# Ultrafast Electron Diffraction

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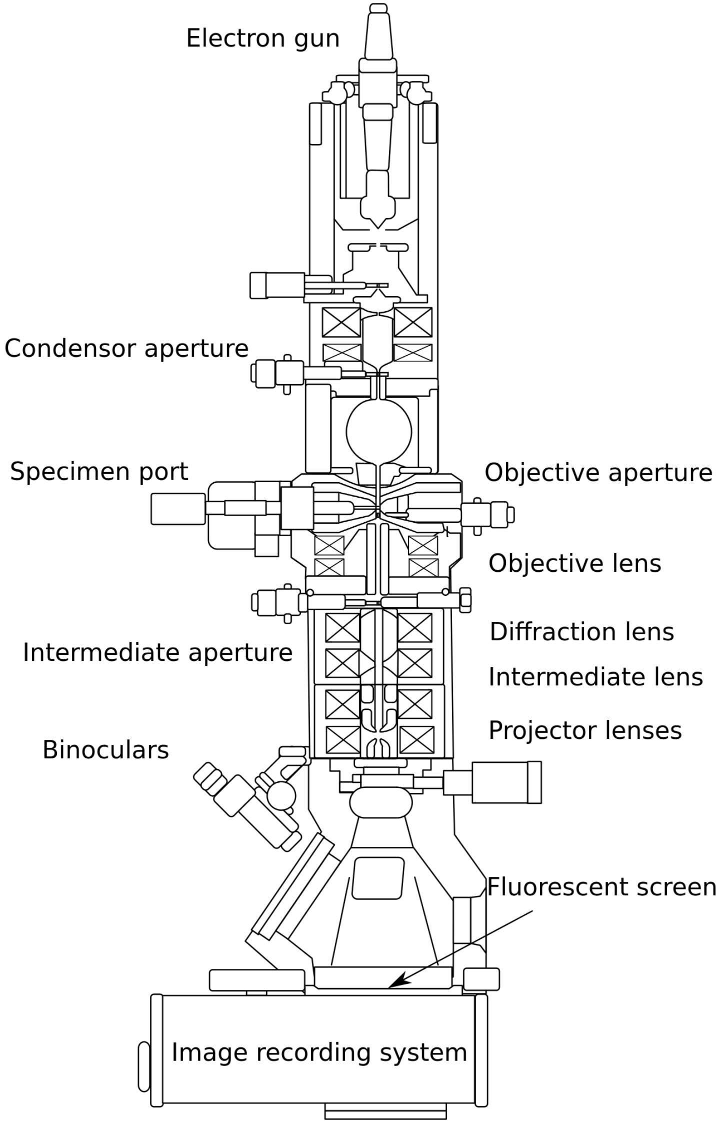
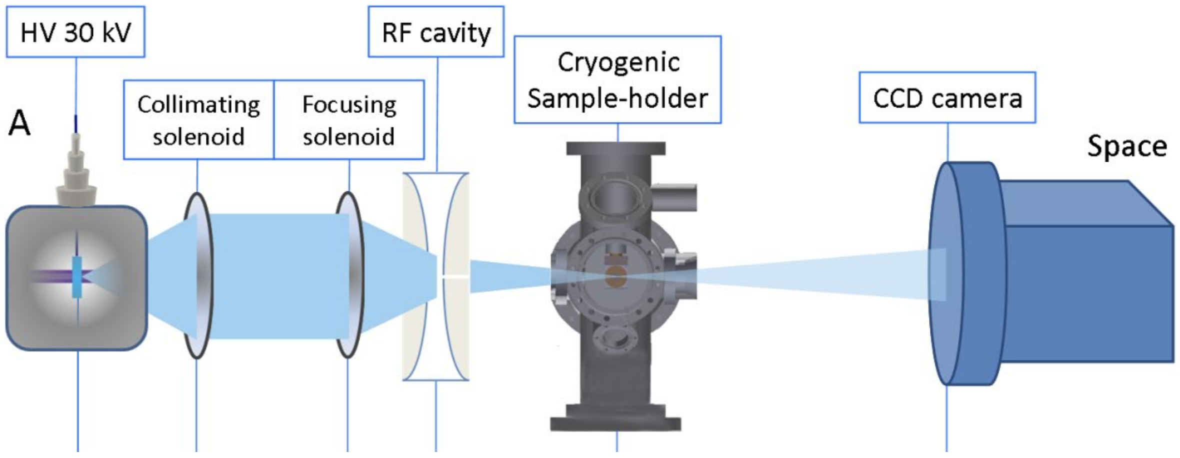
# What is UED ?



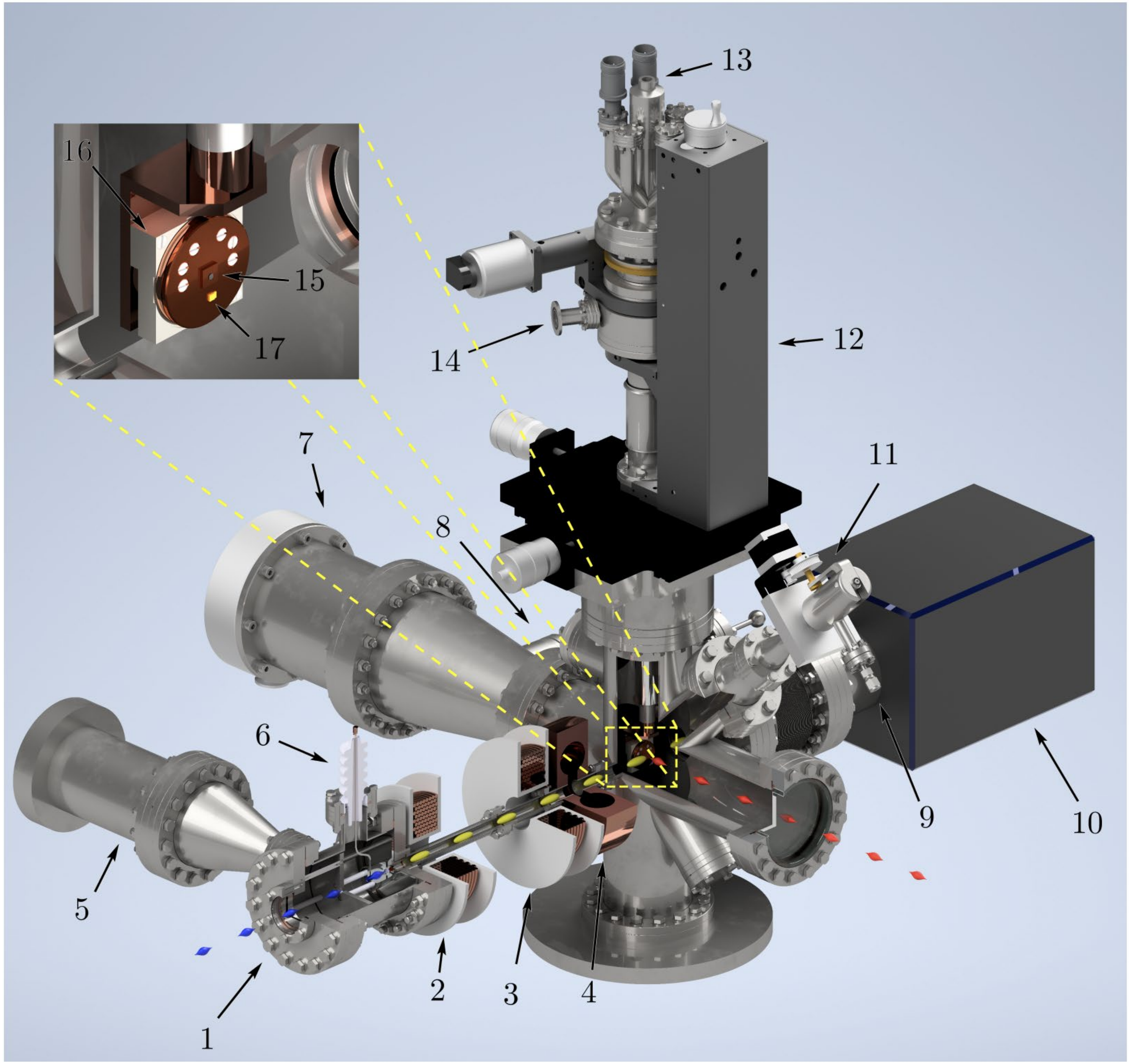




UED is an easy horizontal TEM
Only measure the reciprocal space of a sample whereas the TEM can measure both real and reciprocal spaces

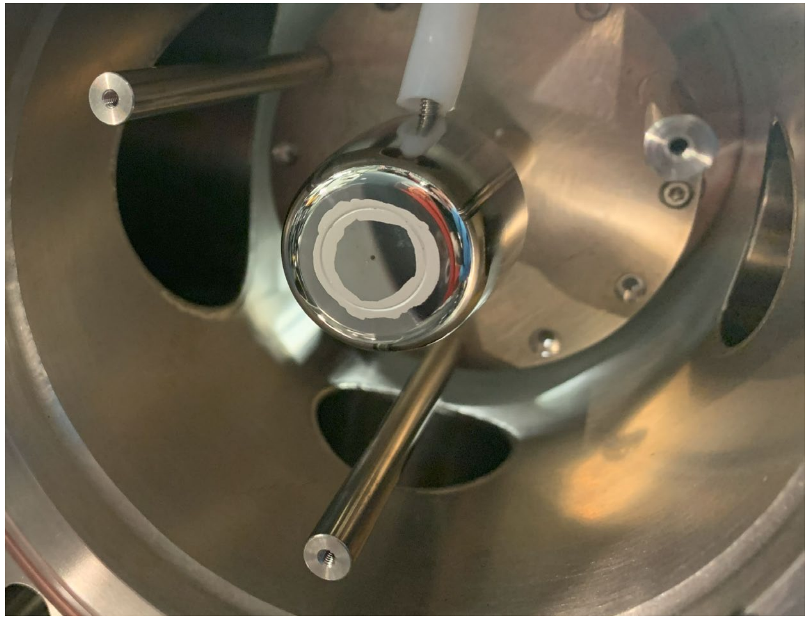
# Content

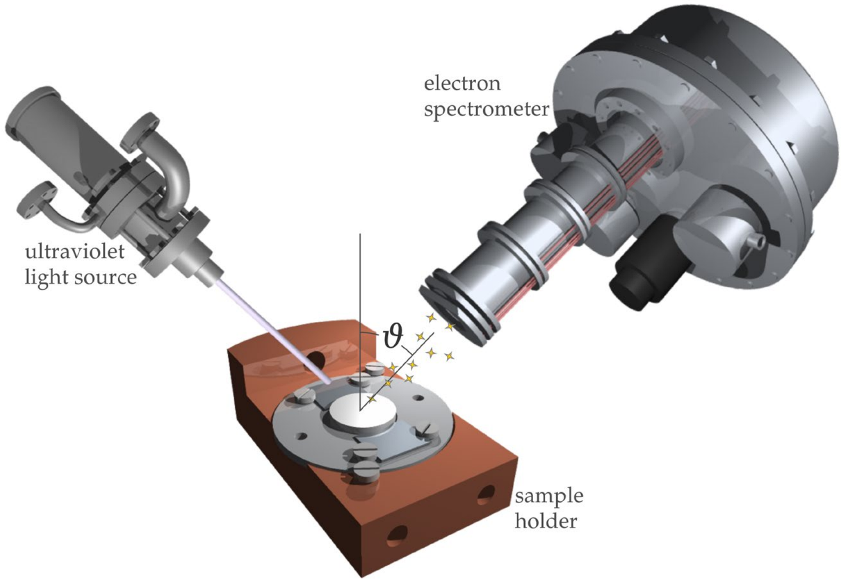
This week:
- Electron photo-generation
- Electron beam acceleration
- Electromagnetic focusing
- Transverse emittance
- Matter-electron interaction

Next week (Ultrafast):
- space charge effect
- RF cavity
- Pulse duration – longitudinal emittance
- SNR
- Pulse front tilting

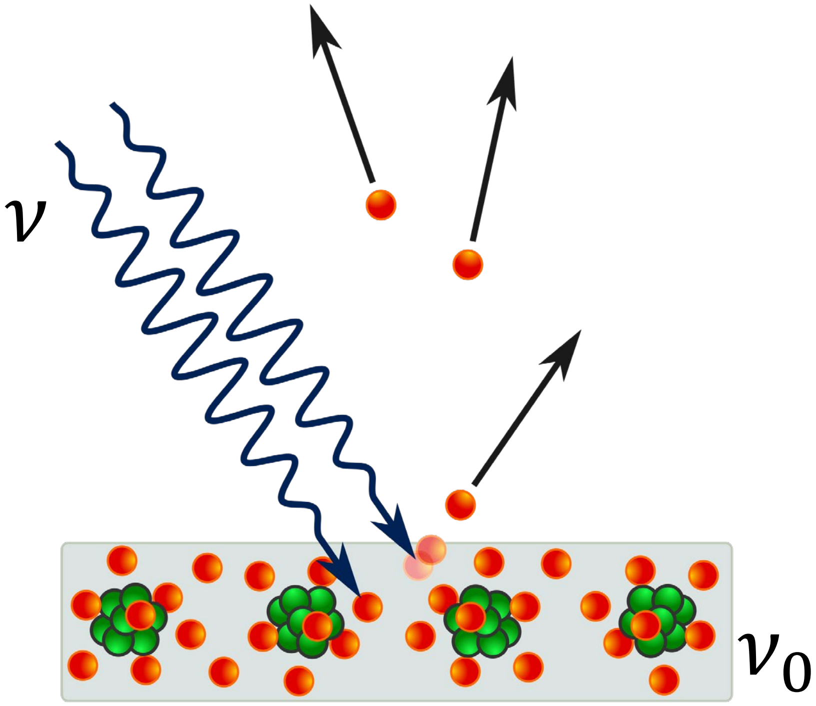


# Electron photogeneration





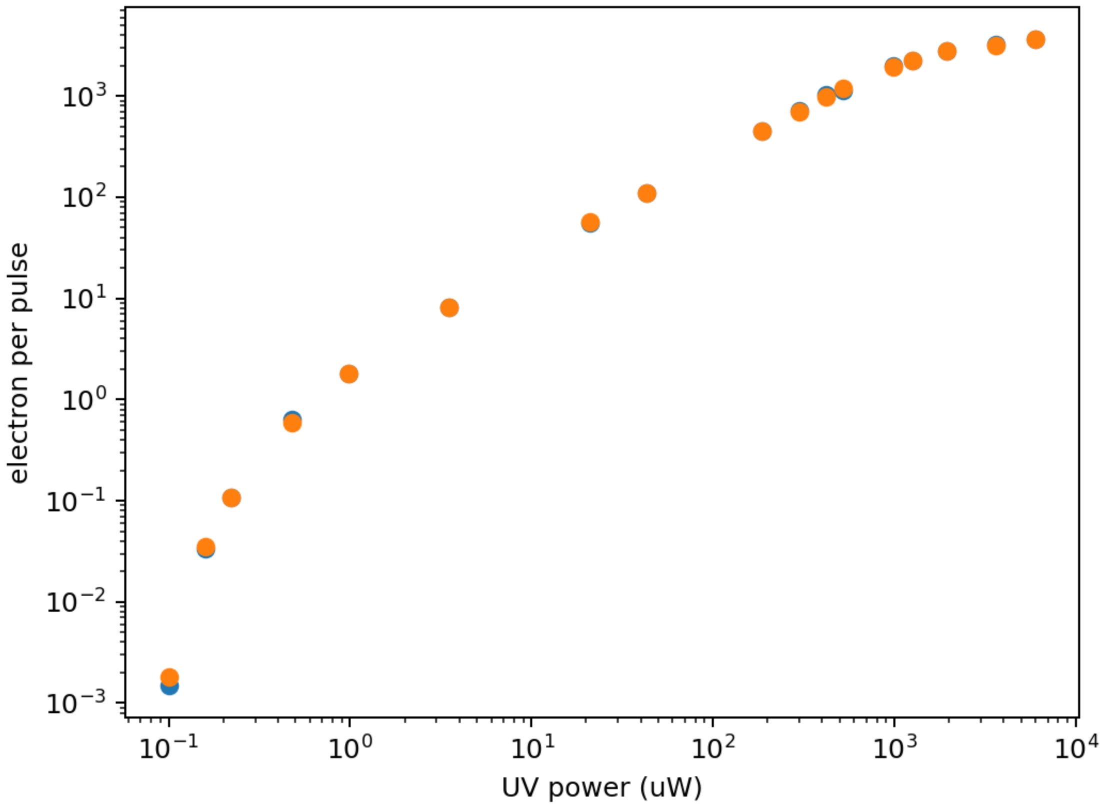

Work function : minimum energy to remove electron from surface solid to the vacuum

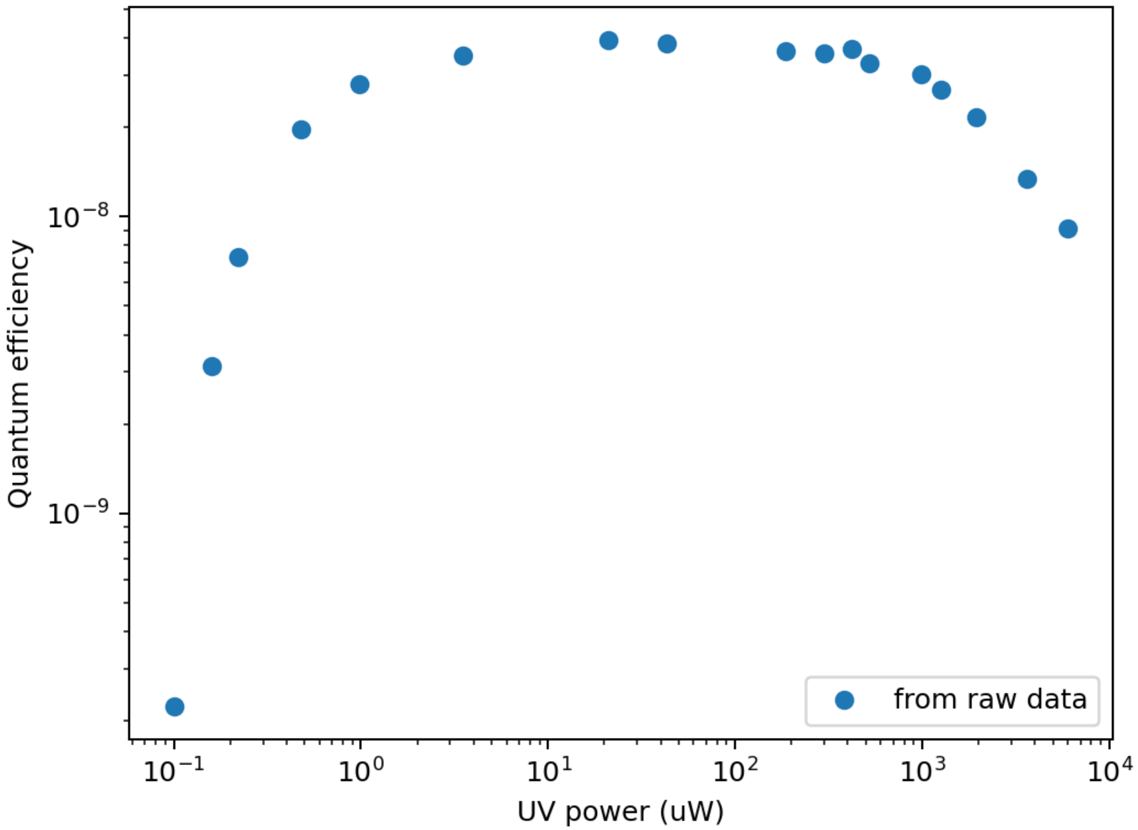



$$K_{max} = h\nu - W = h(\nu - \nu_0)$$

When $K_{max} > 0$ photoelectric effect can occur
For polycrystalline silver : $h\nu_0 = 4.26$ eV
For 266 nm (UV light) : $h\nu = 4.66$ eV

# Quantum efficiency

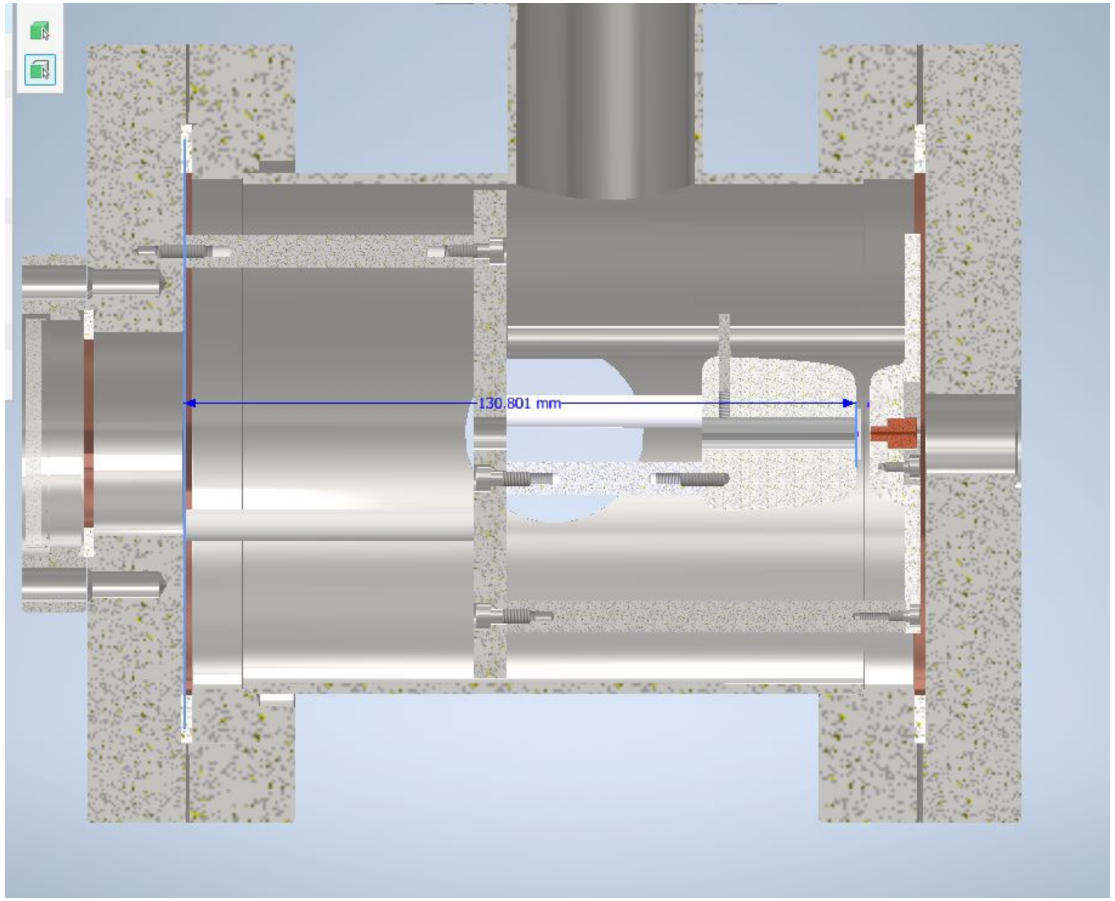


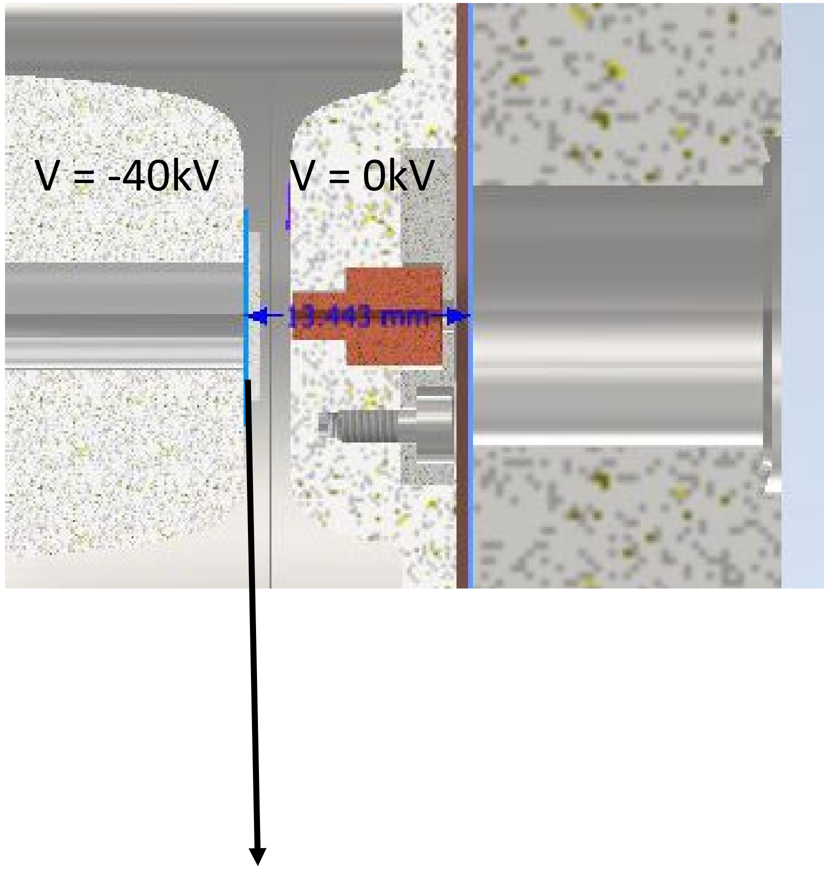

Increasing the UV power implies an increase in the number of photons.
The more photons there are, the more electrons you get

Quantum efficiency : $Q = \frac{n_e}{n_p}$

# Electron beam acceleration




Electron gun




Silver photocathode

# Electron beam acceleration – useful equations

$U = 40$ kV; $d = 3$ mm ; $e = 1.63 \cdot 10^{-19}$ C ; $h = 6.3 \cdot 10^{34}$ J/Hz ; $m = 9.11 \cdot 10^{-31}$ kg

The electric field in the electron gun:

Electron energy :

Electron wavelength :

Electron velocity :

# Electron beam acceleration – useful equations

$U = 40$ kV; $d = 3$ mm ; $e = 1.63 \cdot 10^{-19}$ C ; $h = 6.3 \cdot 10^{34}$ J/Hz ; $m = 9.11 \cdot 10^{-31}$ kg

The electric field in the electron gun:

$$V = \frac{U}{d} = \frac{40 \cdot 10^{3}}{3 \cdot 10^{-3}} = 13.3 \text{ MV/m}$$

Electron energy :

$$E = eU = 1.6 \cdot 10^{19} \cdot 40 \cdot 10^{3} J = 40 \text{ keV}$$

Electron wavelength :

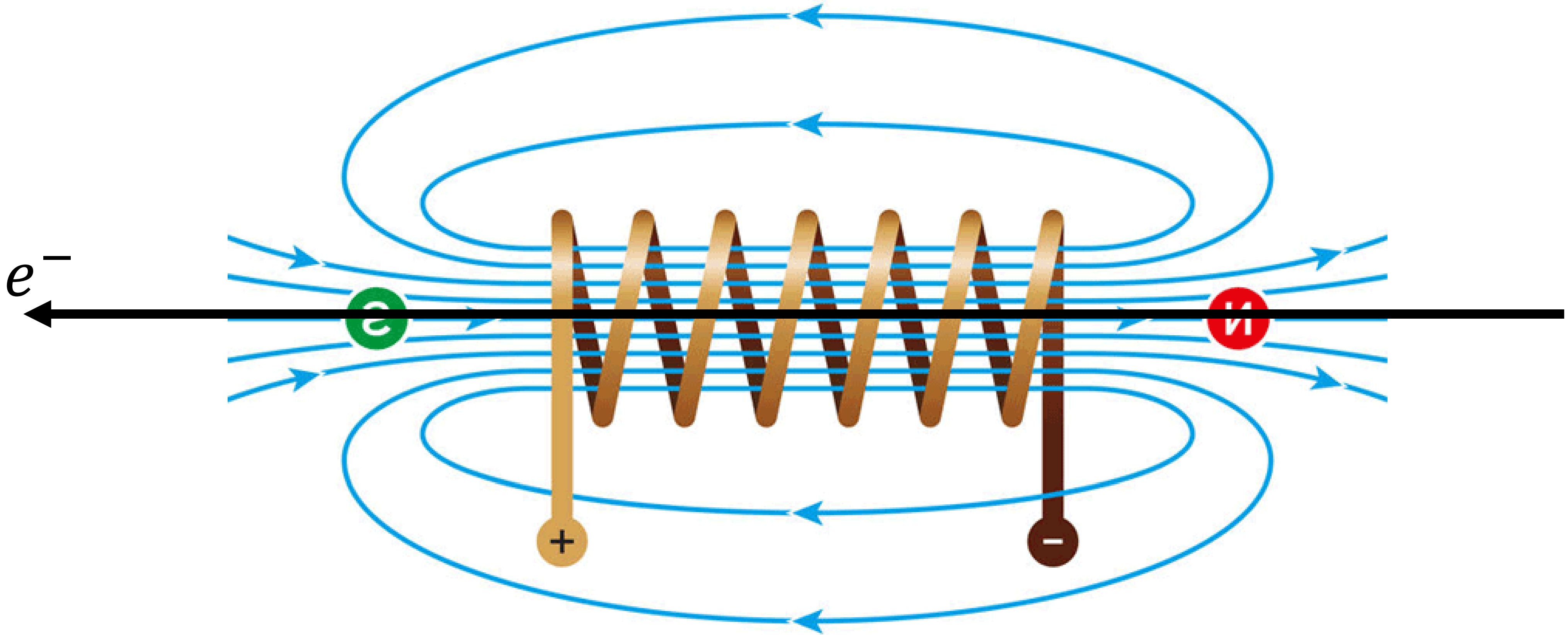
$$\lambda = \frac{h}{p} = \frac{h}{\sqrt{2Em}} = \frac{1.23}{\sqrt{U}} \text{ nm} = 0.19 \text{ nm}$$

$$\text{Since } E = \frac{1}{2}\frac{p^2}{m} \Rightarrow p = \sqrt{2Em}$$

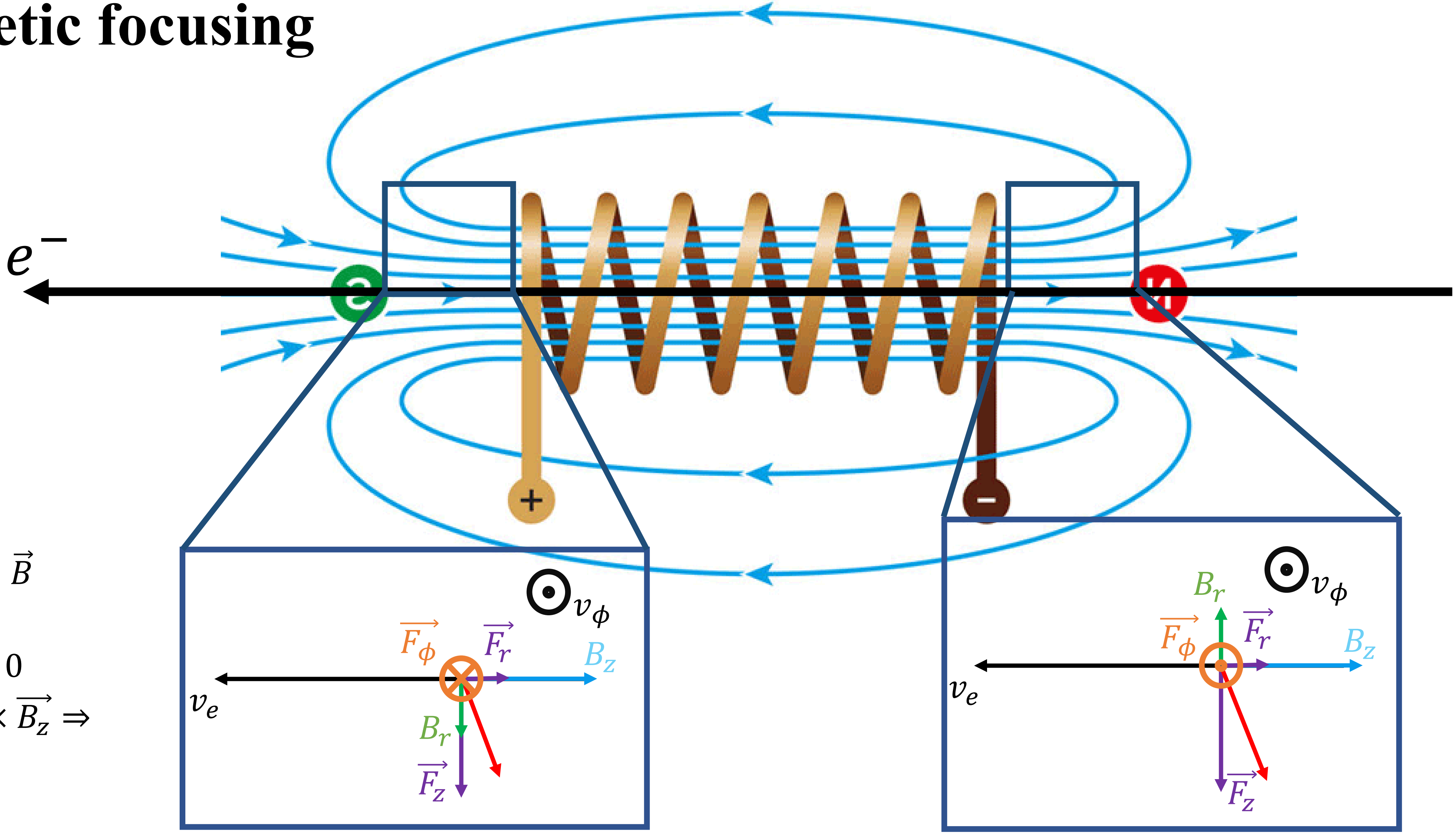
Electron velocity :

$$\frac{1}{2}mv^2 = E \Rightarrow v = \sqrt{\frac{2eU}{m}} = 5.93 \cdot 10^{5} \cdot \sqrt{U} = 1.19 \cdot 10^{8} \text{ m/s} = 0.39c$$

# Electromagnetic focusing



# Electromagnetic focusing




Lorentz force $F = q\vec{v} \times \vec{B}$

$\overrightarrow{v_e} \times \overrightarrow{B_z} = 0$

$\overrightarrow{v_e} \times \overrightarrow{B_r} \Rightarrow \overrightarrow{F_\phi} \Rightarrow \overrightarrow{v_\phi} \neq 0$

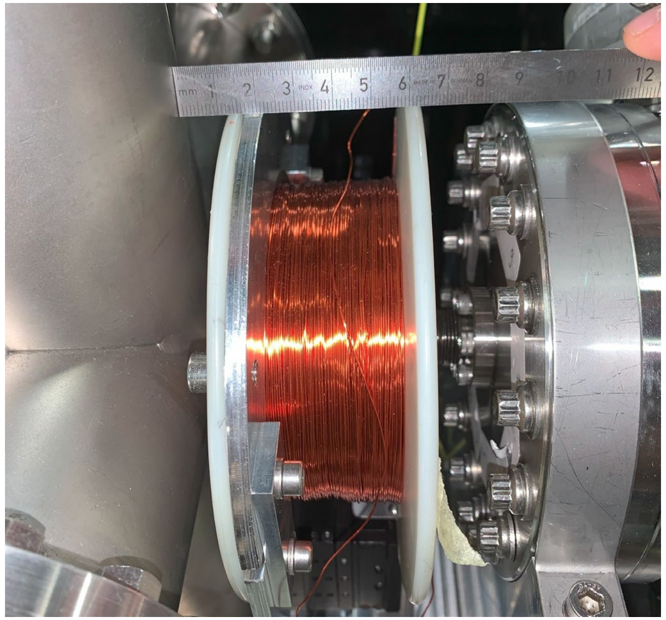
$\overrightarrow{v_\phi} \times \overrightarrow{B_r} \Rightarrow \overrightarrow{F_z}$ and $\overrightarrow{v_\phi} \times \overrightarrow{B_z} \Rightarrow \overrightarrow{F_r}$

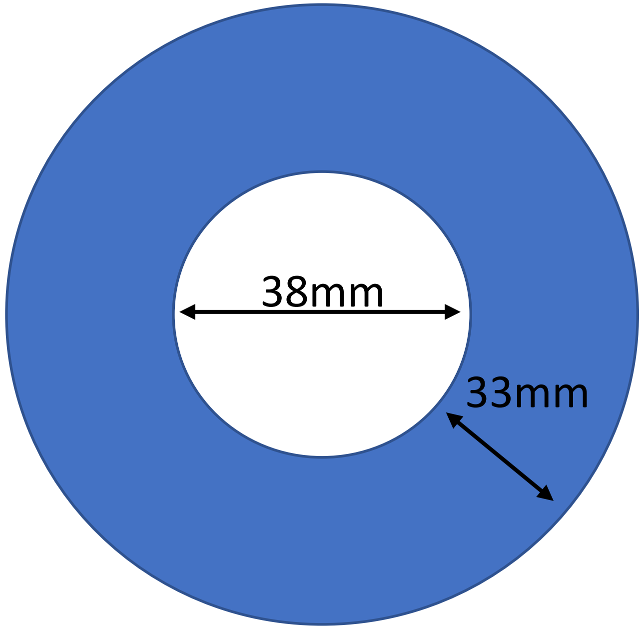
Don't forget $q < 0$

Force going toward the center

When the electrons go out of the solenoid, they still have a velocity anti-clockwise, with a force that decelerates them. The radial force still goes inward. When one changes the polarization, the electrons are circulating clockwise but still inward since the magnetic field goes to the other direction

# Electromagnetic focusing






The focal distance of a solenoid

$$f_{sol} = \frac{8 m_e E}{e^2 \int_{-\infty}^{\infty} B^2(z,0) \mathrm{d}z}$$

Magnetic field at the solenoid's center

$$B(0,z) = \frac{\mu_0 I}{2} \frac{R^2}{(R^2 + z^2)^{3/2}}$$

Its integral

$$\int_{-\infty}^{\infty} B(0,z)^2 dz = \frac{\mu_0^2 I^2}{4} \frac{3\pi}{8R} \qquad \Rightarrow \qquad f_{sol} = \frac{256 m_e R E}{3\pi e^2 \mu_0^2 I^2}$$

Current needed to focus an electron beam ($E = 40$ keV, $f_{sol} = \left(\frac{1}{d_{p-s}} + \frac{1}{d_{s-s}}\right)^{-1} = 57.8$ mm, $R = 52$ mm)

$$I_{tot} = \frac{16}{e\mu_0} \sqrt{\frac{R m_e E}{f_{sol} 3\pi}} = 1.9 \text{ kA}$$

$I_{tot} = NI \Rightarrow I = \frac{I_{tot}}{N} = 625$ mA for 3000 windings

# Emittance

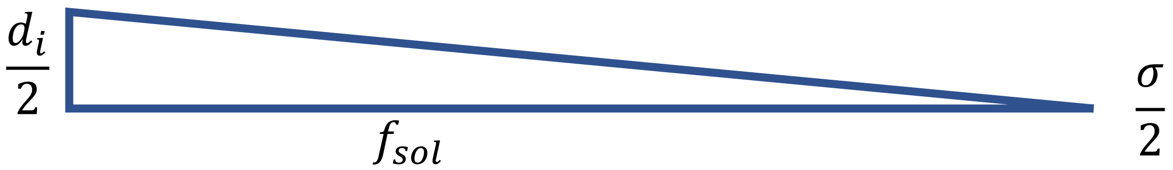
In optics, brilliance is the energy stored by a unit of solid angle and is conserved along the beam propagation

In electronic microscopy, we have a similar quantity called emittance

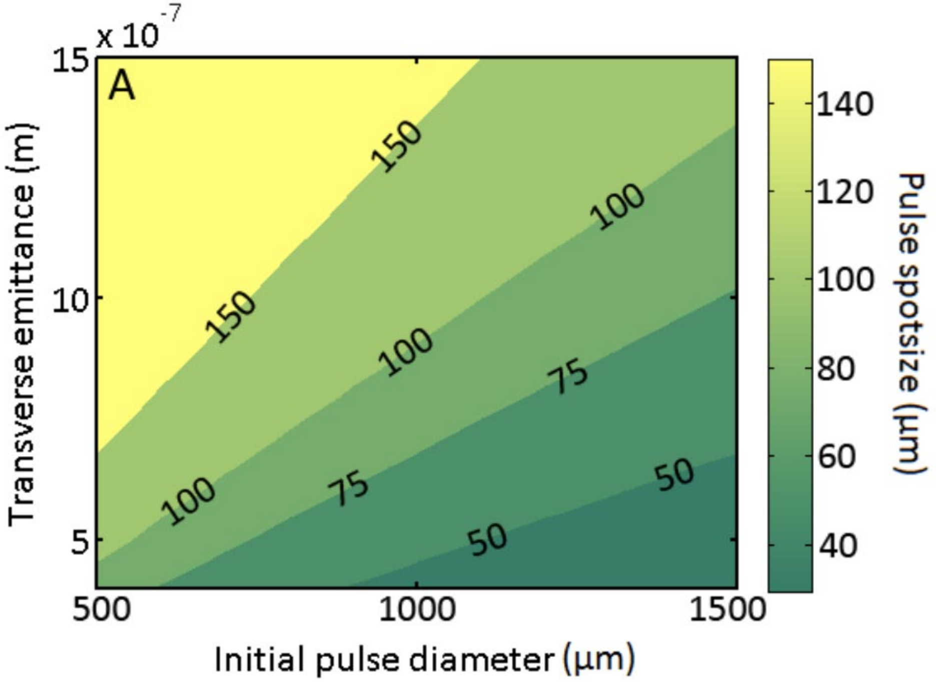
Transverse emittance: momentum spread in space (spatial divergence)

$$\epsilon_x = d_x \cdot \sigma_\theta$$

$d_x$ is the beam size, $\sigma_\theta = \frac{d_i}{f_{sol}}$ is the divergence.




$$\tan\frac{\sigma}{2} \approx \frac{\sigma}{2} = \frac{d_i}{2f_{sol}} \Rightarrow \sigma = \frac{d_i}{f_{sol}}$$

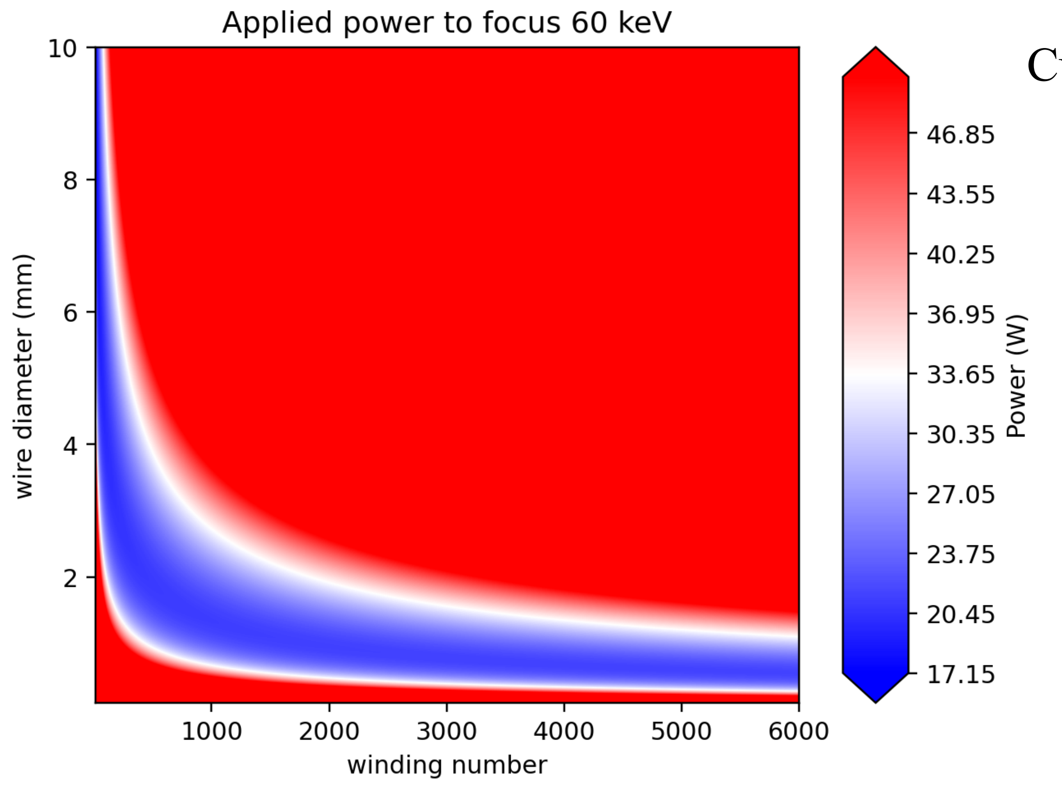



Can measure the focused beam size:

$$d_x = \epsilon_x \cdot \frac{f_{sol}}{d_i}$$

For $\epsilon_x = 10^{-6}$ m and $d_i \sim 1$ mm, $d_x \sim 60\ \mu$m

# Power to drive a solenoid




Current needed to focus an electron beam ($E = 40$ keV, $f_{sol} = 57.8$ mm)

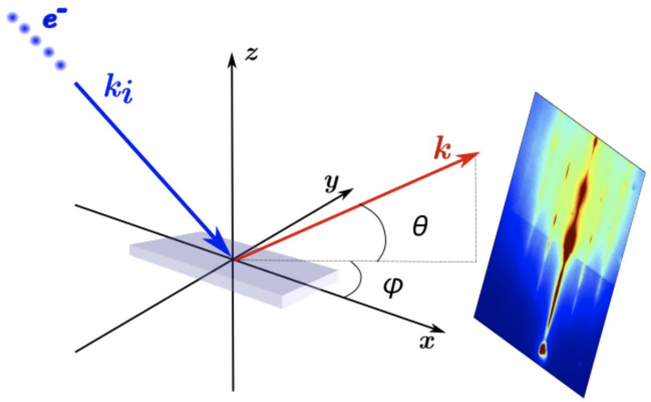
$$I_{tot} = \frac{16}{e\mu_0}\sqrt{\frac{Rm_eE}{f_{sol}3\pi}} = 1.9 \text{ kA}$$

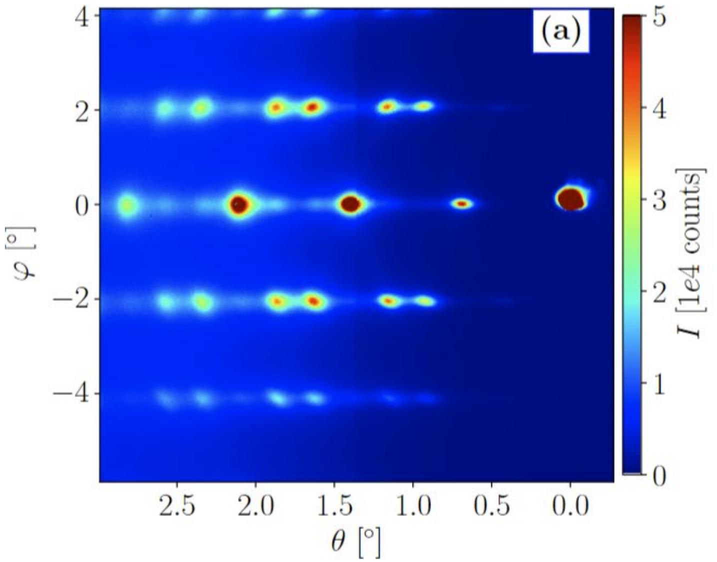
$I_{tot} = NI \implies I = \frac{I_{tot}}{N} = 625$ mA for 3000 windings

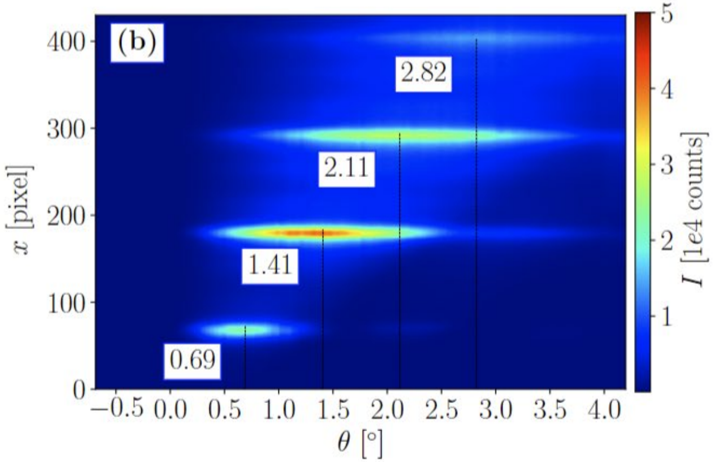
$P = RI^2$ and $R = \frac{\rho L}{A} = 44.25\ \Omega$ with $\rho = 1.77 \cdot 10^{-8}\ \Omega$m, $L = 700$ m the length of wire and $A = 2.8 \cdot 10^{-7}$ m$^2$ the area of the wire (0.6 mm diameter)

For 3000 winding $P = 17.3$ W which represent a lot of power

# Electron matter interaction – reflection

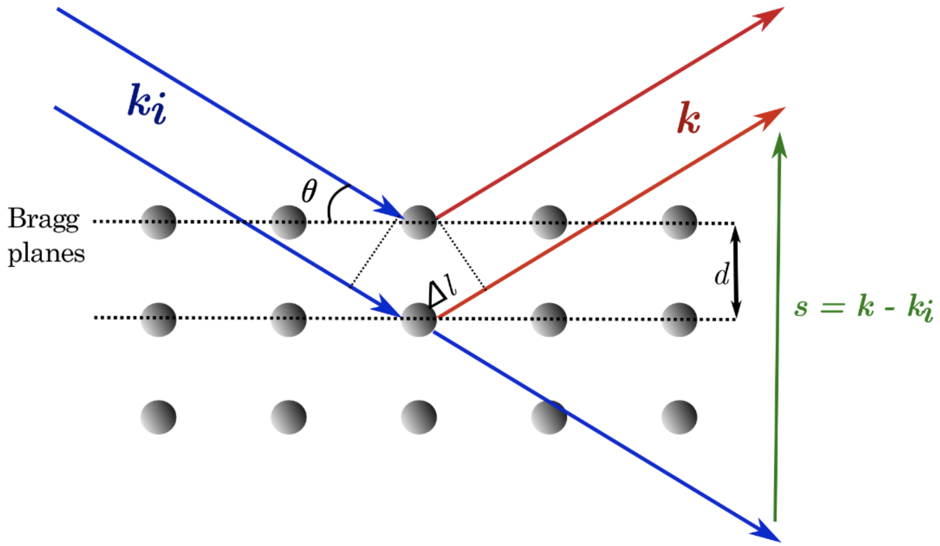



Reflection high electron energy diffraction (RHEED)

Bragg's law : $2d\sin(\theta) = n\lambda$
$d$ the interplanar distance, $\theta$ the angle of diffraction, $\lambda$ the electron wavelength, $n$ the order
There is an intense agglomerate of electrons when there is constructive interference

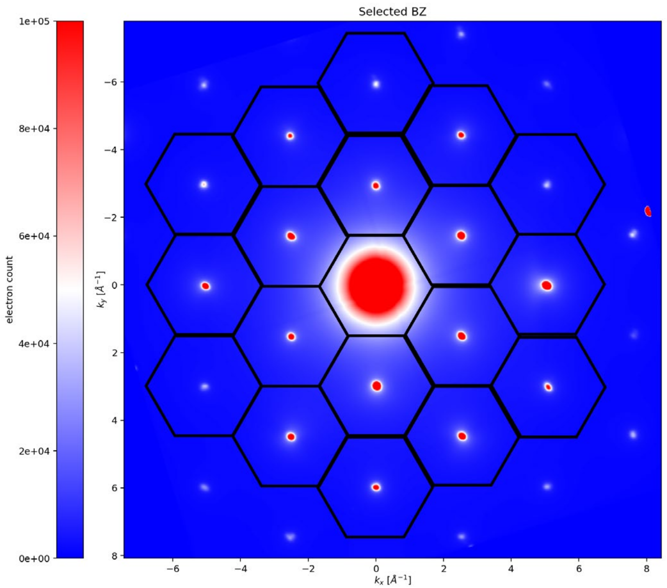


# Electron matter interaction – transmission

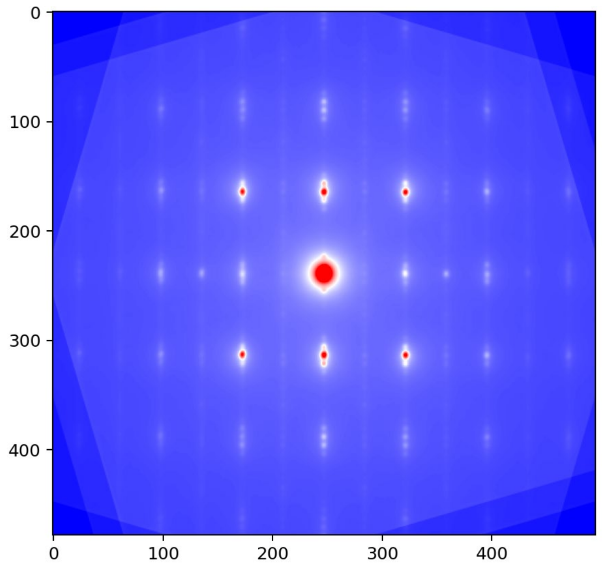
Laue condition: Link the electron intensity to the atomc position in the lattice

$$I_0(\boldsymbol{k}) \propto \sum_j \exp\left(i(\boldsymbol{k}_i - \boldsymbol{k}) \cdot \boldsymbol{R}_j\right)$$

Where $k_i$ is the incident wavevector, $k$ the outgoing wavevector, and $R_j$ the position of the jth atom of the unit cell

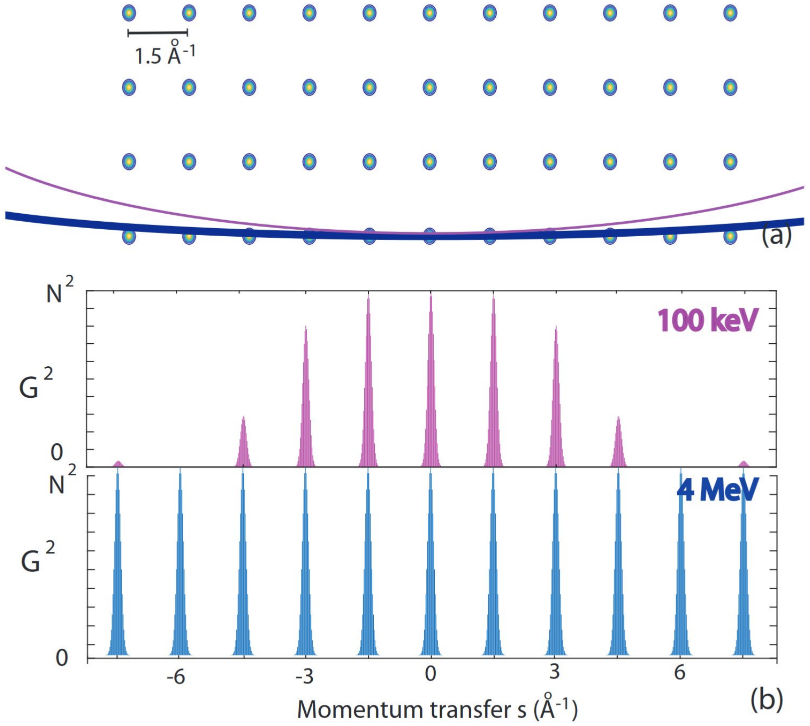



graphite

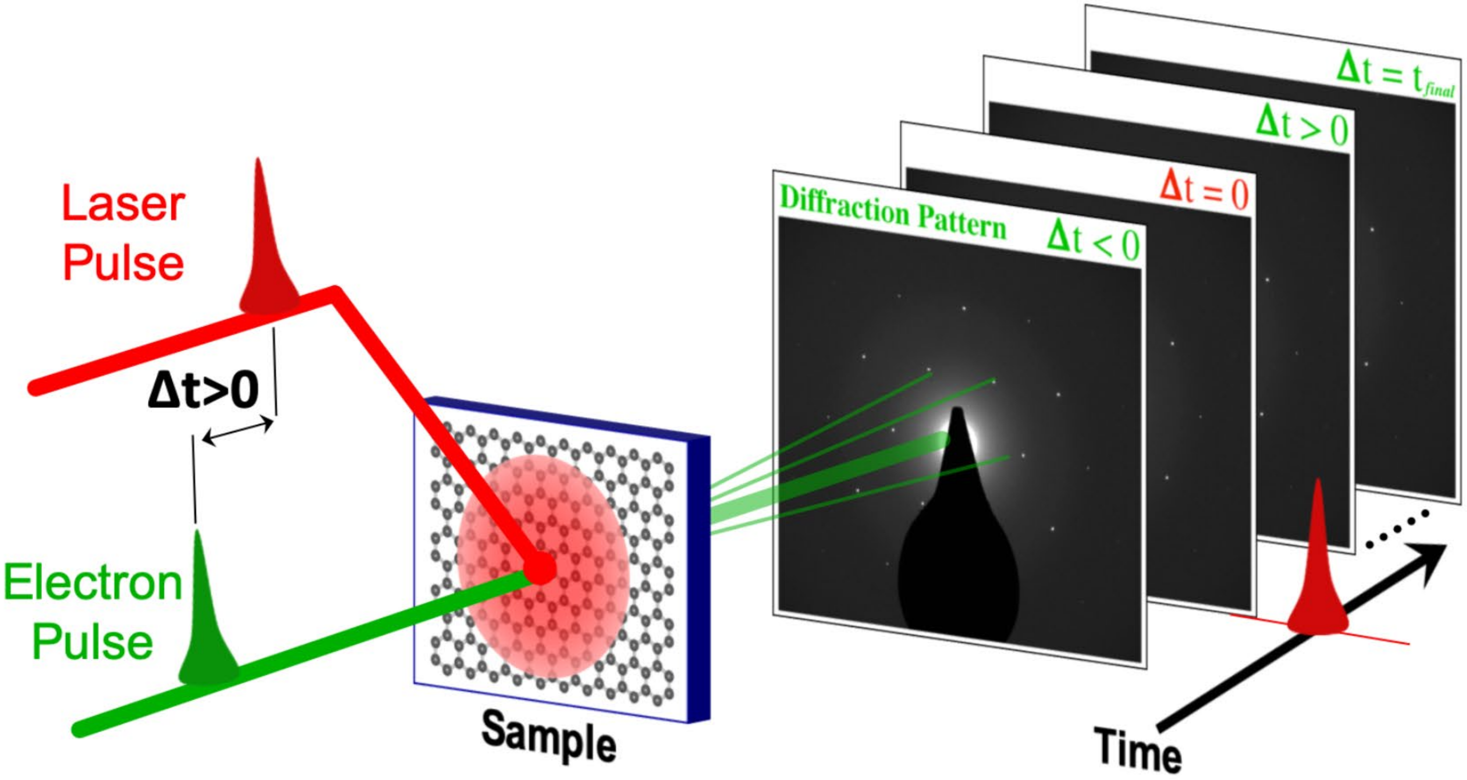



BSCCO

Ewald sphere with radius $k_0 = \frac{2\pi}{\lambda}$ intercept the crystal reciprocal space

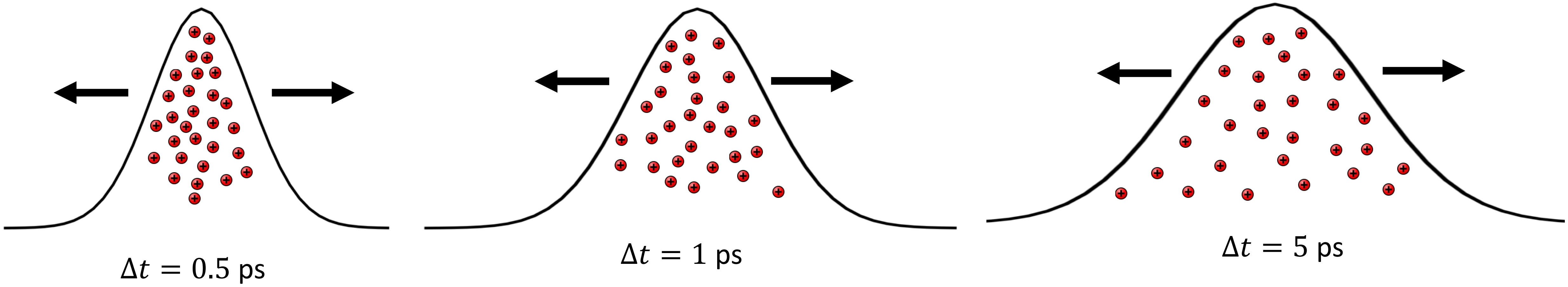


# Ultrafast

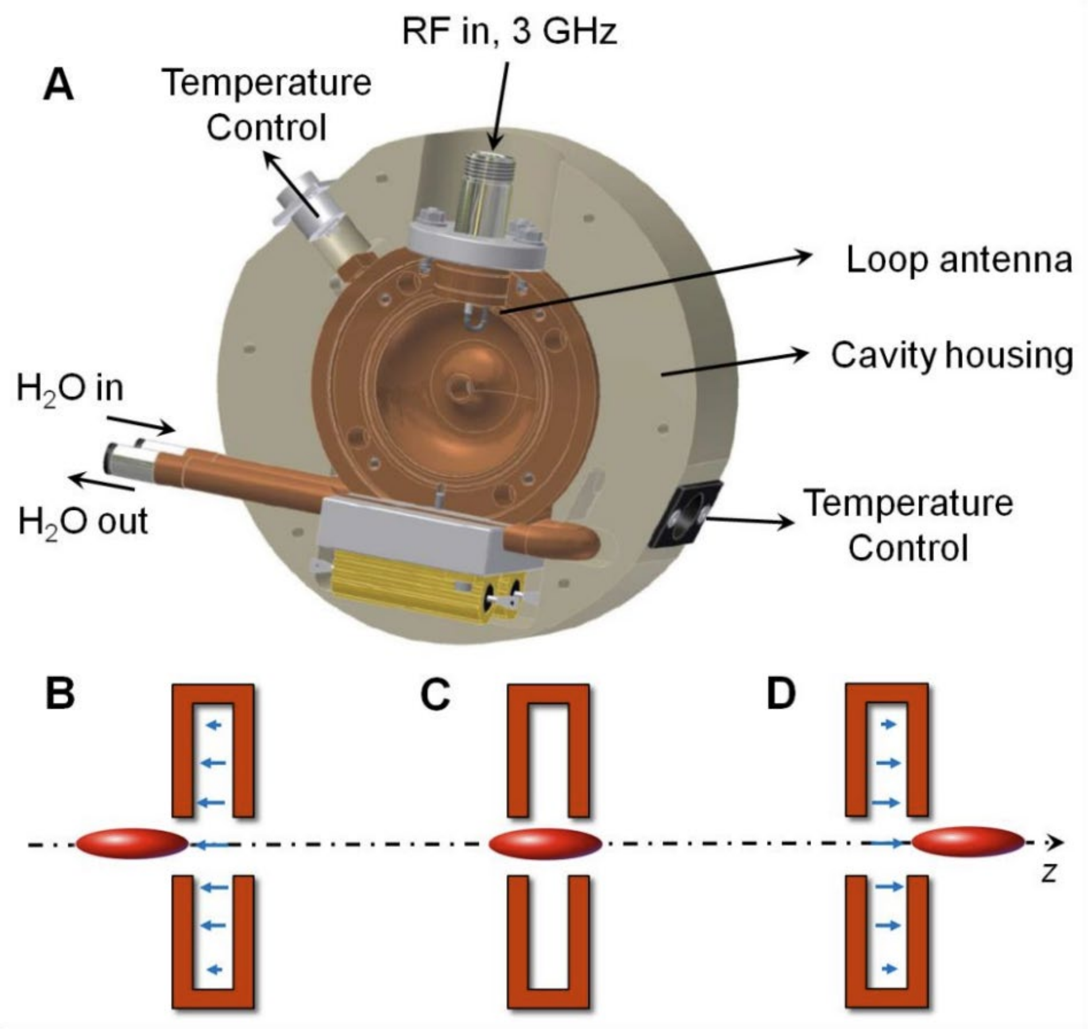


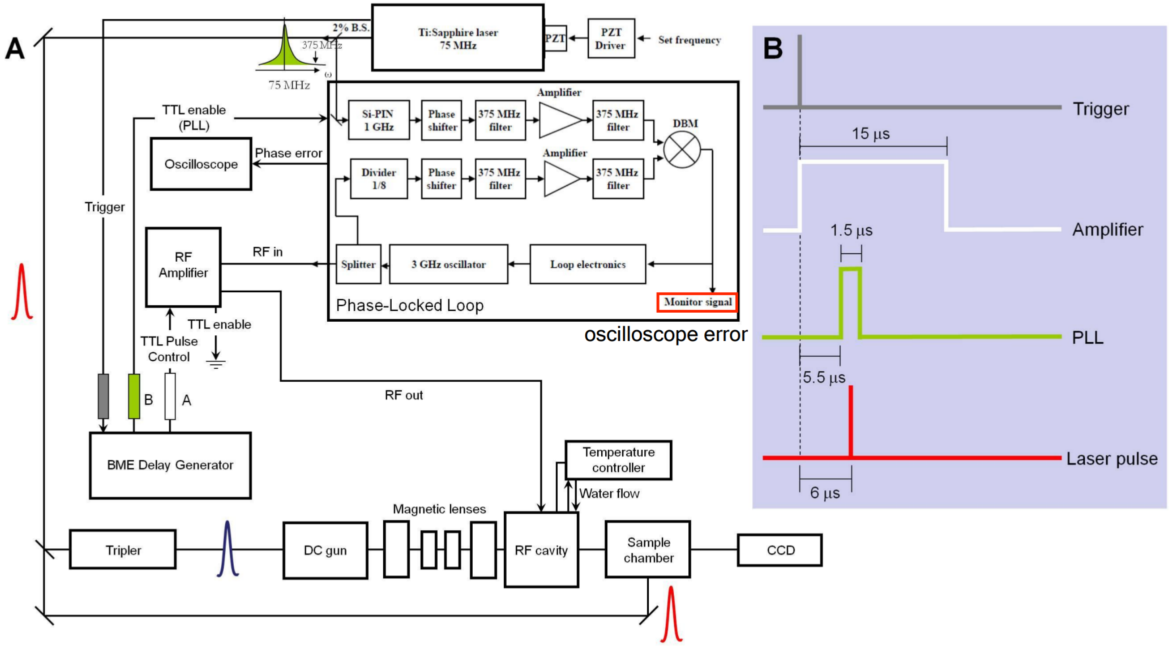
Laser
Pulse
Δt>0
Electron
Pulse
Sample
Diffraction Pattern
Δt < 0
Δt = 0
Δt > 0
Δt = t_final
Time

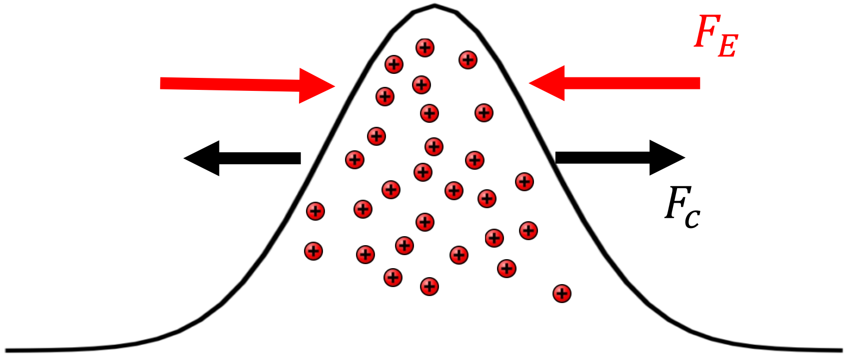
# Space charge effect



# RF cavity




$\Delta t = 1$ ps

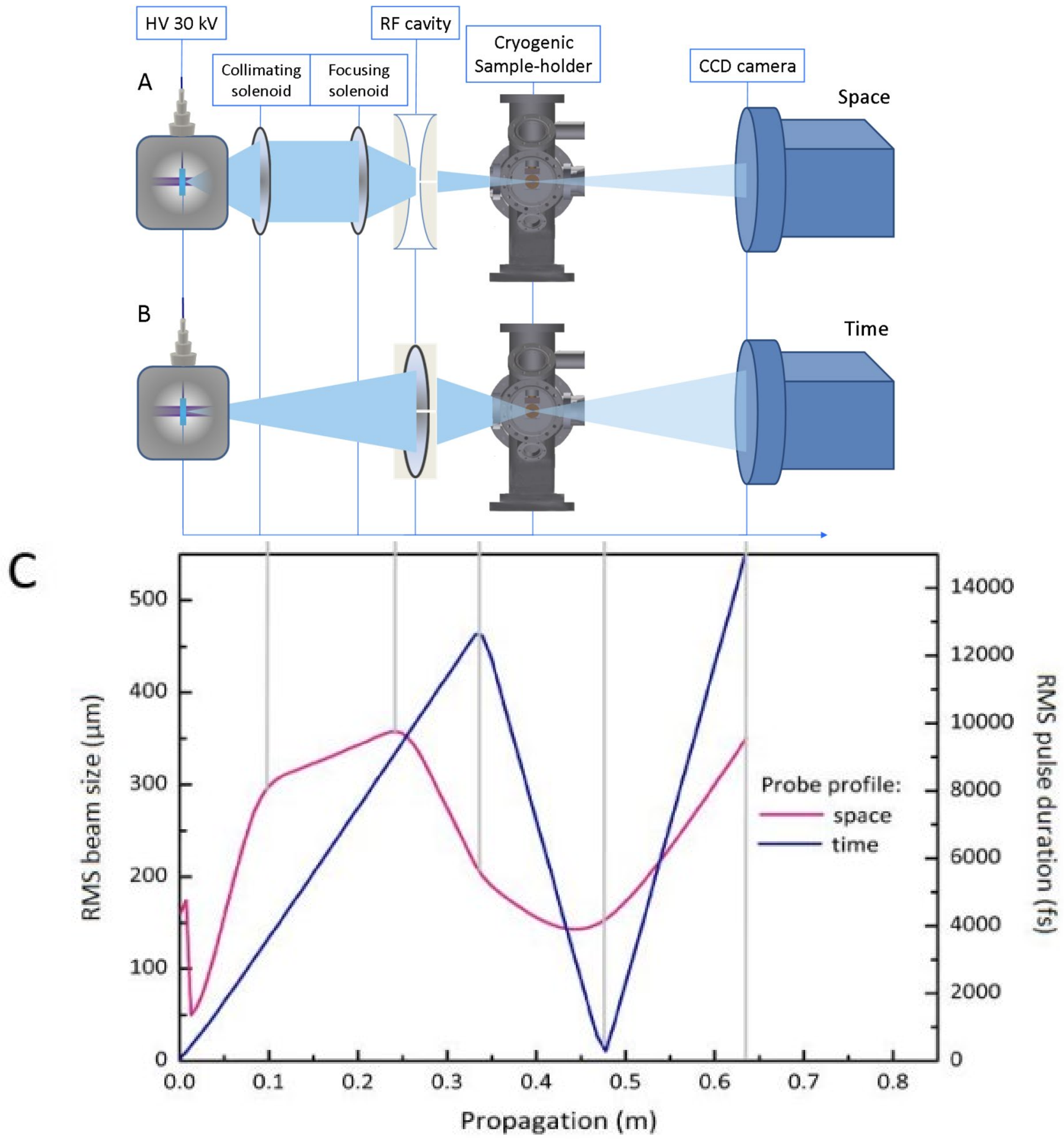
# Longitudinal emittance

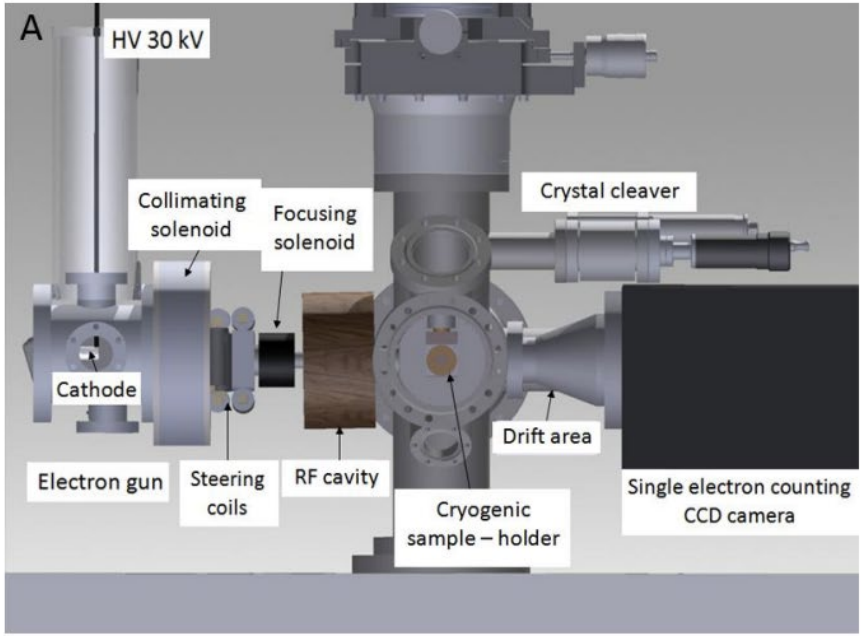
Longitudinal emittance: momentum spread in time (temporal divergence)

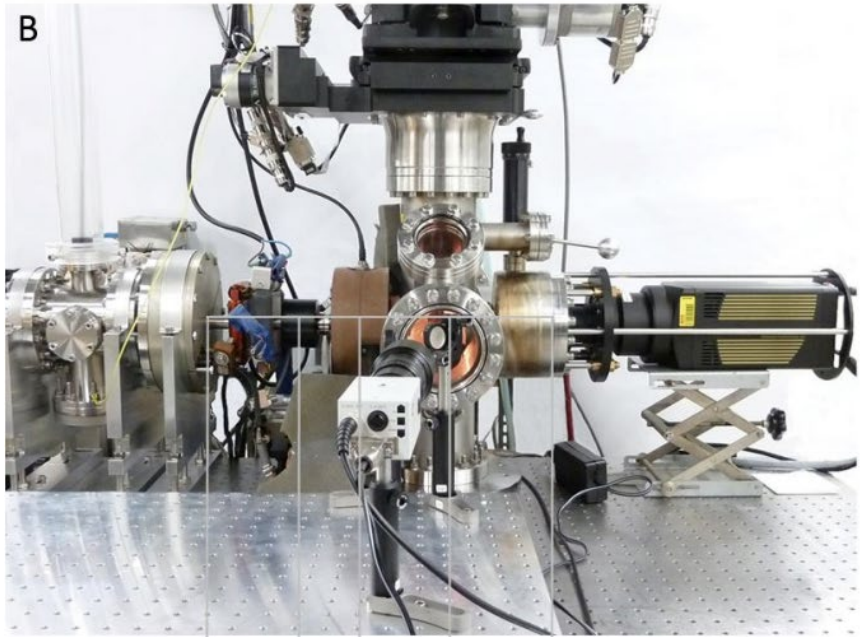
$$\epsilon_z = \frac{\sigma_z \cdot \sigma_{pz}}{m_e \cdot c}$$

$\sigma_z$ the beam dimension along the propagation direction, $\sigma_{pz}$ the pulse duration. Can measure the pulse duration after the RF cavity

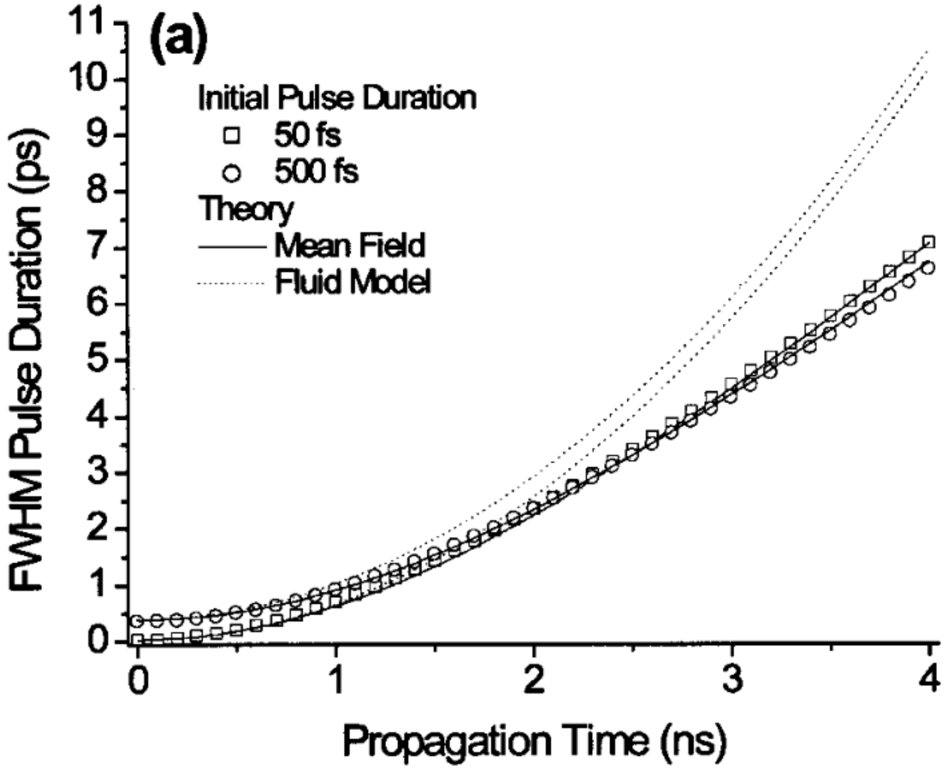
# Temporal and spatial lenses

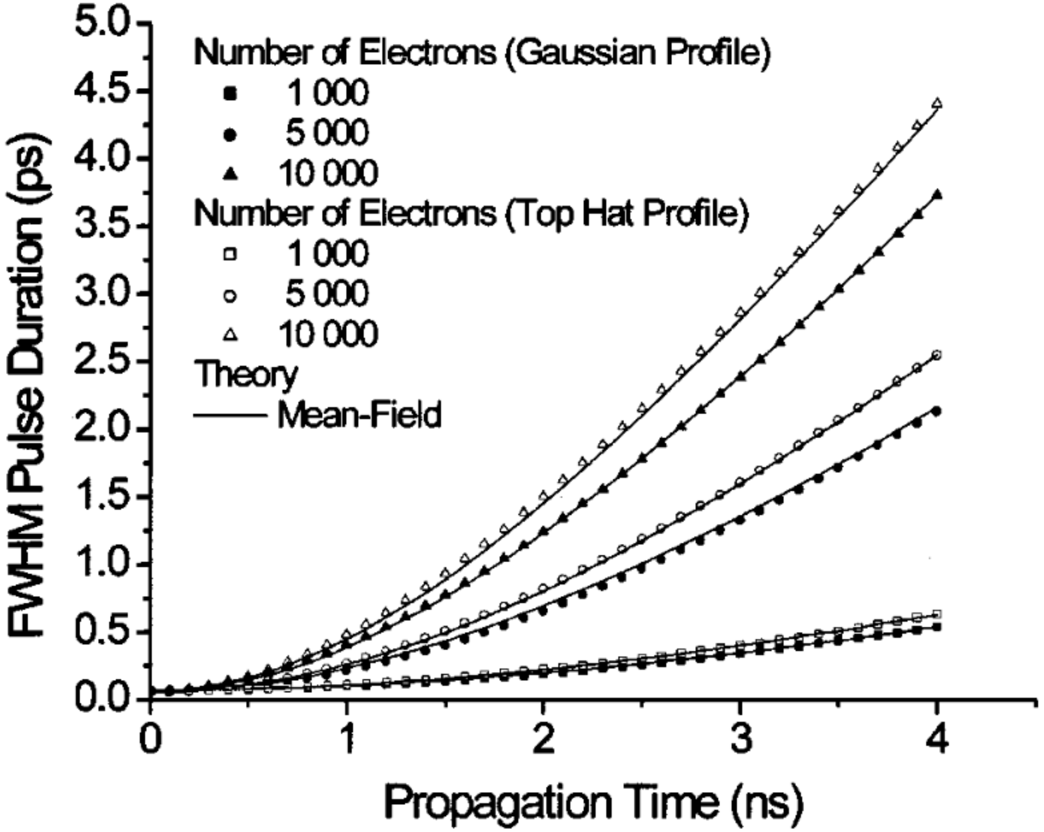


# Space charge effect at low flux



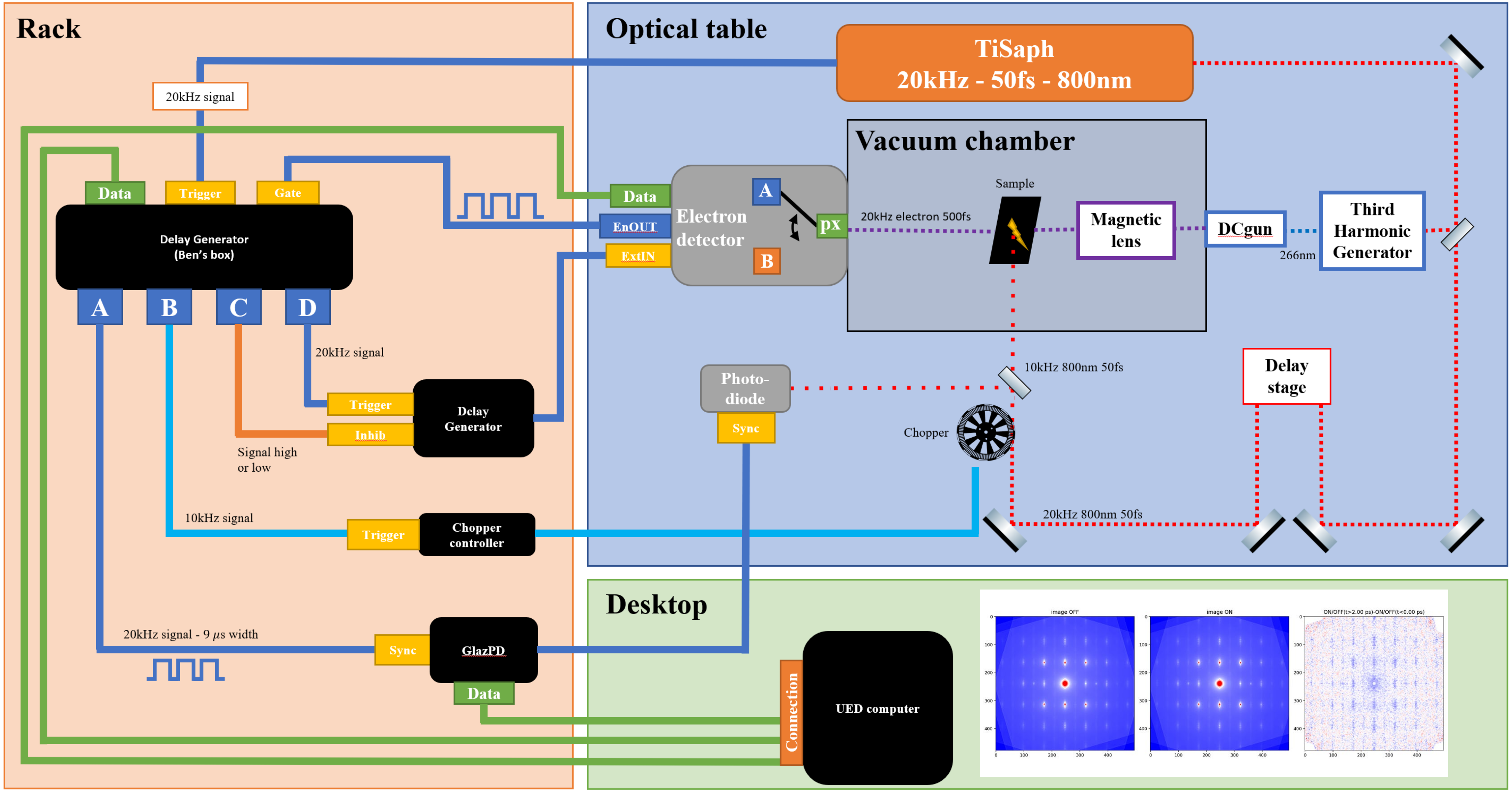



# Signal: low VS high flux

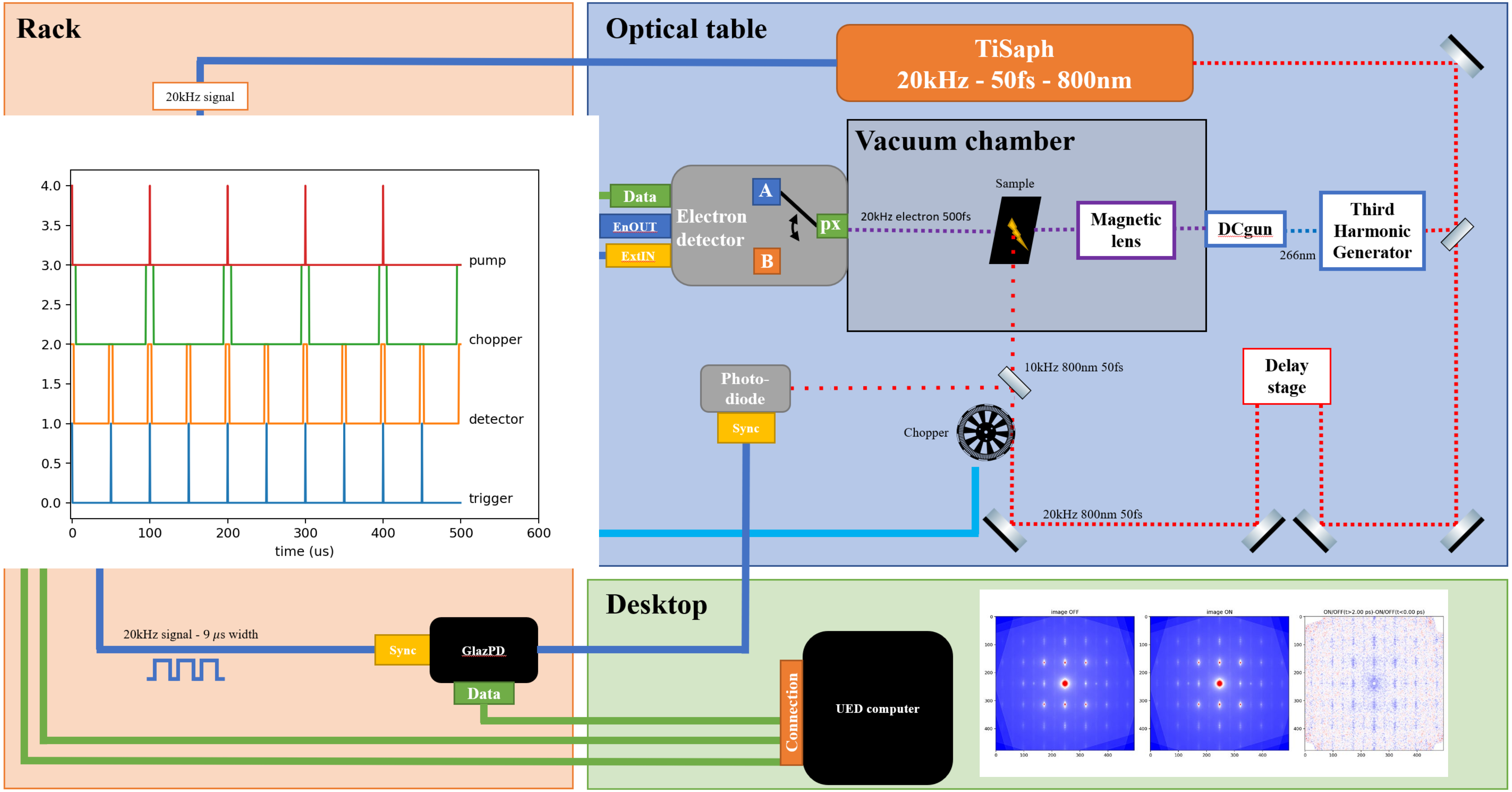
High flux > 1e6 el/pulse : lot of signal, but high .. Need RF cavity to compress the pulse. Not really adapt to single counting electron detector (since it counts 1 el/pulse/pixel)

Low flux < 1e4 el/pulse: less signal, but high-quality beam, low UV power input, less electron damage, no need of RF cavity, but there is a way to improve the signal with chopper

# Signal to noise ratio



# Signal to noise ratio



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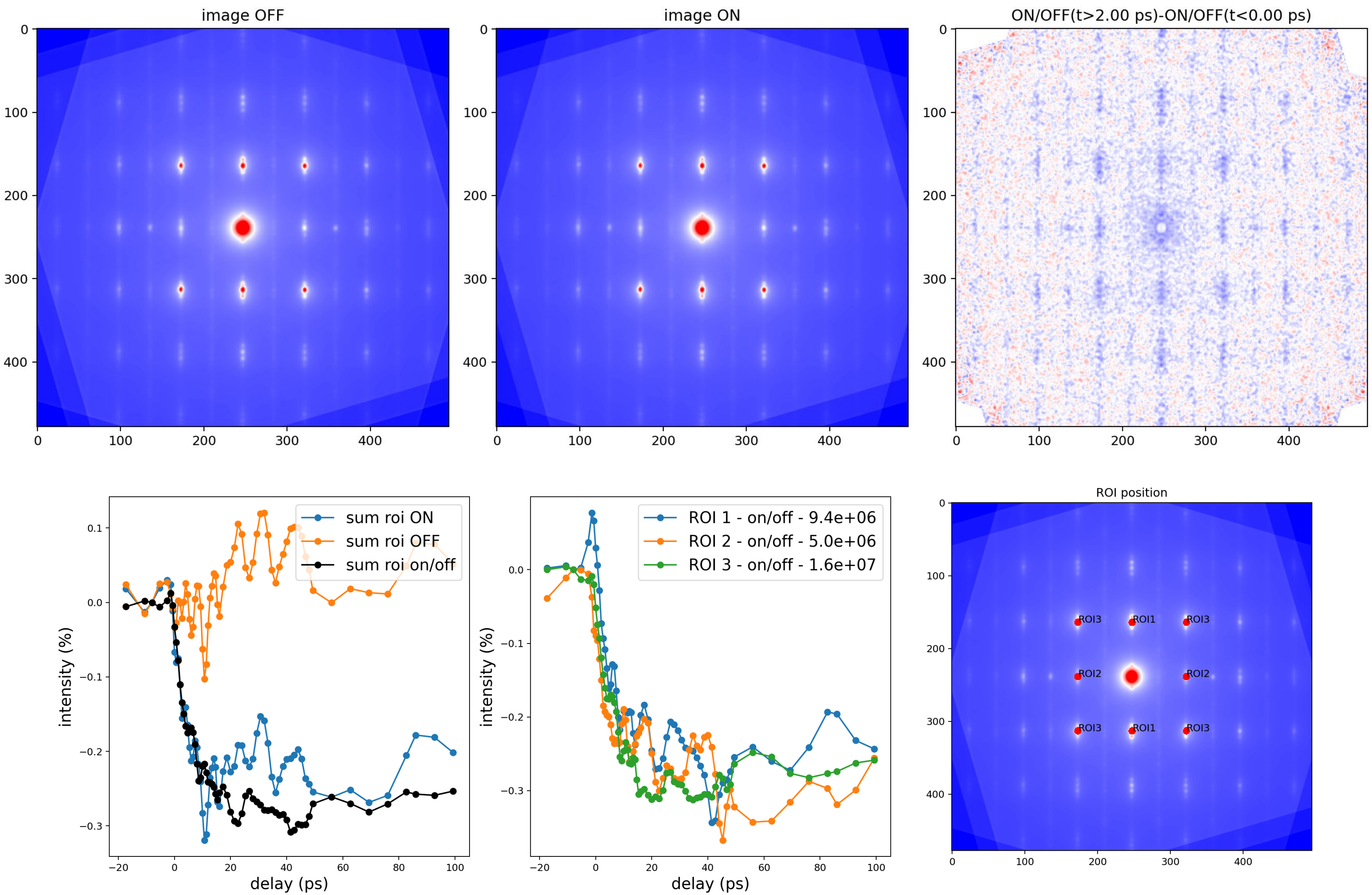
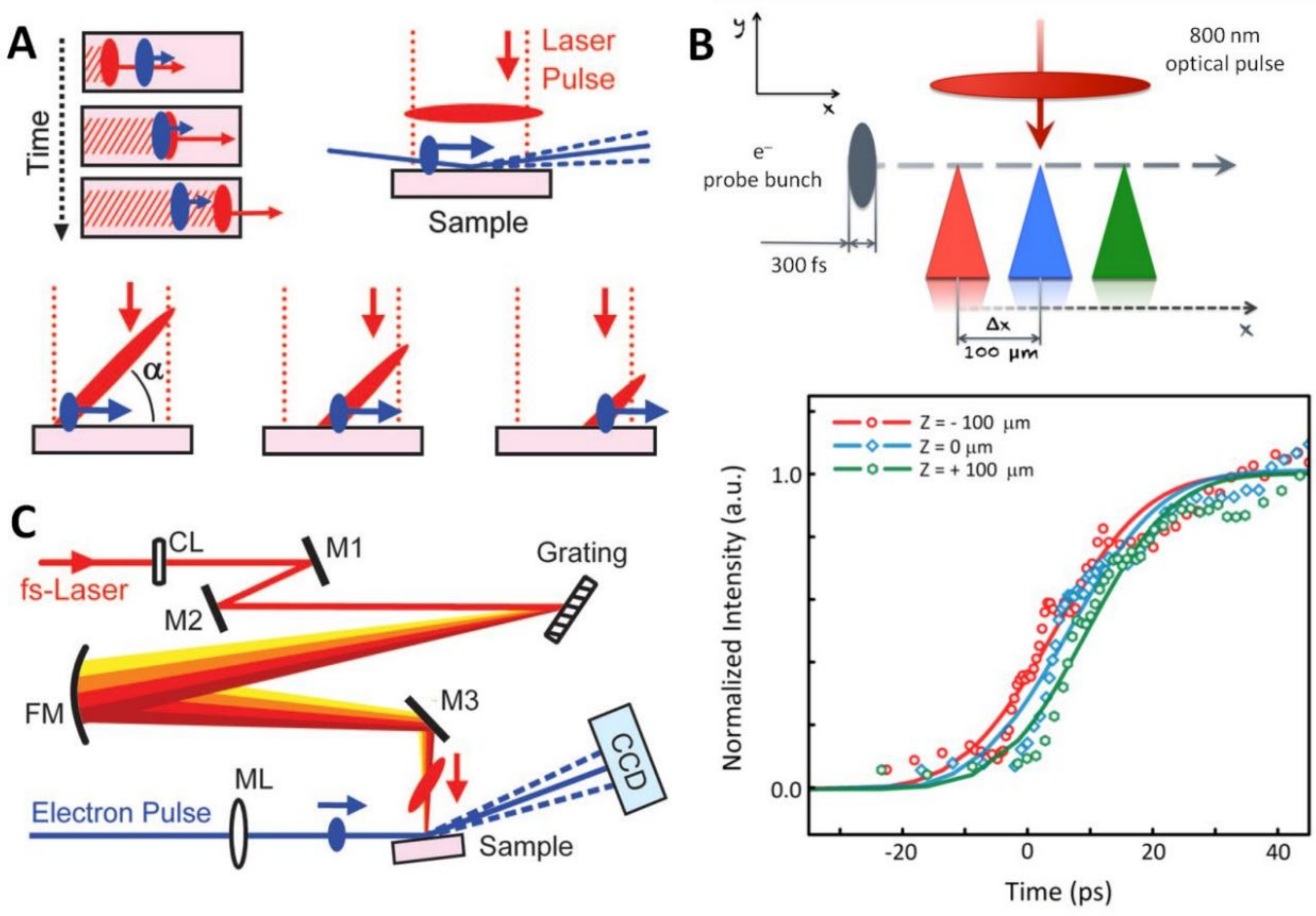


# Pulse front tilting



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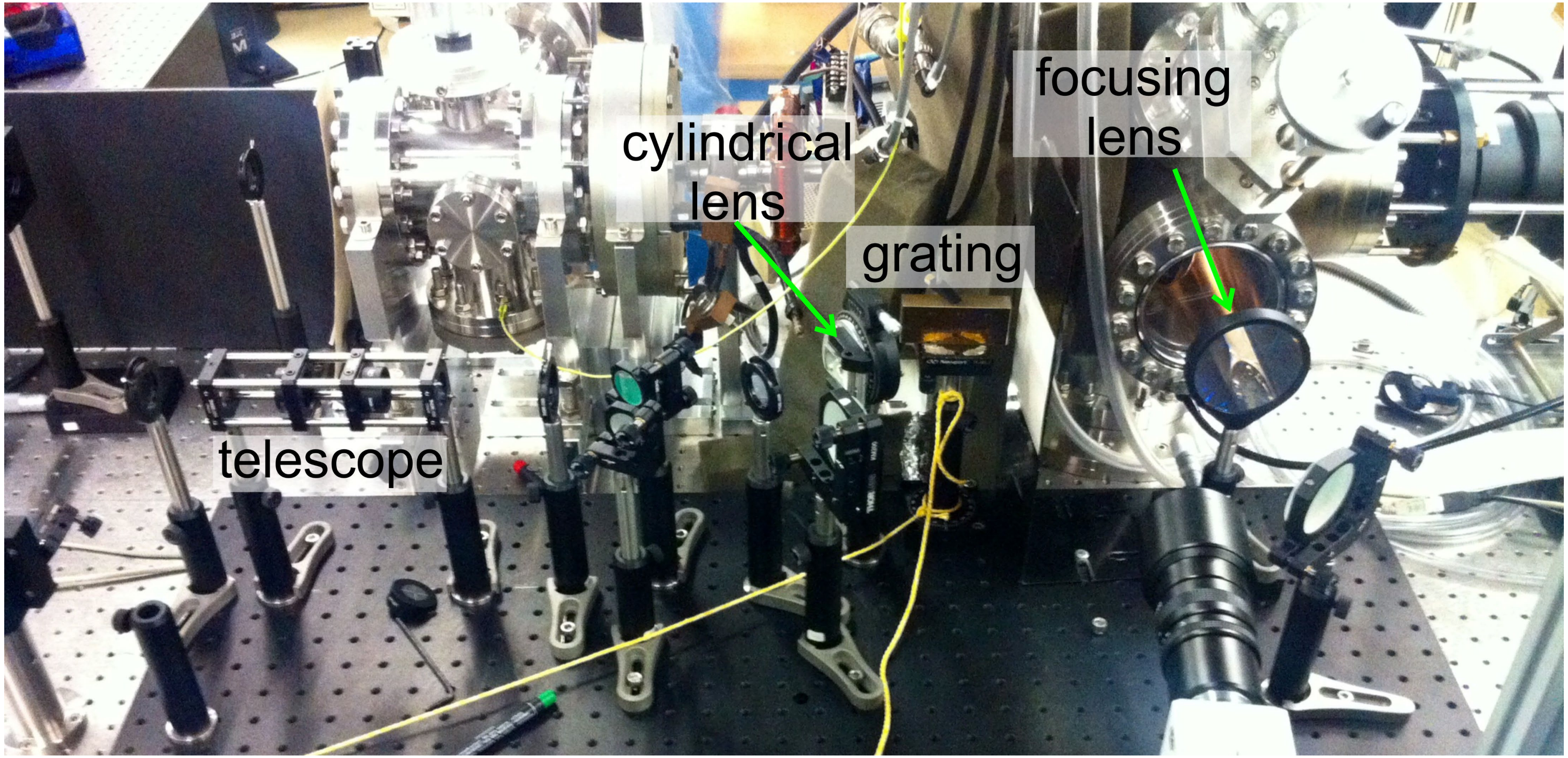
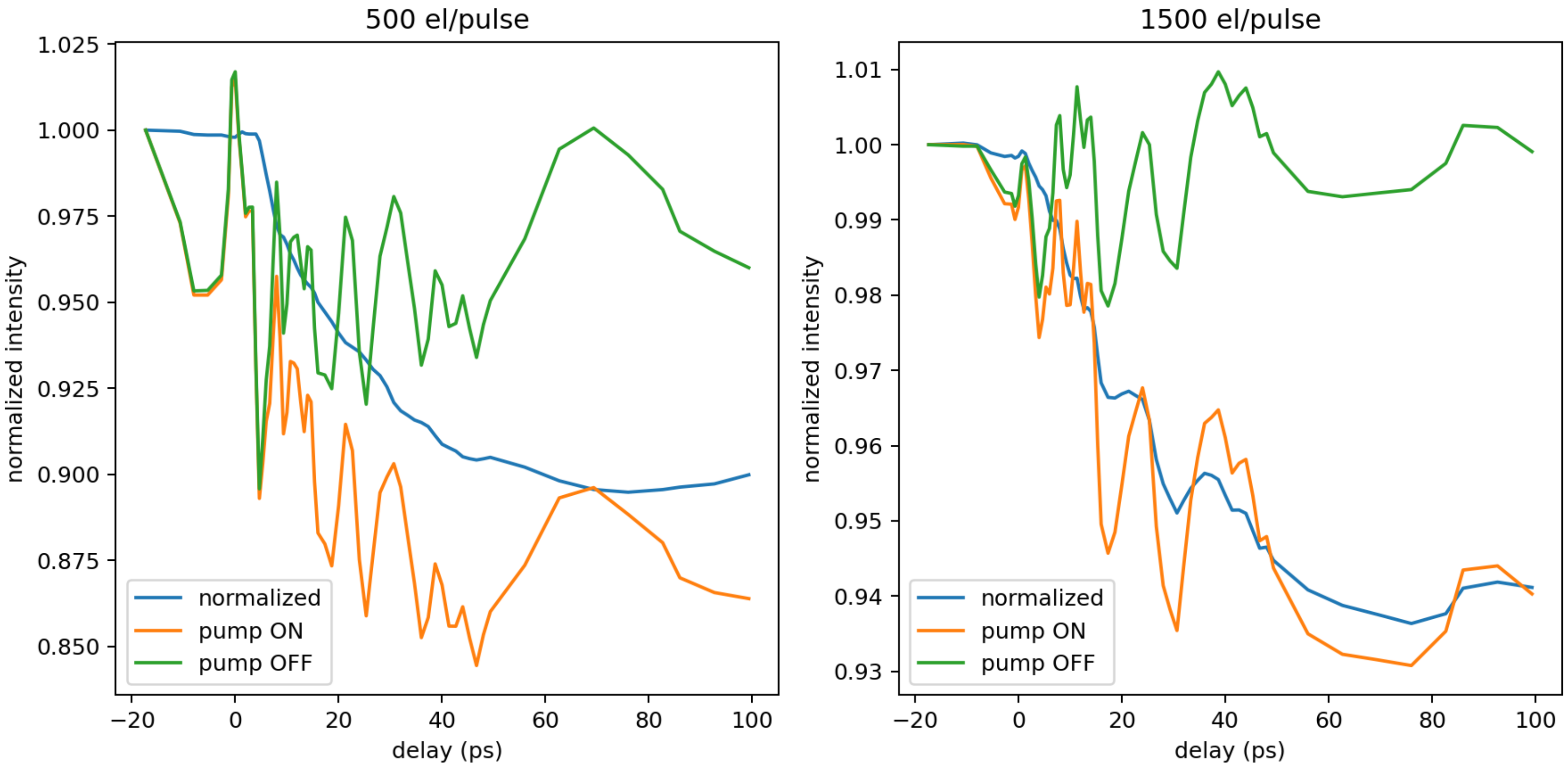
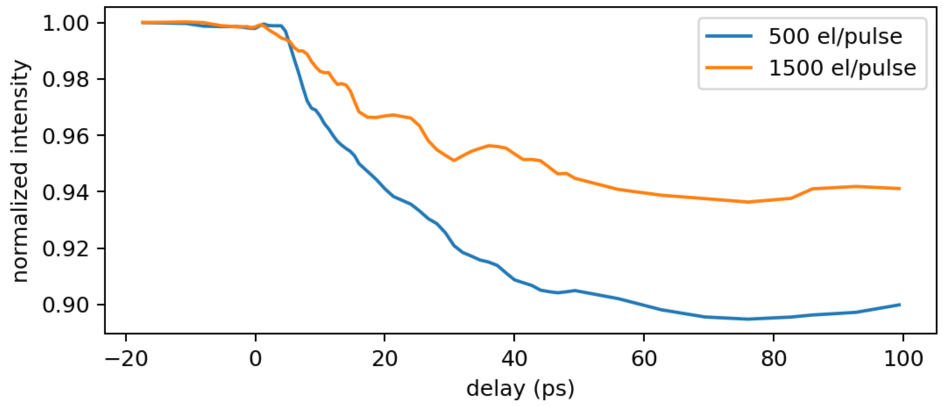
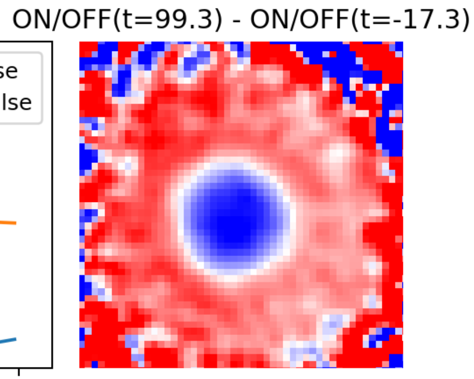


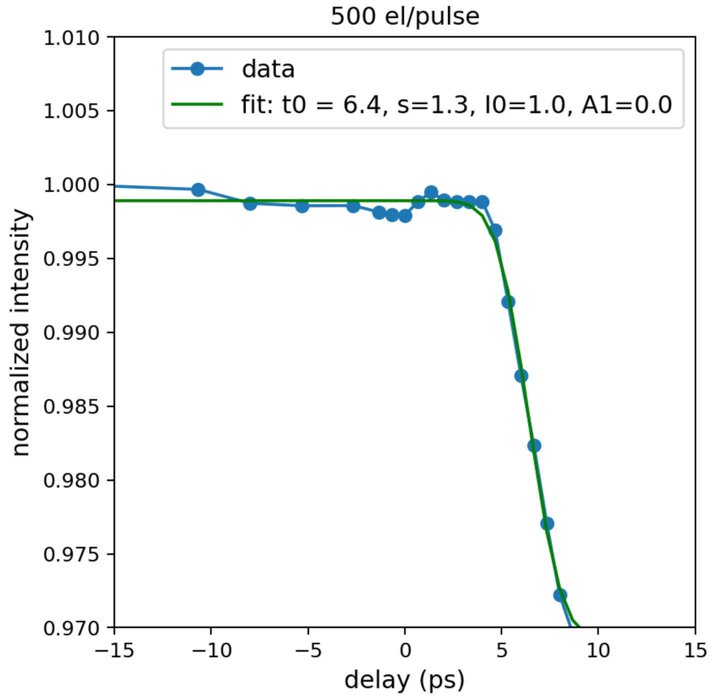
# Signal to Noise Ratio in the lab

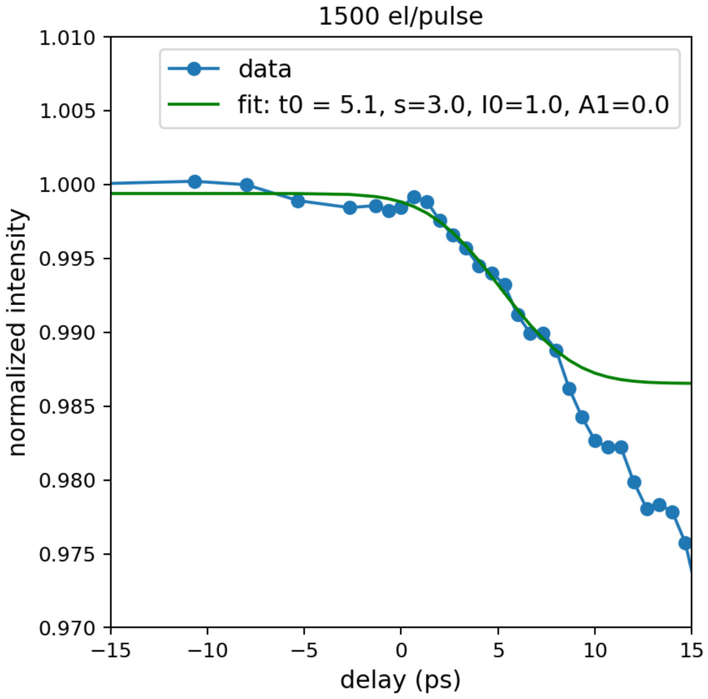


# Pulse charge effect in the lab




$\sigma$ (s) represents the time resolution