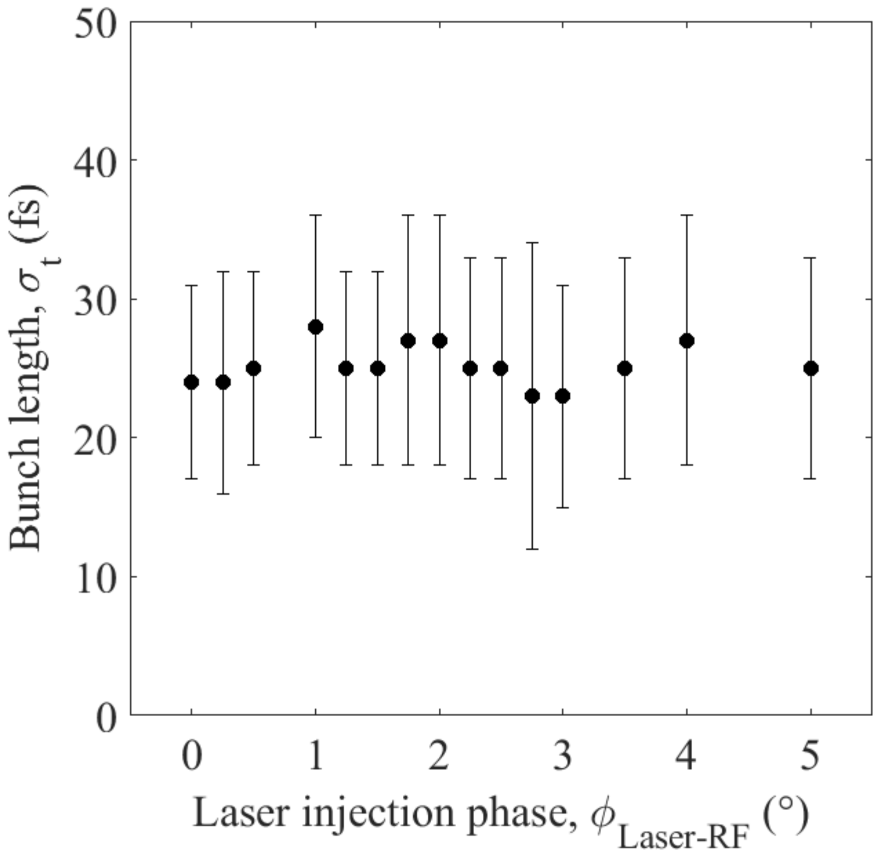


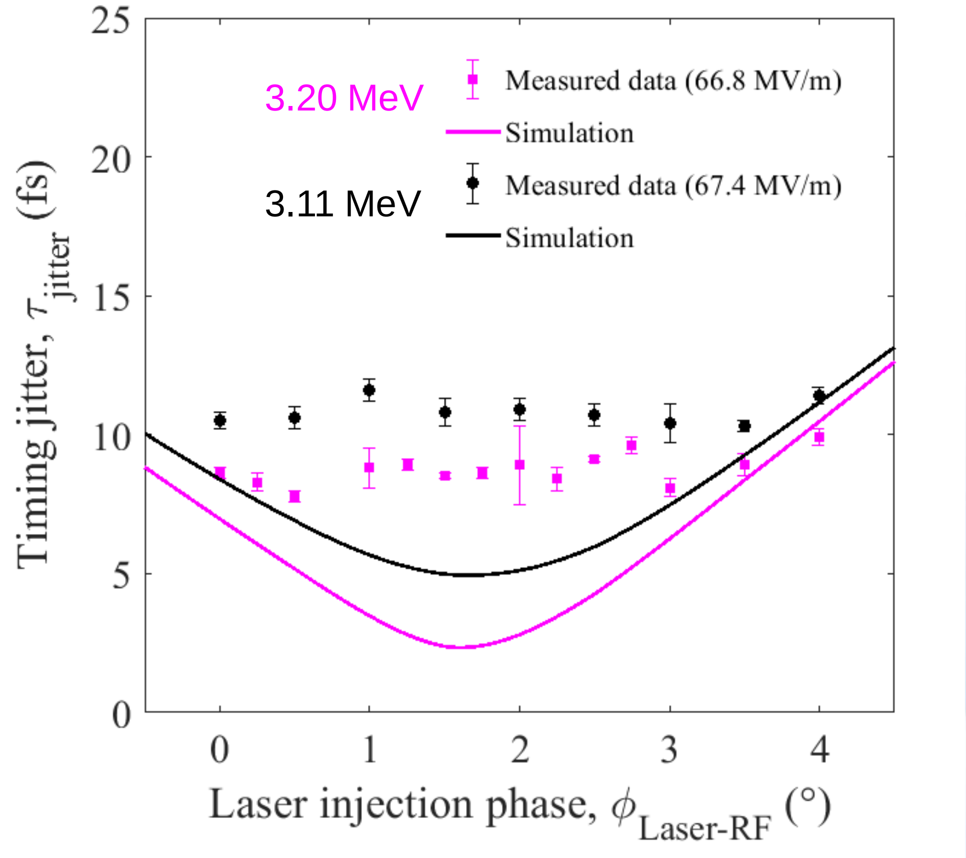


Streaking velocity = 4.8 µrad/fs

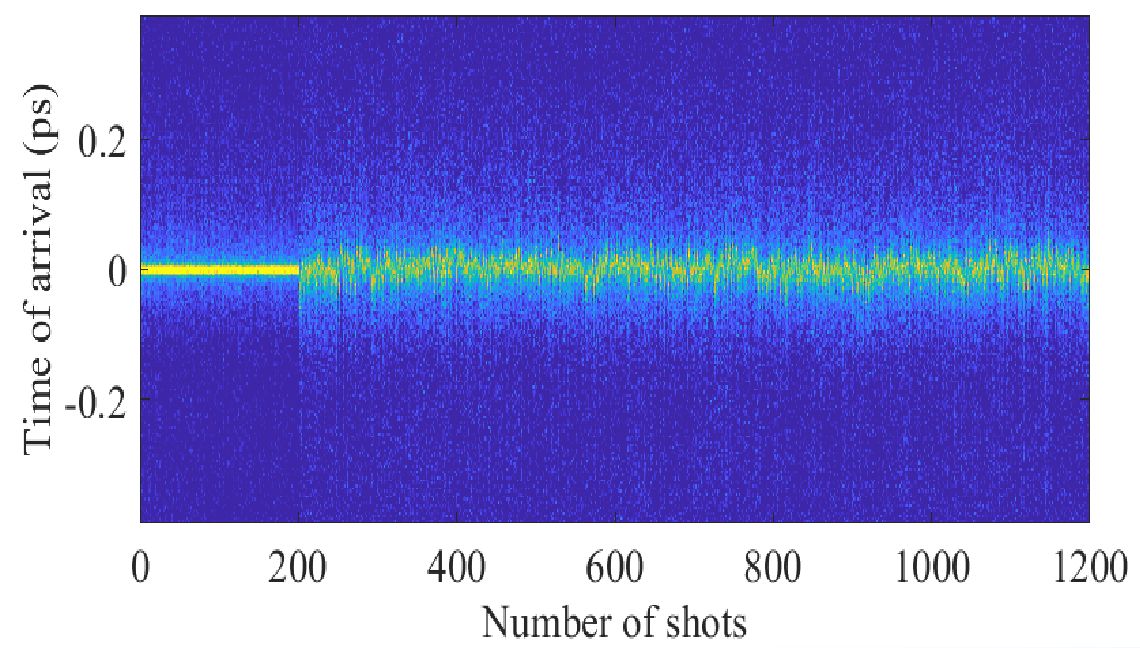
Streaking resolution = 3.8 fs

Experimental Results on THz Streaking





Experimental Results on THz Streaking



Bunch duration = **25 ± 8 fs (rms)** @ 0.57 pC, 3.11 MeV

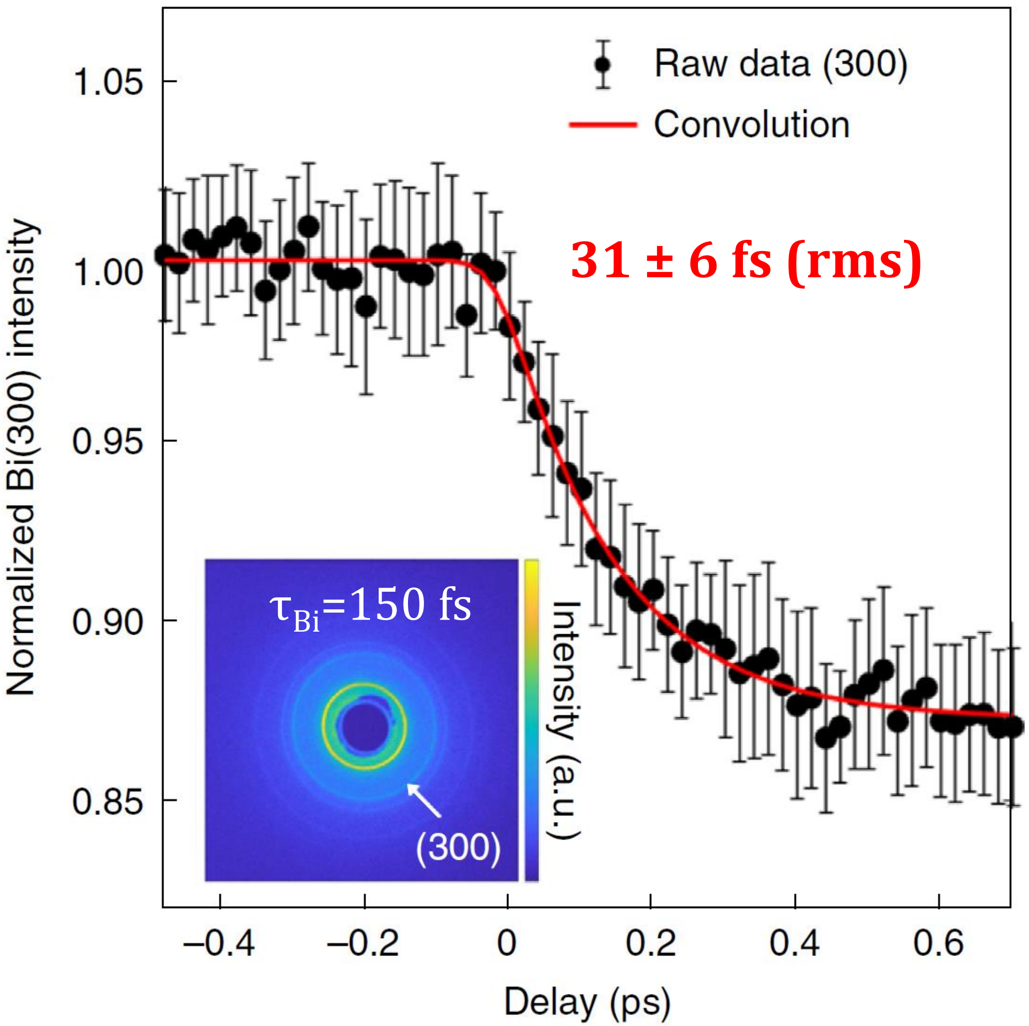
Arrival time jitter b/w THz pulse & electron bunch = **8 fs (rms)**

$$\tau_{IRF} = \sqrt{\tau^2_{pump\ laser} + \tau^2_{electron} + \tau^2_{jitter} + \tau^2_{drift}}$$

τ_{IRF}	$\tau_{pump\ laser}$	$\tau_{electron}$	τ_{jitter}	τ_{drift}
32 fs	**19 fs**	**25 fs**	**8 fs**	**0**

한국원자력연구원
KAERI Korea Atomic Energy Research Institute

Dynamics of Polycrystalline Bismuth Film



$$\tau_{IRF} = \sqrt{\tau^2_{pump\ laser} + \tau^2_{electron} + \tau^2_{jitter} + \tau^2_{drift}}$$

32 fs → τ_{IRF}; **19 fs** → $\tau_{pump\ laser}$; **25 fs** → $\tau_{electron}$; **8 fs** → τ_{jitter}; **0** → τ_{drift}

nature photonics
ARTICLES
https://doi.org/10.1038/s41566-019-0566-4

Towards jitter-free ultrafast electron diffraction technology

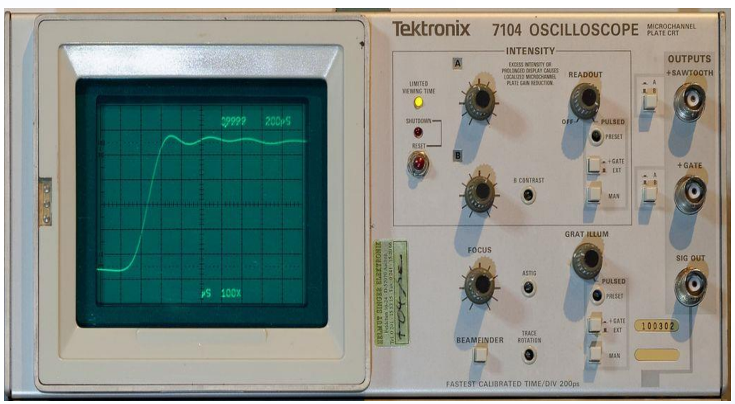
Hyun Woo Kim[1,2], Nikolay A. Vinokurov[3], In Hyung Baek[1,2], Key Young Oang[1], Mi Hye Kim[1], Young Chan Kim[1,4], Kyu-Ha Jang[1,2], Kitae Lee[1,2], Seong Hee Park[5], Sunjeong Park[1], Junho Shin[6], Jungwon Kim[6], Fabian Rotermund[7], Sunglae Cho[8], Thomas Feurer[9] and Young Uk Jeong[1,2*]

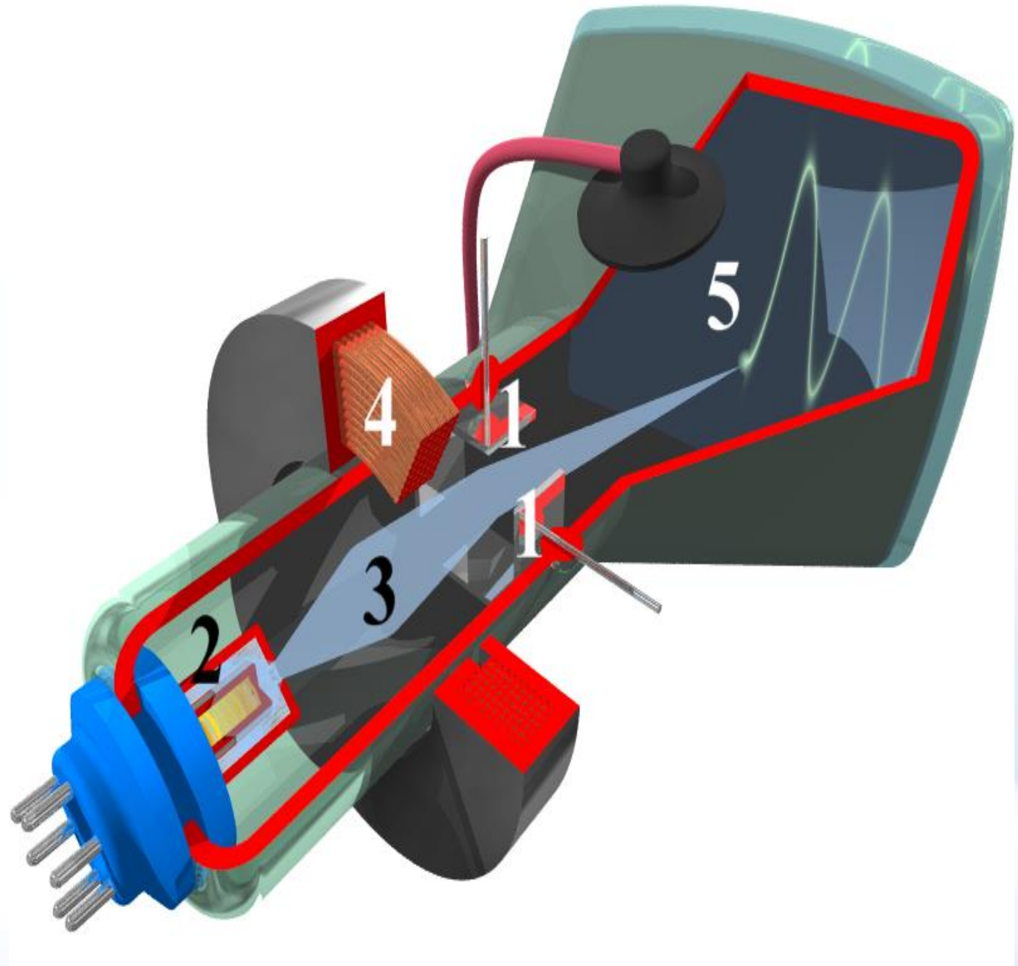
Electron is the most trustful probe of EM-field

The first cathode-ray oscilloscope (1897)

K. F. Braun

1 GHz at 10 mV analog oscilloscope (1979)

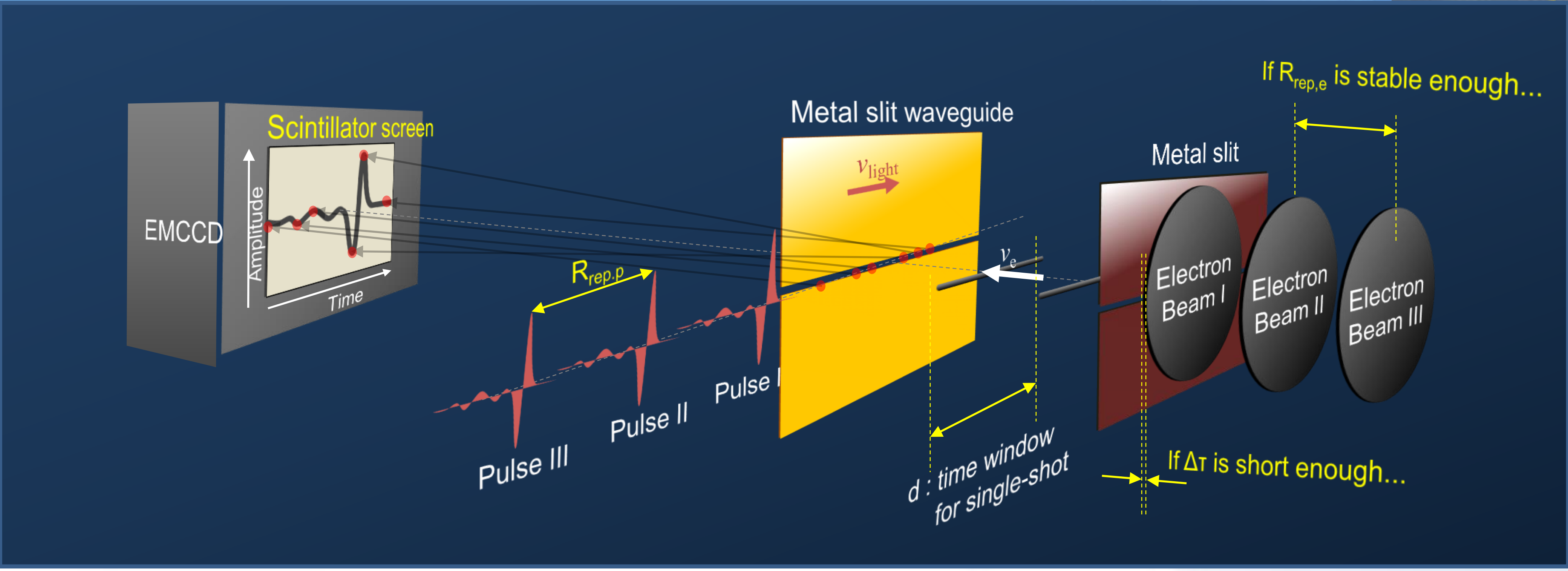




KAERI 한국원자력연구원 Korea Atomic Energy Research Institute

https://upload.wikimedia.org/wikipedia/commons/9/98/CRT_oscilloscope.png

Basic idea; Momentary waveform stamping on e-beam

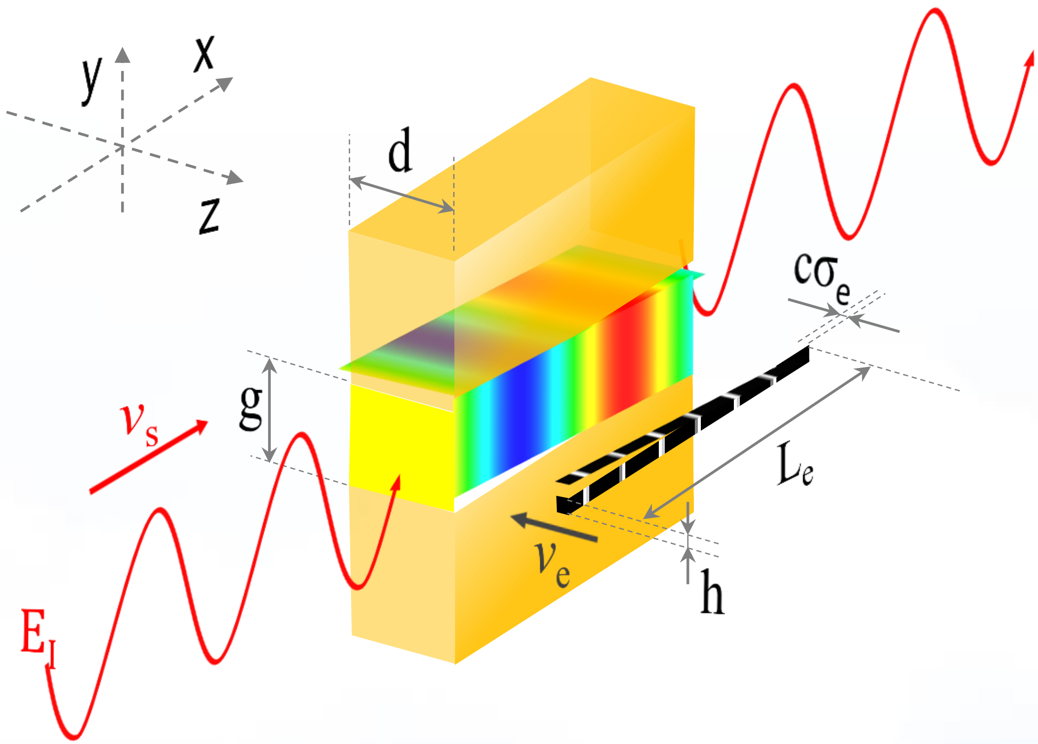


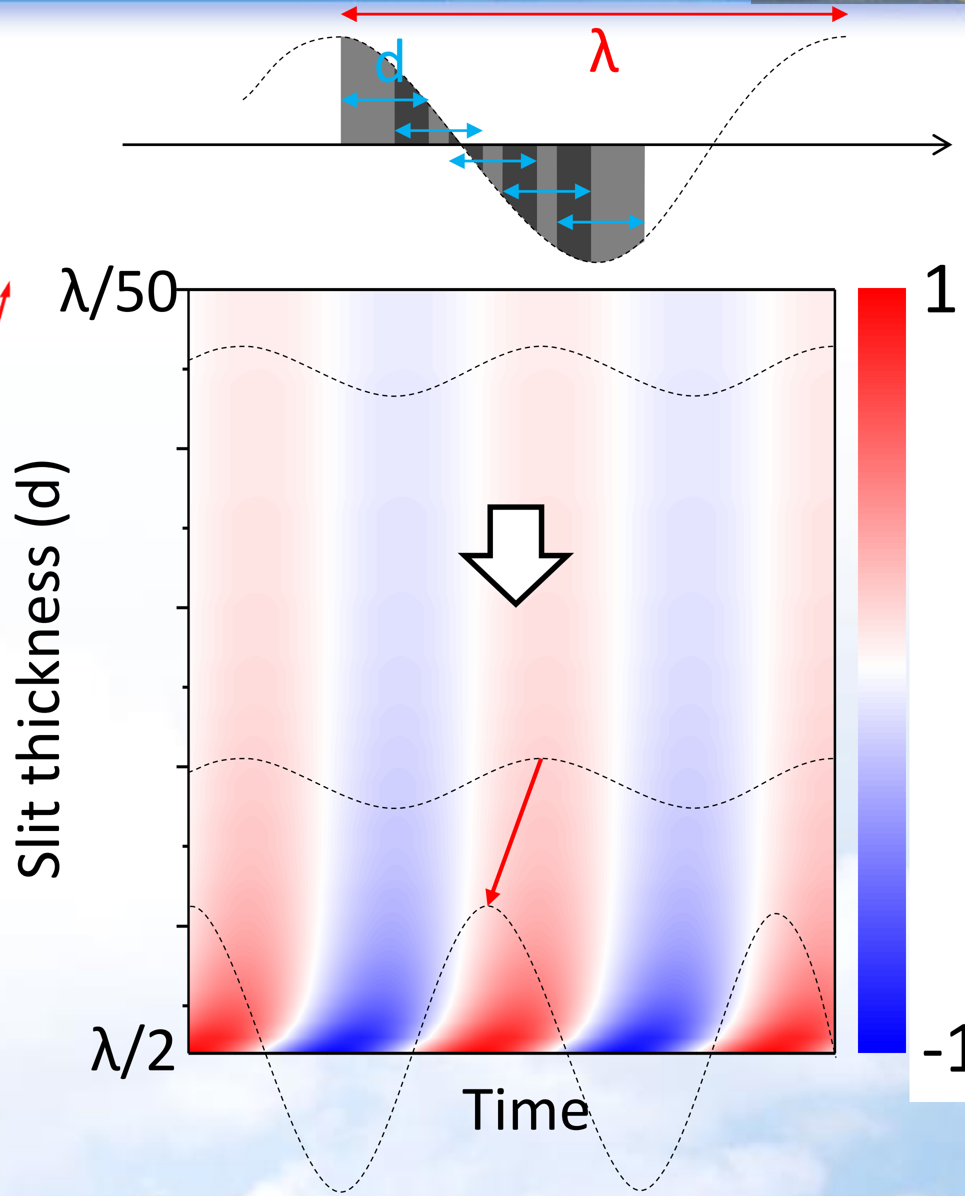
1. In this real-time ultrafast oscilloscope, what determines its bandwidth?

2. Propagating signal inside a slit waveguide is analogous to the incident signal ?

Waveform distortion depending on slit thickness (d)

1D electron array ($d > c\sigma_e$)



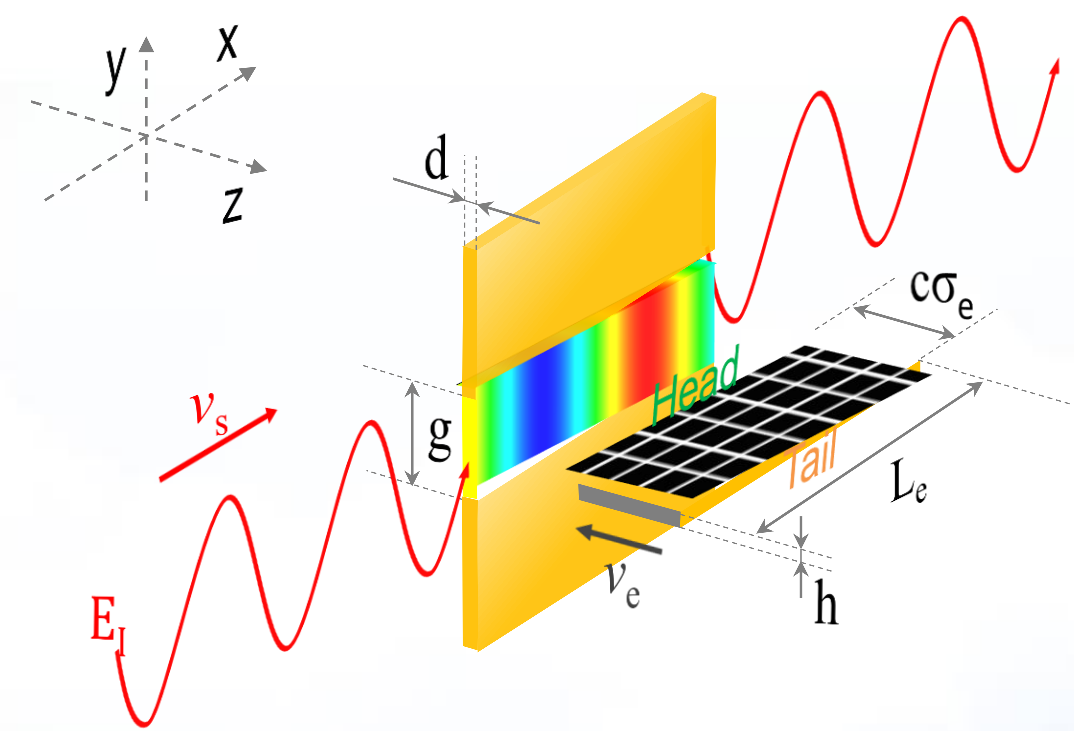


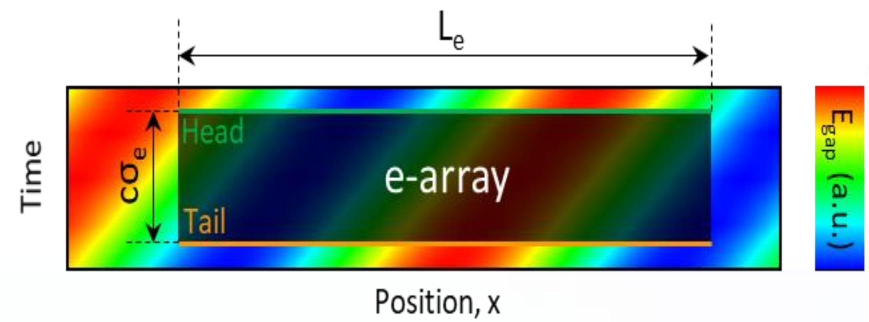
If d is smaller than λ/15, there is no distortion of waveform.

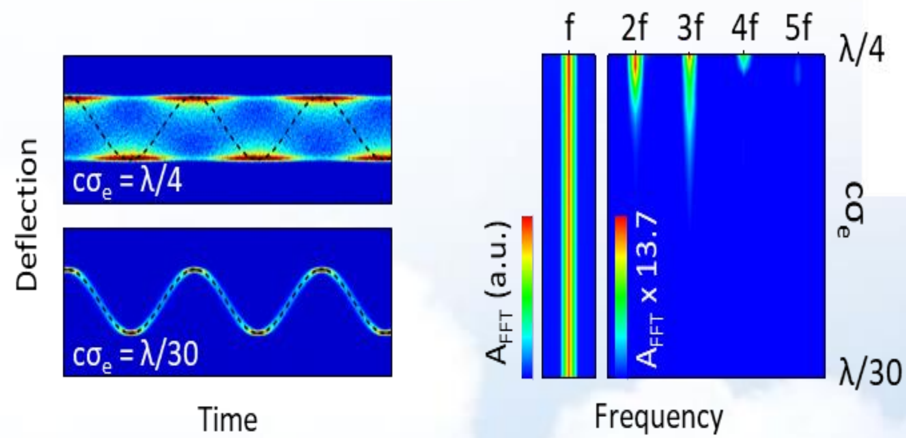
한국원자력연구원
KAERI Korea Atomic Energy Research Institute

Waveform distortion depending on bunch duration ($c\sigma_e$)

Quasi-1D electron array ($d < c\sigma_e$)





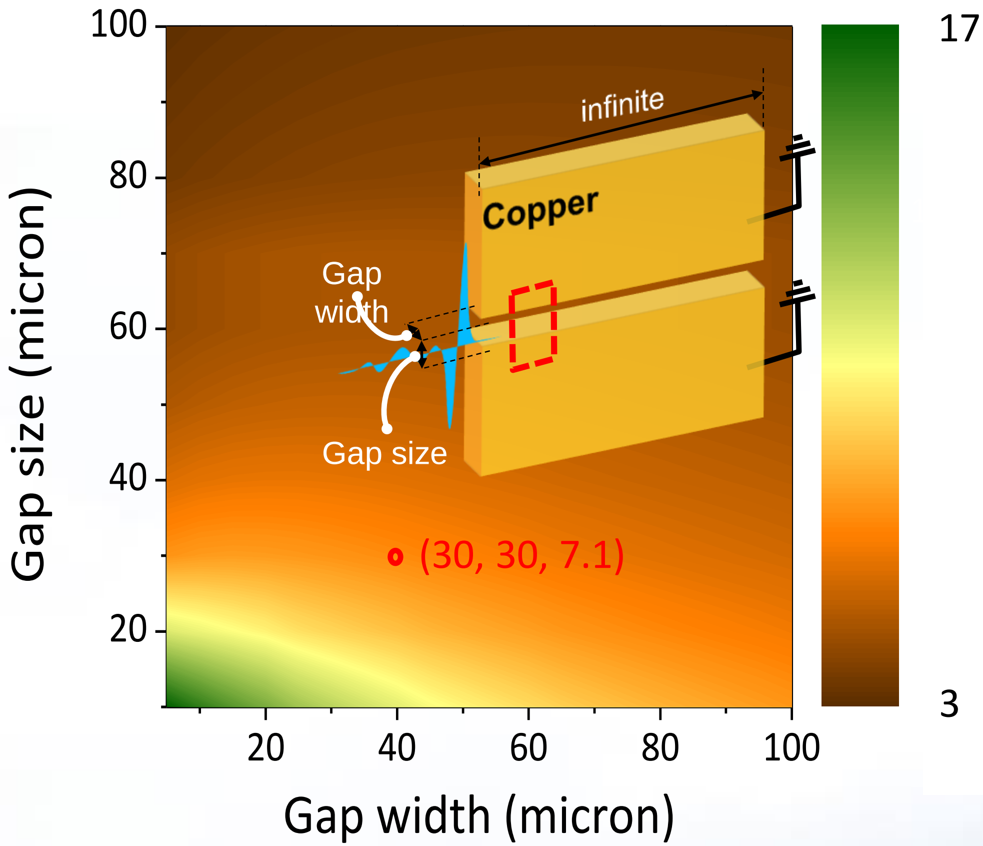


If $c\sigma_e$ is smaller than $\lambda/15$, there is no distortion of waveform.

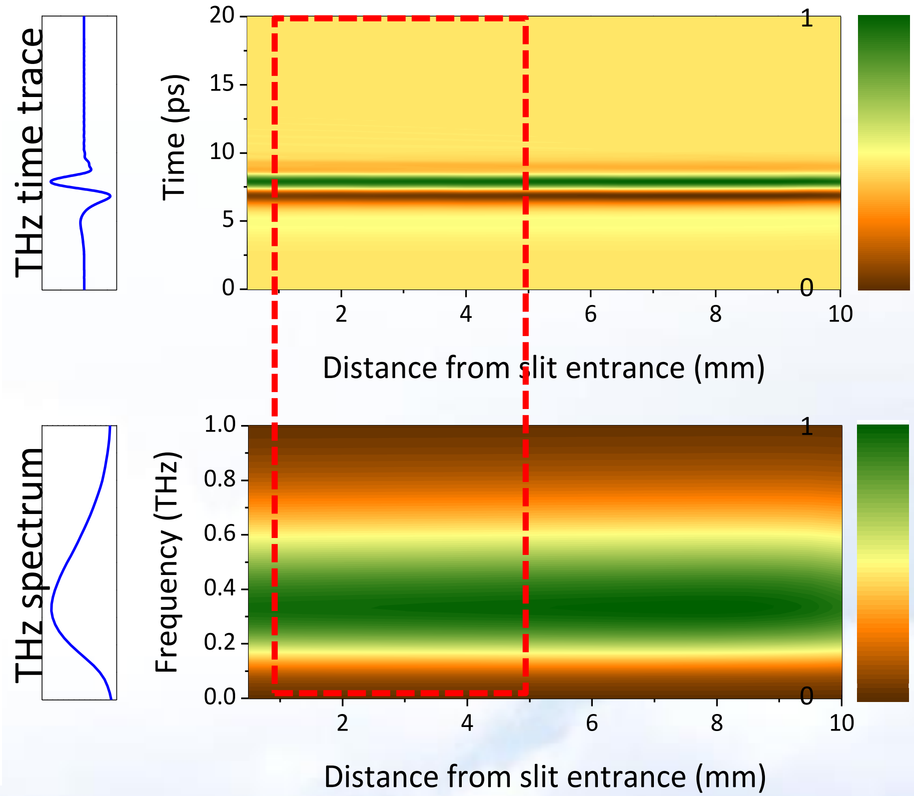
한국원자력연구원 KAERI Korea Atomic Energy Research Institute

Simulation on E-field propagation inside a Cu slit

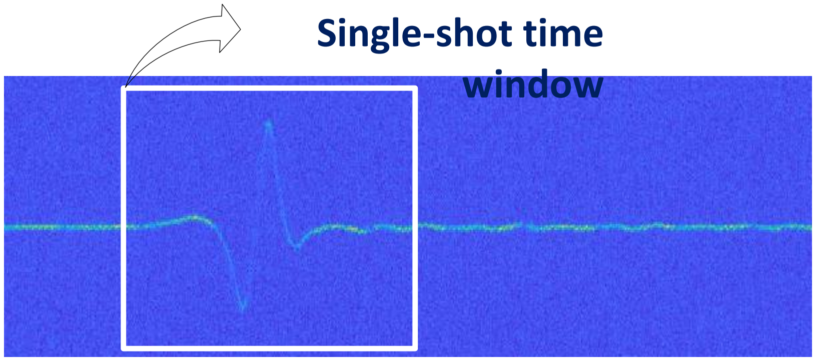
E-field enhancement

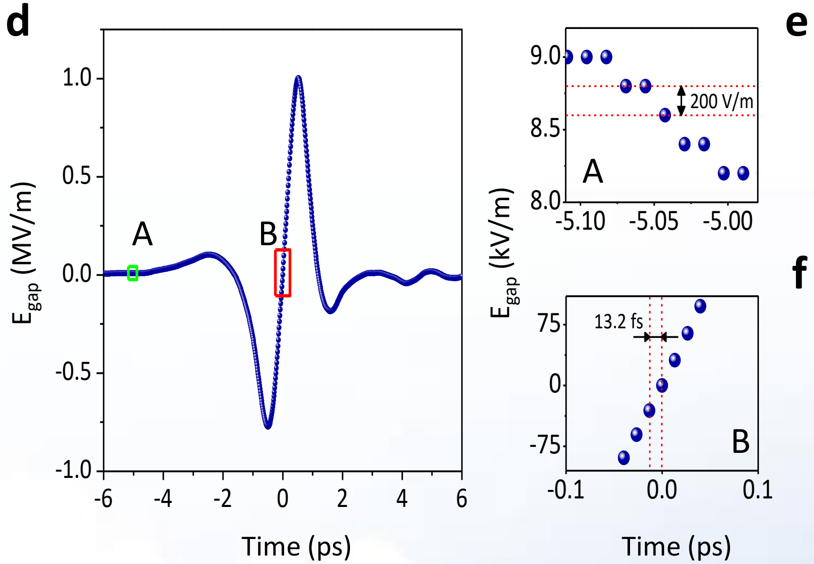


Waveform conservation @ both 30 microns



Recorded THz waveform



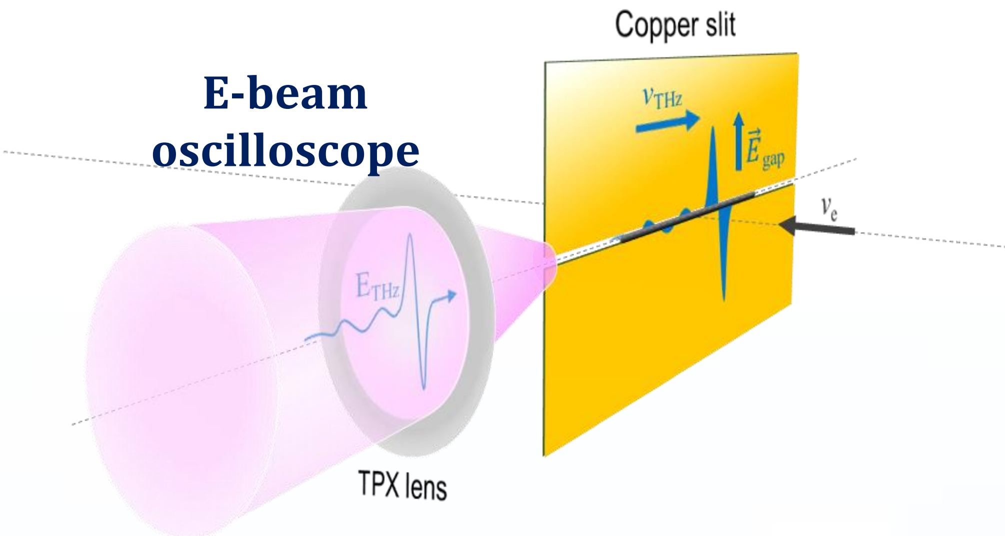


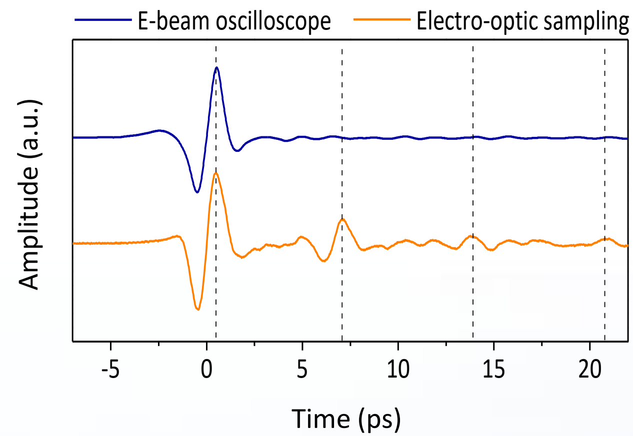
- **Horizontal beam size @ slit = 3.7 mm**
- **Single-shot time window = 12.3 ps**
- **~100 electrons/pixel for single-shot image**
- **Electron bunch : 0.5 pC, 3.101 MeV @ 50 Hz**

- **Time resolution per pixel = 13.2 fs (Sampling rate ~ 75.7 TS/s)**
- **Resolution of E-field amplitude = 200 V/m**

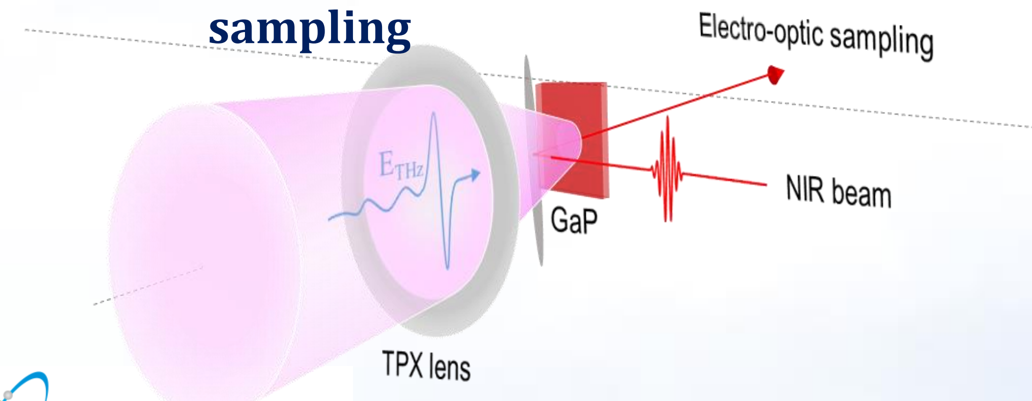
Signal integrity

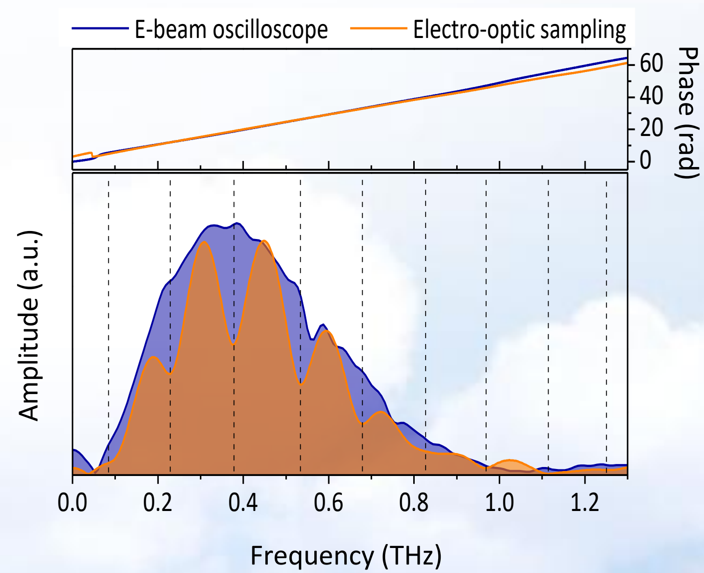
E-beam oscilloscope



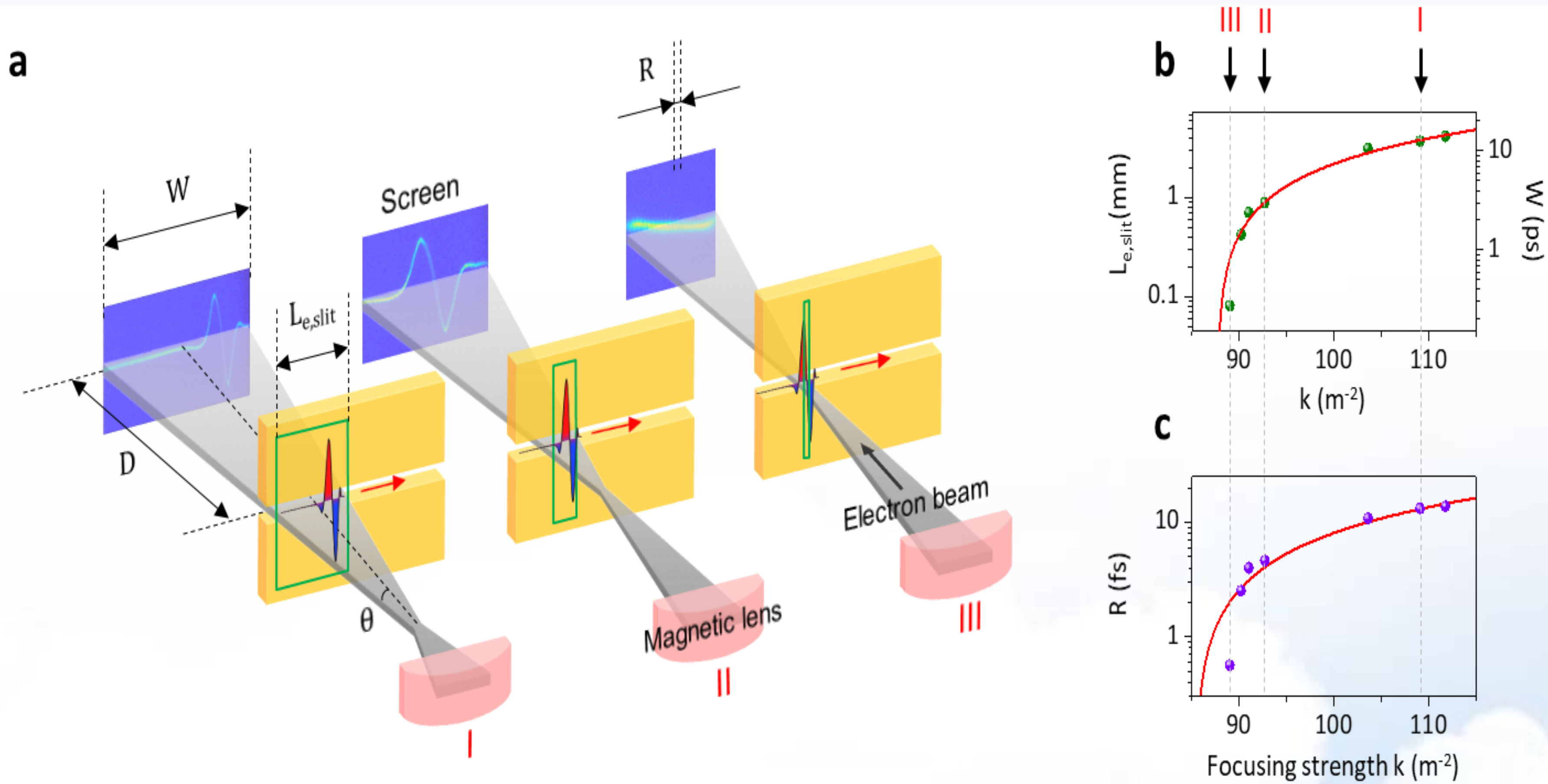


Electro-optic sampling





Feasibility of real-time PHz oscilloscope

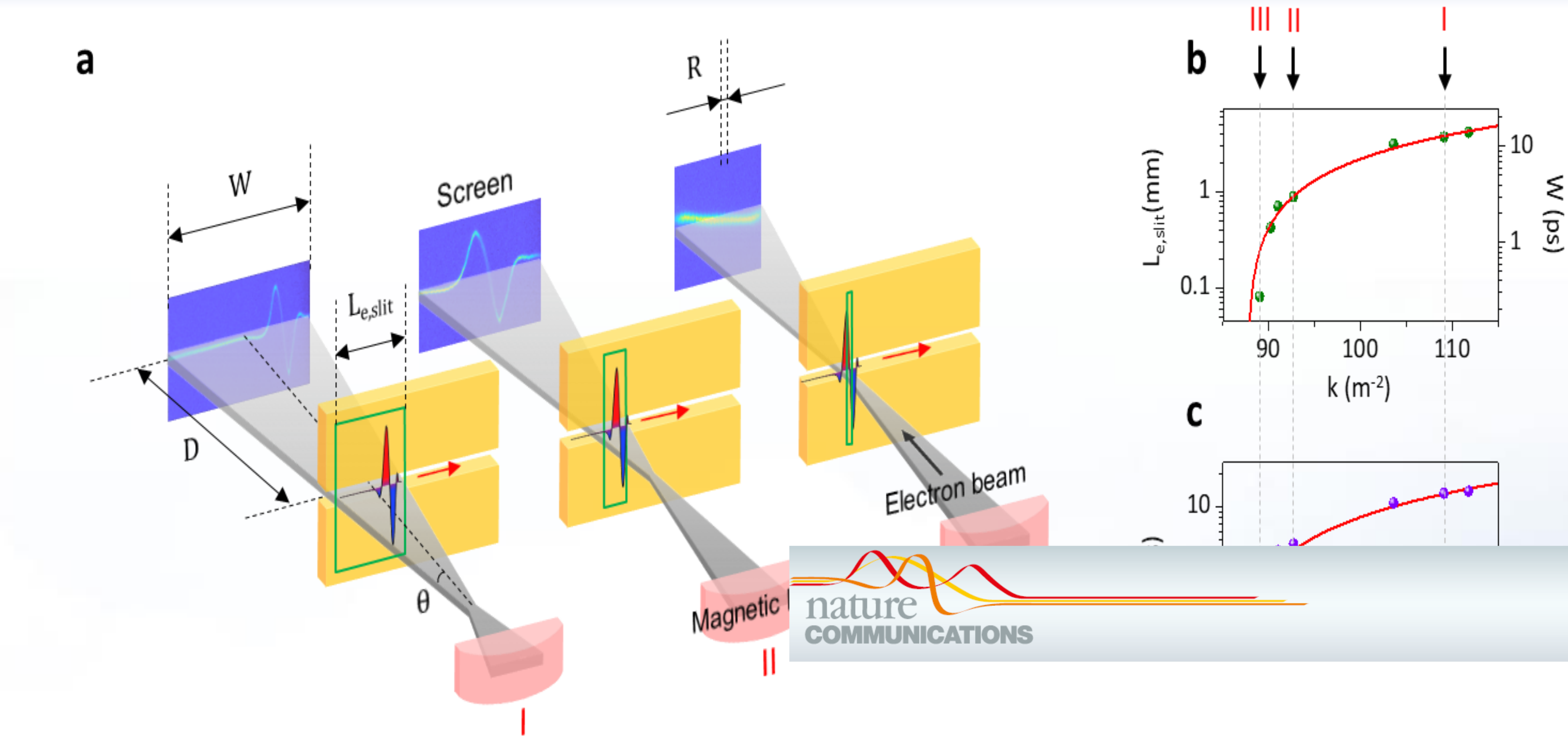


For 800 nm pulse visualization,

1. Electron pulse duration should be 170 as.

2. Thickness of metal slit should be 53 nm.

Feasibility of real-time PHz oscilloscope



For 800 nm pulse visualization,

1. Electron pulse duration should be

2. Thickness of metal slit should be 5

nature COMMUNICATIONS

ARTICLE

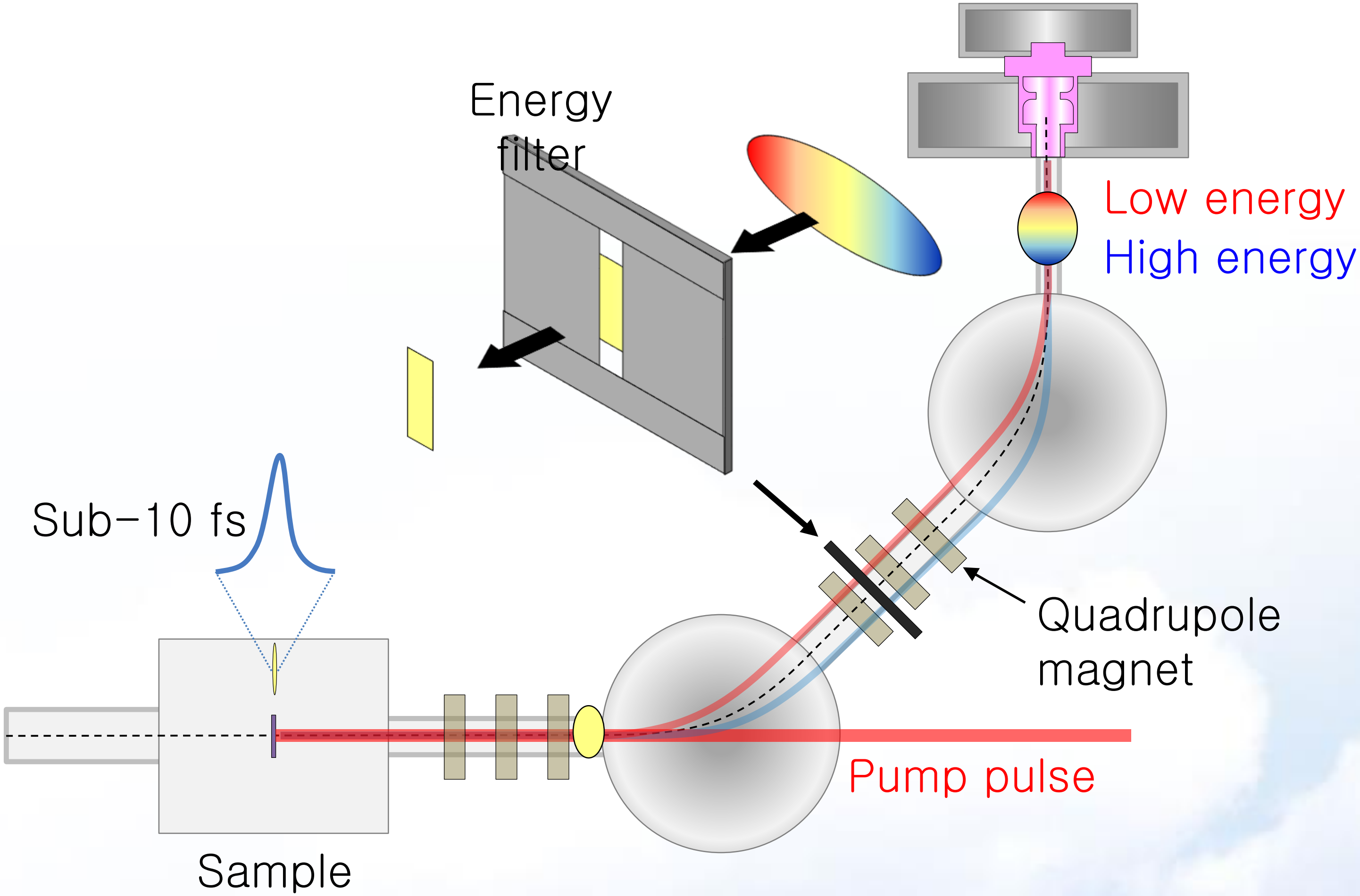
https://doi.org/10.1038/s41467-021-27256-x OPEN

Check for updates

Real-time ultrafast oscilloscope with a relativistic electron bunch train

In Hyung Baek[1,6], Hyun Woo Kim[1,6], Hyeon Sang Bark[1,6], Kyu-Ha Jang[1], Sunjeong Park[1], Junho Shin[1], Young Chan Kim[1], Mihye Kim[1], Key Young Oang[1], Kitae Lee[1,2], Fabian Rotermund[3], Nikolay A. Vinokurov[4,5] & Young Uk Jeong[1,2]✉

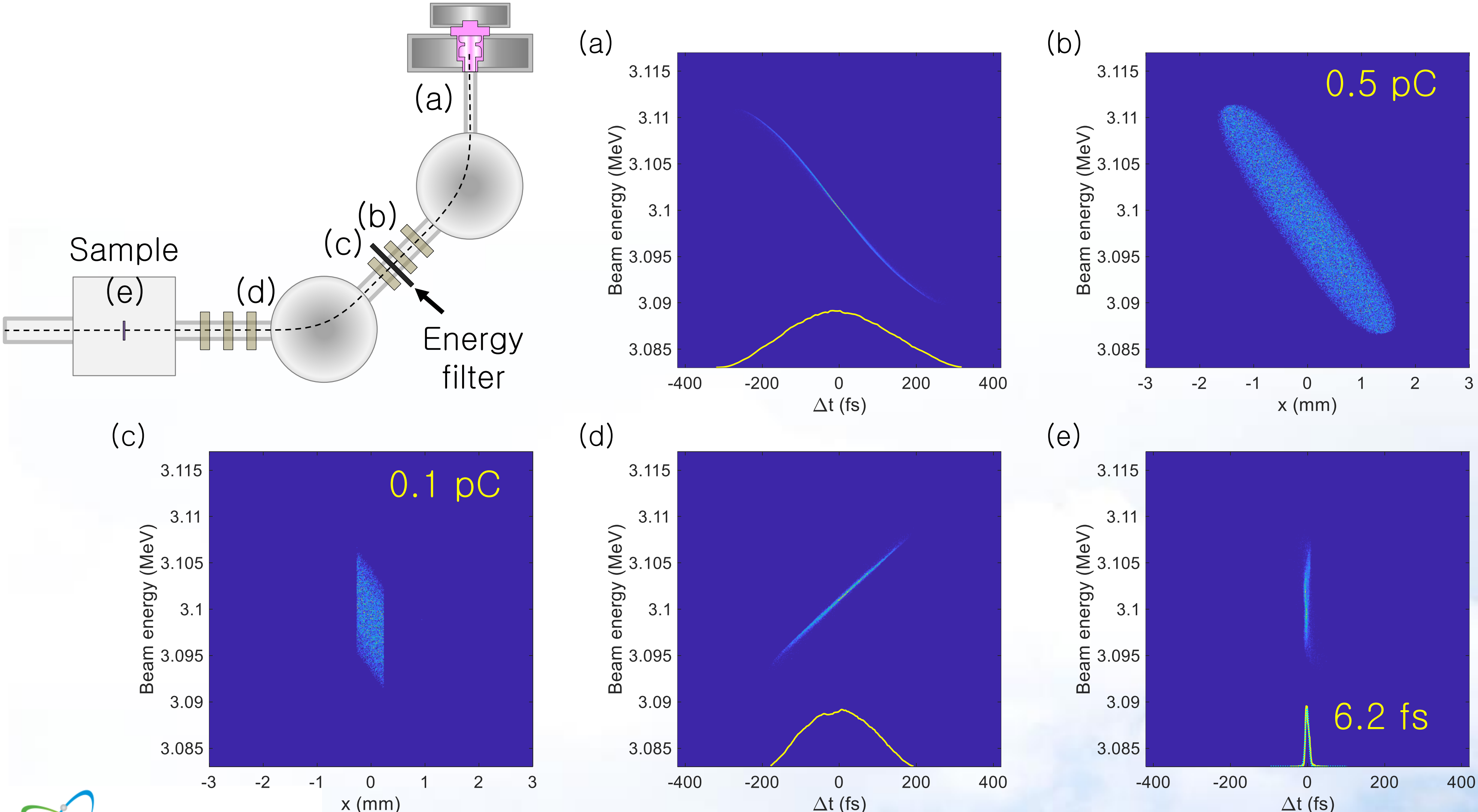
Sub-10 fs UED by using an Energy Filter



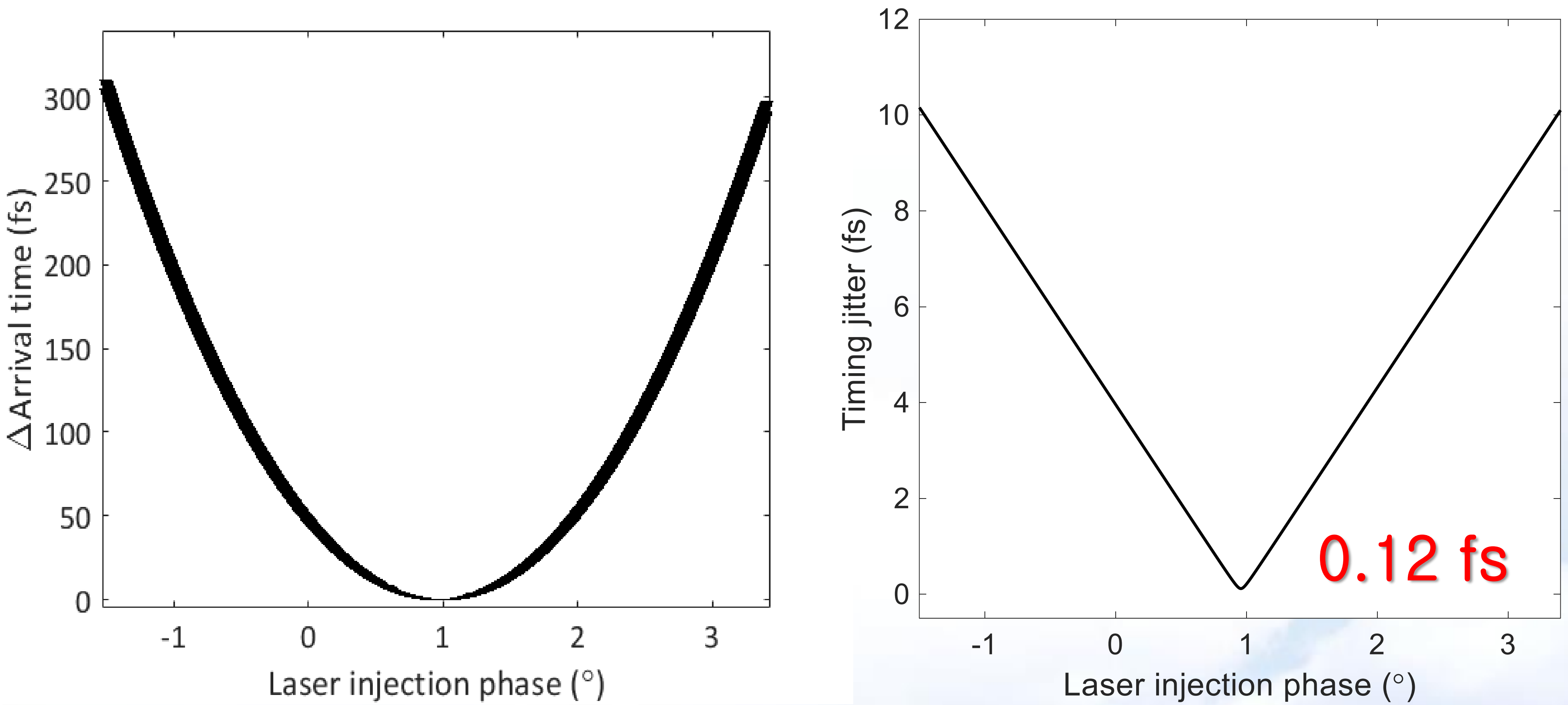
한국원자력연구원
KAERI Korea Atomic Energy Research Institute

H. W. Kim et al., Structural Dynamics, 7, 034301 (2020).

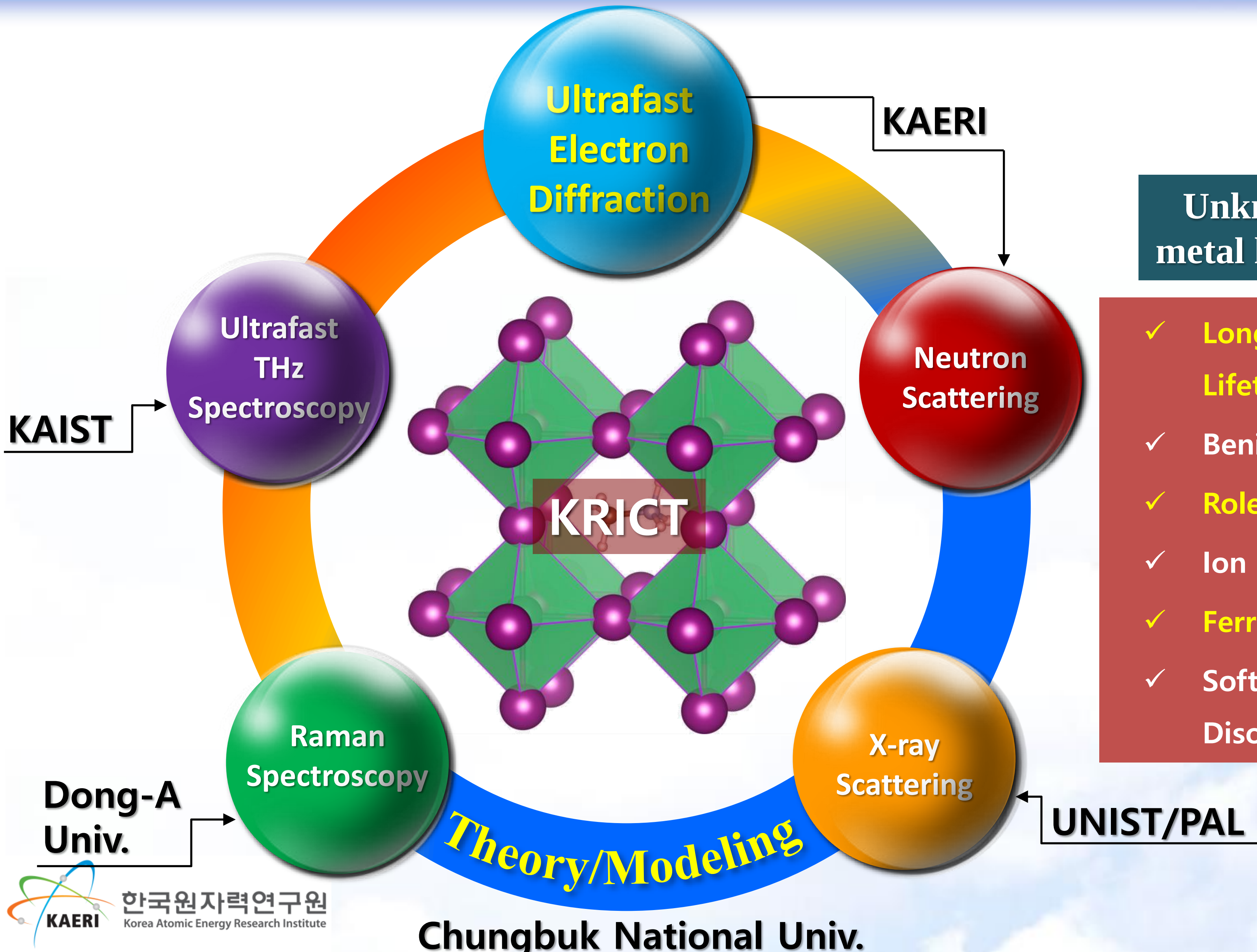
Sub-10 fs UED by using an Energy Filter



Sub-10 fs UED by using an Energy Filter



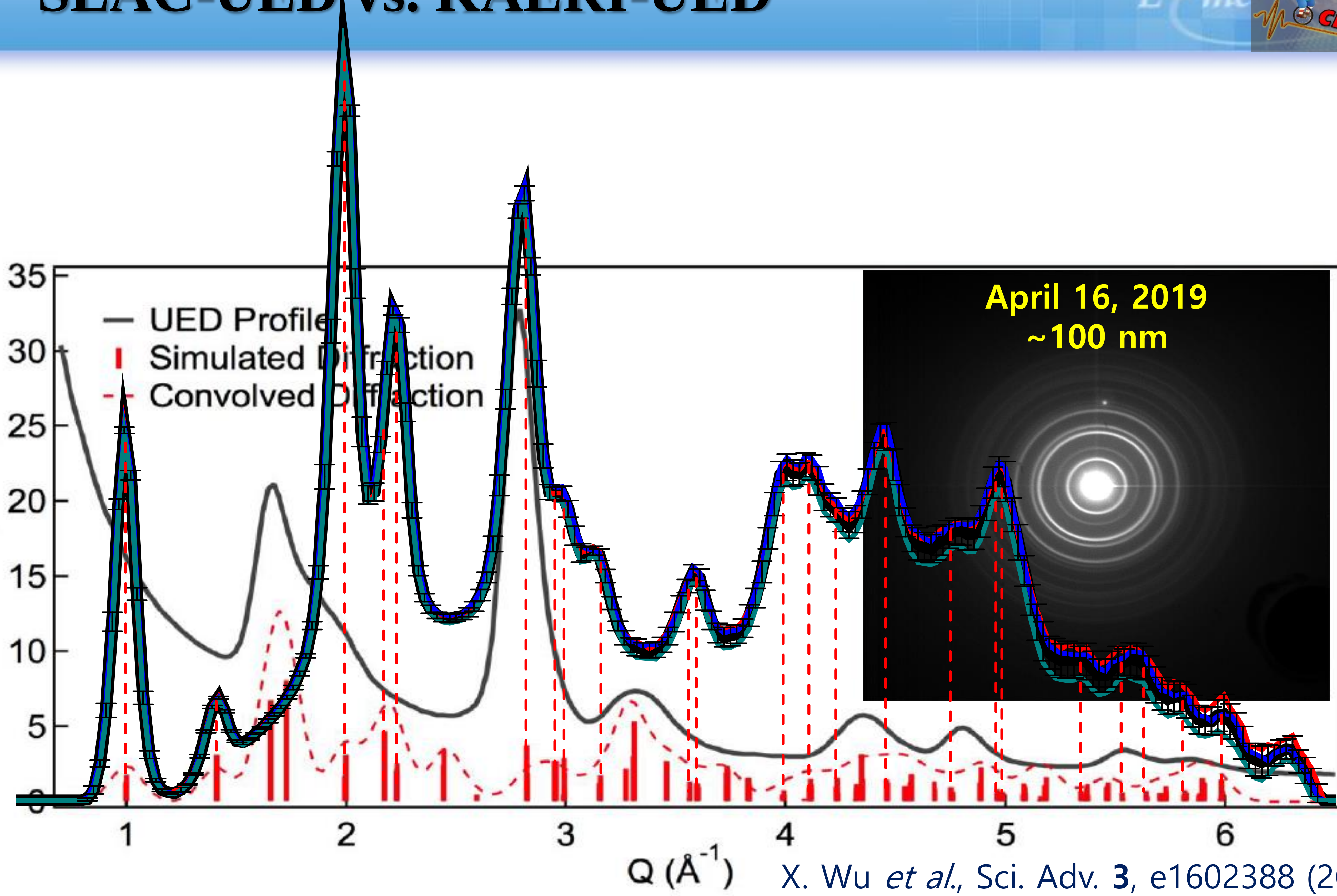
Collaboration for New Understanding



Unknown physics of metal halide perovskites

- ✓ Long Charge-carrier Lifetime
- ✓ Benign Defects
- ✓ Role of the Organic Cation
- ✓ Ion Migration
- ✓ Ferroelectricity
- ✓ Soft Lattice & Dynamic Disorder

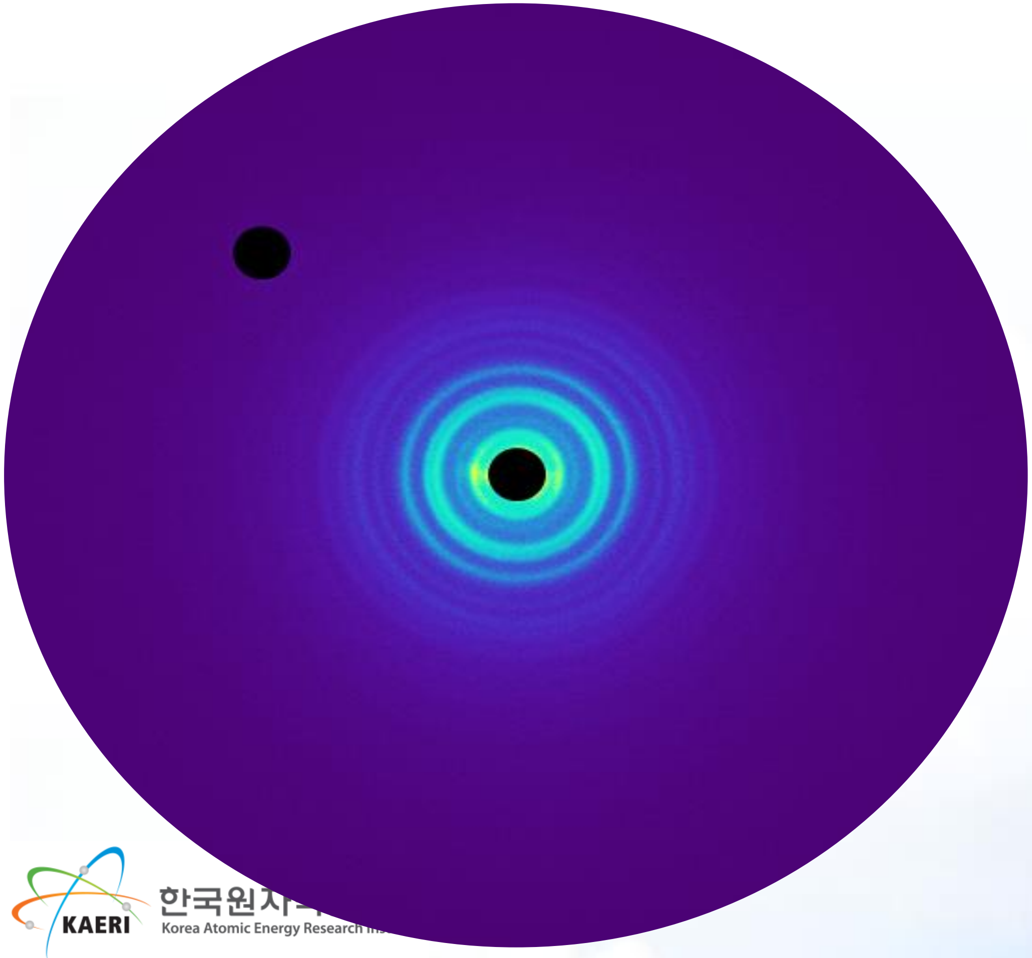
SLAC-UED vs. KAERI-UED



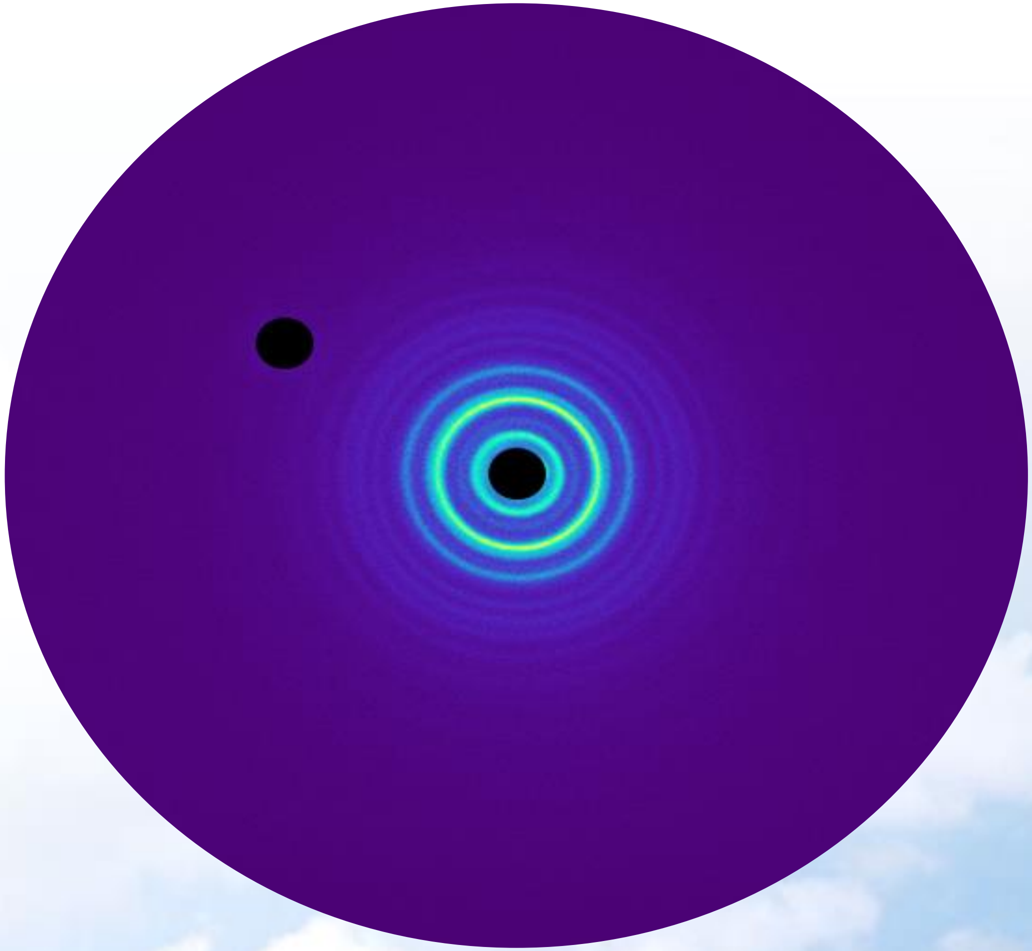
X. Wu *et al.*, Sci. Adv. **3**, e1602388 (2017)

UED Data of $(FAPbI_3)_x(MAPbBr_3)_{1-x}$

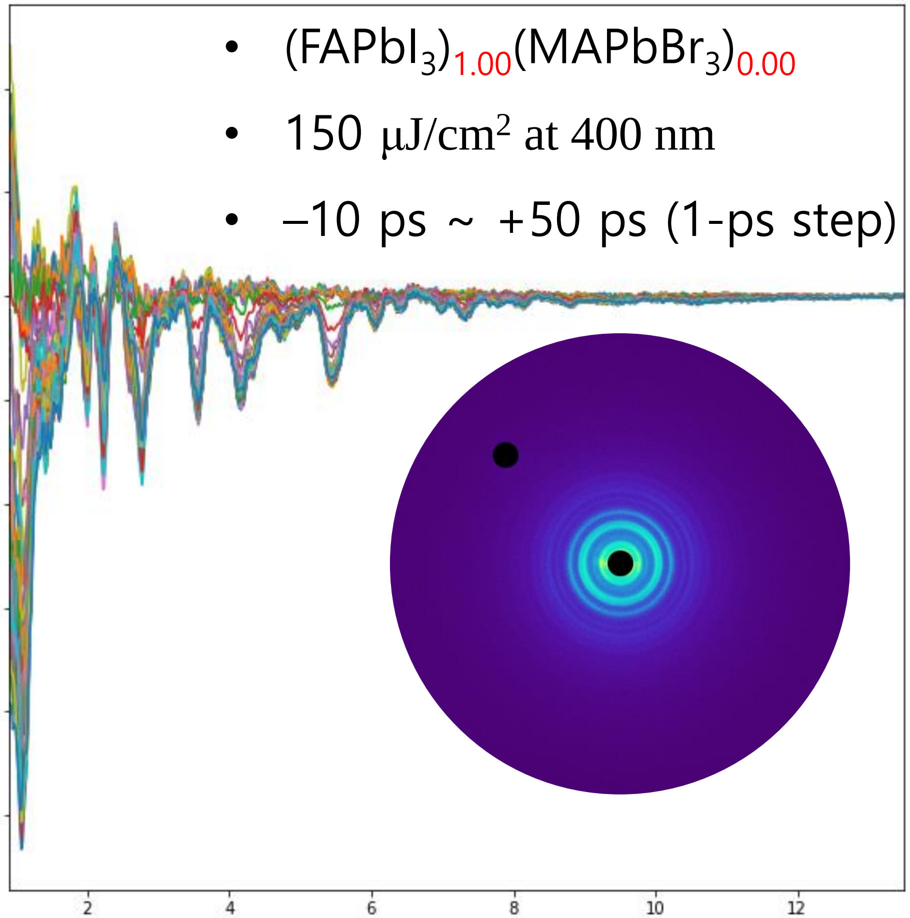
125-nm-thick
$(FAPbI_3)_{1.00}(MAPbBr_3)_{0.00}$



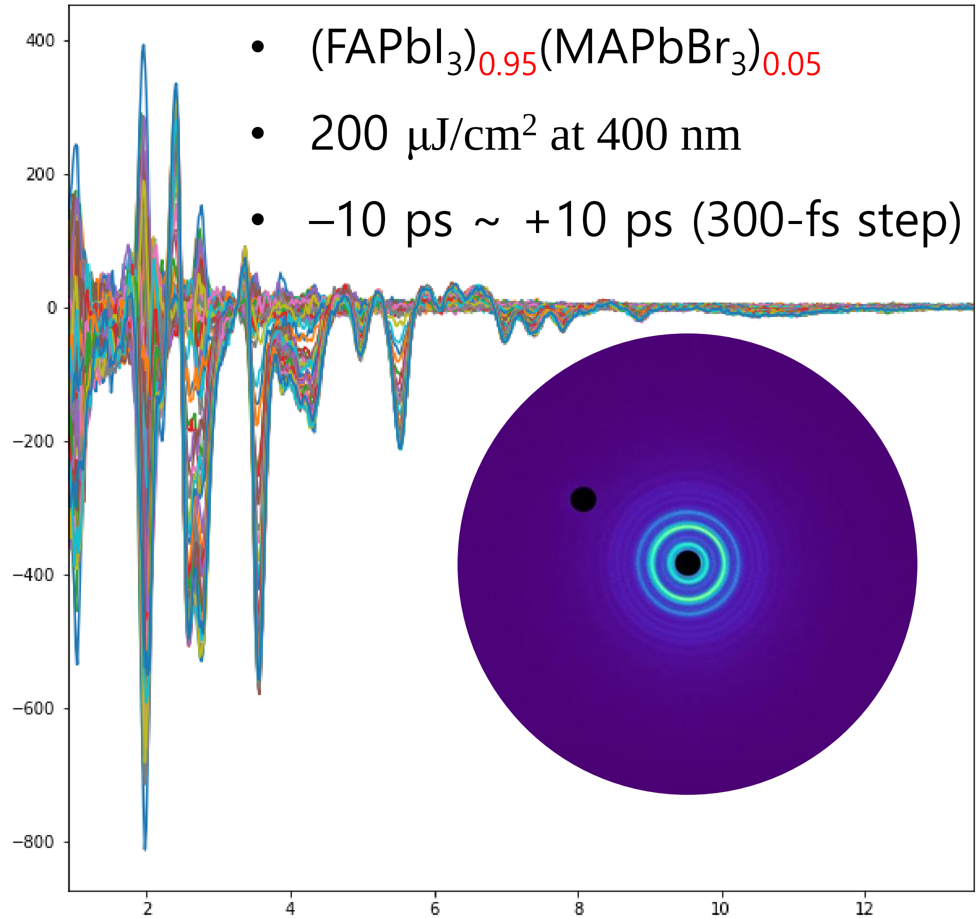
125-nm-thick
$(FAPbI_3)_{0.95}(MAPbBr_3)_{0.05}$



Overall 1D difference curves; $\Delta I(q,t) = I(q,t) - I(q,t_{ref})$



q (Å^{-1})



q (Å^{-1})

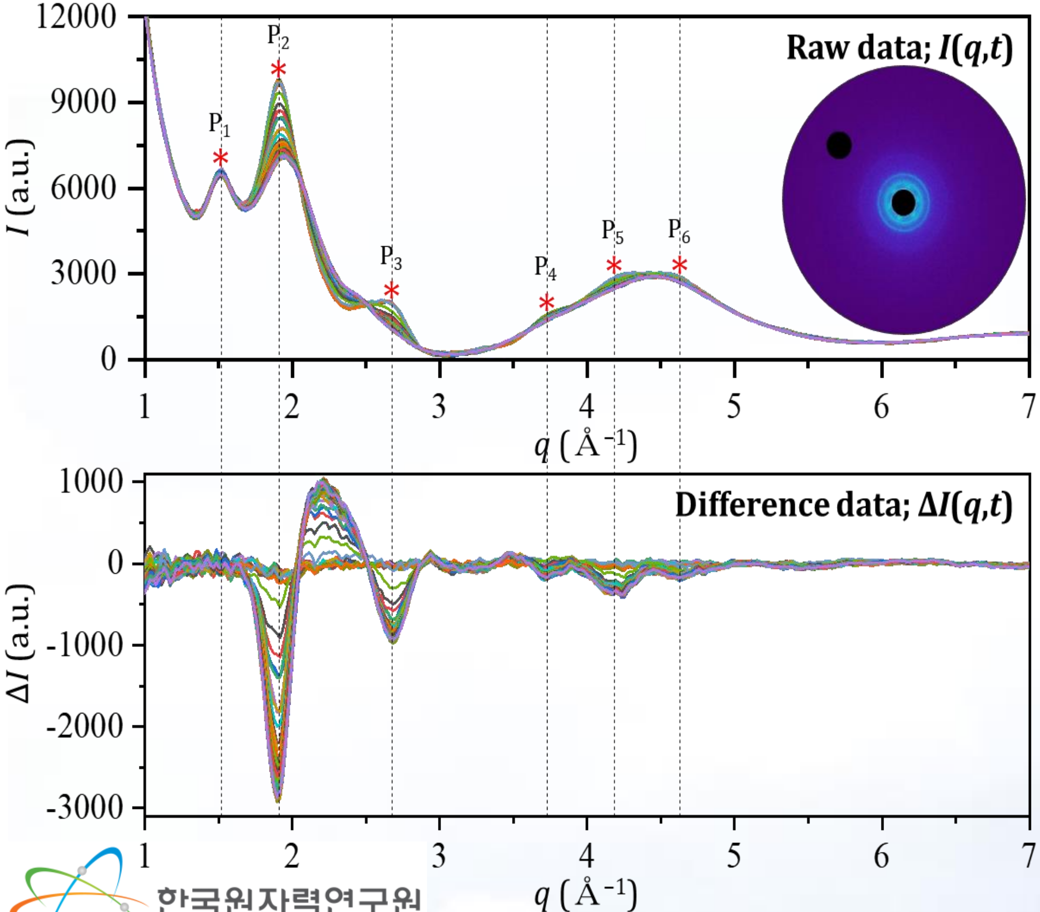
KAERI 한국원자력연구원 Korea Atomic Energy Research Institute

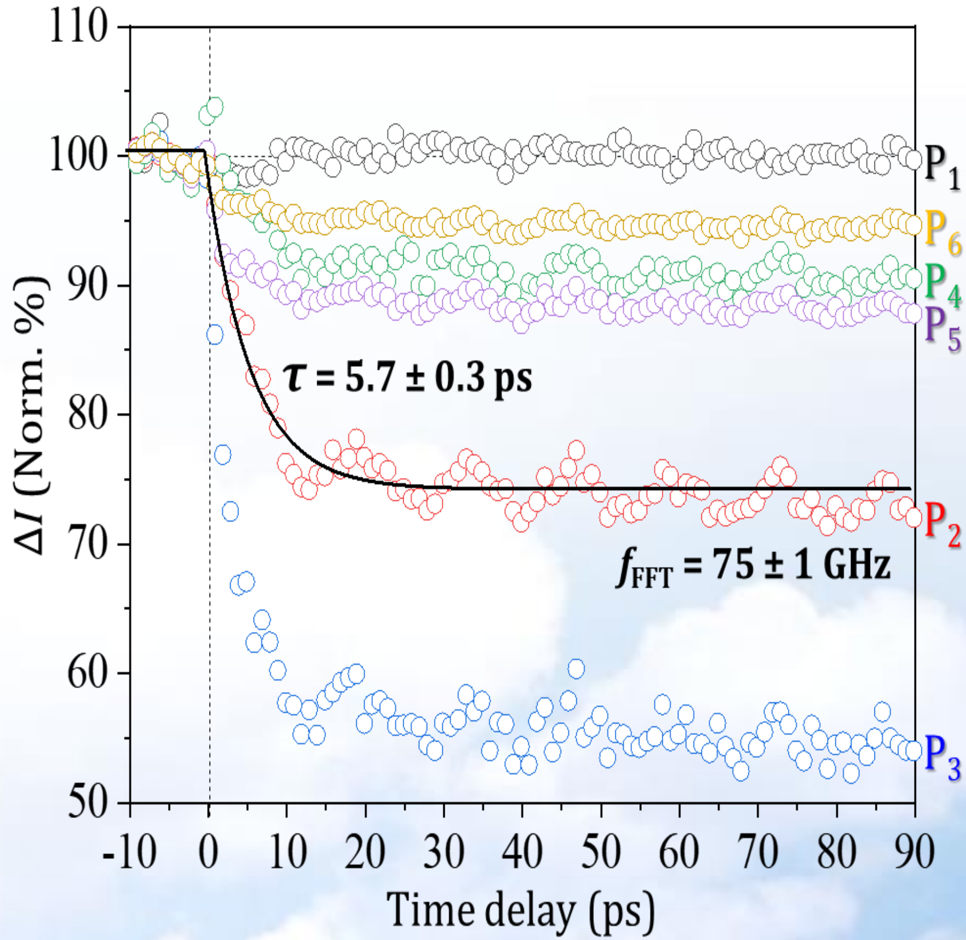
circus

Bi Photo-excited Dynamics Study

20-nm-thick polycrystalline Bismuth

(700 μJ/cm² at 400 nm; –10 ps ~ +90 ps with 1-ps step)





PAL X-FEL

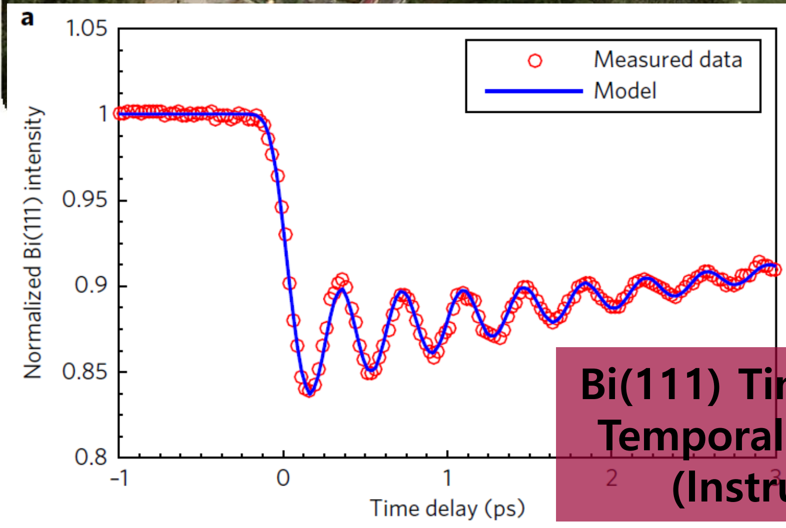
Table 1 | Designed and measured parameters for hard and soft XFELs

Parameter	Designed value (hard/soft)	Hard	Soft
FEL radiation wavelength (nm)	0.1/1.0	0.104	1.52
Electron energy (GeV)	10/3.15	9.47	3.0
Slice emittance (mm mrad)	0.5	0.55	0.55
Beam charge (nC)	0.2	0.14	0.14
Peak current at undulator (kA)	3.0/2.5	2.5	2.2
Pulse repetition rate (Hz)	60	30	30
FEL gain length (m)	3.6/1.8	3.61	2.08
Photons per pulse (10^{11})	2.6/10	1.8	10.0

ARTICLES
nature photonics
https://doi.org/10.1038/s41566-017-0029-8

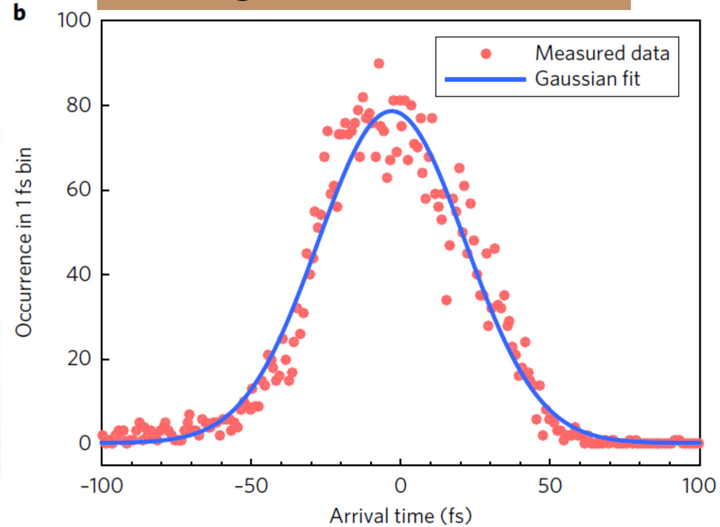
Hard X-ray free-electron laser with femtosecond-scale timing jitter

Heung-Sik Kang[1*], Chang-Ki Min[1], Hoon Heo[1], Changbum Kim[1], Haeryong Yang[1], Gyujin Kim[1], Inhyuk Nam[1], Soung Youl Baek[1], Hyo-Jin Choi[1], Geonyeong Mun[1], Byoung Ryul Park[1], Young Jin Suh[1], Dong Cheol Shin[1], Jinyul Hu[1], Juho Hong[1], Seonghoon Jung[1], Sang-Hee Kim[1], KwangHoon Kim[1], Donghyun Na[1], Soung Soo Park[1], Yong Jung Park[1], Jang-Hui Han[1], Young Gyu Jung[1], Seong Hun Jeong[1], Hong Gi Lee[1], Sangbong Lee[1], Sojeong Lee[1], Woul-Woo Lee[1], Bonggi Oh[1], Hyung Suck Suh[1], Yong Woon Parc[1], Sung-Ju Park[1], Min Ho Kim[1], Nam-Suk Jung[1], Young-Chan Kim[1], Mong-Soo Lee[1], Bong-Ho Lee[1], Chi-Won Sung[1], Ik-Su Mok[1], Jung-Moo Yang[1], Chae-Soon Lee[1], Hocheol Shin[1], Ji Hwa Kim[1], Yongsam Kim[1], Jae Hyuk Lee[1], Sang-Youn Park[1], Jangwoo Kim[1], Jaeku Park[1], Intae Eom[1], Seungyu Rah[1], Sunam Kim[1], Ki Hyun Nam[1], Jaehyun Park[1], Jaehun Park[1], Sangsoo Kim[1], Soonam Kwon[1], Sang Han Park[1], Kyung Sook Kim[1], Hyojung Hyun[1], Seung Nam Kim[1], Seonghan Kim[1], Sun-min Hwang[1], Myong Jin Kim[1], Chae-yong Lim[1], Chung-Jong Yu[1], Bong-Soo Kim[1], Tai-Hee Kang[1], Kwang-Woo Kim[1], Seung-Hwan Kim[1], Hee-Seock Lee[1], Heung-Soo Lee[1], Ki-Hyeon Park[1], Tae-Yeong Koo[1], Dong-Eon Kim[1] and In Soo Ko[2]



Bi(111) Time-resolved Diffraction
Temporal Accuracy : 137 fs rms
(Instrumental Response)

Timing Jitter : 25 fs rms



X-FEL v.s. UED 엑스선과 전자 비교

X-FEL (PAL X-FEL)

Big molecules of bio & nano-bio complex

X-ray → Low scattering power → Long penetration

↕ Complementary Tools

Electron → Strong scattering power → Short penetration

Sparse materials like 2-D, gas and liquid

UED (KAERI)

UED for Future

Nature | Vol 596 | 26 August 2021 | 531

Article

Direct observation of ultrafast hydrogen bond strengthening in liquid water

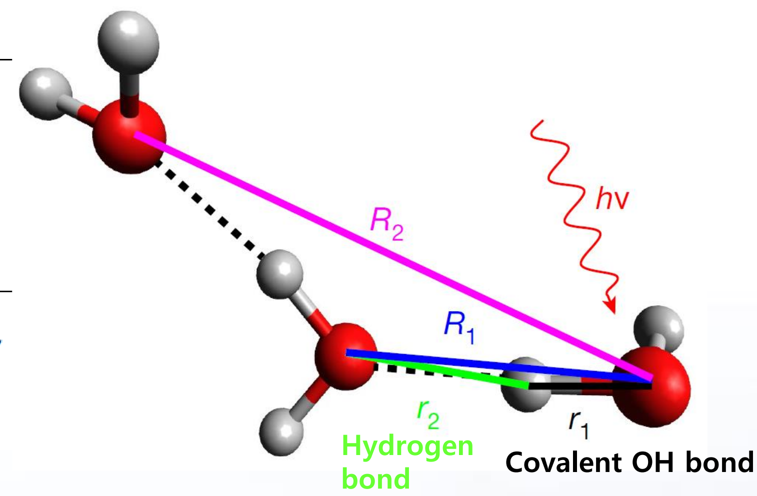
https://doi.org/10.1038/s41586-021-03793-9

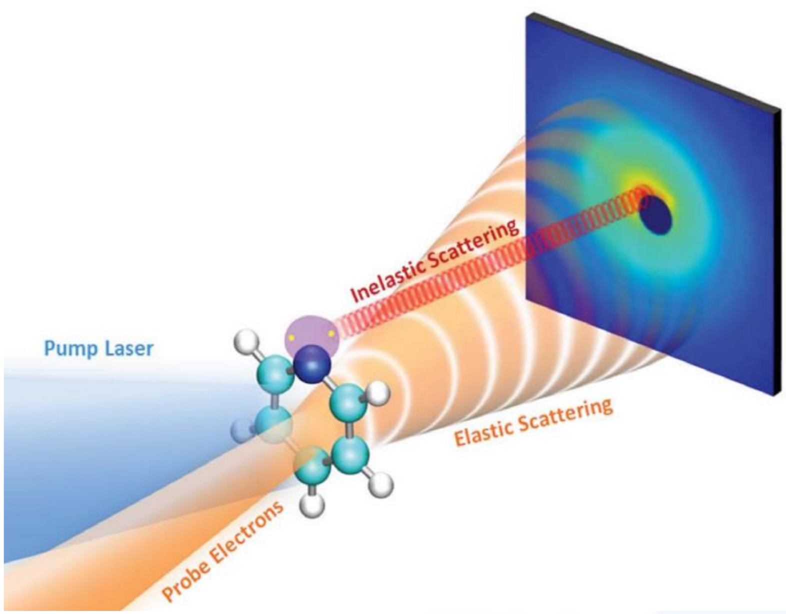
Received: 28 September 2020

Accepted: 1 July 2021

Published online: 25 August 2021

Jie Yang[1,2,11]✉, Riccardo Dettori[3], J. Pedro F. Nunes[4], Nanna H. List[1,2,5], Elisa Biasin[1,2], Martin Centurion[4], Zhijiang Chen[1], Amy A. Cordones[2], Daniel P. Deponte[1], Tony F. Heinz[2,6], Michael E. Kozina[1,2], Kathryn Ledbetter[2,7], Ming-Fu Lin[1], Aaron M. Lindenberg[2,8,9], Mianzhen Mo[1], Anders Nilsson[10], Xiaozhe Shen[1], Thomas J. A. Wolf[1,2], Davide Donadio[3]✉, Kelly J. Gaffney[2]✉, Todd J. Martinez[1,2,5]✉ & Xijie Wang[1]✉





RESEARCH

Science **368**, 885–889 (2020)

CHEMICAL PHYSICS

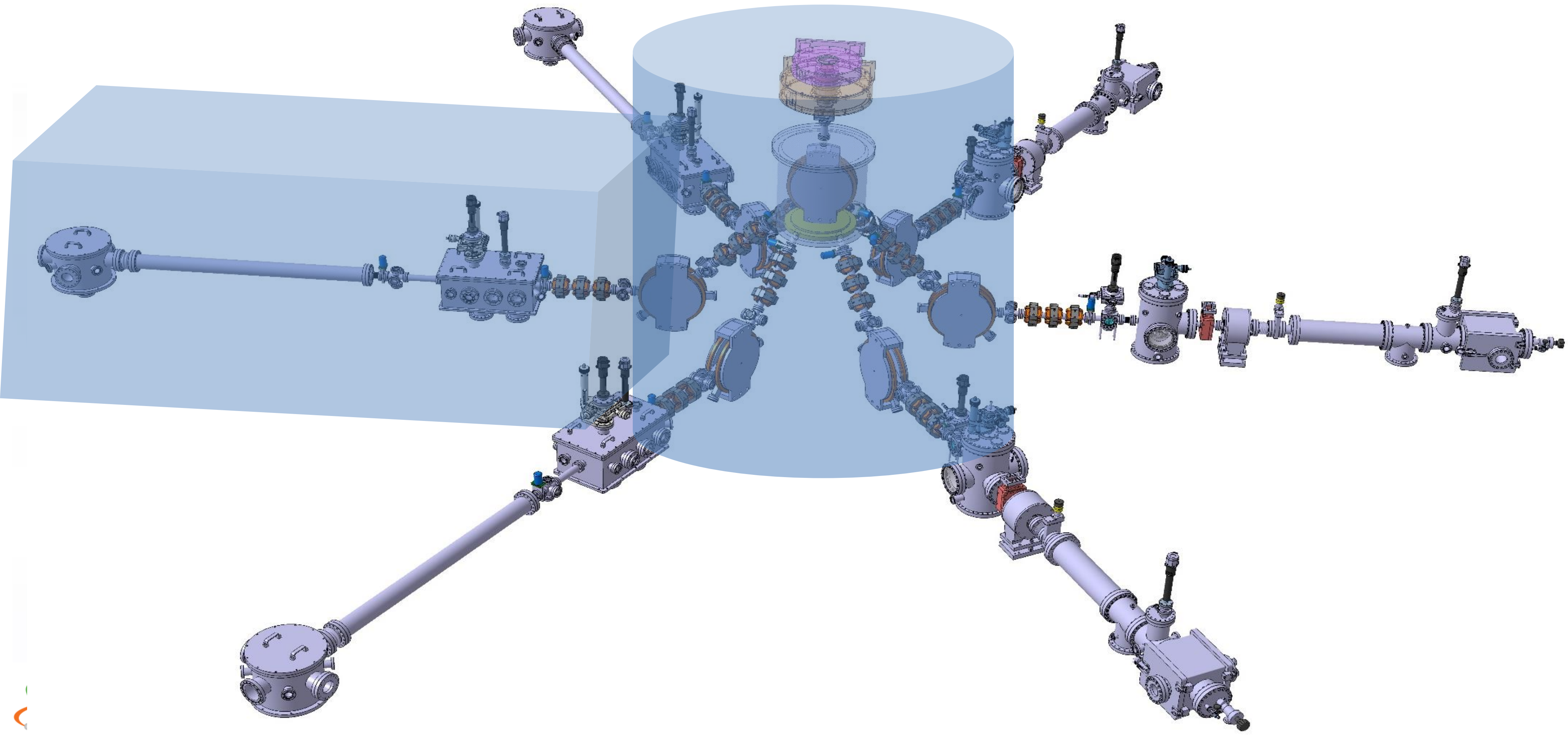
Simultaneous observation of nuclear and electronic dynamics by ultrafast electron diffraction

Jie Yang[1,2]*†, Xiaolei Zhu[1,2,3]†, J. Pedro F. Nunes[4], Jimmy K. Yu[2,3,5], Robert M. Parrish[1,2,3], Thomas J. A. Wolf[1,2], Martin Centurion[4], Markus Gühr[6], Renkai Li[1]‡, Yusong Liu[7], Bryan Moore[4], Mario Niebuhr[6], Suji Park[1]§, Xiaozhe Shen[1], Stephen Weathersby[1], Thomas Weinacht[7], Todd J. Martinez[1,2,3]*, Xijie Wang[1]*

UED User Facility

90도 휨구조를 3차원으로 배치하면 6~8 빔라인 구축

5대권역 설치시 차세대 방사광의 1/10 예산으로 4세대급 방사선 30개 빔라인 구축



Acknowledgements

Development & characterization of UED Apparatus

Dr. Hyun Woo Kim, Dr. In Hyung Baek, Ms. Mi Hye Kim, Mr. Young Chan Kim, Dr. Sunjeong Park, Dr. MoonSik Chae, Dr. Key Young Oang, Dr. Junho Shin, Mr. Sangyoon Bae, Dr. Jungho Moon, Dr. Kyu-Ha Jang, Dr. Kitae Lee, Dr. Boris Gudkov, Dr. Sergey Miginsky

RF-laser synchronization

Prof. Jungwon Kim

THz wave generation

Prof. Fabian Rotermund

RF deflector

Prof. Seong Hee Park

RF gun design

Dr. Jang-Hee Han

System configuration

Prof. Nikolay A. Vinokurov

Split ring resonator

Dr. Zoltan Ollmann,
Ms. Mozhgan Hayati,
Prof. Thomas Feurer

Sample preparation

Prof. Sunglae Cho

KAERI 한국원자력연구원 Korea Atomic Energy Research Institute

감사합니다!!

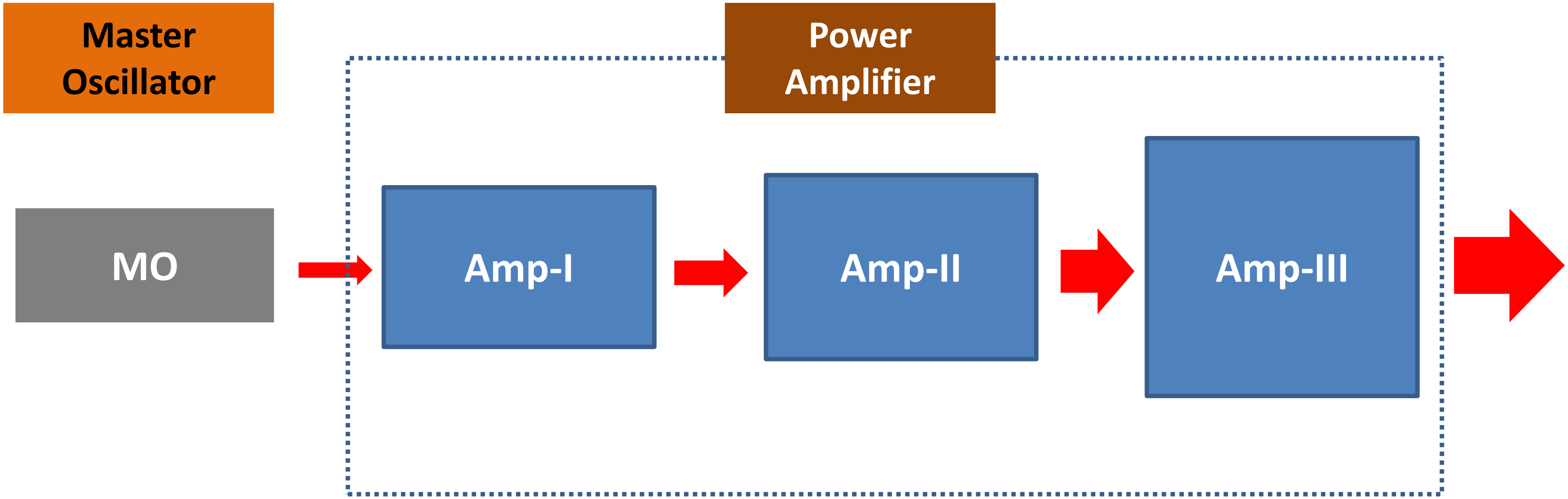
EUV Source for Lithography

2022. 7. 13

WORLD CLASS INSTITUTE

Young UK JEONG

Master Oscillator & Power Amplifier



High Quality Beam

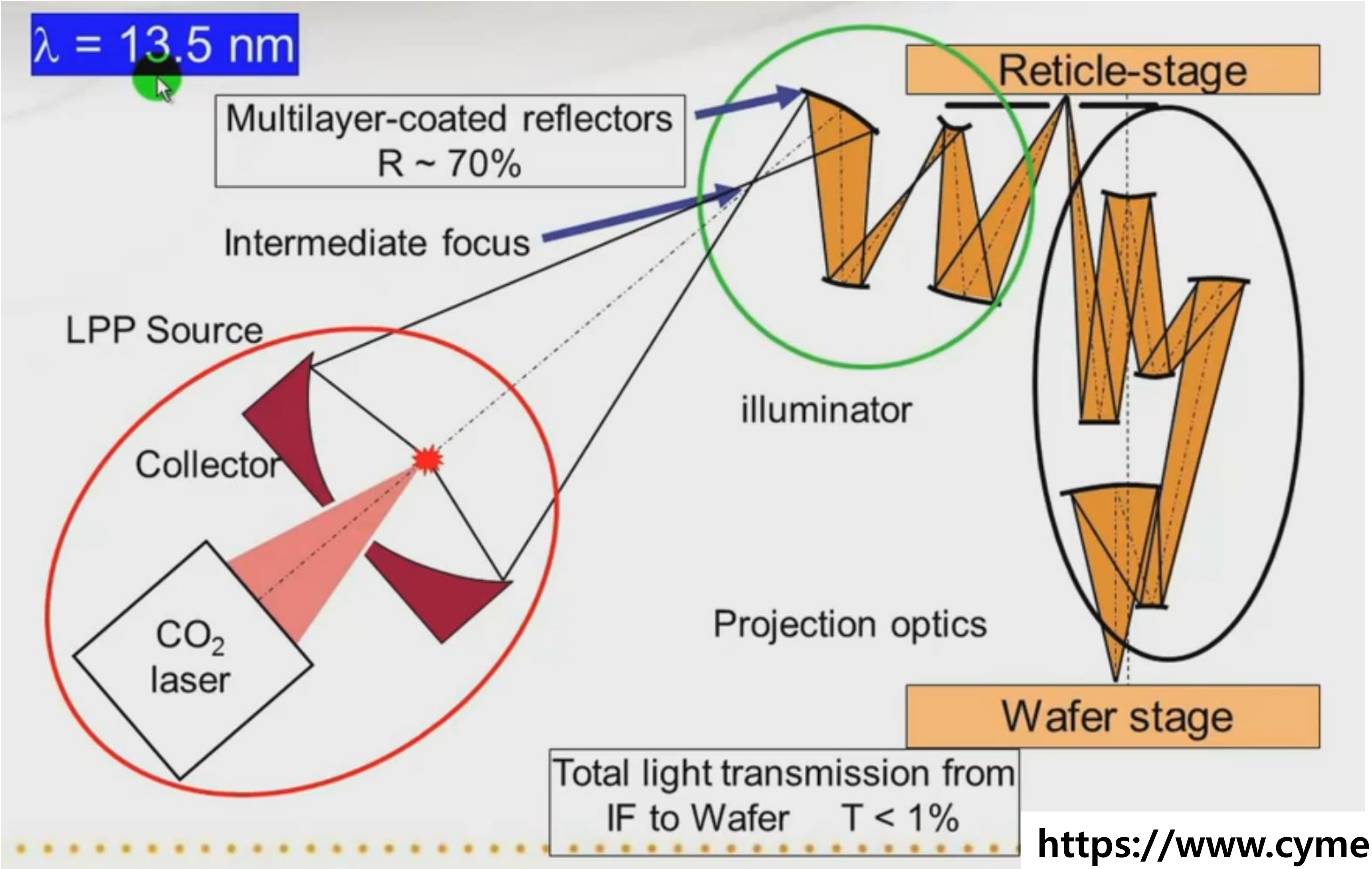
Pulse Energy

Laser-produced plasma (LPP) Source

- Pulsed Laser + Laser-produced plasma
  (CO_2 pulsed laser + Sn plasma)

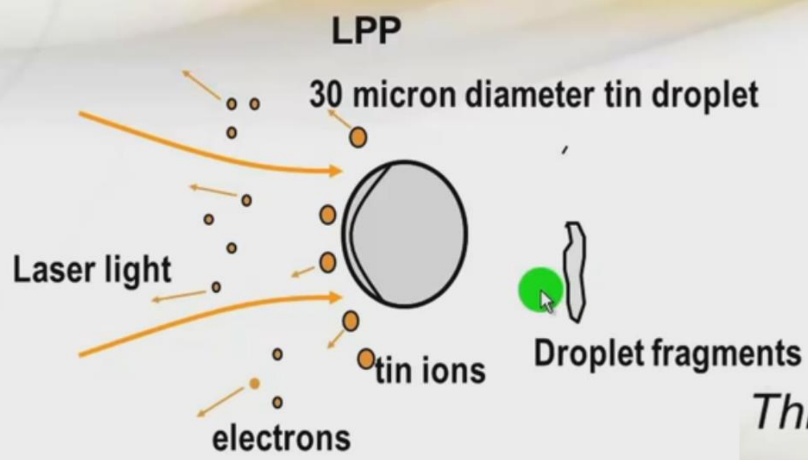
- Requirements for EUV source, ASML
  ※ > 100 wph (@ photo-register sensitivity 15 mJ/cm^2)
  - Wavelength : 13.5 nm (7 nm node, R: 60-70%)
  - Power : 250 W (@ IF, bandwidth 2%)

Laser-produced plasma (LPP) Source



https://www.cymer.com/

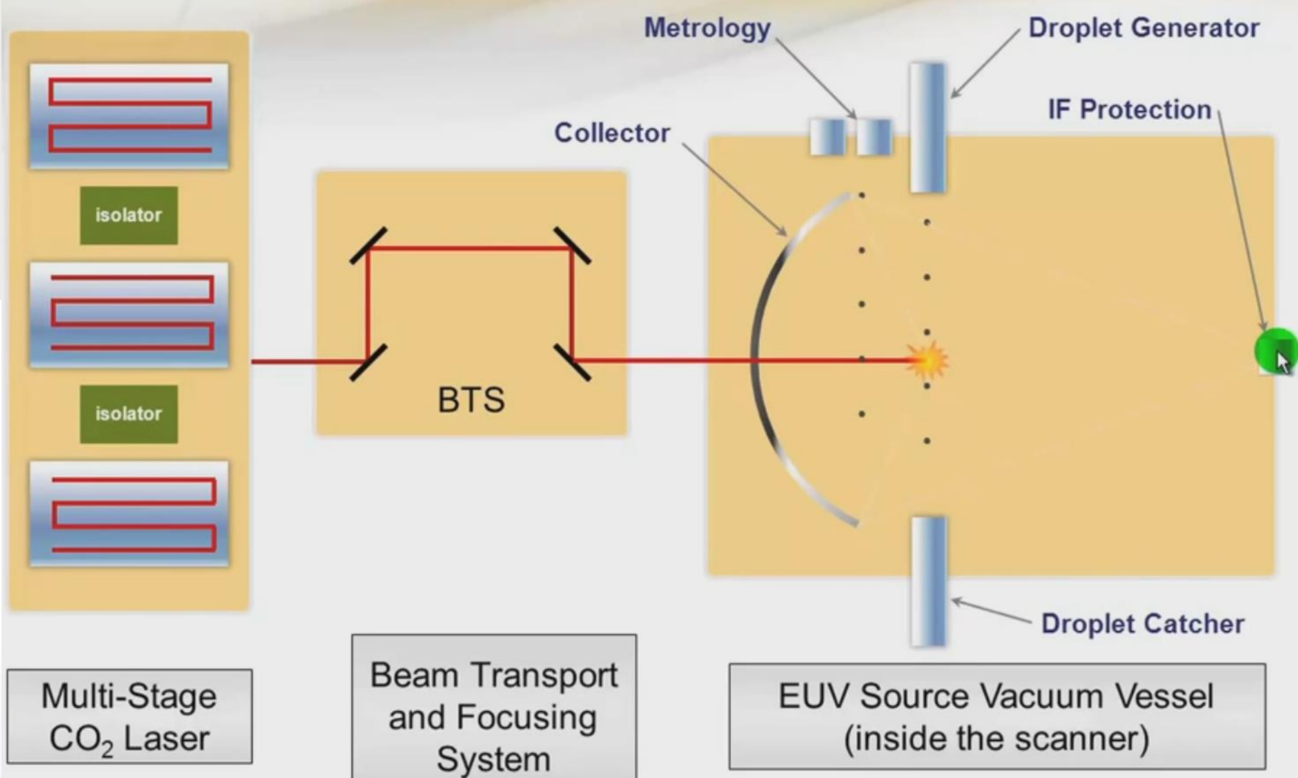
Laser-produced plasma (LPP) Source



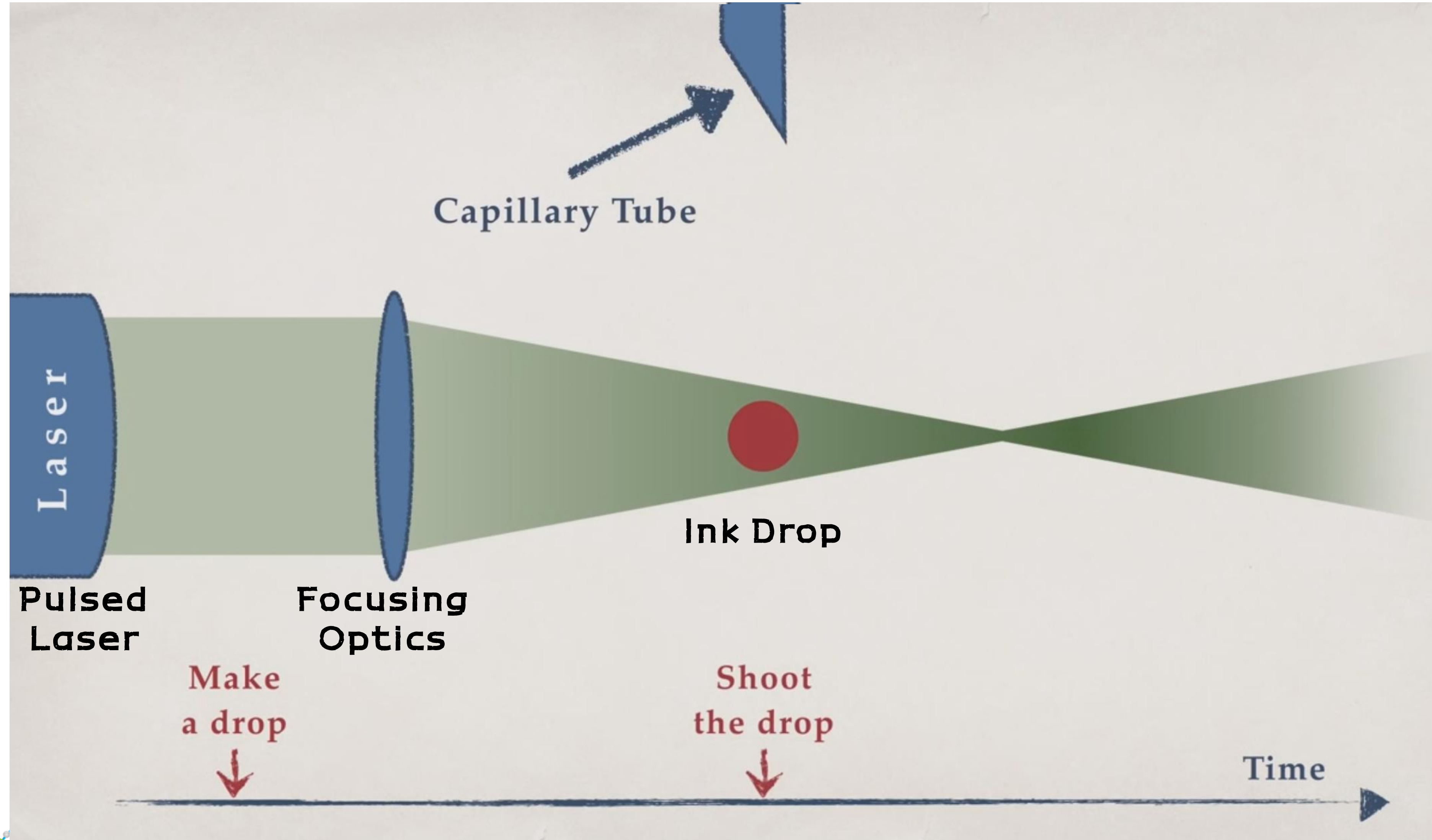
- A high power laser evaporates a tin droplet, then heats the vapor to critical temperature where electrons are shed, leaving behind ions, which are further heated until they start emitting photons

https://www.cymer.com/

Three key technologies: laser, droplet generation, collector

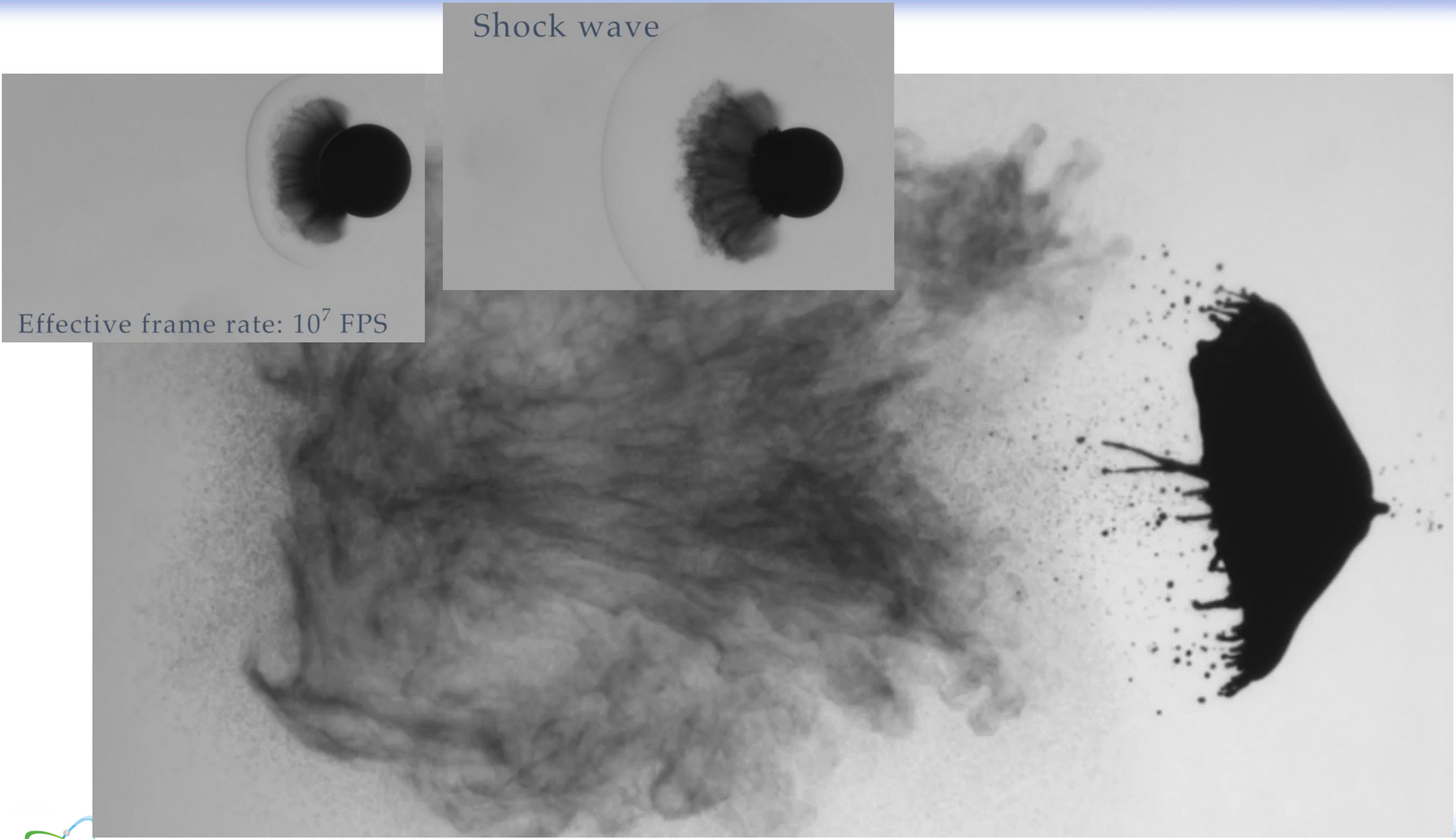


Laser-produced plasma (LPP) Source



https://www.youtube.com/watch?v=bRbHDtPbHe0

Laser-produced plasma (LPP) Source



https://www.youtube.com/watch?v=bRbHDtPbHe0

Laser-produced plasma (LPP) Source

Plasma generation

https://www.youtube.com/watch?v=bRbHDtPbHe0

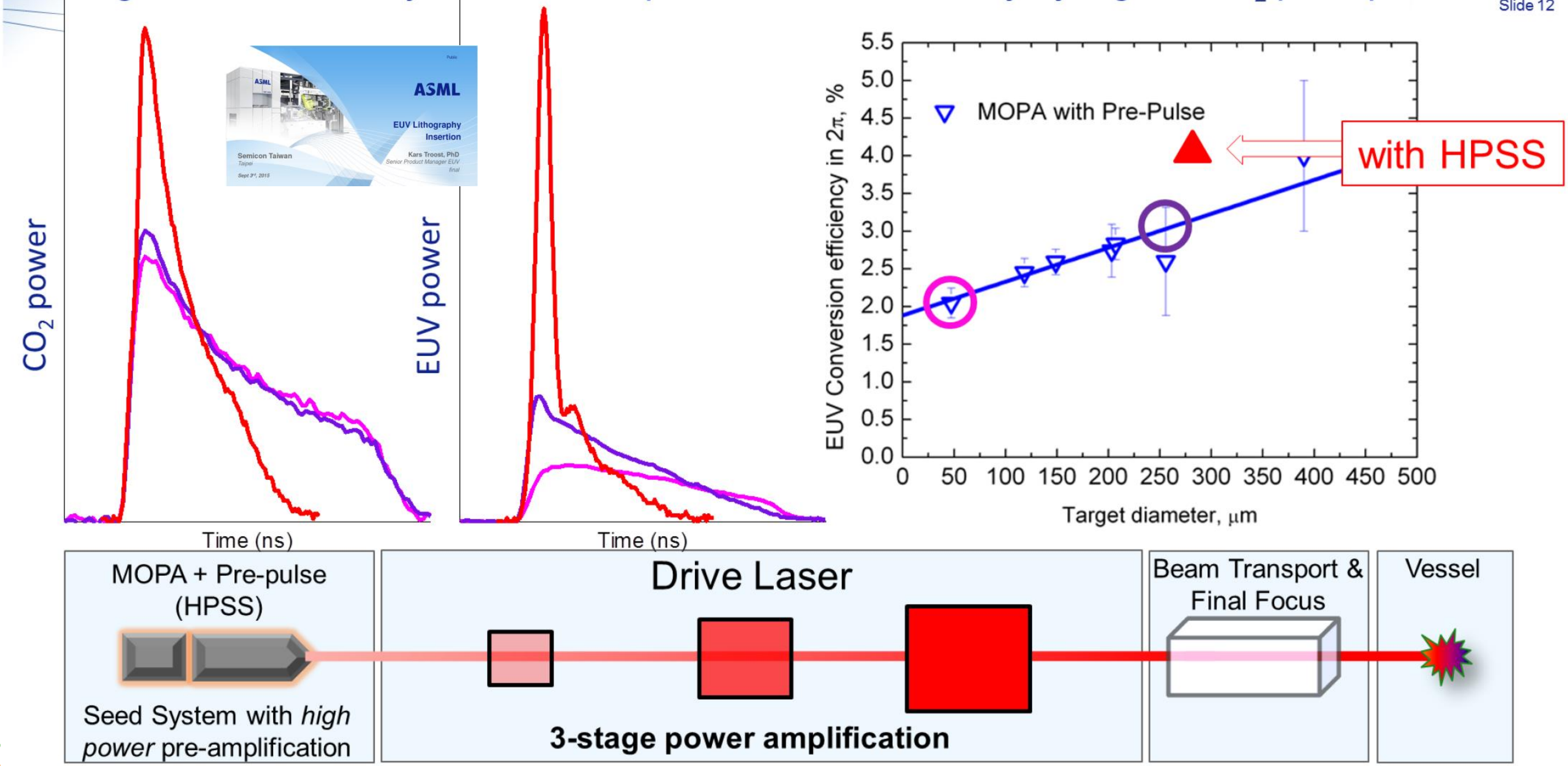
Laser-produced plasma (LPP) Source

EUV power above 100W by improved conversion efficiency

High Power Seed System drives up conversion efficiency by higher CO_2 peak power

ASML

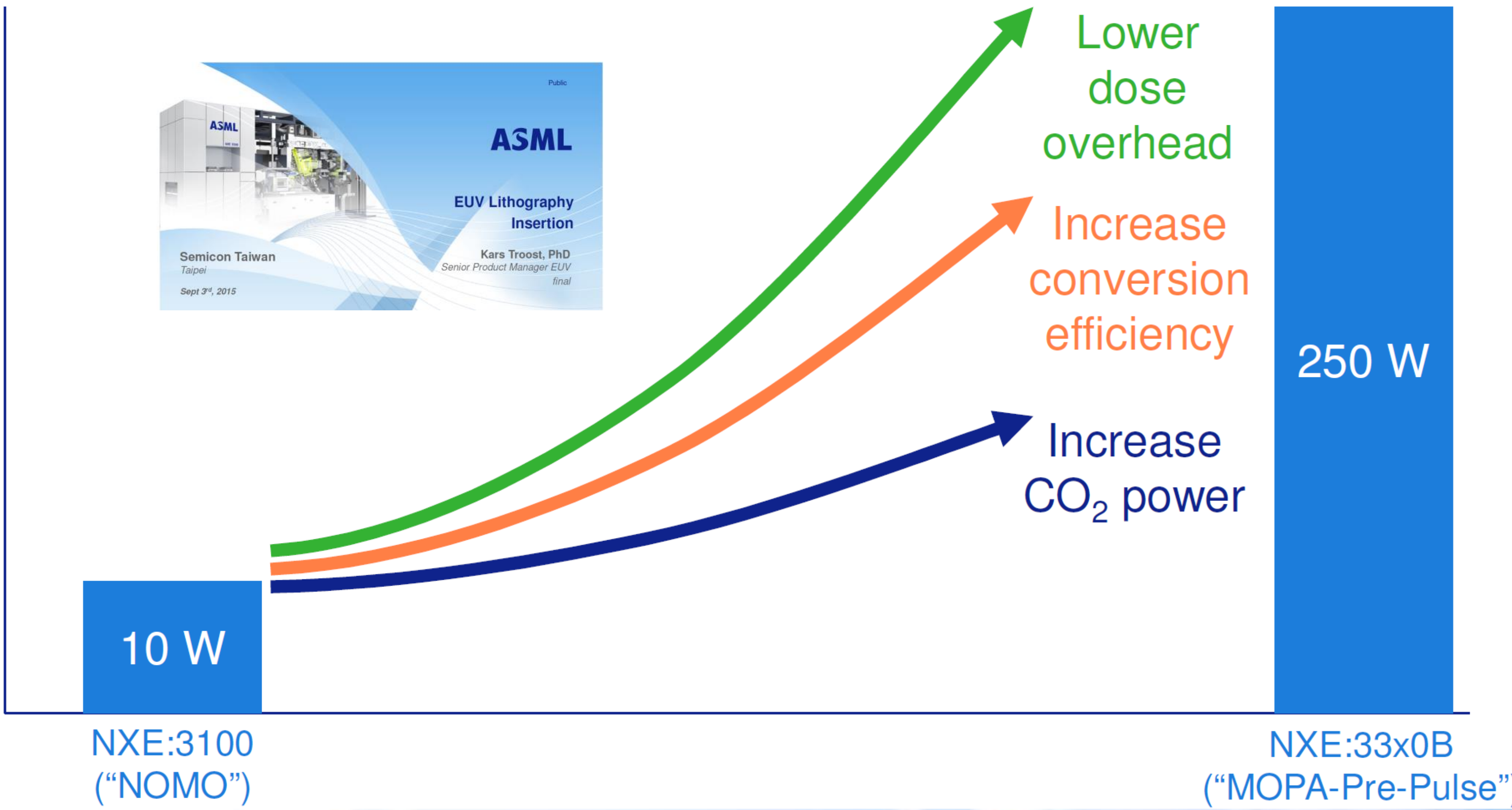
Public
Slide 12



Laser-produced plasma (LPP) Source

EUV power scaling: three levers

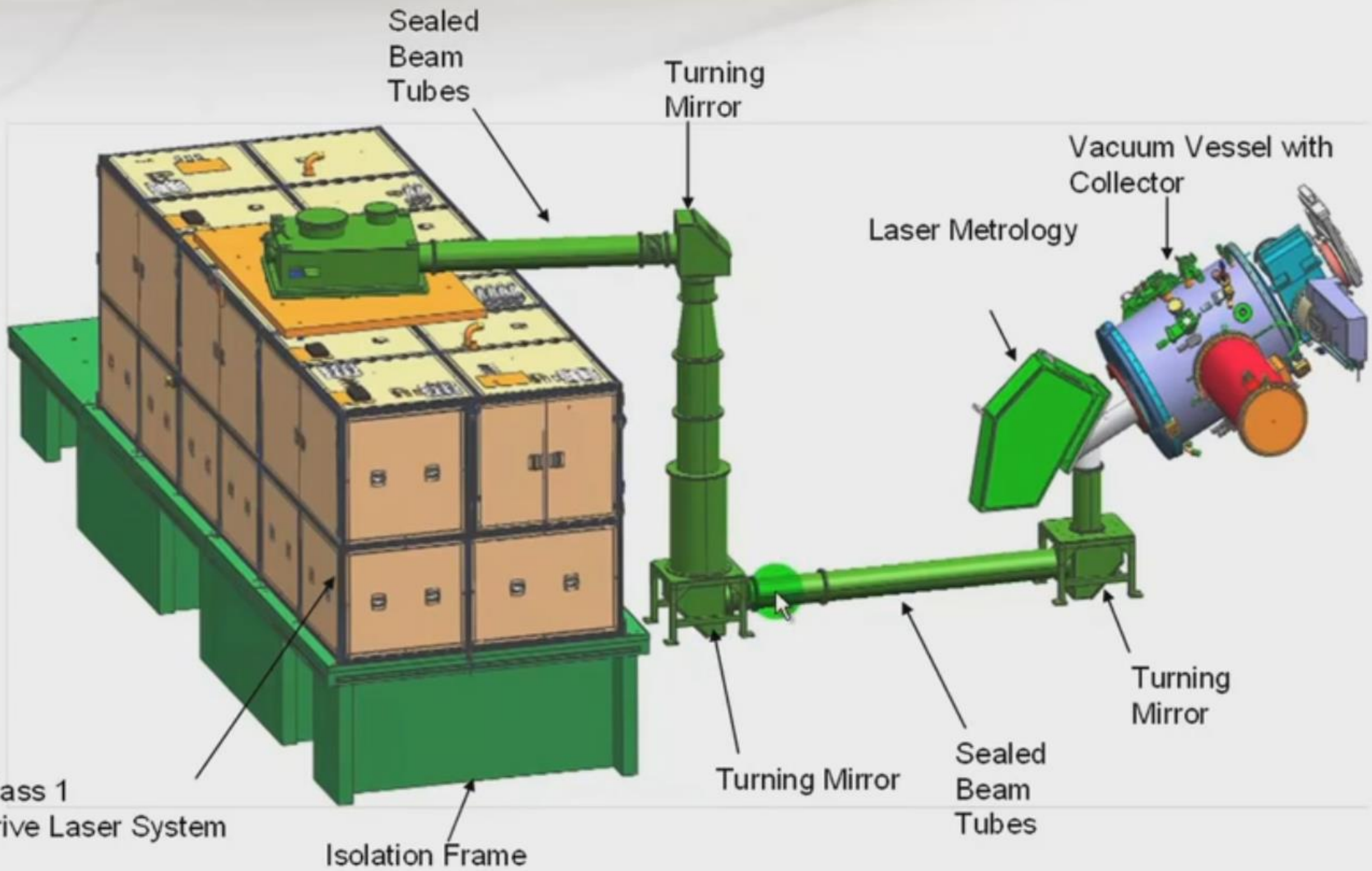
CO_2 power, conversion efficiency, EUV energy available for exposure



Laser-produced plasma (LPP) Source

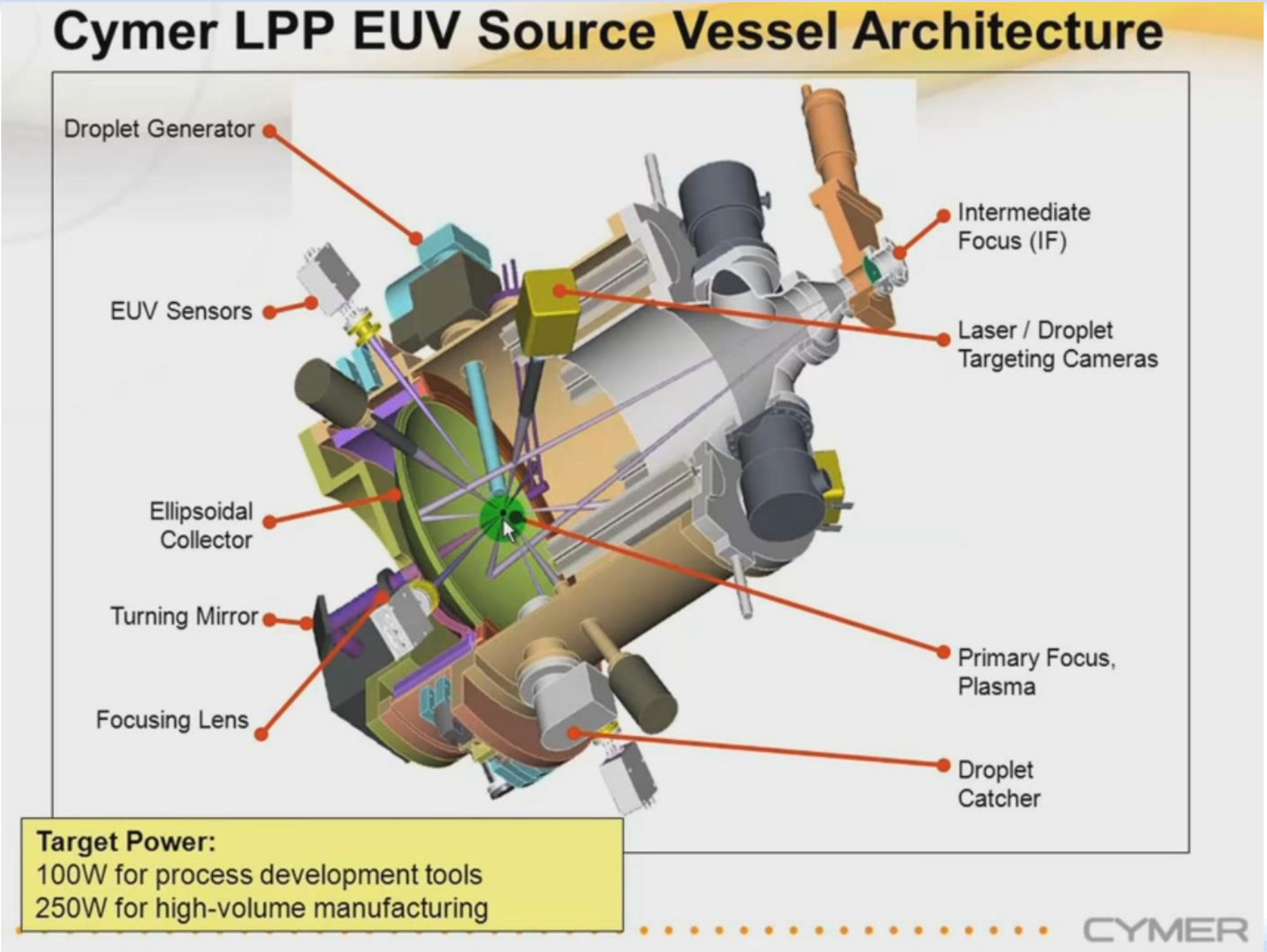
Cymer LPP EUV source layout

Drive laser system, beam transport system, and source vessel



https://www.cymer.com/

Laser-produced plasma (LPP) Source



https://www.cymer.com/

Laser-produced plasma (LPP) Source

EUV Industrialization Roadmap supports 7nm insertion

By >1500 wafers per day in 2016

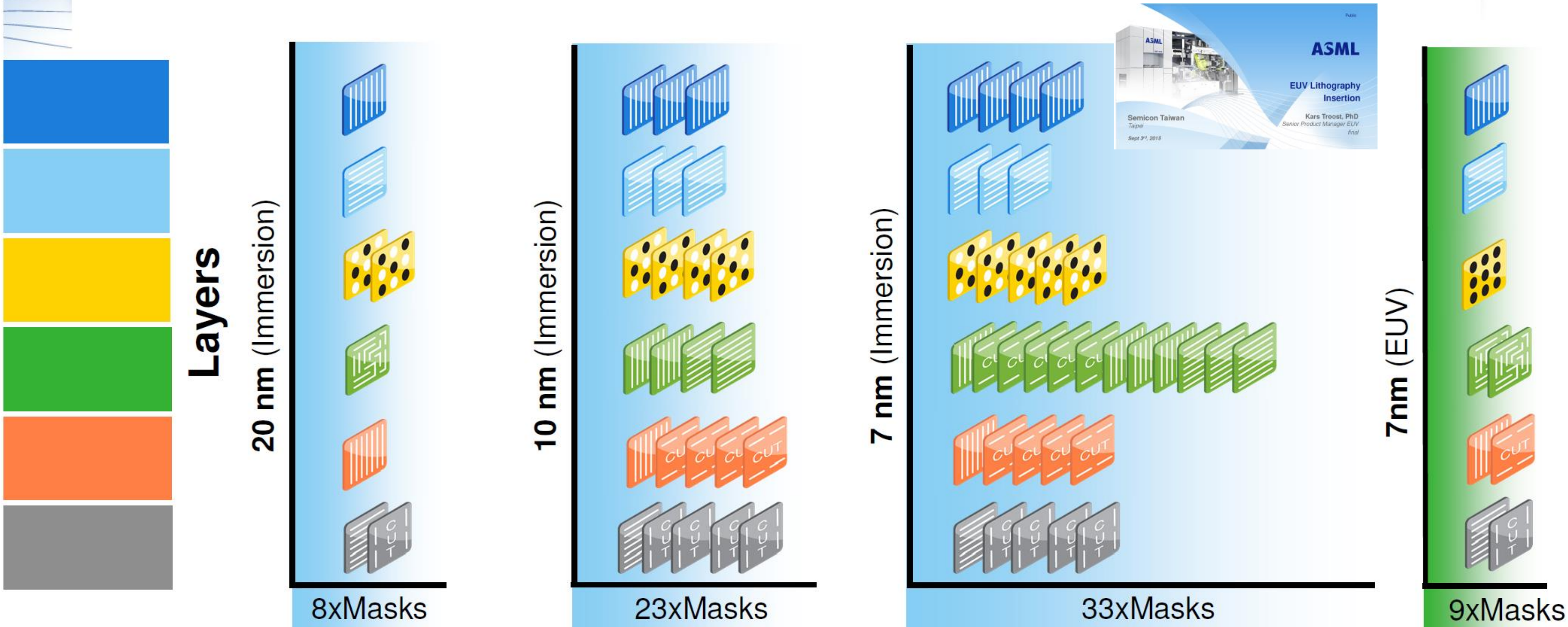
Timing	Source power [W]	Throughput [Wafers/hr]	Efficiency* [%]	Productivity [Wafers/day]
2014	80	>55	<50%	>500
2015	125	>75	>50%	>1000
2016	250	>125	>55%	>1500

*Efficiency = system availability x customer utilization x customer rate efficiency
Logic typically 55%, for DRAM 70-75% (>2000 WPD)
Illustrative numbers used for WPD model

Laser-produced plasma (LPP) Source

EUV reduces complexity and thus cycle time

ASML
Public
Slide 6



Node	20 nm	10 nm	7 nm	7 nm
# of litho steps	8 (Immersion)	23 (Immersion)	33 (Immersion)	9 (EUV)
# OVL Metrology	9-11	36-40	59-65	12
# max metrology / litho steps	2	3	4	3

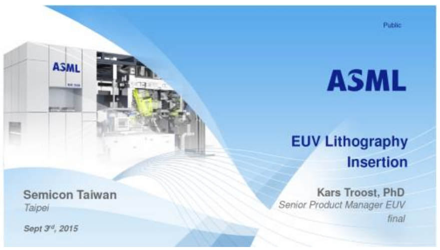
Laser-produced plasma (LPP) Source

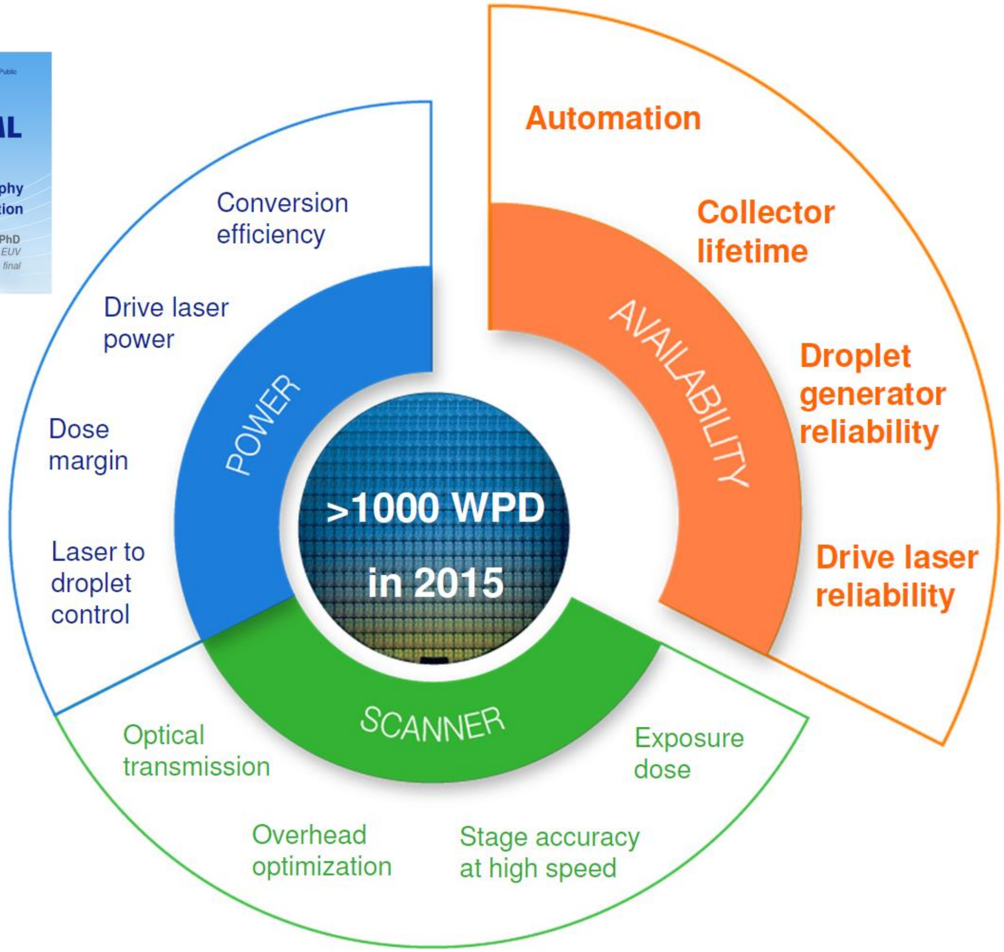
Focus 2015: improving source availability

More than 50 improvement items identified, field upgrades throughout 2015

ASML

Public
Slide 14



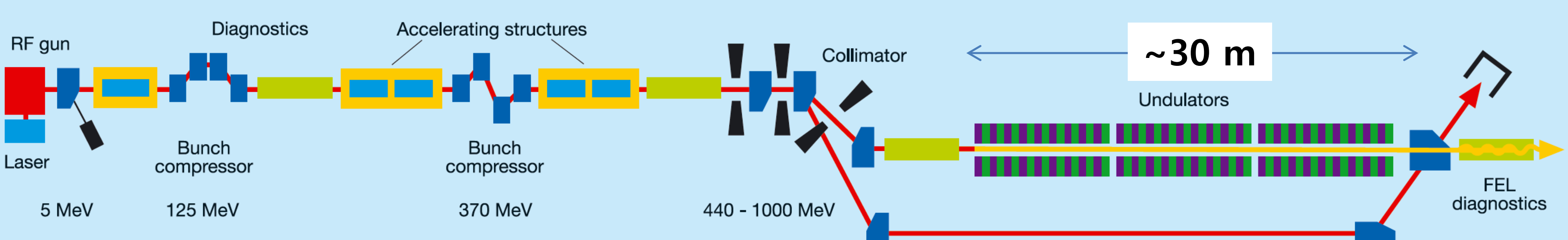


More than 50 availability improvement items have been identified.

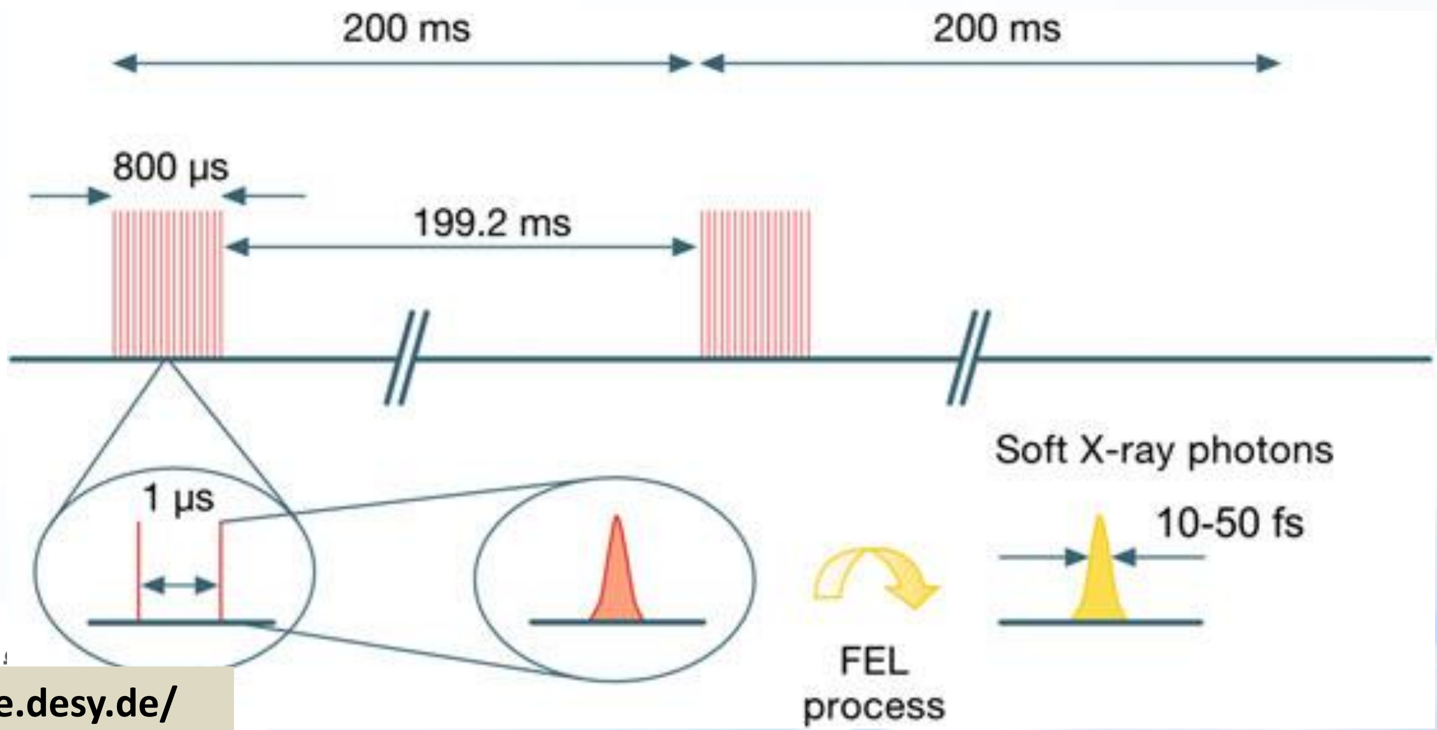
Projects are underway to make these improvements available on customer systems throughout this year.

Example of EUV FEL

FLASH, the **F**ree-electron **LAS**er in **H**amburg : the first FEL for VUV & soft X-ray from 2005



Acceleration Gradient : 15~20 MeV/m



http://photon-science.desy.de/

Example of EUV FEL

FLASH, the **F**ree-electron **LAS**er in **H**amburg : the first FEL for VUV & soft X-ray from 2005

Number of Bunches per second	1 - 8000	
Pulse Repetition Rates (within pulse train)+	40, 50, 100, 200, 250, 500, 1000	kHz
Wavelength	4.2 - 45	nm
Pulse Duration (FWHM)	30 - 300	fs
Average Pulse Energy (single bunch)*	1 - 500	µJ
Average Pulse Energy (pulse trains)*	1 - 200	µJ

http://photon-science.desy.de/

EUV FEL for Lithography

Requirements for EUV FEL

- Beam Energy : ~1 GeV
- Wavelength : 13.5 nm
- Average Power : > 1 kW

EUV FEL Specification

- Size : ~100 m
- Cost : ? (>100M$)[a]
- Number of FEL : 2

[a]PAL X-FEL : 400M$ (3 GeV, 0.1 nm)