Phase shaping of the free-electrons wavefunction with fs-laser pulses in an RF-cavity-based UTEM

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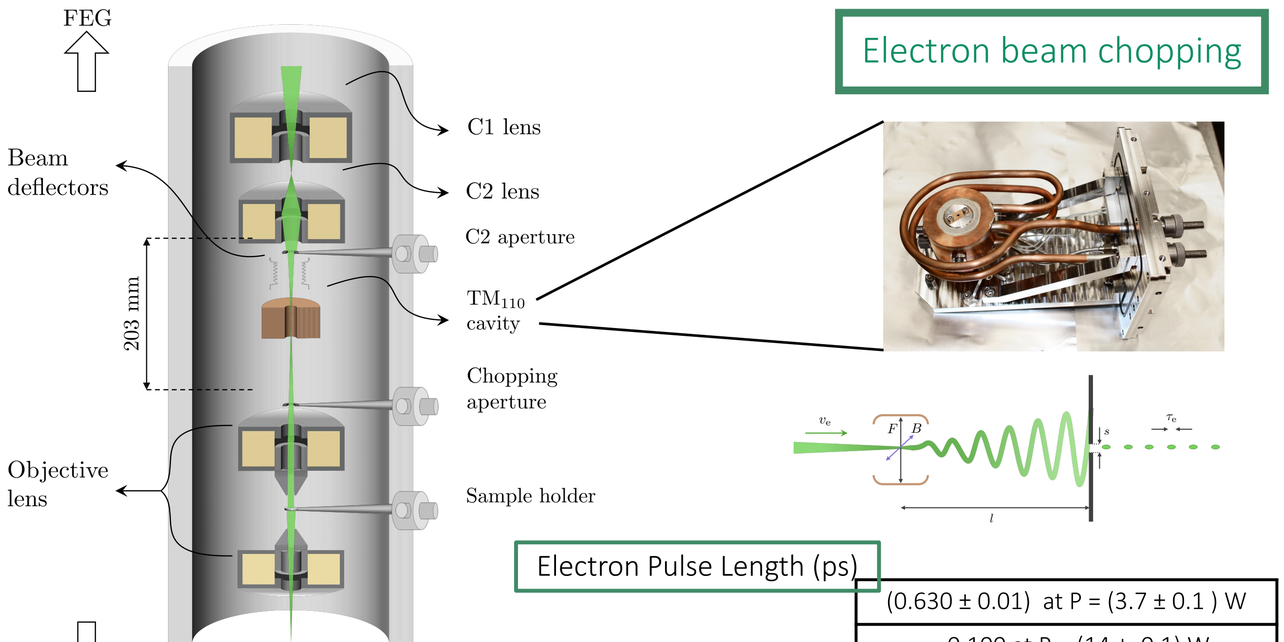
RF-cavity-based ultrafast transmission electron microscope



Electron beam chopping

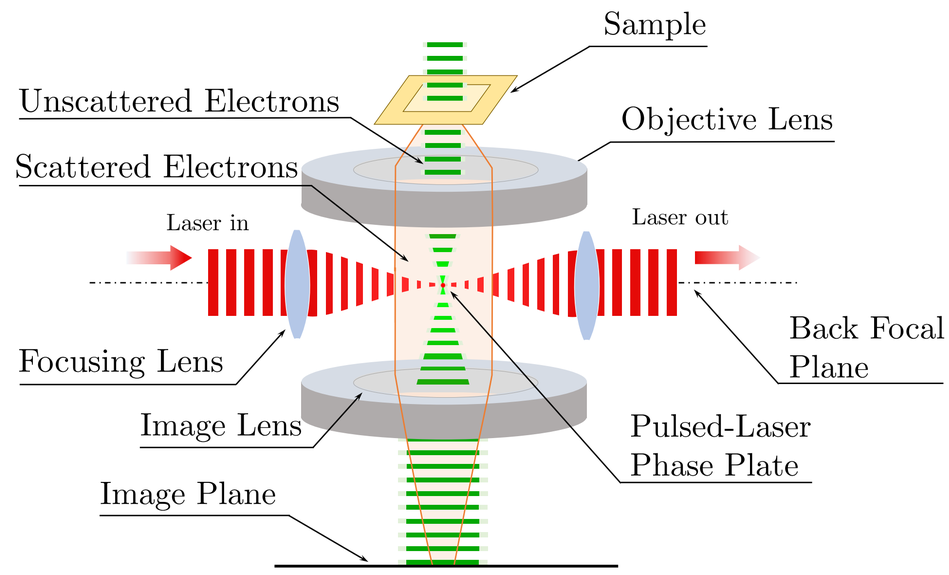
Electron Pulse Length (ps)

(0.630 ± 0.01) at P = (3.7 ± 0.1) W
~ 0.100 at P = (14 ± 0.1) W

Horizontal normalized emittance $\varepsilon_{n,x}$ (pm rad) Vertical normalized emittance $\varepsilon_{n,y}$ (nm rad)	(2.1 ± 0.2) (1.3 ± 0.2)
Energy spread (eV)	(0.9 ± 0.05)
Normalized peak brightness (A/m^2 sr V)	(7 ± 1) x 10^6

Electron wavefunction's phase shaping with Light

Phase Plate based on ponderomotive interaction between a tightly focused pulsed laser and the pulsed zero-order electron (unscattered) beam transmitted by a sample.



$\frac{\pi}{2}$ —phase shift between scattered and scattered electrons

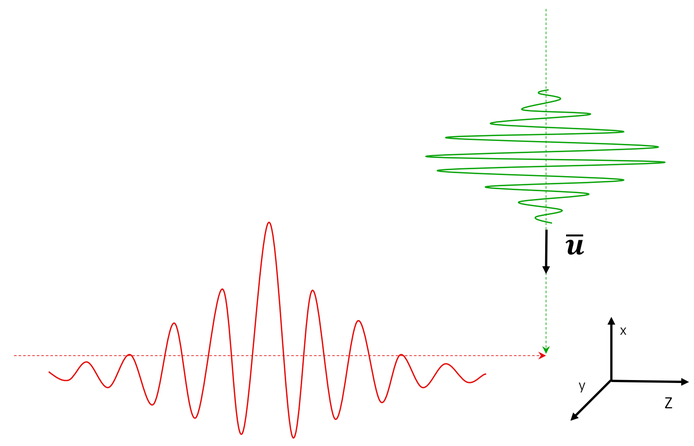
Theoretical Framework

Interaction between laser and electron pulses modeled usign the relativistic ponderomotive potential

$$U_p = \frac{e^2}{c\,\epsilon_0\,\gamma\,m\,\omega_0^2}\,\frac{W}{\pi^{3/2}\,w(z)^2\,\tau}\,e^{-\frac{(t-z/c)^2}{\tau^2}}\,e^{-2\frac{x^2+y^2}{w(z)^2}}$$

Phase Shift on an electron crossing the laser spot w(z) at $\bar{r} = (z, y)$ at time t_0

$$\Delta\varphi = -\frac{1}{\hbar}\int_{-\infty}^{+\infty} dt\; U_p(u(t-t_0), y, z, t)$$



Maximum Phase Shift for perfect space-time synchronization between laser and electron pulses (t_0 = y = z = 0)

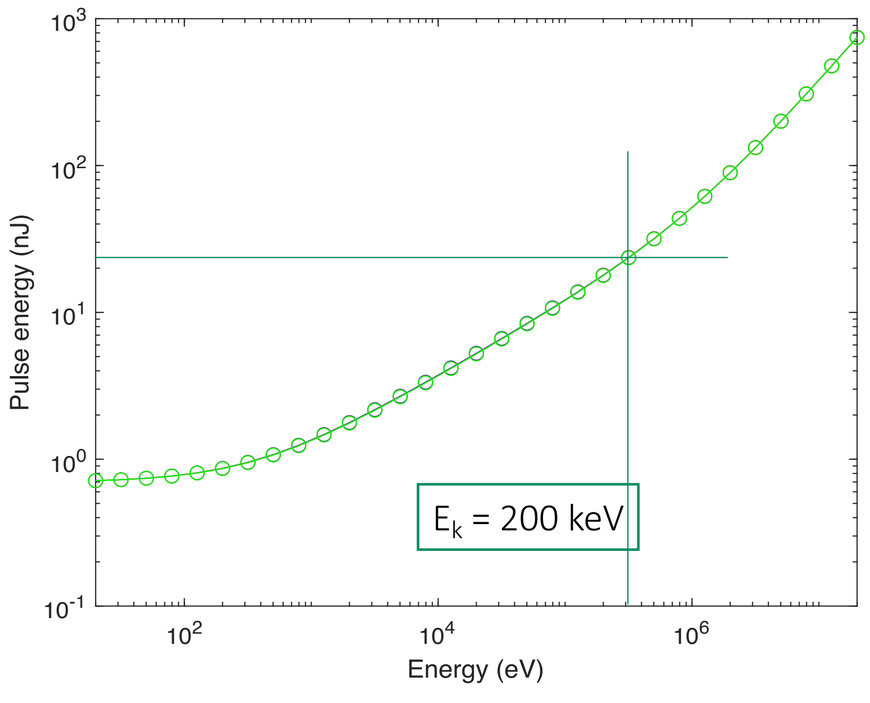
Long pulse limit

$$\Delta\varphi_{max} \sim -\frac{e^2}{\hbar\,c\,\epsilon_0\,\gamma\,m\,\omega_0^2}\,\frac{W}{\pi\,w_0^2}\,\frac{\tau_t}{\tau}$$

Phase shift depends on the synchronization between laser and electron pulses, on the laser parameters (pulse energy *W*, duration τ, waist w_0) and electron pulse length

Experimental Parameters

Phase Shift $\Delta\varphi_{max} = -\frac{\pi}{2}$

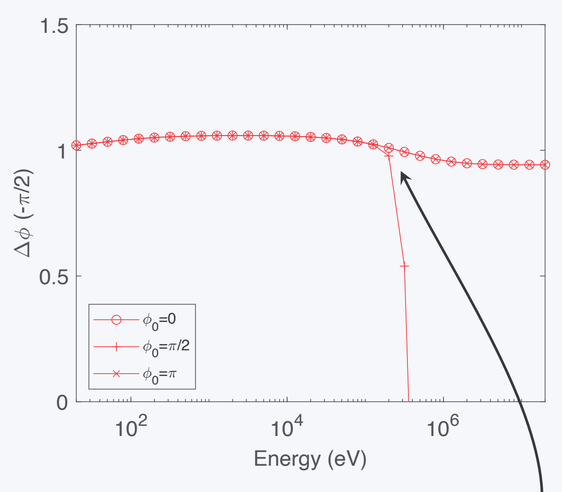


Laser waist	$w_0 = 2\lambda = 1.6\ \mu m$
Laser pulse duration	$\tau = 100$ fs

Realistic Field Model

$$\Delta\varphi = \frac{1}{\hbar}\int_P dt\; L(x,y,z,t) = \int_P dt\left(-\frac{mc^2}{\gamma} - e\frac{\boldsymbol{p}\cdot\boldsymbol{A}}{m\gamma} - \frac{e^2\boldsymbol{A}\cdot\boldsymbol{A}}{m\gamma} + eV\right)$$

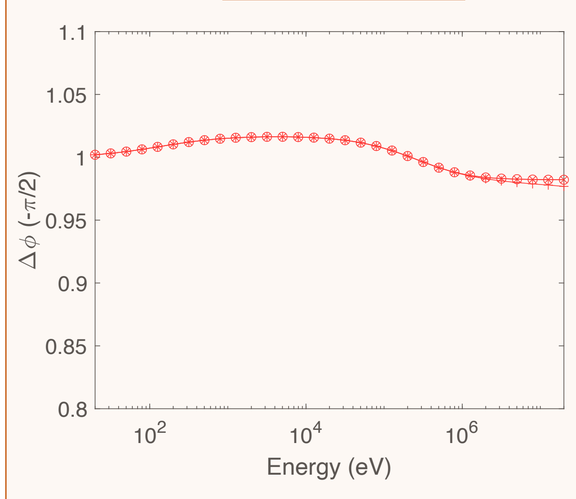
$w_0 = 0.75\,\lambda$



Phase shift at high electron energies depends on:

- field phase
- field polarization
- field model chosen

$w_0 = 1.25\,\lambda$



Agreement between ponderomotive approximation and real field model

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[1] S. Borrelli , S.T. Kempers, P.H.A. Mutsaers, O.J. Luiten. *RF-cavity-based Ultrafast Transmission Electron Microscopy.* In *Structural dynamics with X-ray and electron scattering.* (*Accepted for publication*)

[2] K.A.H. van Leeuwen, W.J. Schaap, B. Buijsse, S. Borrelli, S.T. Kempers, W. Verhoeven, O.J. Luiten. *Feasibility of a Pulsed Ponderomotive Phase Plate for Electron Beams*, arXiv, 2022.