Asymmetries in photoionization by ultrashort laser Pulses: importance of Coulomb potential correction to SFA models.

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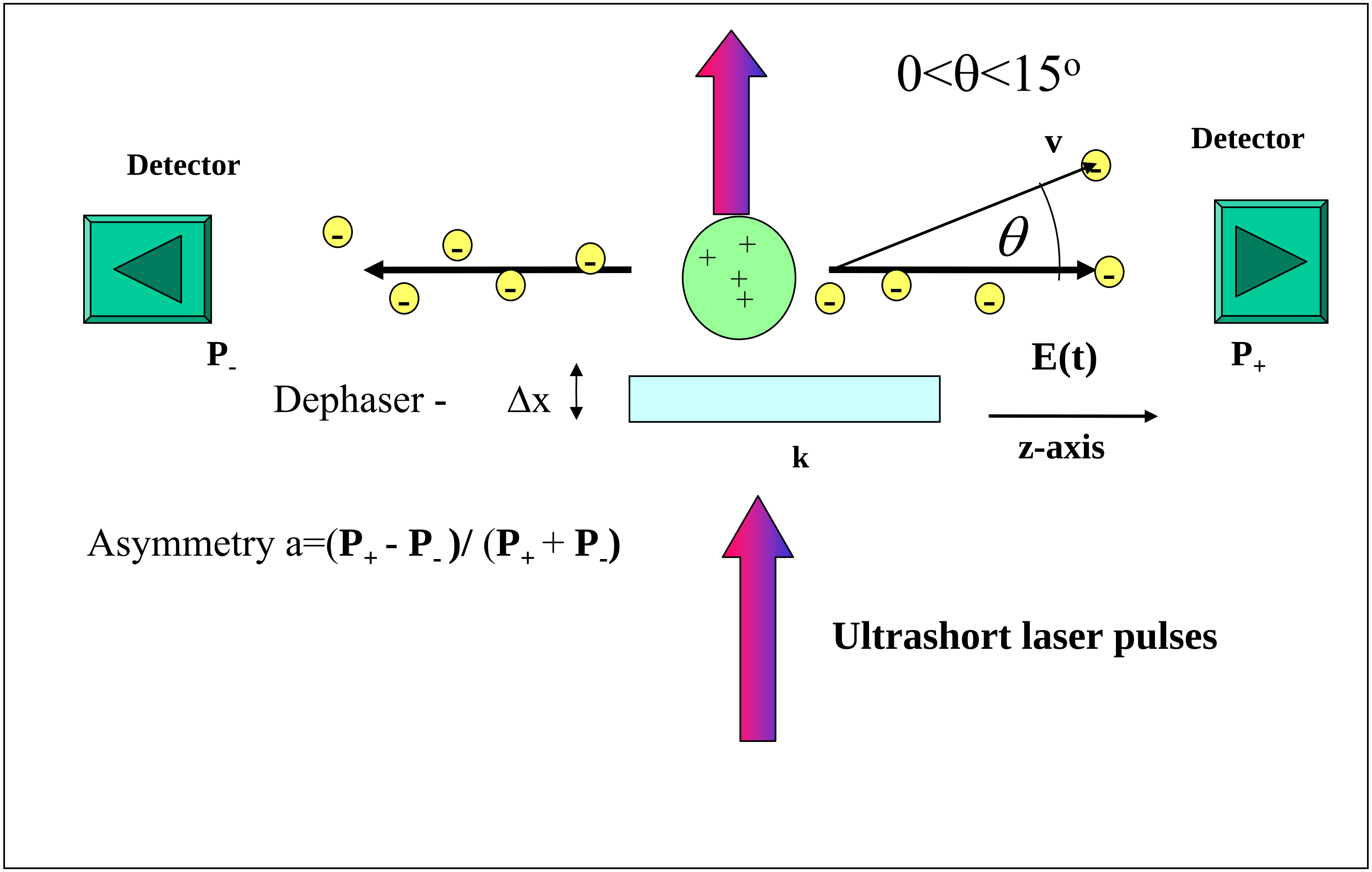
Measurement scheme of the asymmetry: two detectors along the electric field: $E(t)=\varepsilon(t)\cos(\omega t+\varphi)$ or two-color field

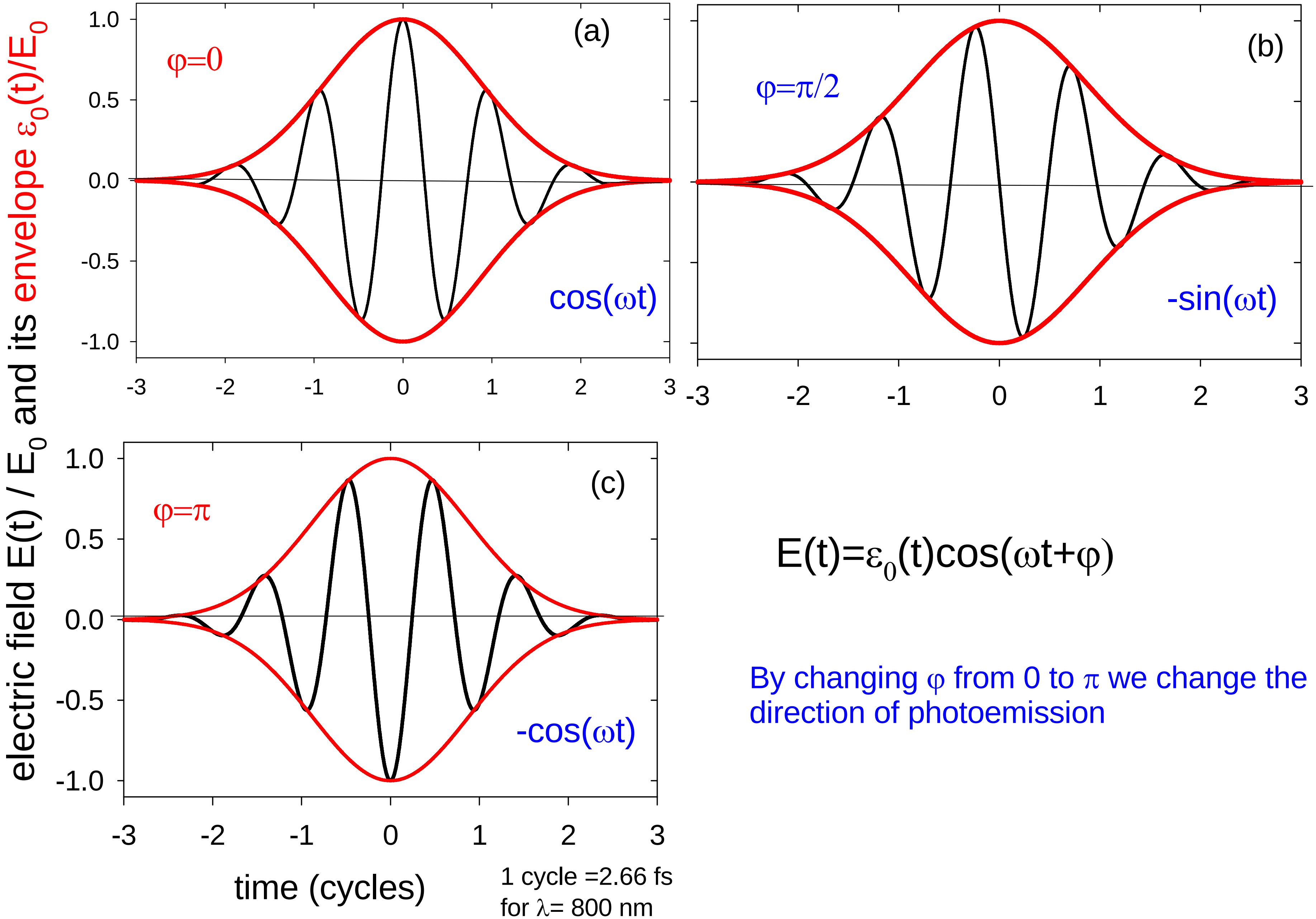
Linear polarization

1-color, long monochromatic pulses:

no asymmetry: $P_+ = P_-$



Asymmetry $a=(\mathbf{P}_+ - \mathbf{P}_-)/(\mathbf{P}_+ + \mathbf{P}_-)$



1 cycle =2.66 fs
for λ= 800 nm

$$E(t)=\varepsilon_0(t)\cos(\omega t+\varphi)$$

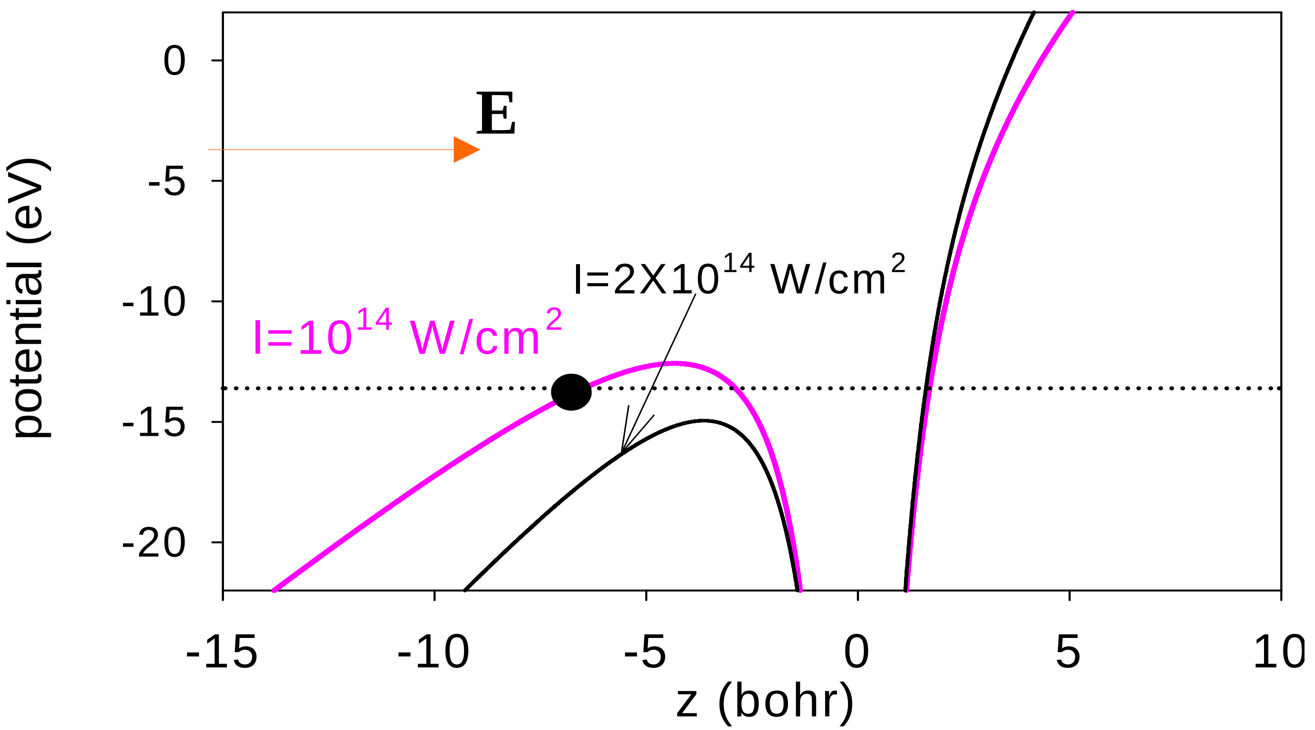
By changing φ from 0 to π we change the direction of photoemission

We show that Coulomb corrections to simple tunneling Keldysh models are very significant for angular distributions of photoelectrons in the case of few cycle pulse or in the case of two-color pulses.

It is convenient to analyze the effect via normalized forward-backward asymmetries: a=(**P+ - P-)/ (P+ + P-).**

For long (more than 10 cycles) pulse the asymmetry coefficient "a" is zero. The asymmetry appears when the pulse is very short or when two-colors are used.

Our earlier studies:
"ω+2 ω" case : PRA 63, 023409 (2001),
Carrier-Envelope effects: PRA 70, 013615 (2004),
PRA 71, 053815 (2005)

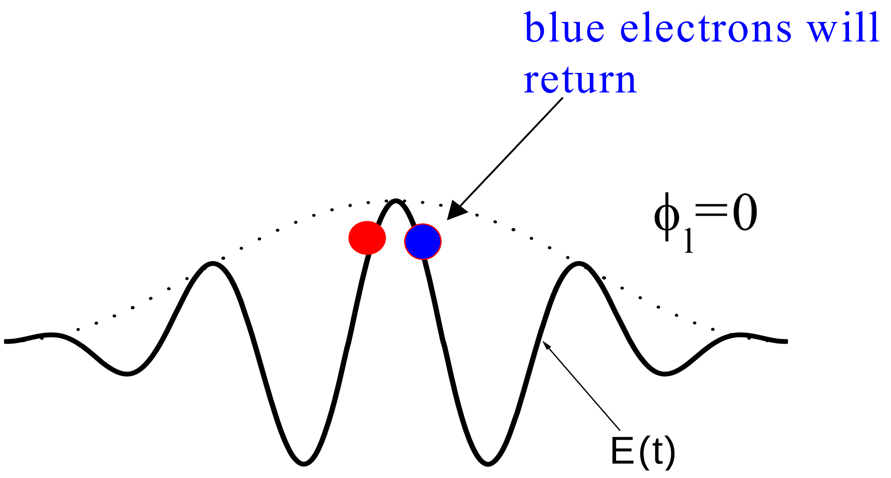


For $\Phi_1=0$

$E(-t)=E(t)$

$A_1(-t_0)=-A(t_0)$

Half electrons
go right,
Others go left
(prediction of SFA)



Newton equation describing the electron
Motion after tunneling (along z-axis, **A$_l$** || O-z)

$$\frac{d\,\mathrm{v}}{\mathrm{d}\,\mathrm{t}} = \frac{1}{c}\frac{\partial A_l}{\partial t} - \frac{\partial \mathrm{V}_\mathrm{C}}{\partial \mathrm{z}}$$

If we neglect the Coulomb potential:

$$\vec{\mathrm{v}}(\mathrm{t}_\mathrm{f}) = \vec{\mathrm{v}}_0 - \vec{\mathrm{A}}_\mathrm{l}(\mathrm{t}_0)/c$$

We solve numerically the time-dependent Schrödinger equation:

$$i\frac{\partial\psi(r,\theta,t)}{\partial t}=-\frac{1}{2}\left(\frac{\partial^2}{\partial r^2}+\frac{2}{r}\frac{\partial}{\partial r}-\frac{L^2}{r^2}\right)\psi+[V_C(r)+r\cos(\theta)E(t)]\psi$$

Where $V_C(r)=-\frac{1}{r}$ for a hydrogen atom.

The electric field E(t) is defined via the vector potential A(t)

$$E(t)=-\frac{1}{c}\frac{\partial}{\partial t}A(t)=\varepsilon(t)\cos(\omega(t-t_M)+\varphi)+E_{corr}$$

with $A(t)=-c\,\varepsilon(t)\sin(\omega(t-t_M)+\varphi)/\omega$,

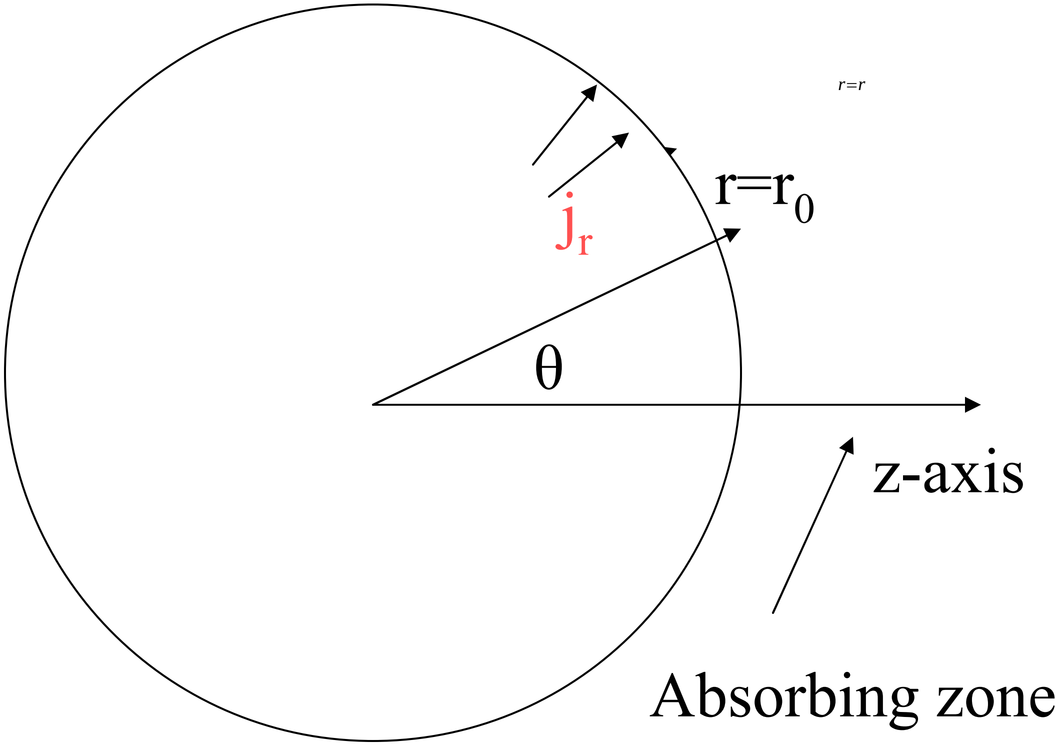
$$E_{corr}=\frac{1}{\omega}\sin(\omega(t-t_M)+\varphi)\frac{\partial\varepsilon(t)}{\partial t},\quad \varepsilon(t)=E_M\exp\left(-\frac{2\ln 2(t-t_M)^2}{\tau_p^2}\right)$$

Probabilties $\mathbf{P_+, P_-}$ in both detectors is obtained from the probability flux j_r calculated near the absorbing boundaries :

$$P_+ = 2\pi \int_0^{t_f} dt \int_0^{\theta_0} d\theta \, \sin(\theta) r^2 \, j_r(\theta, t), \quad P_- = 2\pi \int_0^{t_f} dt \int_{\pi-\theta_0}^{\pi} d\theta \, \sin(\theta) r^2 \, j_r(\theta, t),$$

where $j_r(\theta, t) = \mathrm{Re}[-i\psi^*(r, \theta, t) \dfrac{\partial}{\partial r} \psi(r, \theta, t)] \,|_{r=r_0}$ is the probability flux.

$$\theta < \theta_0 = 15^{\circ}$$



asymmetry coefficient:

$$a = \frac{P_+ - P_-}{P_+ + P_-}$$

Gaussian Pulses τ_p=3.9 fs (FWHM)

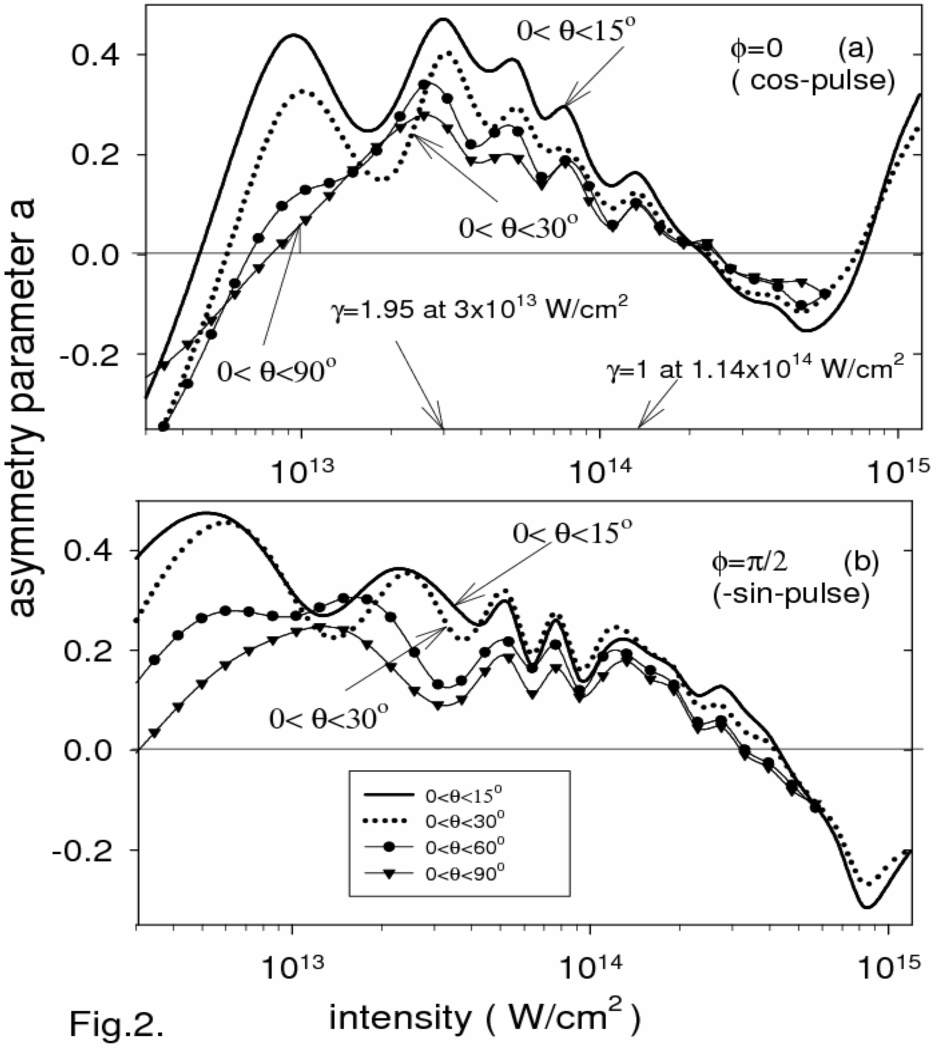
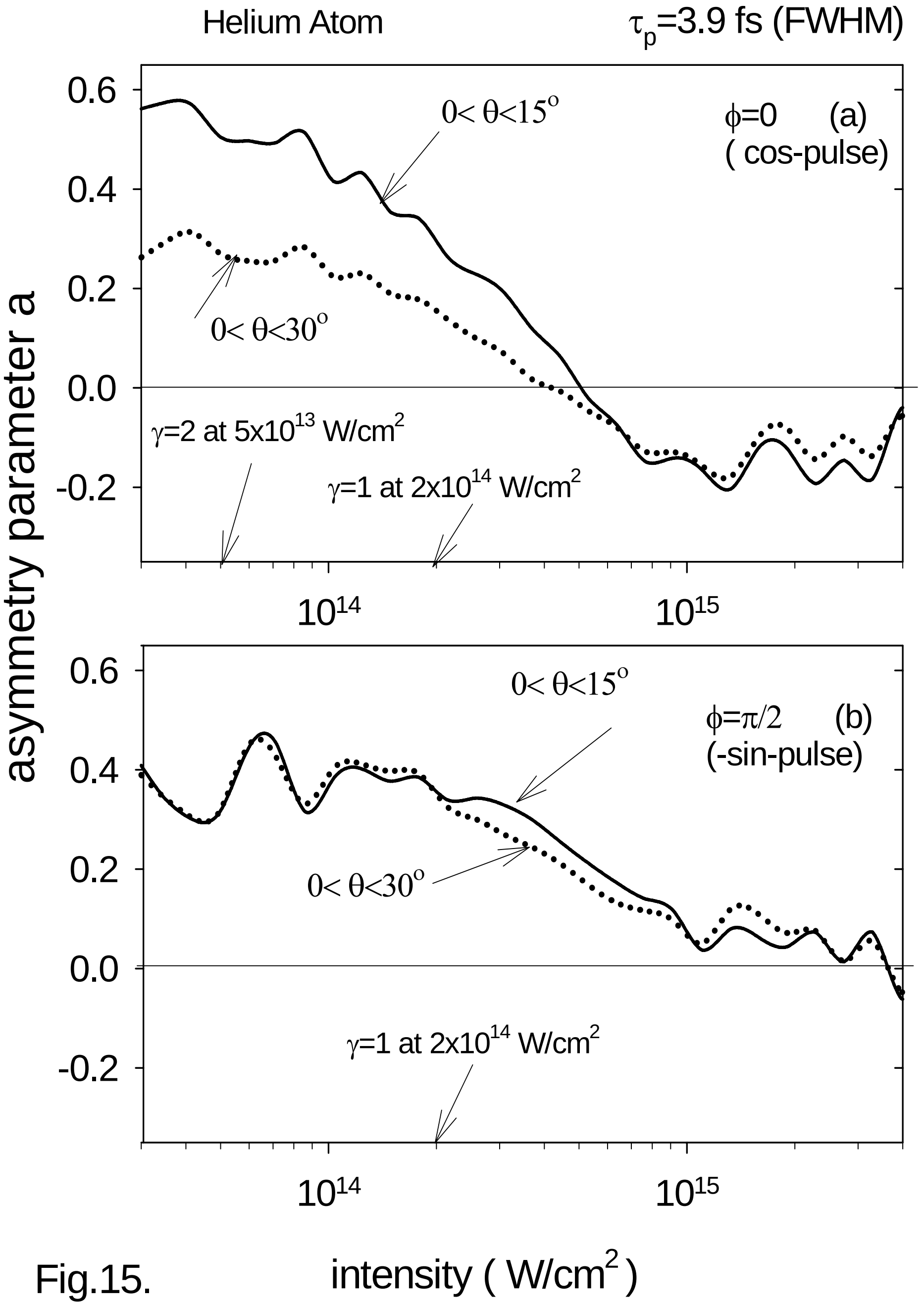


Fig.2.

$a=(P_+ - P_-) / (P_+ + P_-)$



Helium Atom
τp=3.9 fs (FWHM)
asymmetry parameter a
0.6
0.4
0.2
0.0
-0.2
0< θ<15°
0< θ<30°
φ=0 (a)
(cos-pulse)
γ=2 at 5x10^13 W/cm^2
γ=1 at 2x10^14 W/cm^2
10^14
10^15
0< θ<15°
0< θ<30°
φ=π/2 (b)
(-sin-pulse)
γ=1 at 2x10^14 W/cm^2
intensity (W/cm^2)

Fig.15.

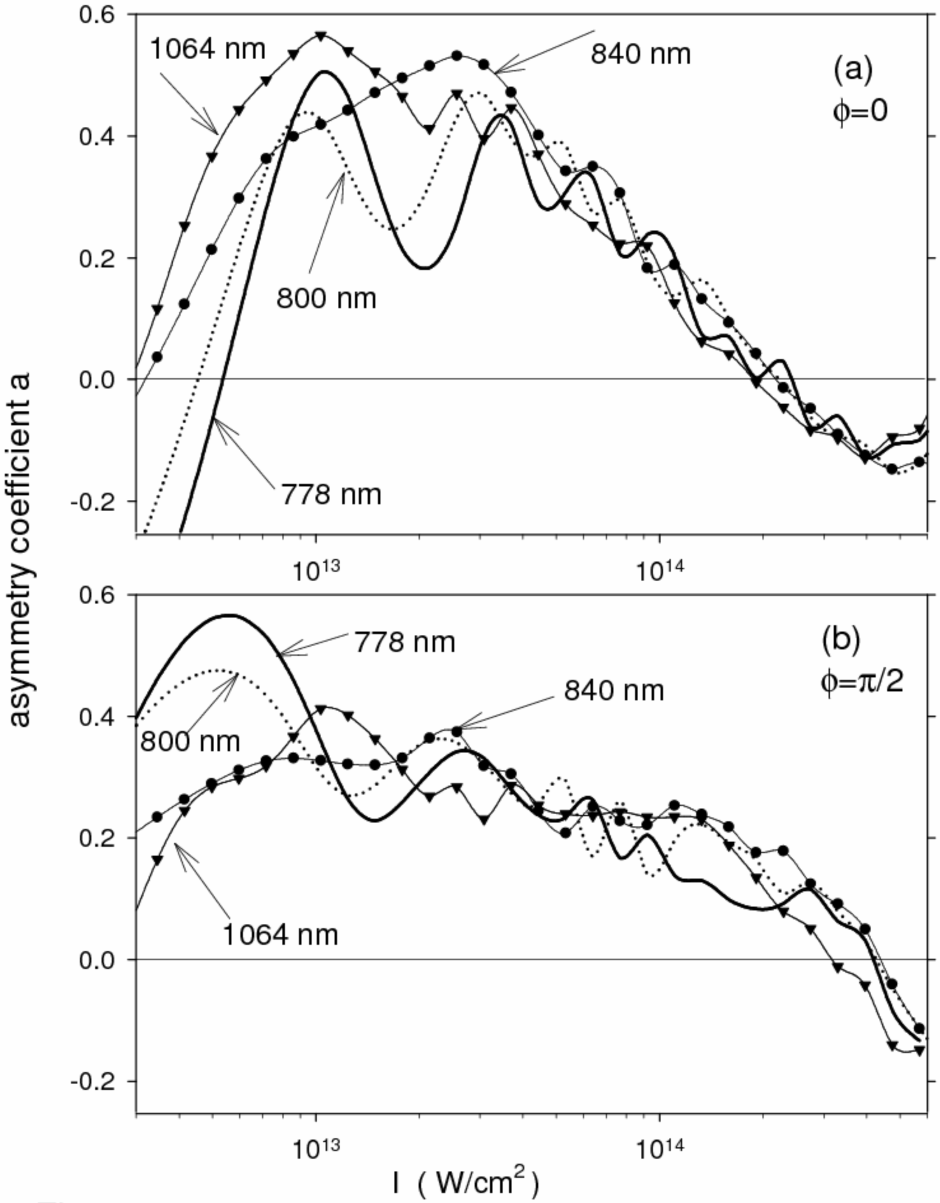

0.6
0.4
0.2
0.0
-0.2
1064 nm
840 nm
(a)
ϕ=0
800 nm
778 nm
10^{13}
10^{14}
asymmetry coefficient a
0.6
0.4
0.2
0.0
-0.2
778 nm
(b)
ϕ=π/2
840 nm
800 nm
1064 nm
10^{13}
10^{14}
I (W/cm^2)

Fig. 3.

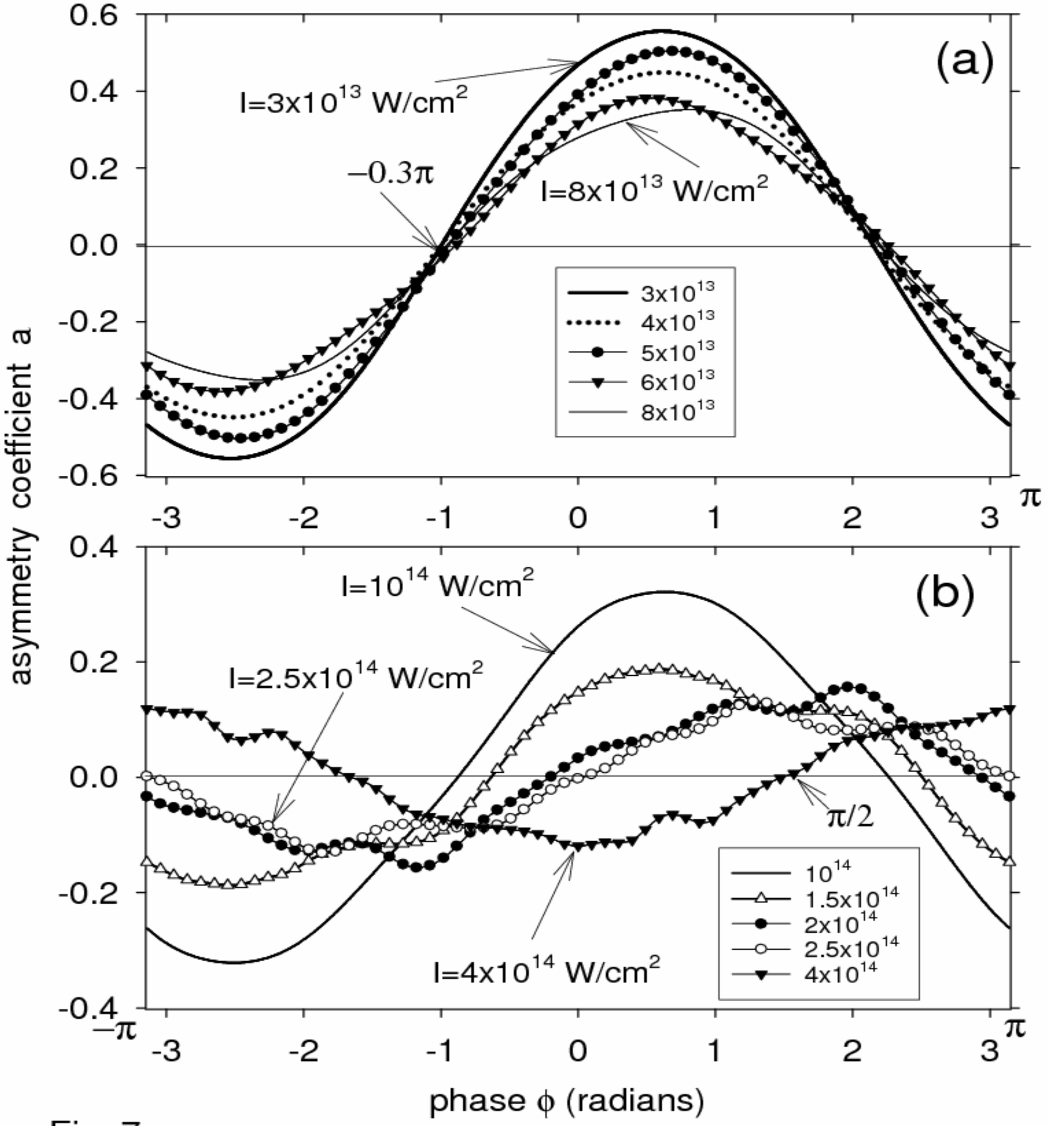
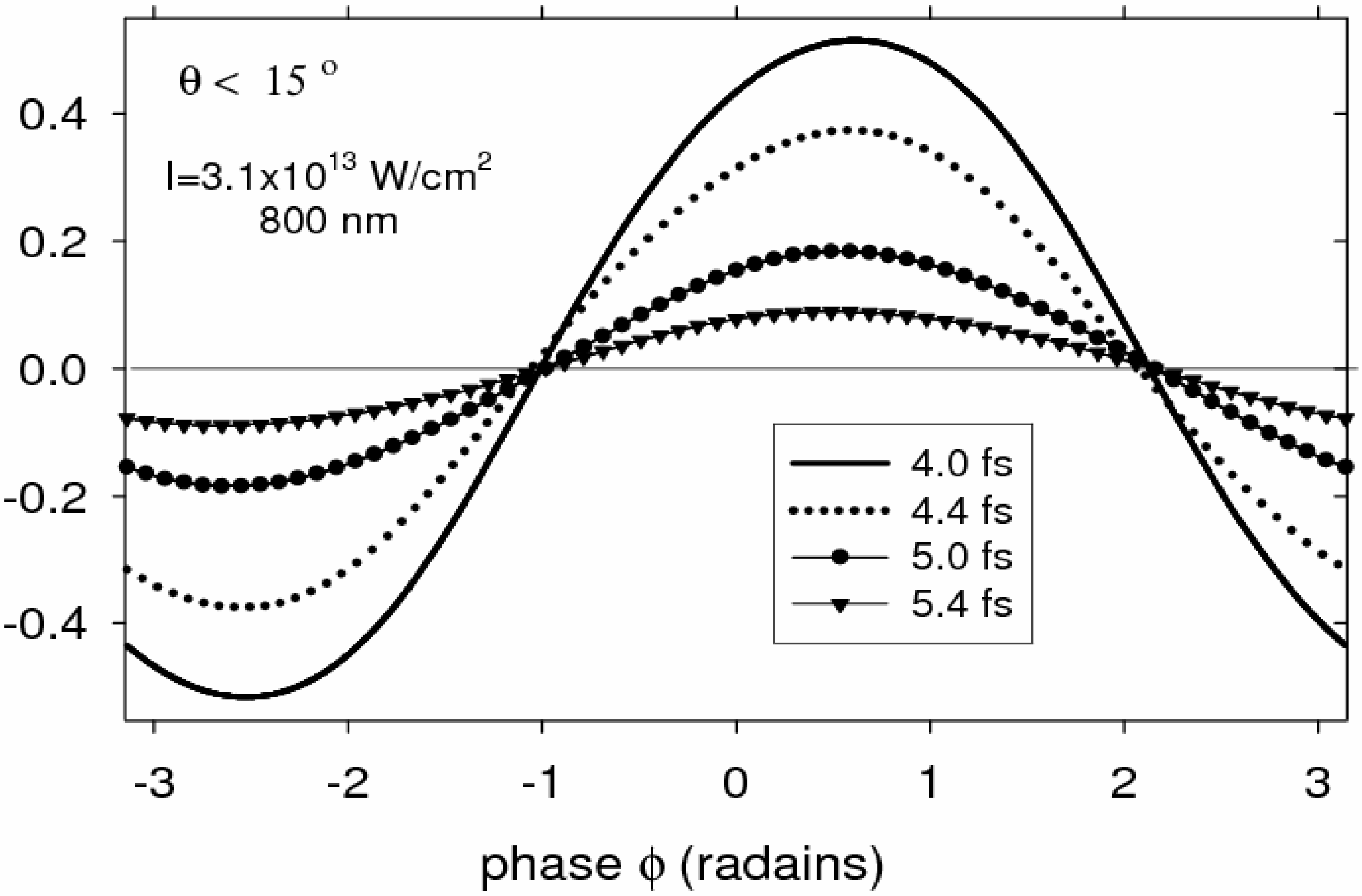

(a)
I=3x10^13 W/cm^2
−0.3π
I=8x10^13 W/cm^2
3x10^13
4x10^13
5x10^13
6x10^13
8x10^13
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-3
-2
-1
0
1
2
3
π
asymmetry coefficient a
(b)
I=10^14 W/cm^2
I=2.5x10^14 W/cm^2
π/2
I=4x10^14 W/cm^2
10^14
1.5x10^14
2x10^14
2.5x10^14
4x10^14
0.4
0.2
0.0
-0.2
-0.4
−π
π
phase ϕ (radians)

Fig. 7


θ < 15°
I=3.1x10^13 W/cm^2
800 nm
0.4
0.2
0.0
-0.2
-0.4
4.0 fs
4.4 fs
5.0 fs
5.4 fs
-3
-2
-1
0
1
2
3
phase ϕ (radains)

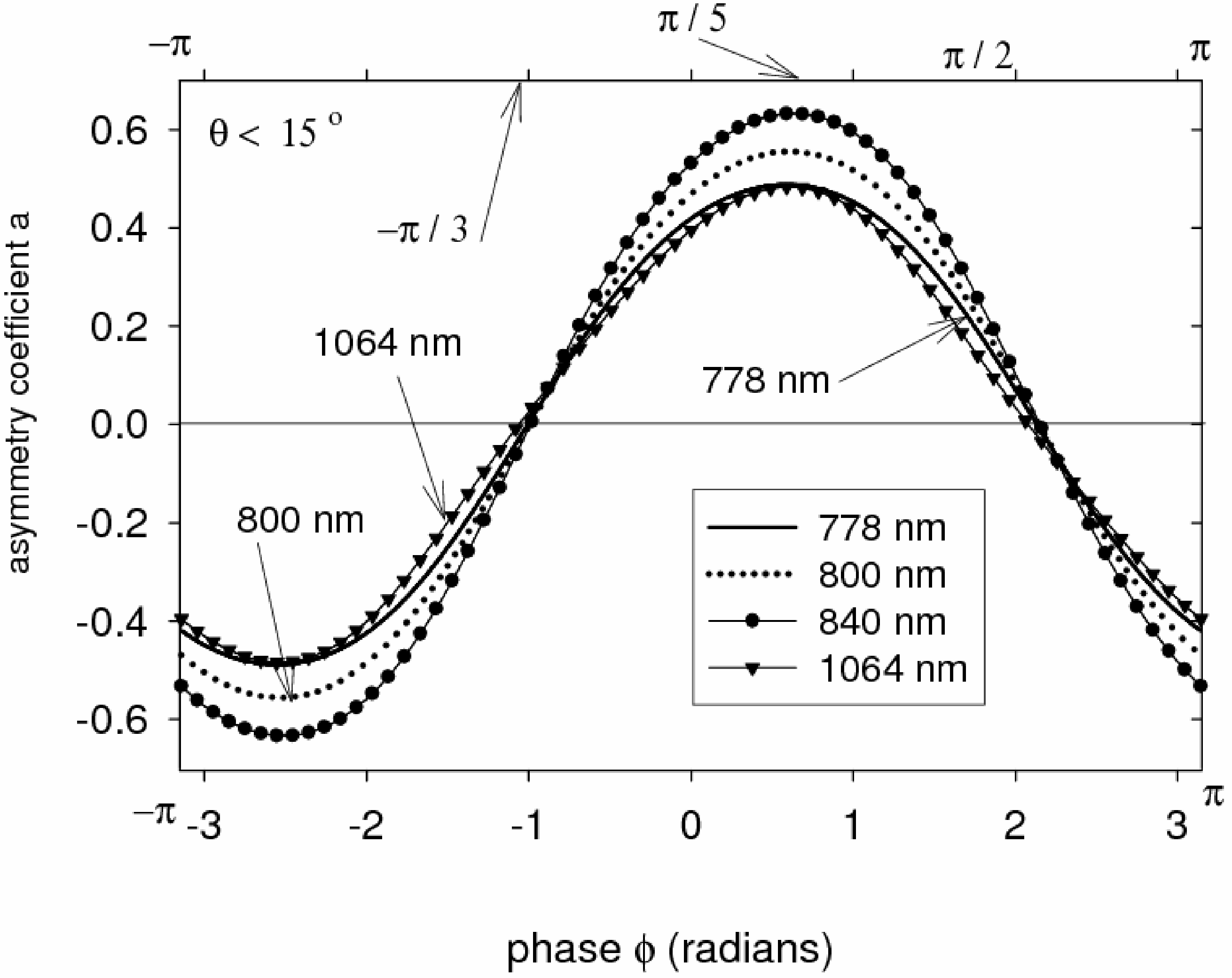
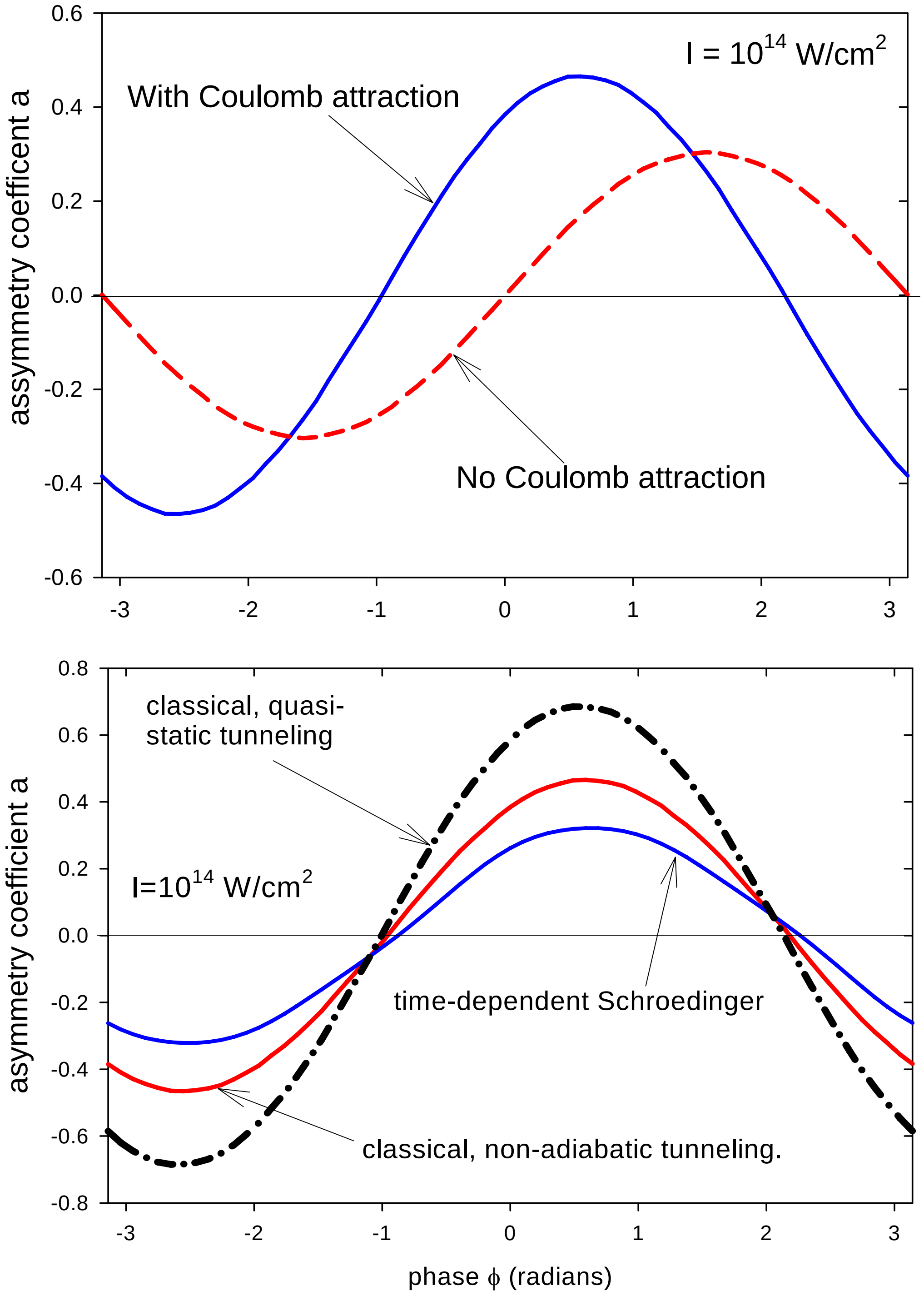

π / 5
−π
π / 2
π
θ < 15°
−π / 3
1064 nm
778 nm
800 nm
778 nm
800 nm
840 nm
1064 nm
asymmetry coefficient a
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
−π
-3
-2
-1
0
1
2
3
π
phase ϕ (radians)

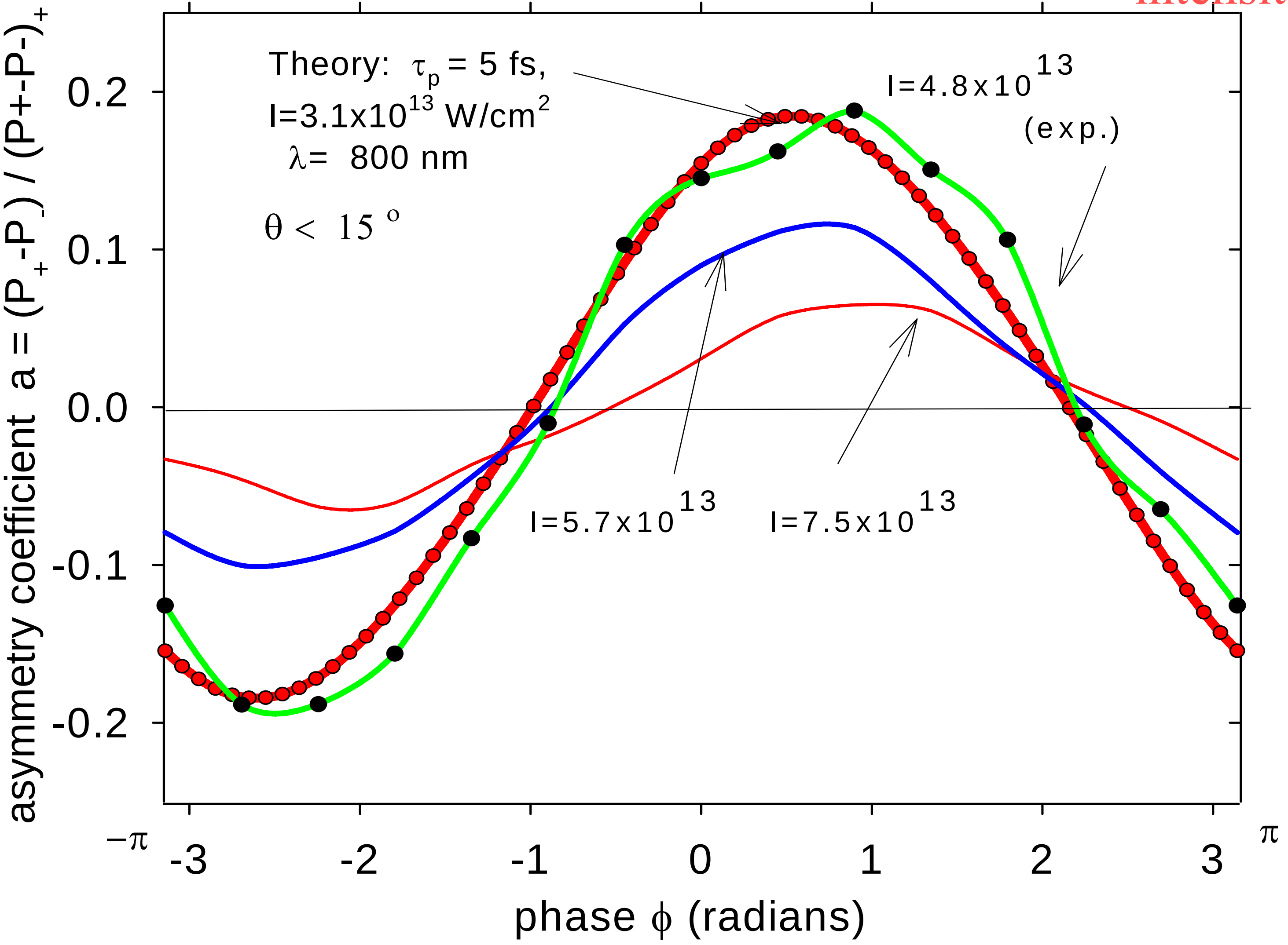
Fig. 6.



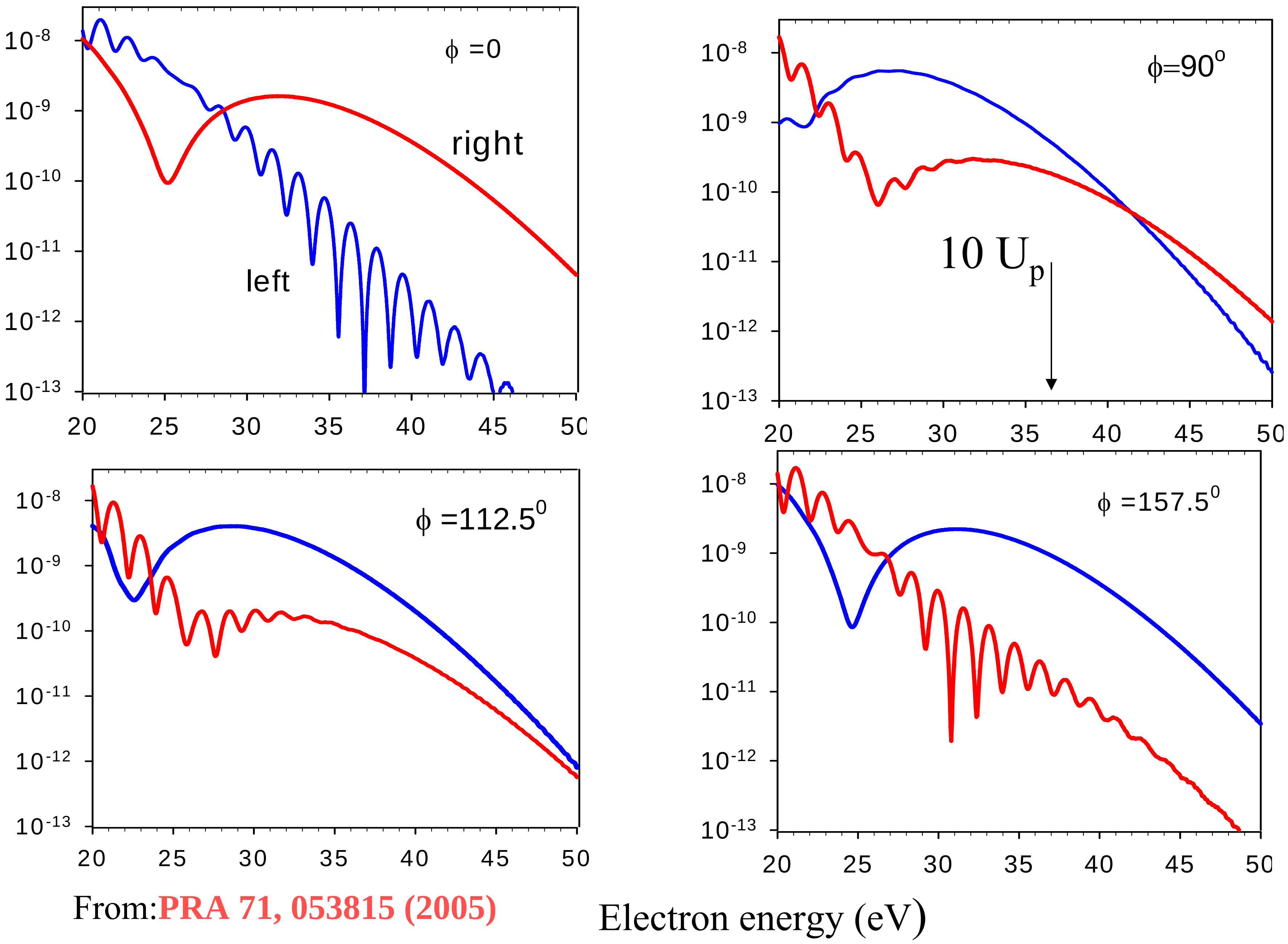
Classical calculation
of electron trajectories
initialized at tunneling
Time, close to the
maxima of |E(t)| .
Each trajectory was
Weighed by the tunneling
Probability.

Experimental asymmetries (Garching).
F. Lindner, Ph.D. Thesis.
λ=760 nm, τ_p=5 fs .

Less asymmetry for higher intensities



Phase dependence of fast electron ATI spectra, $I=6\mathrm{x}10^{13}$ W/cm^2, $t_p=3.9$ fs



From:**PRA 71, 053815 (2005)**

1. Few cycle pulses ($\tau_p < 2$cycles) lead to considerable forward /backward asymmetries along the laser polarization vector very sensitive to the carrier-envelope phase. Several regimes of intensites and ranges of electron energy were identified.

2. Asymmetry exhibits simple patterns in the intermediate intensity
regime, between tunneling and multiphoton regime, $\gamma \cong 1$.

3. The asymmetry of slow electrons originates from the Coulomb attraction on the returning electron from the core.