Ultrafast Electron Diffraction

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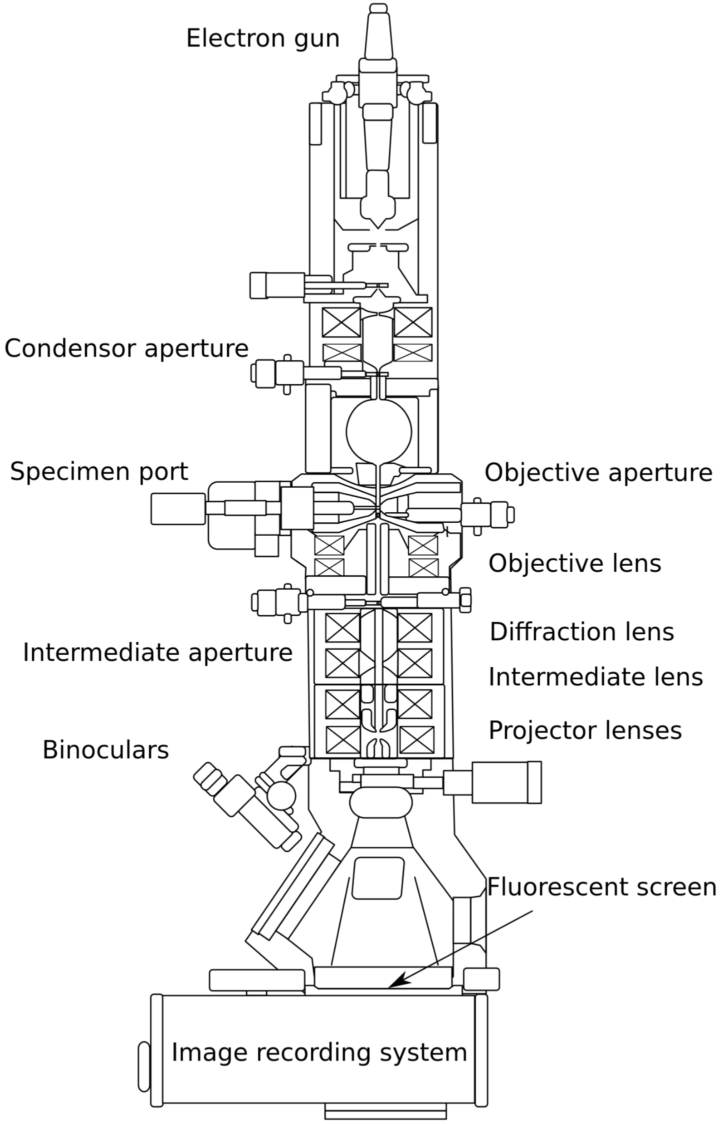
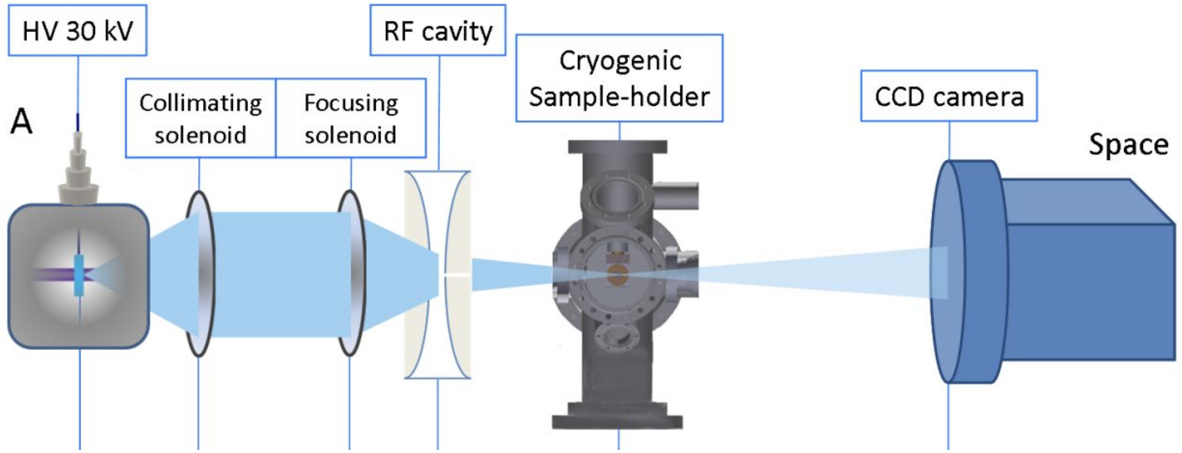
What is UED ?



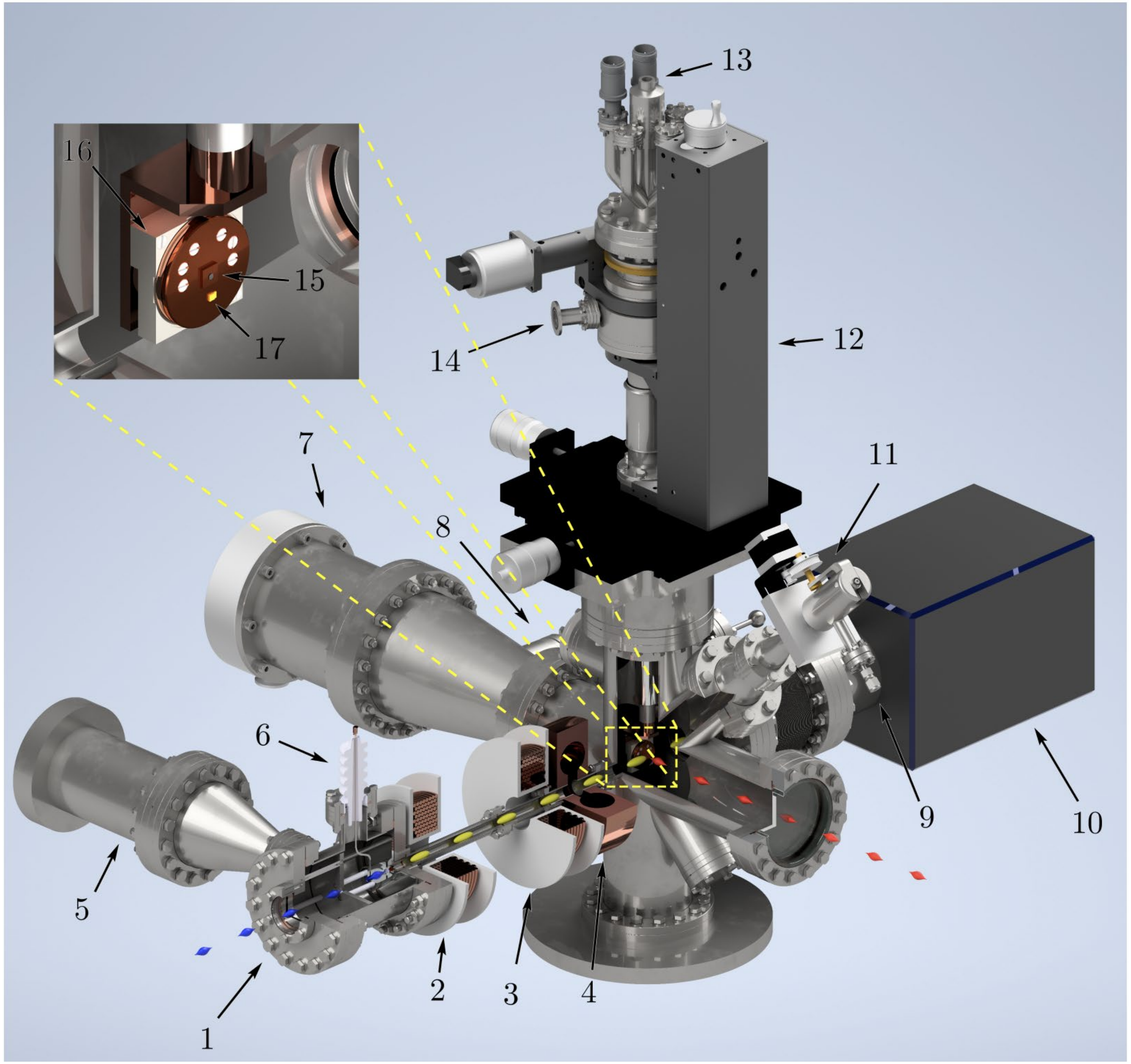


UED is an easy horizontal TEM

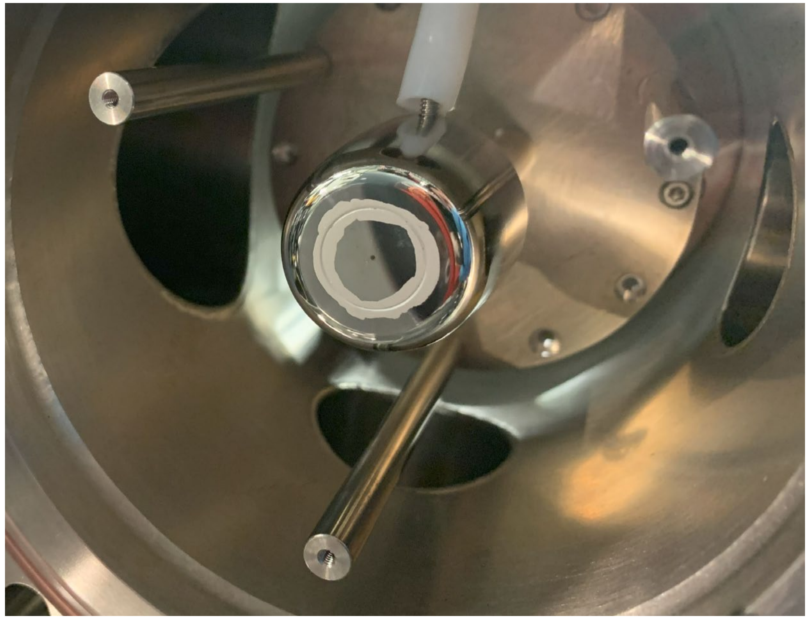
Content

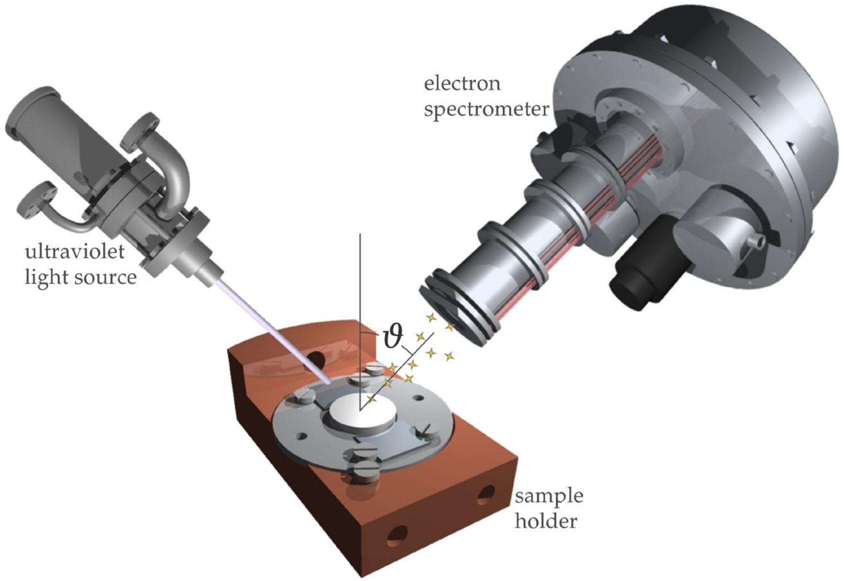
This week:
- Electron photo-generation
- Electron beam acceleration
- Electromagnetic focusing
- Transverse emittance
- Matter-electron interaction

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

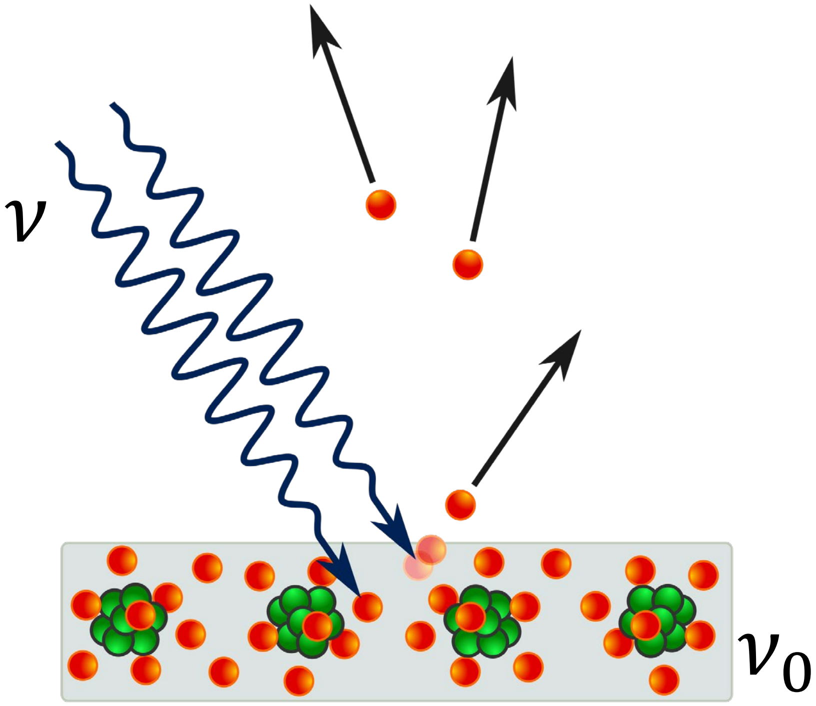


Electron photogeneration





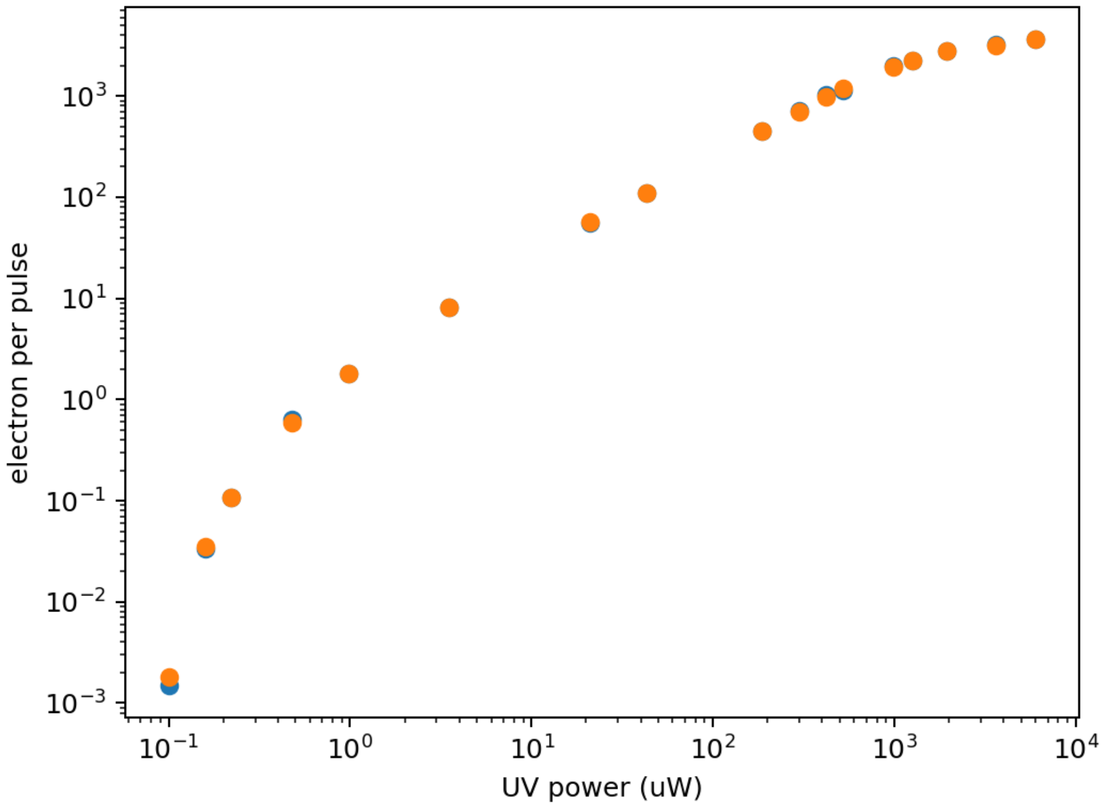
Work function : minimum energy to remove electron from surface solid to the vacuum

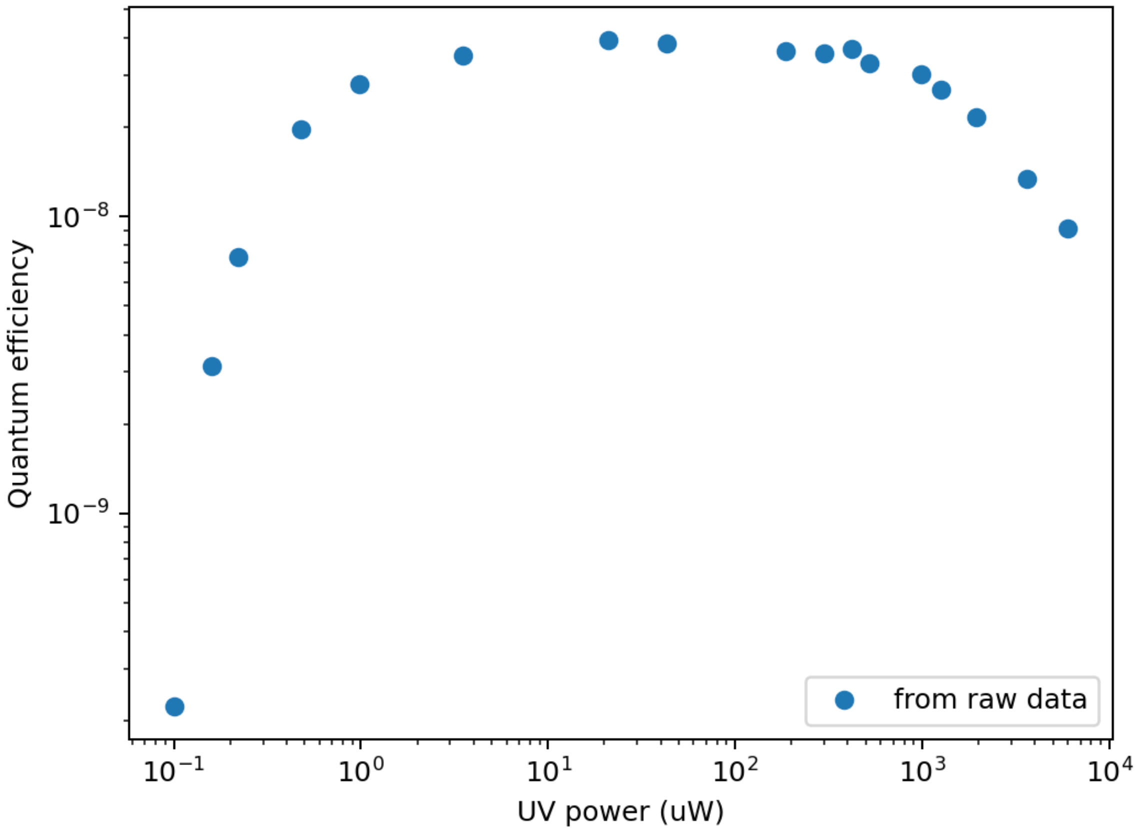


$$K_{max} = h\nu - W = h(\nu - \nu_0)$$

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

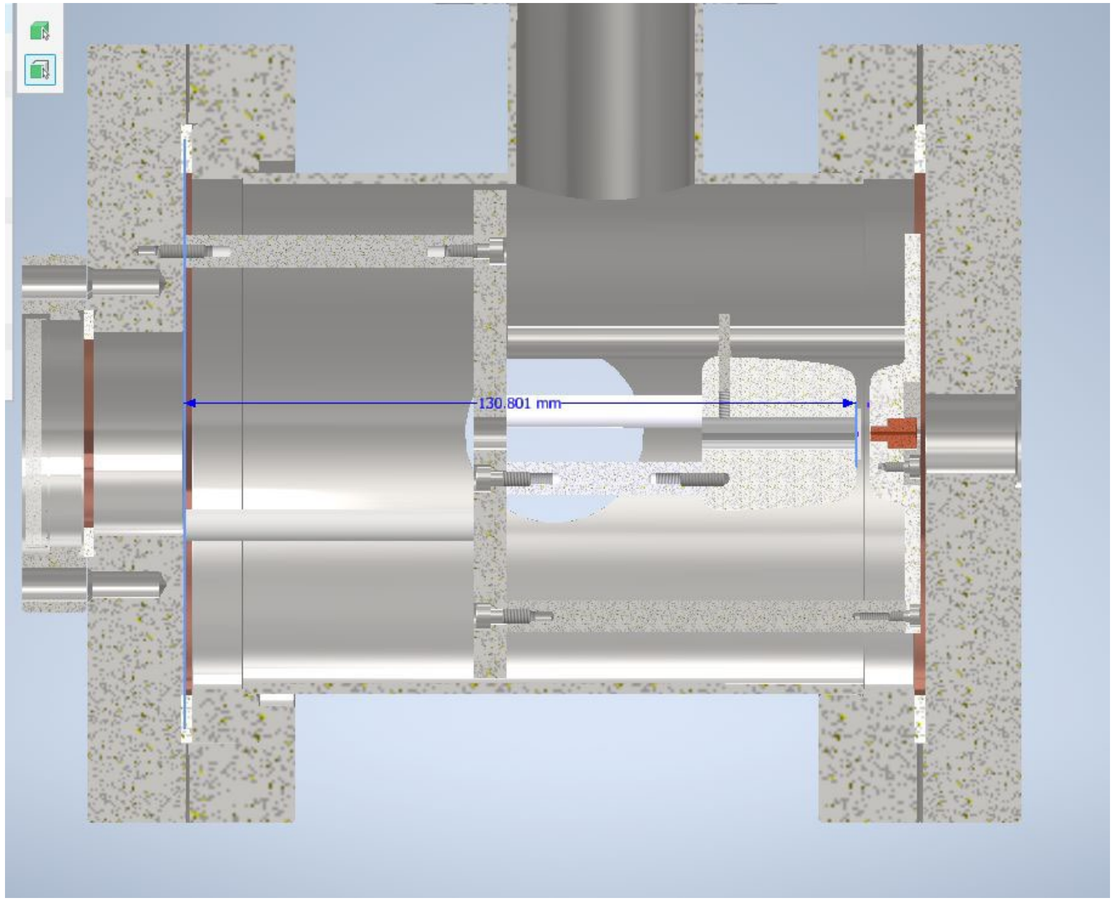
Quantum efficiency



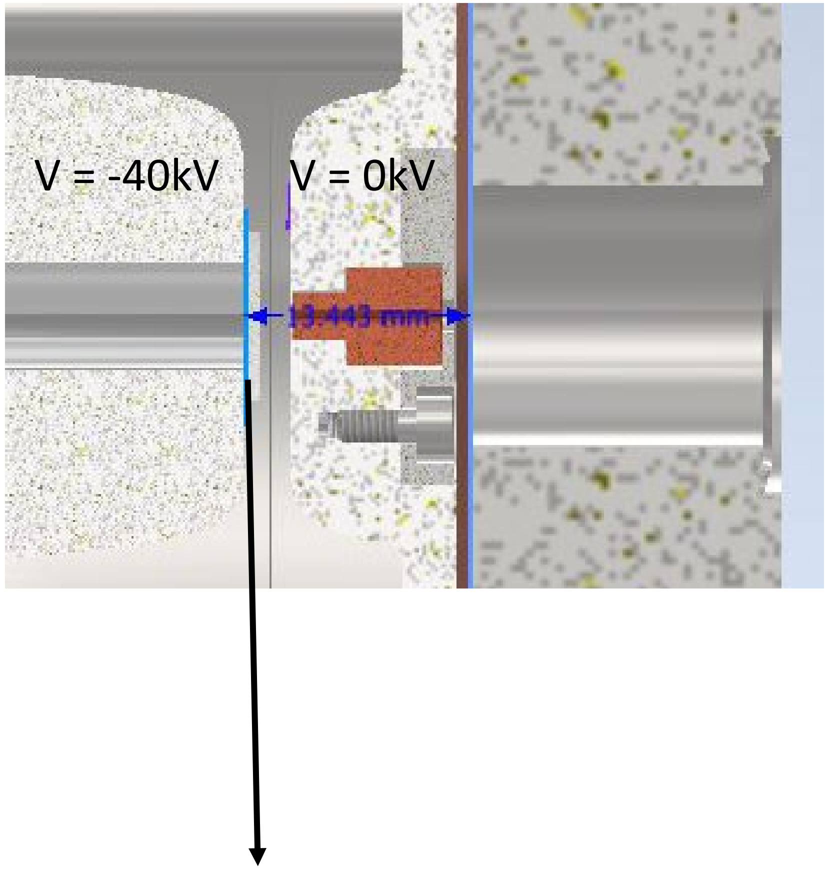


Quantum efficiency : $Q = \frac{n_e}{n_p}$

Electron beam acceleration



Electron gun



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 :

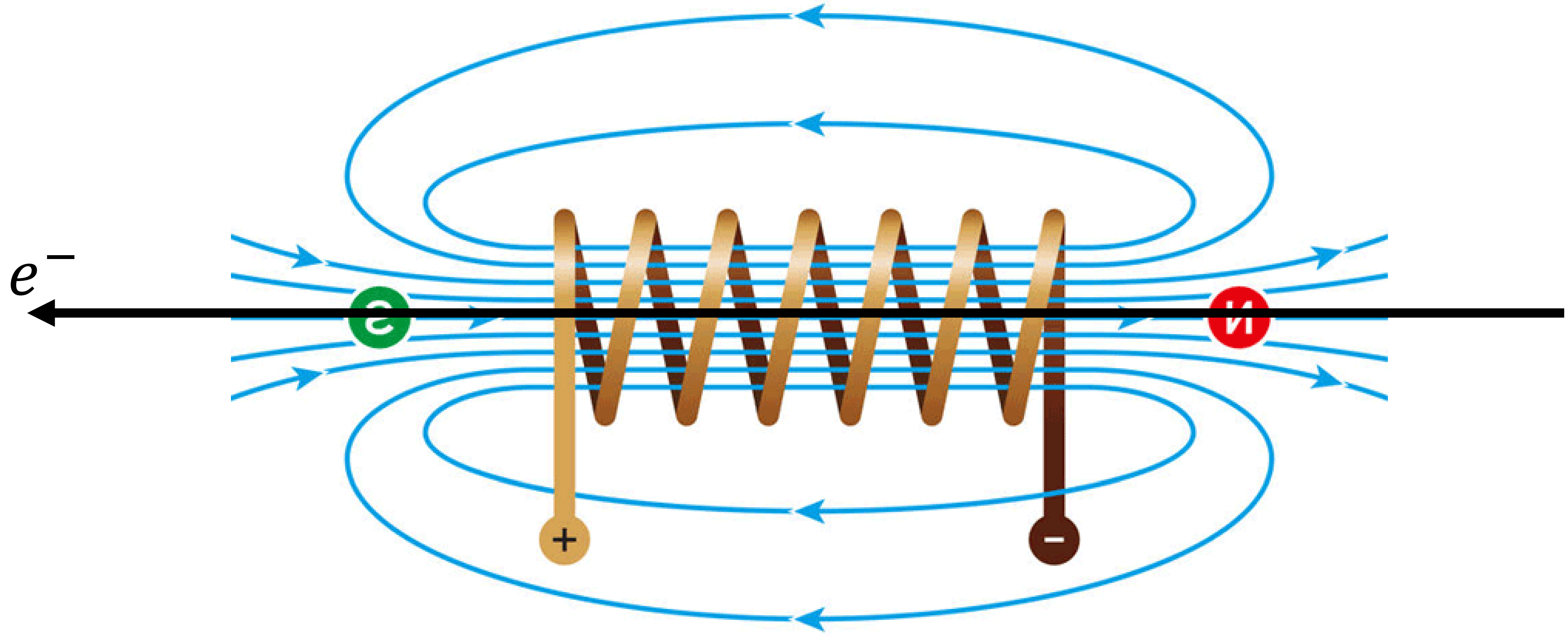
$$\lambda = \frac{h}{p} = \frac{h}{\sqrt{2Em}} = \frac{1.23}{\sqrt{U}} \text{ nm} = 0.19 \text{ nm}$$

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

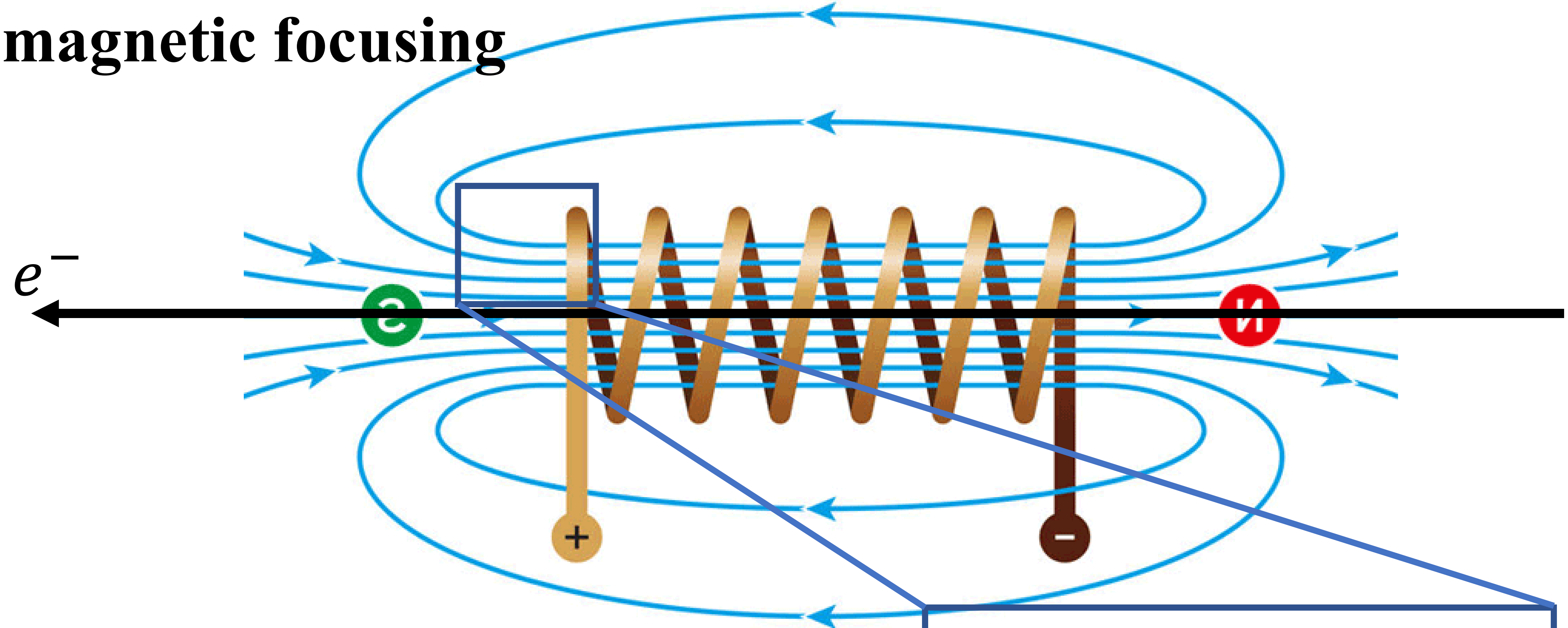
Electron velocity :

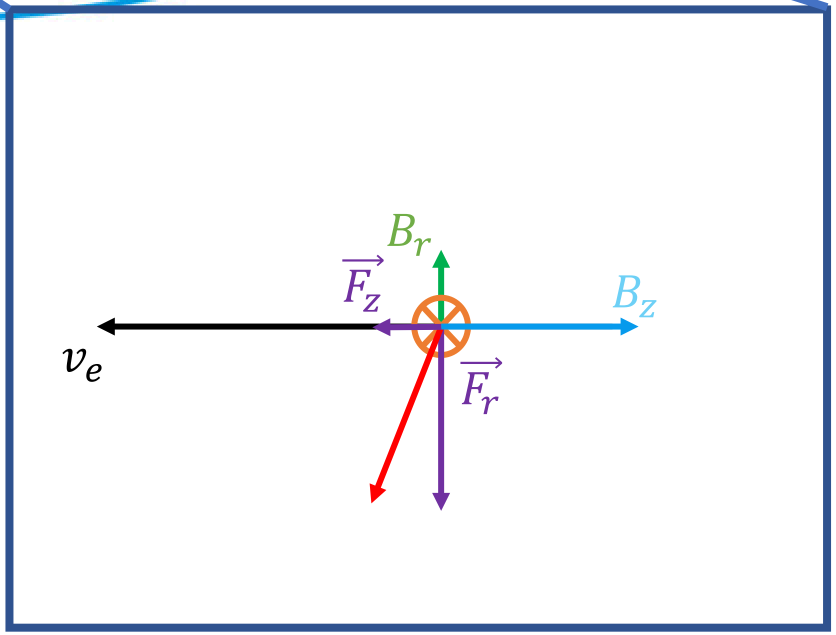
$$\frac{1}{2}mv^2 = E \Rightarrow v = \sqrt{\frac{2eU}{m}} = 5.93 \cdot 10^5 \cdot \sqrt{U} = 1.19 \cdot 10^8 \text{ m/s} = 0.39c$$

Electromagnetic focusing



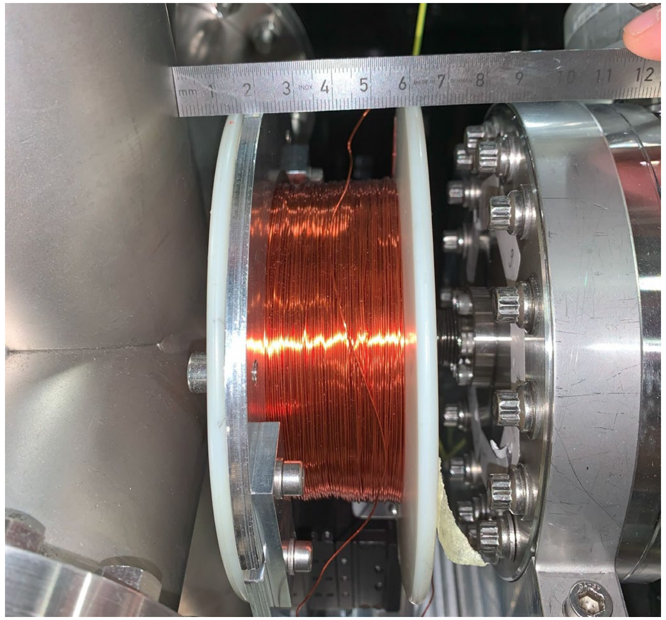
Electromagnetic focusing

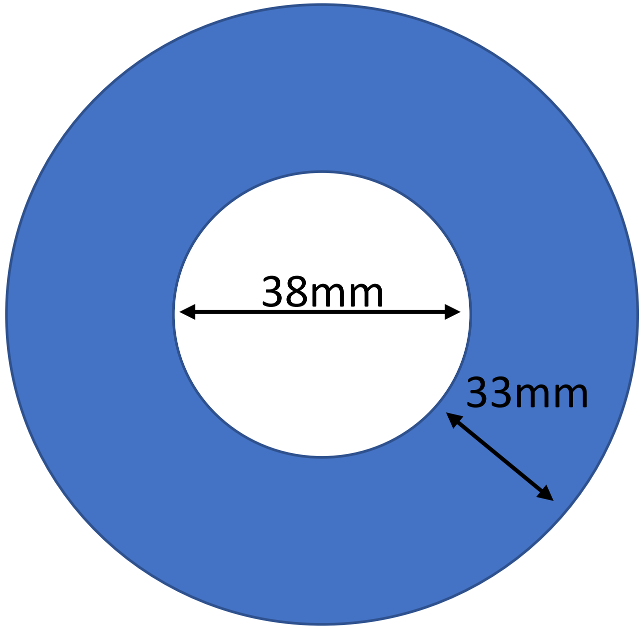




Lorentz force $F = q\vec{v} \times \vec{B}$
$\overrightarrow{v_e} \times \overrightarrow{B_z} = 0$
$\overrightarrow{v_e} \times \overrightarrow{B_r} \Rightarrow \overrightarrow{F_\phi} \;\Rightarrow \overrightarrow{v_\phi} \neq 0$
$\overrightarrow{v_\phi} \times \overrightarrow{B_r} \Rightarrow \overrightarrow{F_z}$ and $\overrightarrow{v_\phi} \times \overrightarrow{B_z} \Rightarrow \overrightarrow{F_r}$
Don't forget $q < 0$
Force going toward the center

Electromagnetic focusing





The focal distance of a solenoid

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

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

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

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

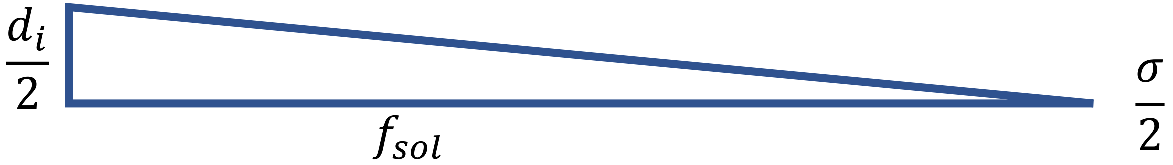
In optics, brilliance is the energy stored by a unit of solid angle and is conserved along the beam propagation

In electronic microscopy, we have a similar quantity called emittance

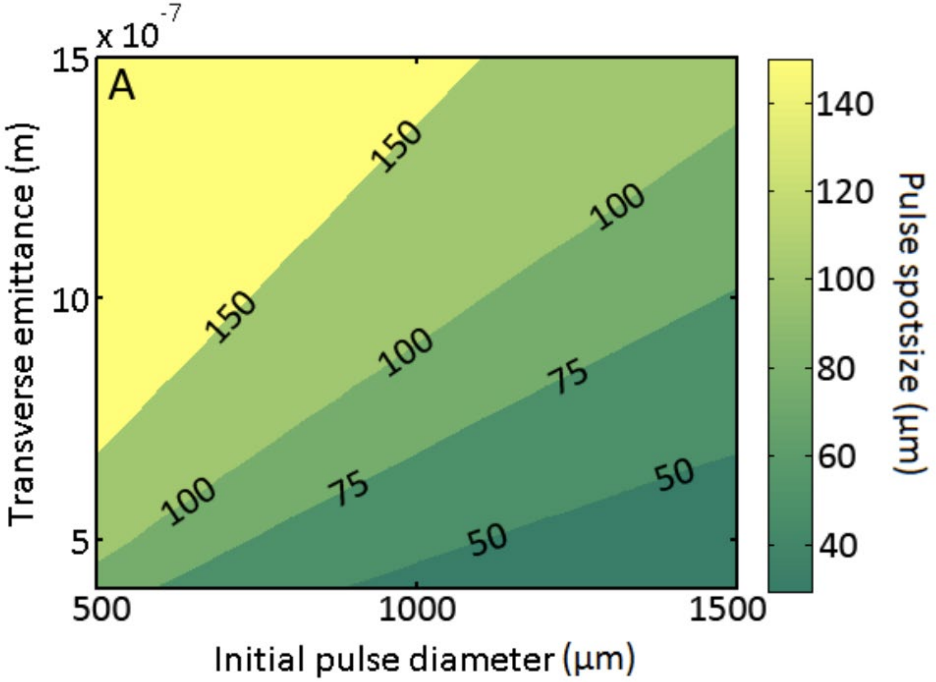
Transverse emittance: momentum spread in space (spatial divergence)

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

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



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

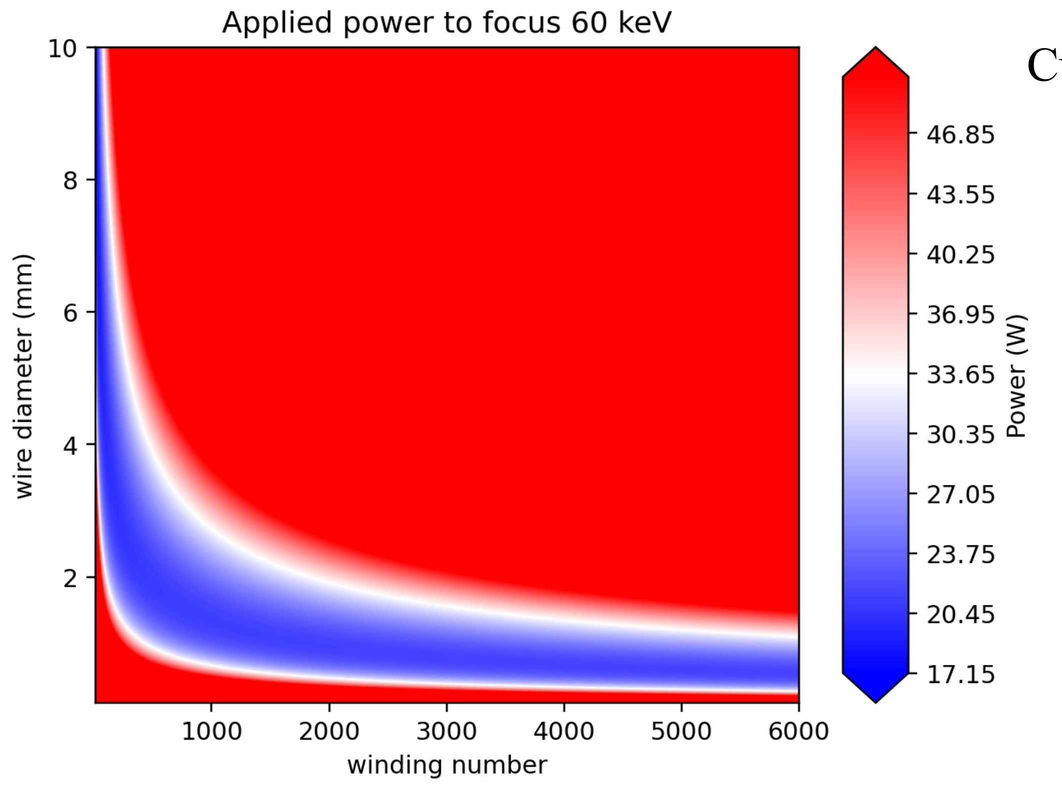


Can measure the focused beam size:

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

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)

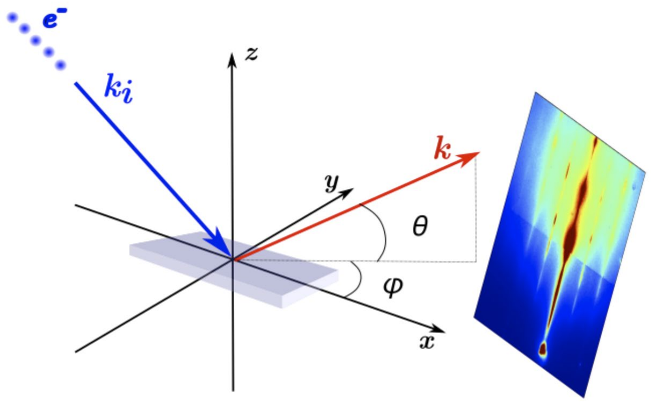
$$I_{tot} = \frac{16}{e\mu_0}\sqrt{\frac{Rm_eE}{f_{sol}3\pi}} = 1.9 \text{ kA}$$

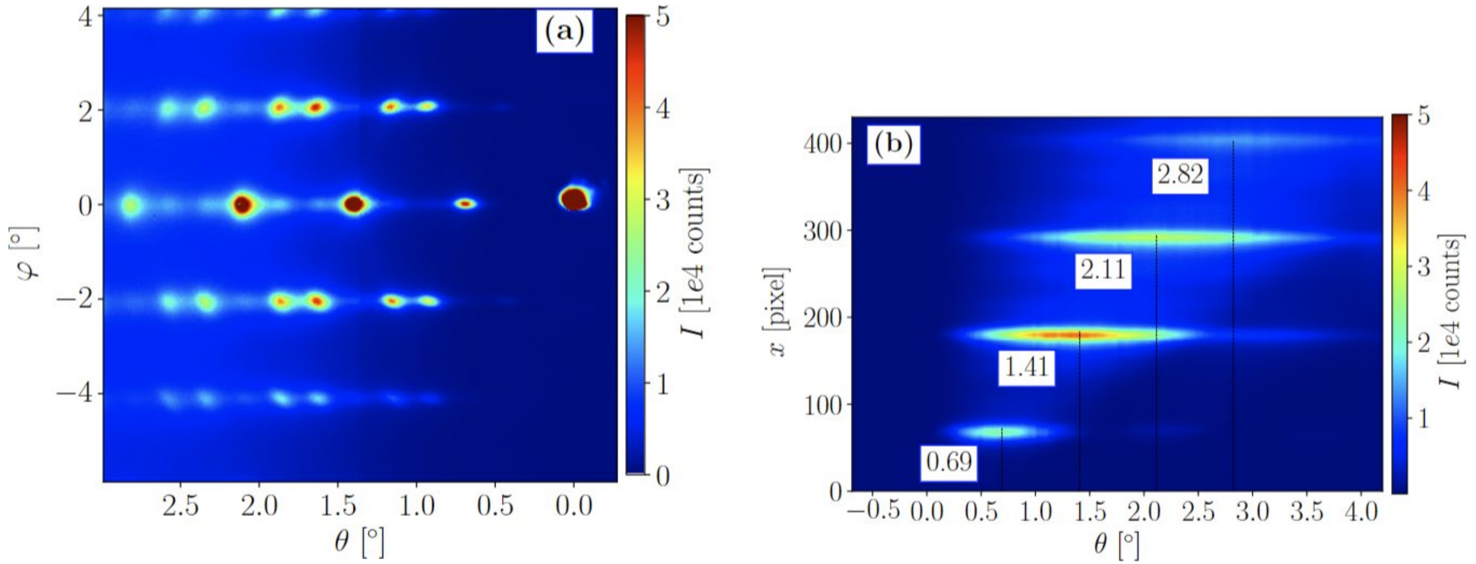
$I_{tot} = NI \implies I = \frac{I_{tot}}{N} = 625$ mA for 3000 windings

$P = RI^2$ 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

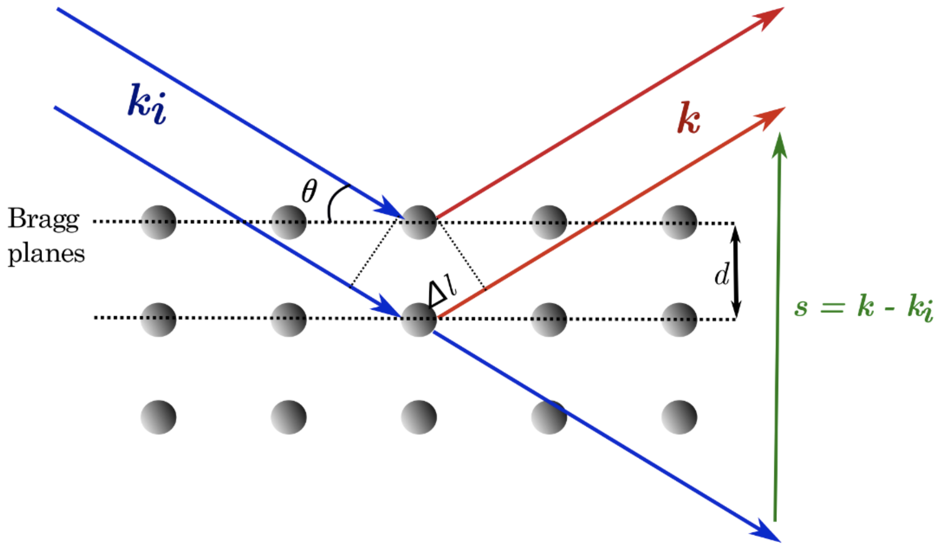
Electron matter interaction – reflection





Reflection high electron energy diffraction (RHEED)

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



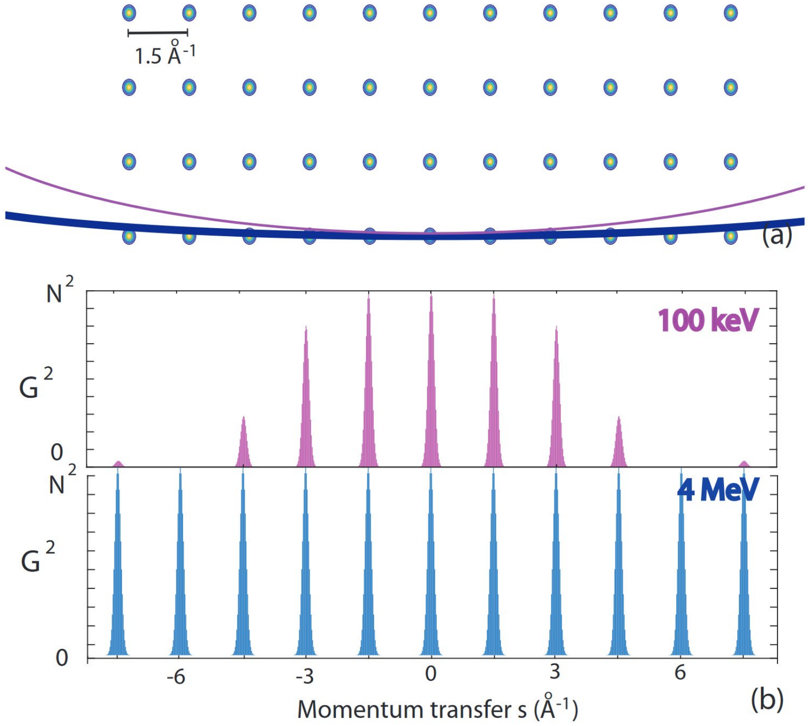
Electron matter interaction – transmission

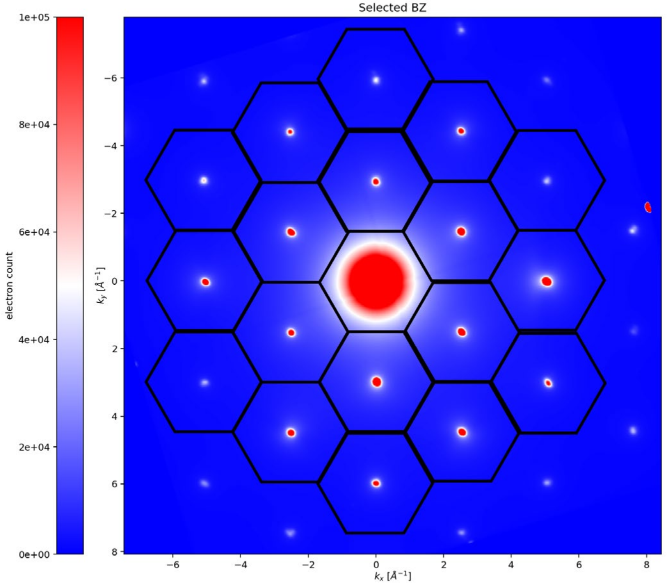
Laue condition: Link the electron intensity to the atomc position in the lattice

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

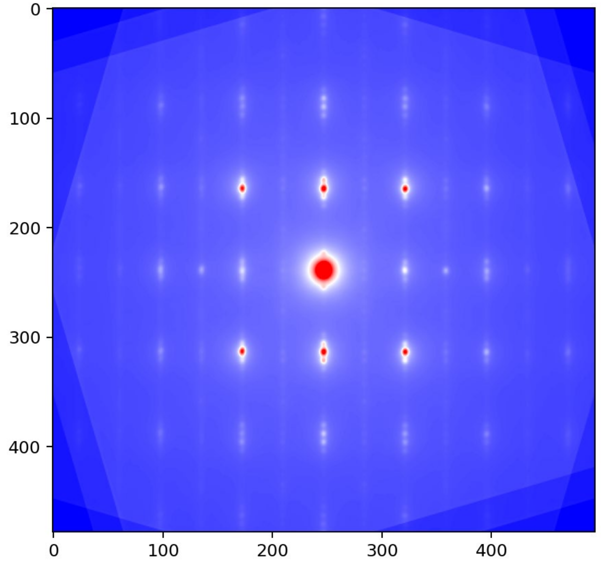
Where k_i is the incident wavevector, k the outgoing wavevector, and R_j the position of the jth atom of the unit cell

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





graphite



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