Atomic physics in Intense Laser Field

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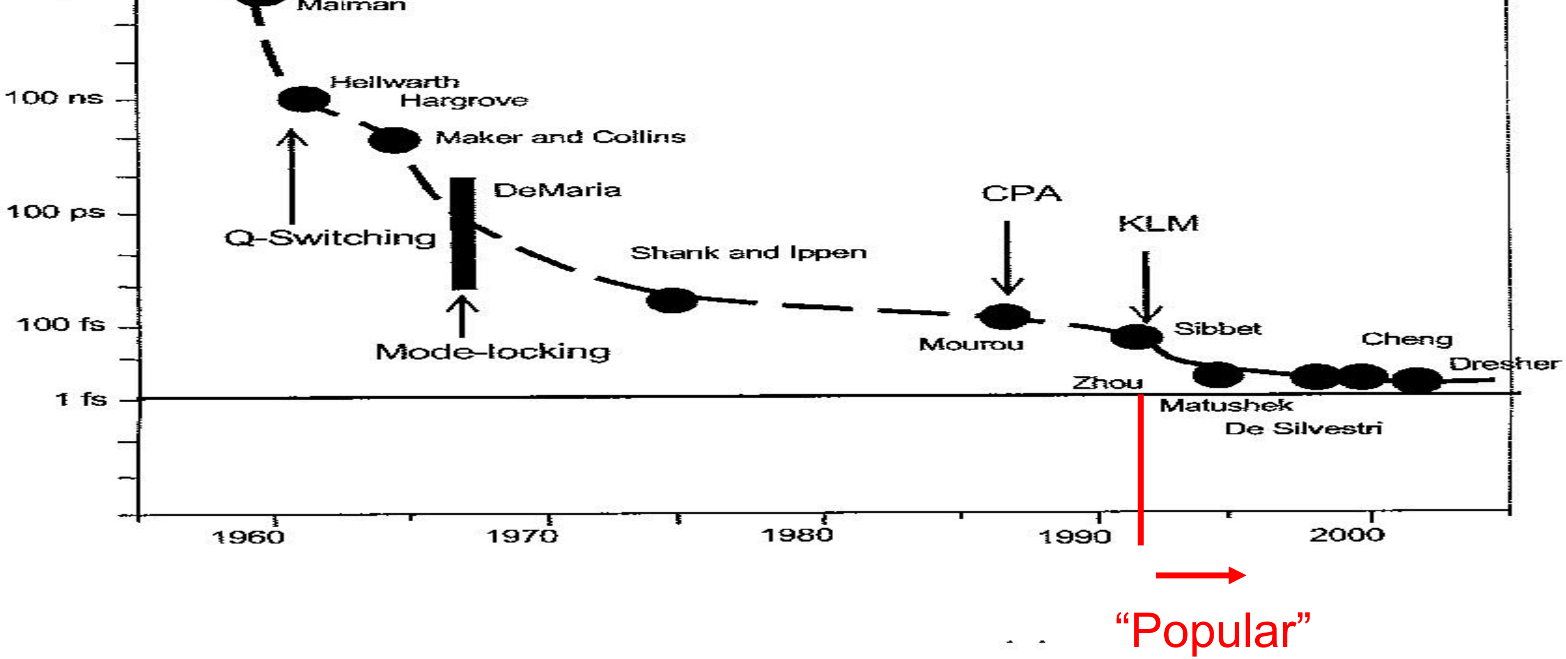
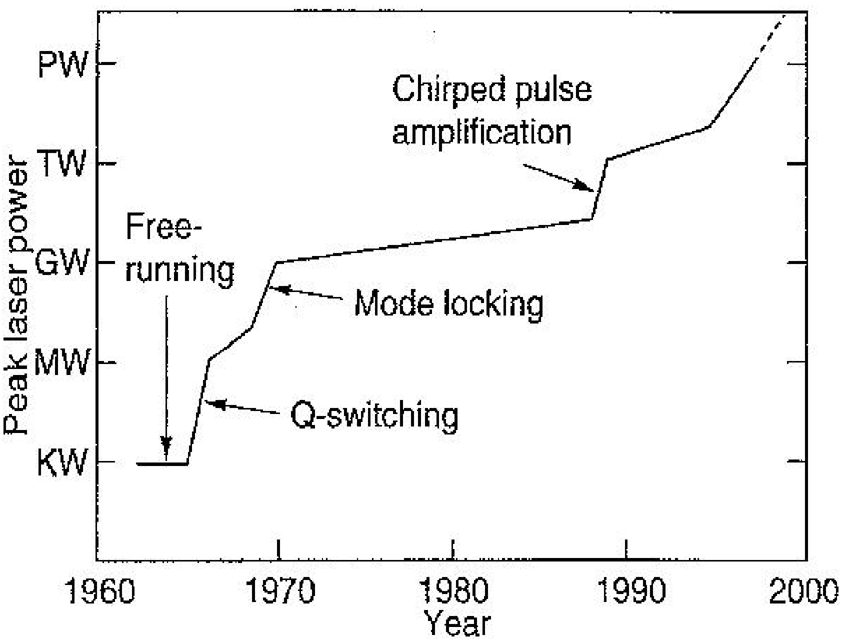

Maiman
100 ns
Hellwarth
Hargrove
Maker and Collins
DeMaria
100 ps
Q-Switching
Shank and Ippen
CPA
KLM
100 fs
Mode-locking
Mourou
Sibbet
Cheng
Dresher
Zhou
1 fs
Matushek
De Silvestri
1960
1970
1980
1990
2000
“Popular”


Peak laser power
PW
TW
GW
MW
KW
Chirped pulse
amplification
Free-
running
Mode locking
Q-switching
1960
1970
1980
1990
2000
Year

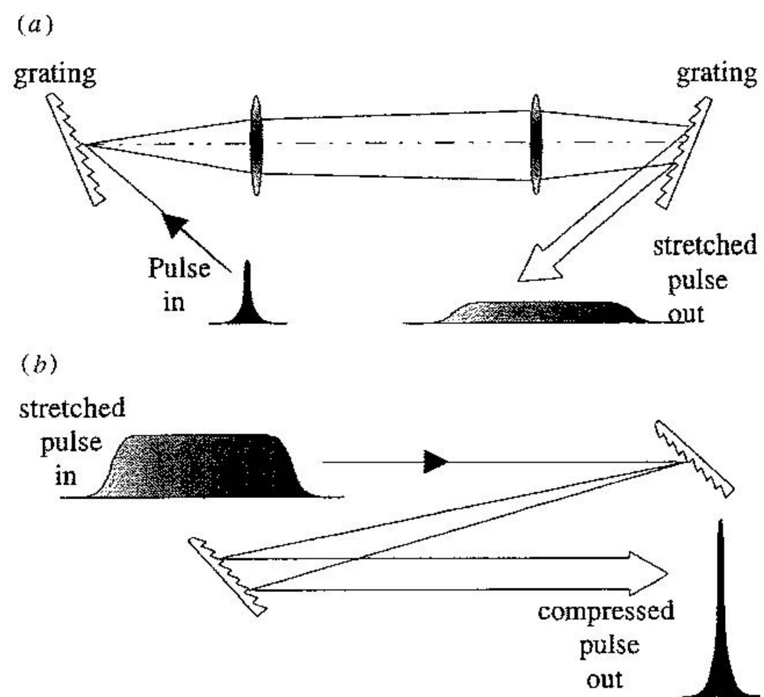

(a)
grating
grating
Pulse
in
stretched
pulse
out
(b)
stretched
pulse
in
compressed
pulse
out

Table 1.1 Multi-Terawatt laser systems and laboratories worldwide.

Name	Laboratory	Country	Type	λ (nm)	Energy (J)	Pulse length (fs)	Power (TW)	Focal spot (μm)	Intensity (Wcm^{-2})
Petawatt[a]	LLNL	USA	Nd:glass	1053	700	500	1300	-	$> 10^{20}$
VULCAN[b]	RAL	UK	Nd:glass	1053	423	410	1030	10	1.06×10^{21}
PW laser[c]	ILE	Japan	Nd:glass	1054	420	470	1000	30	10^{20}
PHELIX[d]	GSI	Germany	Nd:glass	1064	500	500	1000	-	-
LULI 100TW	LULI	France	Ti:Sa	800	30	300	100		-
APR 100 TW	APR	Japan	Ti:Sa	800	2	20	100	11	2×10^{19}
HERCULES	FOCUS	USA	Ti:Sa	800	1.2	27	45	(1)	(8×10^{21})
ALFA 2	FOCUS	USA	Ti:Sa	800	4.5	30	150	(1)	(10^{22})
Salle Jaune	LOA	France	Ti:Sa	800	0.8	25	35		10^{19}
Lund TW	LLC	Sweden	Ti:Sa	800	1.0	30	30	10	$> 10^{19}$
MBI Ti:Sa	MBI	Germany	Ti:Sa	800	0.7	35	20		$> 10^{19}$
Jena TW	IOQ	Germany	Ti:Sa	800	1.0	80	12	3	5×10^{19}
ASTRA	RAL	UK	Ti:Sa	800	0.5	40	12		10^{19}
USP	LLNL	USA	Ti:Sa	800	1 (10)	100 (30)	10 (100)		5×10^{19}
UHI 10	CEA	France	Ti:Sa	800	0.7	65	10		5×10^{19}

[a] 1996–1999

[b] Petawatt performance achieved on October 5, 2004.

[c] Projected upgrade of PWM — PetaWatt Module.

[d] Commissioned for end 2005.

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xtr.
LO:
eality

adit.
LO

Table 1.1. Light intensities I (in units of W/cm^2) from the very dim to the extremely bright.

10^{+30}	→ generation of real electron–positron pairs from vacuum
10^{+28}	→ electron acceleration by light comparable to edge of black hole
10^{+26}	
10^{+24}	→ nonlinear optics of the vacuum ?
10^{+22}	
10^{+20}	→ photonuclear fission – light splits nuclei
10^{+18}	→ relativistic nonlinear optics of vacuum electrons
10^{+16}	
10^{+14}	→ electrostatic tunneling of electrons from atoms
10^{+12}	→ Rabi flopping in semiconductors becomes optical
10^{+10}	
10^{+8}	
10^{+6}	→ laser intensity in the first experiment on nonlinear optics in 1961
10^{+4}	
10^{+2}	→ a continuous-wave laser of that intensity hurts
1	→ total intensity of the sun on the earth's surface (10^{-1} W/cm^2)
10^{-2}	→ thermal radiation from a human
10^{-4}	
10^{-6}	
10^{-8}	
10^{-10}	→ total intensity of the cosmic 2.8 K background radiation
10^{-12}	
10^{-14}	
10^{-16}	
10^{-18}	
10^{-20}	
10^{-22}	→ visible intensity in a "dark" room at 300 K (10^{-23} W/cm^2)

OUTLOOK

I- Free electron in an EM field:
- Classical treatment
- Relativistic treatment
- Quantum treatment

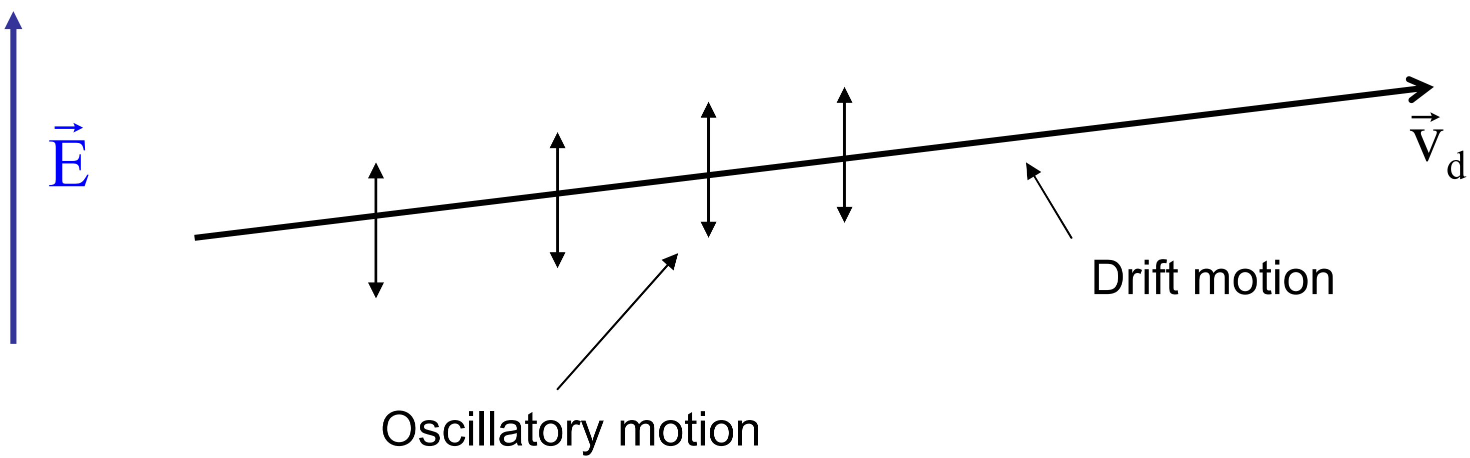
II- Atom is a strong Laser field:
- Scenario with I
- Experimental results

III- Above Threshold Ionisation

IV- Tunnel ionisation

I-Free electron in an EM field: Classical treatment

$$\vec{F} \simeq q\vec{E} \qquad \left(\frac{F_{magn}}{F_{elec}} = \frac{\left|\vec{v}\times\vec{B}\right|}{E} = \frac{v}{c} << 1\right); \qquad E = E_0 \cos\omega t$$



$$= m\frac{d\vec{v}}{dt} \quad \rightarrow \quad \left\langle E_k \right\rangle_{T=\frac{2\pi}{\omega}} = m\frac{v_d^2}{2} + \frac{q^2E_0^2}{4m\omega^2}$$

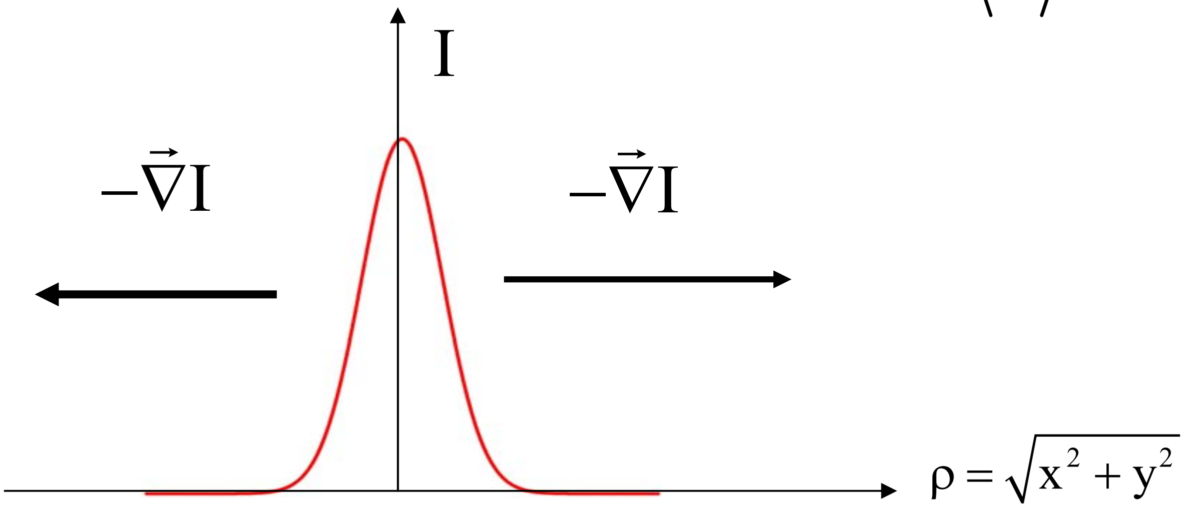
PONDEROMOTIVE ENERG

U_P

$$U_P(eV) = 9.34\,10^{-14}\,\lambda^2_{\mu m}\,I_{W/cm^2}$$

$$U_P = \begin{cases} 1eV \text{ for } I \simeq 10^{13}\,W/cm^2 \\ 100keV \text{ for } I \simeq 10^{18}\,W/cm^2 \quad (U_P \simeq 0.2mc^2) \end{cases}$$

Force on the electron in a laser spot: $I = I(\vec{r}) \rightarrow \langle \vec{F} \rangle = -\vec{\nabla} U_P$

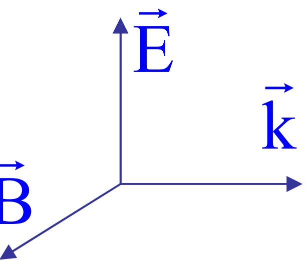


The electron is ejected

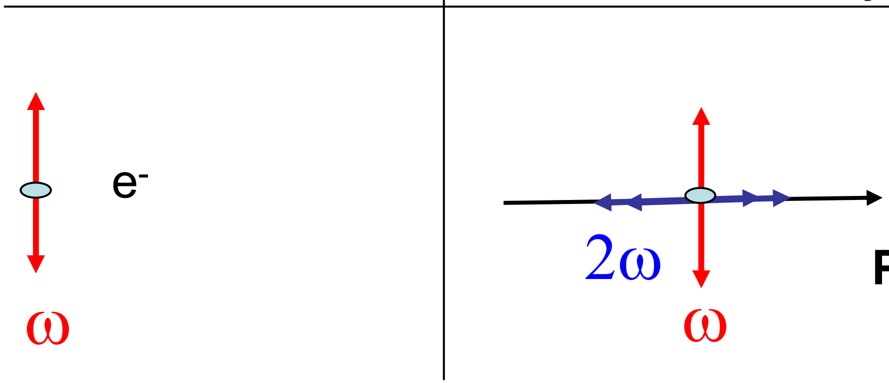
I-Free electron in an EM field: Relativistic treatment

$$\vec{F} = q\left(\vec{E} + \vec{v} \times \vec{B}\right); \quad E_x = E_0 \cos\omega t; \quad B_y = B_0 \cos\omega t$$

electron at rest

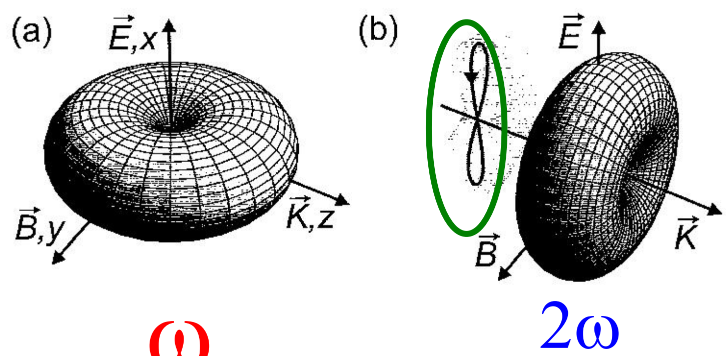


Newton | Relat. (pert reg. $U_p / mc^2 \leq 1$)



Photon draggin

Radiation pattern



General case: analytical solution

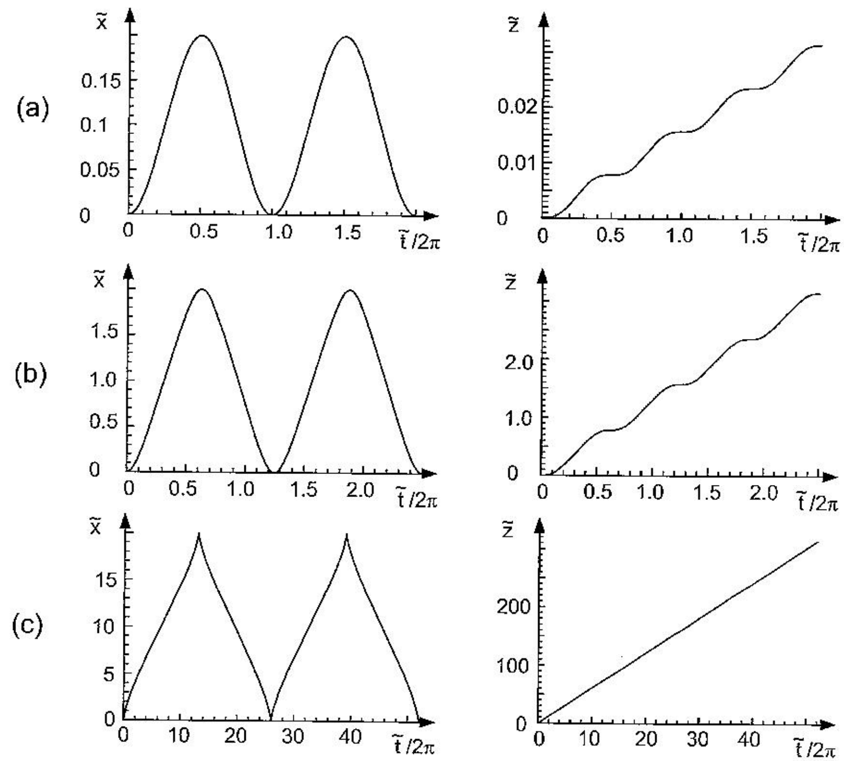
$$\varepsilon = \frac{4U_P}{m_e c^2} \qquad \tilde{t} = \omega t; \tilde{x} = kx; \tilde{z} = kz$$

$$\tilde{z}(0) = -\xi_0$$

$$) = (\zeta - \zeta_0)\left[1 + \frac{\mathcal{E}^2}{2}\left(\frac{1}{2} + \sin^2\zeta_0\right)\right] + \frac{\mathcal{E}^2}{2}\left[-\frac{\sin(2\zeta)}{4} + 2\cos\zeta\,\sin\zeta_0 - \frac{3\sin(2\zeta_0)}{4}\right]$$

$$(\zeta) = \mathcal{E}\left((\cos\zeta_0 - \cos\zeta) - (\zeta - \zeta_0)\sin\zeta_0\right),$$

$$(\zeta) = \tilde{t} - \zeta,$$



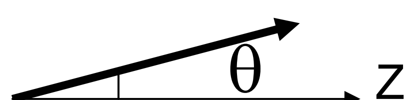
Periodic motion

ARMONIC DECOMPOSITION

undamental oscillation frequency: $$\frac{\omega_{osc}}{\omega} = \frac{1}{1 + \frac{\varepsilon^2}{2}\left(\frac{1}{2} + \sin^2\xi_0\right)}$$

$$\frac{\omega_{em}}{\omega} \overset{\xi_0 = 0}{=} \frac{1}{1 + \frac{\varepsilon^2}{\cdot}(1 - \cos\theta)}$$

undamental emission frequency :



I-Free electron in an EM field: Quantum treatment

amiltonian:

$$H = \frac{\left(\vec{P} - q\vec{A}\right)^2}{2m}; \quad \vec{E} = -\frac{\partial \vec{A}}{\partial t} = \vec{E}_0 \cos \omega t$$

chrödinger equation:

$$i\hbar \frac{\partial \Psi(\vec{r},t)}{\partial t} = H\Psi(\vec{r},t)$$

nalytical solution!

$$\Psi(\vec{r},t) = \Psi_0\, e^{i\left(\vec{k}\,\vec{r} - \left(\frac{E_d + U_p}{\hbar}\right)t\right)}\, e^{i\frac{U_p}{\hbar}\left(\frac{\sin 2\omega t}{2\omega}\right)}\, e^{-i\frac{q\vec{k}\vec{E}_0}{m\omega}(\cos \omega t - 1)} \qquad E_{drift} = \frac{\hbar^2 k^2}{2m}$$

VOLKOV STATE

- STATIONNARY STATE BUT TIME DEPENDENT ENERGY

VOLKOV STATE

$$\Psi(\vec{r},t) = \Psi_0\, e^{i\left(\vec{k}\vec{r} - \left(\frac{E_d + U_p}{\hbar}\right)t\right)} e^{i\frac{U_p}{\hbar}\left(\frac{\sin 2\omega t}{2\omega}\right)} e^{-i\frac{q\vec{k}\vec{E}_0}{m\omega}(\cos\omega t - 1)}$$

Classical part

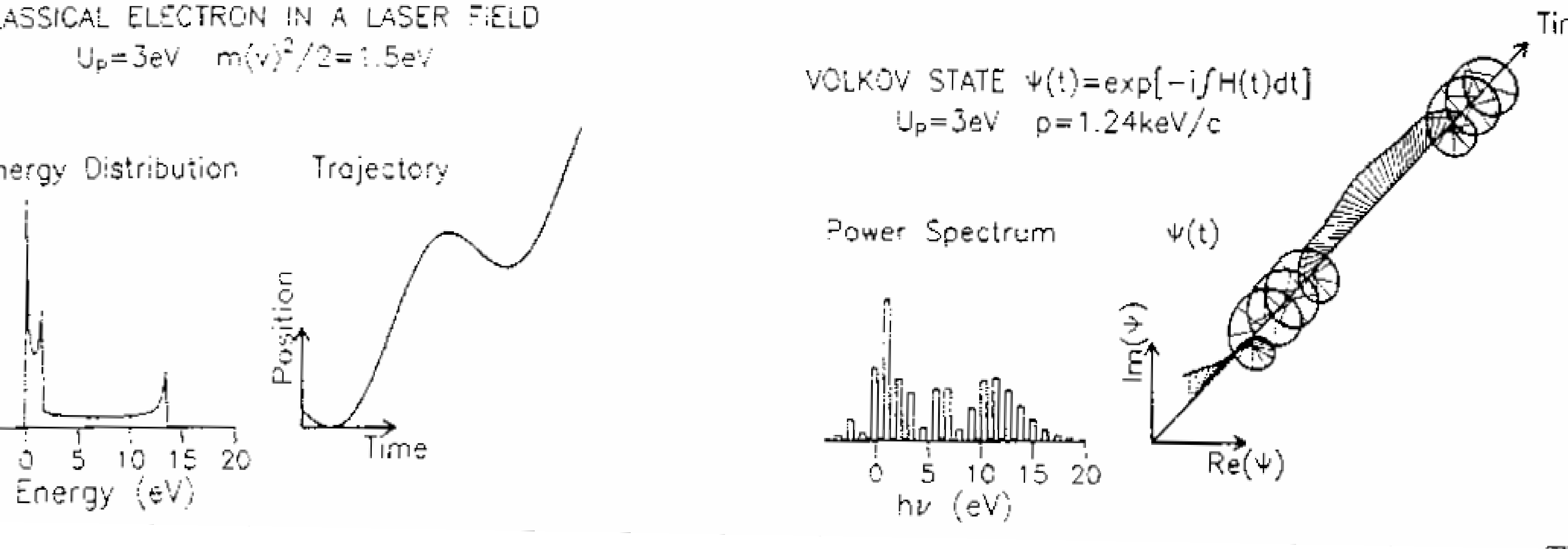
$$e^{i\alpha\cos\theta} = \sum_{m=-\infty}^{m=\infty} i^m J_m(\alpha) e^{im\theta} \longrightarrow$$

$$(\vec{r},t) = \Psi_0\, e^{i\left(\vec{k}\vec{r} - \left(\frac{E_d + U_p}{\hbar}\right)t\right)} \sum_n J_n\left(\frac{U_P}{2\hbar\omega}\right) e^{i2n\omega t} \sum_m i^m J_m\left(-2\sqrt{2}\,\frac{\sqrt{U_P E_d}}{\hbar\omega}\right) e^{im\omega}$$

Even harmonics

Odd + Even harmonics:
Needs $E_d \neq 0$

New effects : $U_p, E_d \geq \hbar\omega$

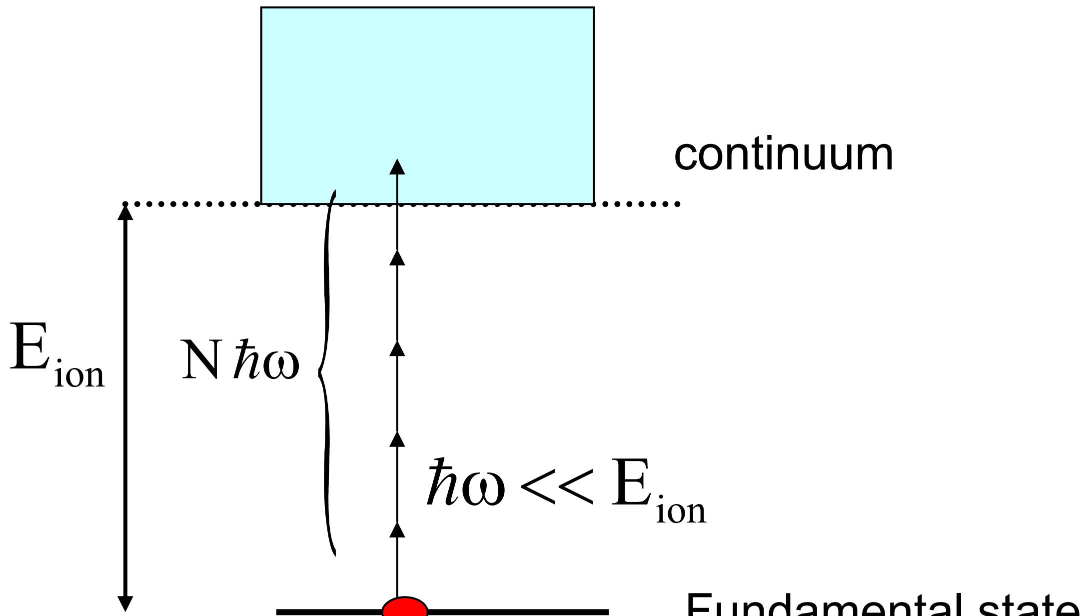


$$\vec{V} = \vec{V}_0 - \frac{q\vec{E}_0}{m\omega}\sin\omega t;$$

$$E_k = \left(\sqrt{E_d} - \sqrt{2U_p}\sin\omega t\right)^2 \qquad E = E_d + U_p + n\hbar\omega$$

II- Atom in a strong laser field

Model: Bound - Unbound transition for a single electron

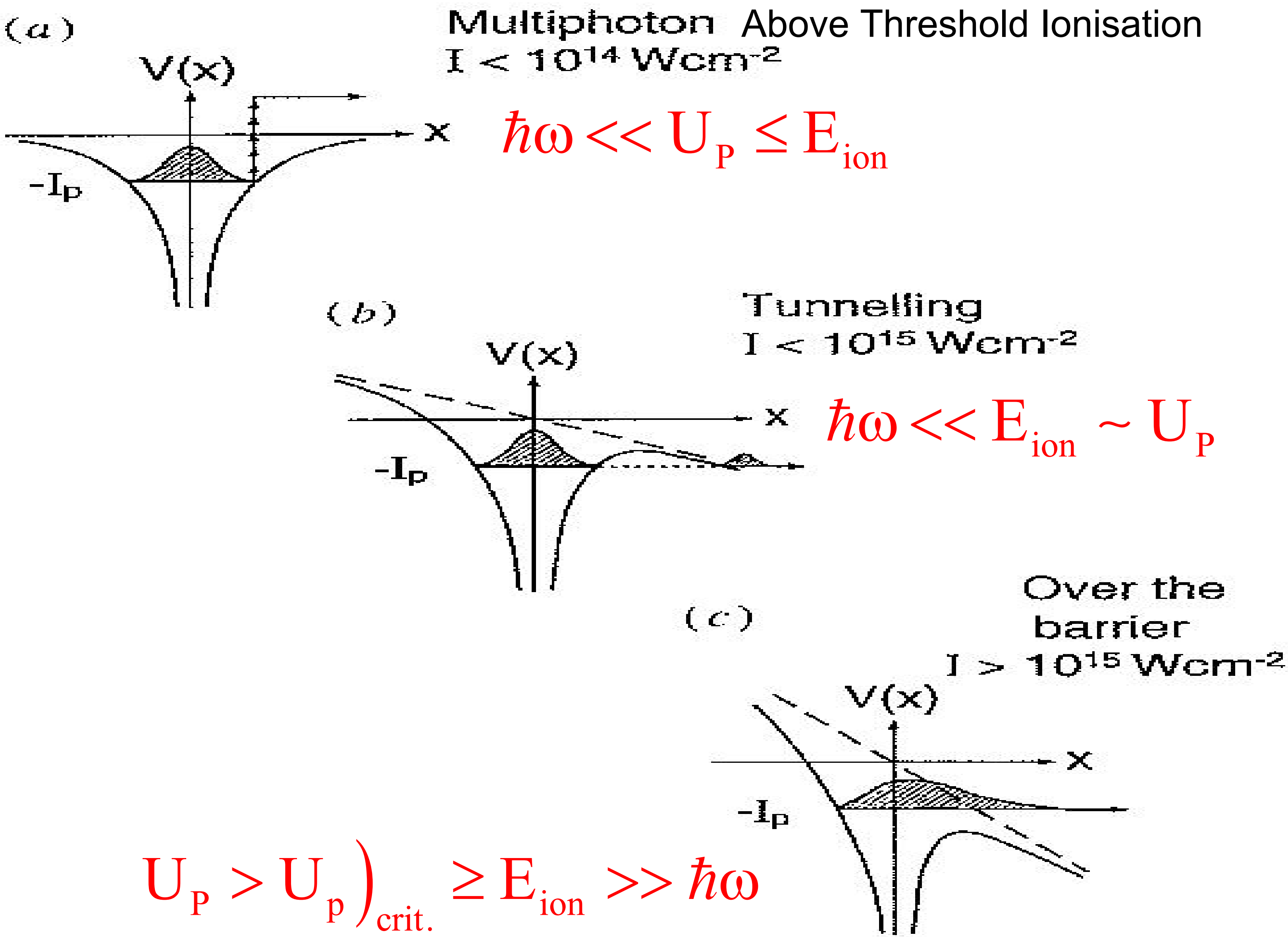


erturbative multiphoton ionisation :

$$U_P << \hbar\omega << E_{ion};\ I \leq 10^{12}\ W/cm^2; \quad P_{ion} \propto I^N$$

$I \nearrow$ Dynamics depends strongly on the laser intensity

Scenario with I



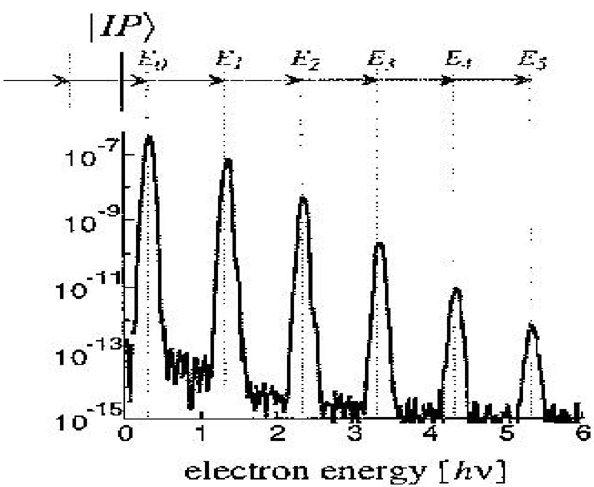
$\hbar\omega << U_P \leq E_{ion}$

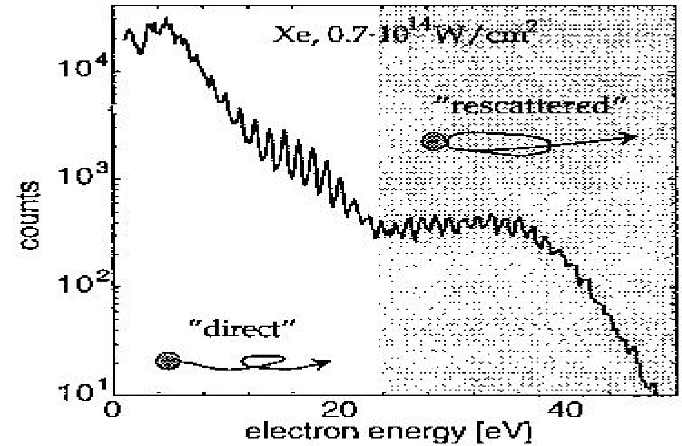
$\hbar\omega << E_{ion} \sim U_P$

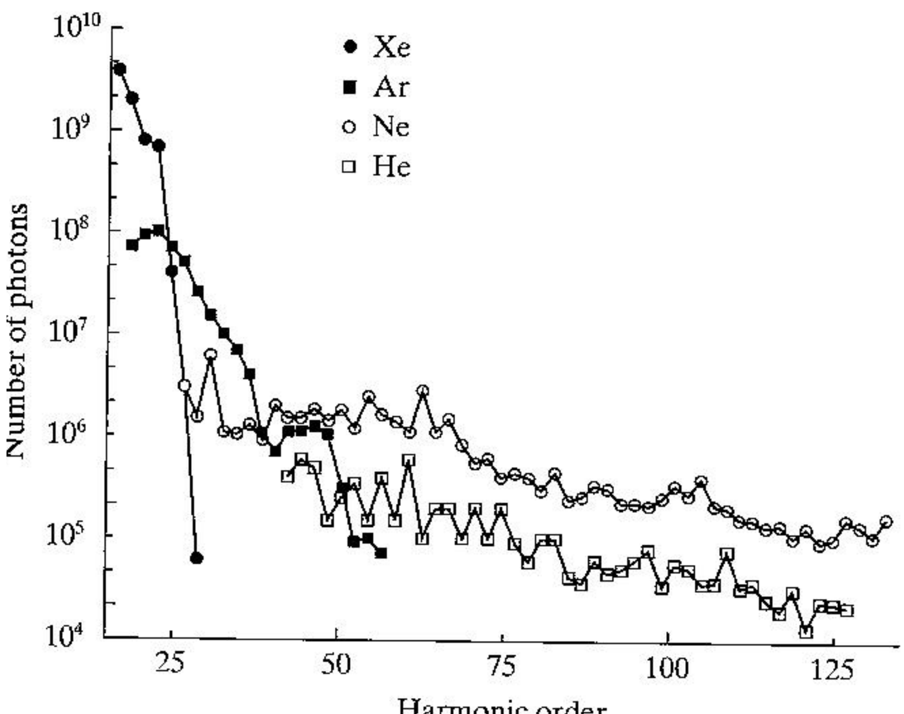
$U_P > U_p\big)_{crit.} \geq E_{ion} >> \hbar\omega$

VALID IF I < I (depletion of the ground state)

Experimental manifestation







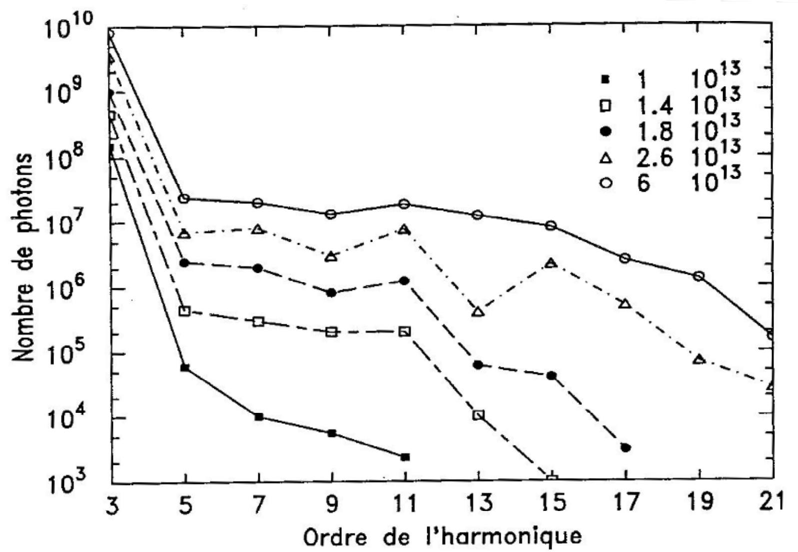
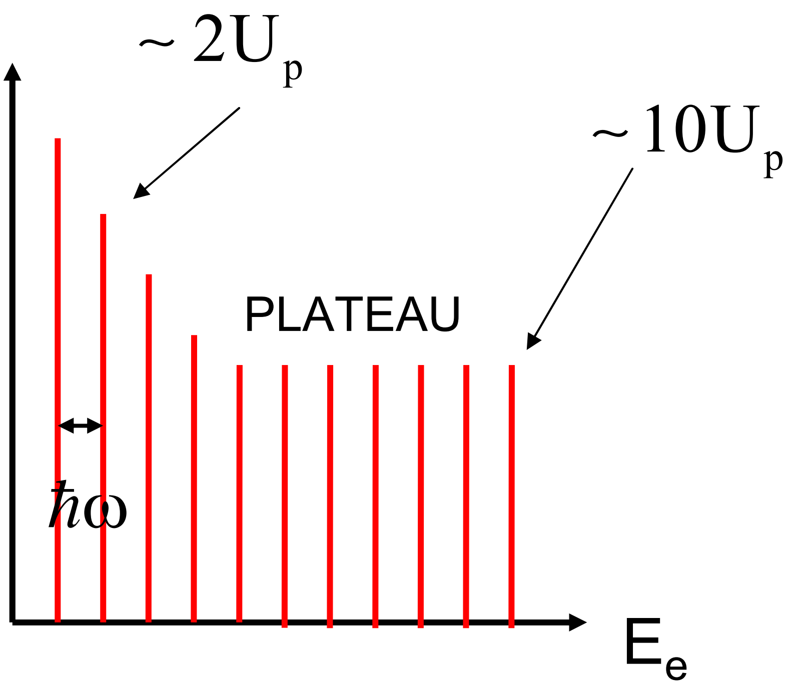


Figure I-1. Spectres d'harmoniques obtenus à 1064 nm dans le xénon, à différents éclairements.

Electron spectrum

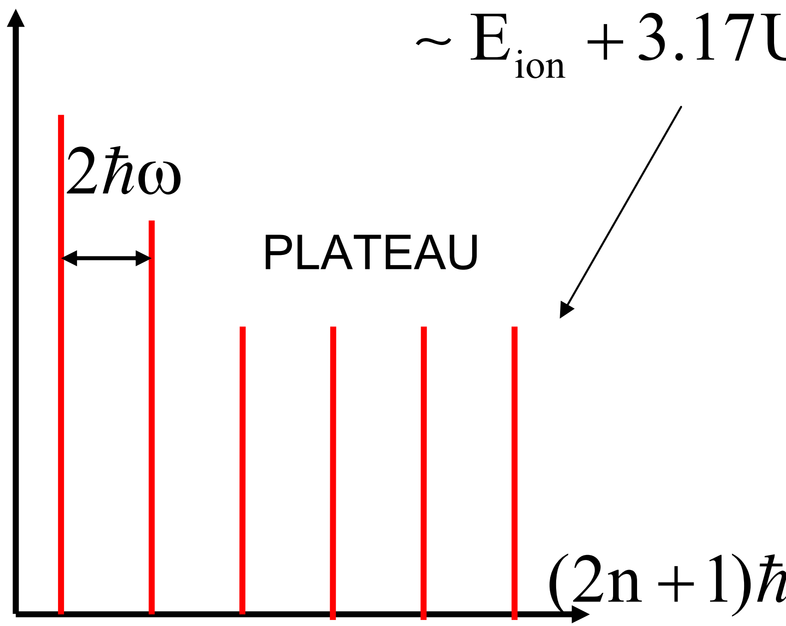


$$\text{ATI} \rightarrow \text{Tunneling}$$

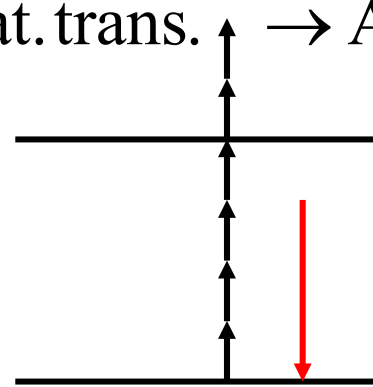
- Quantification: transition into a Volkov state

- Cut-off energy?

Radiation spectrum



$$\text{Intra at. trans.} \rightarrow \text{ATI} + \text{Tunnelin}$$



-Odd harmonics: inversion symmetry

-Cut-off energy?

Above Threshold Ionisation: Important features

1- Cut off energy

$$2U_P$$

Classical explanation.

$$E = E_0 \cos \omega t; v(t_0) = 0 \text{ (electron created at rest)}$$

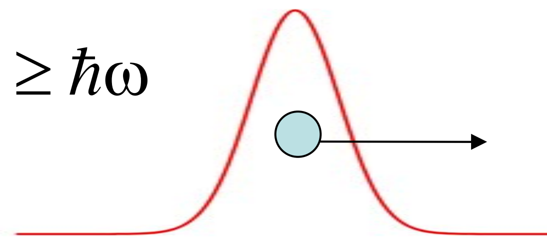
$$E_{kin} = 2U_P \cos^2 \omega t_0 : 0 \rightarrow 2U_P$$

Drift motion even if $v(t_0)= 0$
(phase shift effect)

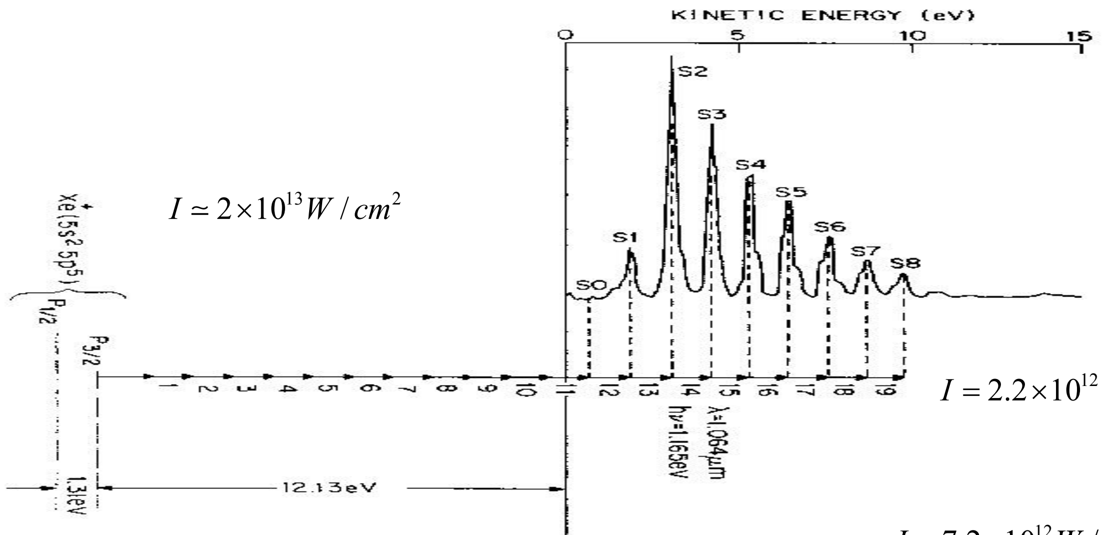
2- Peak suppression

$$E_{elec.} = (n+s)\hbar\omega - E_{ion} \begin{cases} \geq U_P \text{ if conversion potential} \leftrightarrow \text{kinetic} & (1) \\ \geq 0 \text{ else} & (2) \end{cases}$$

(1) long pulse $\rightarrow$ Peak supression when $U_P \geq \hbar\omega$



$I \simeq 2\times10^{13} W/cm^2$

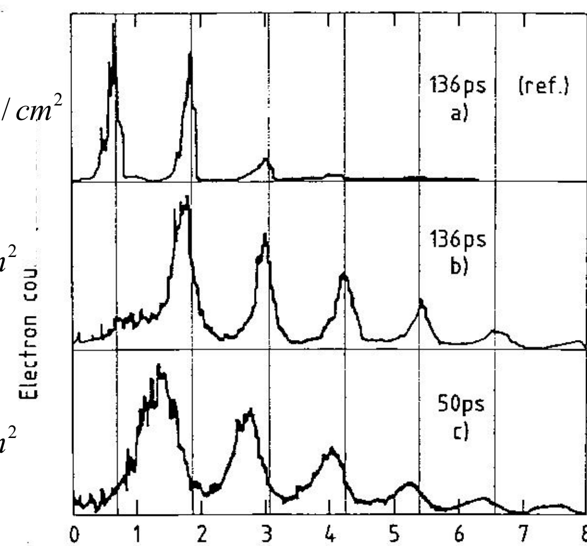


$I = 2.2\times10^{12} W/cm^2$

$I = 7.2\times10^{12} W/cm^2$

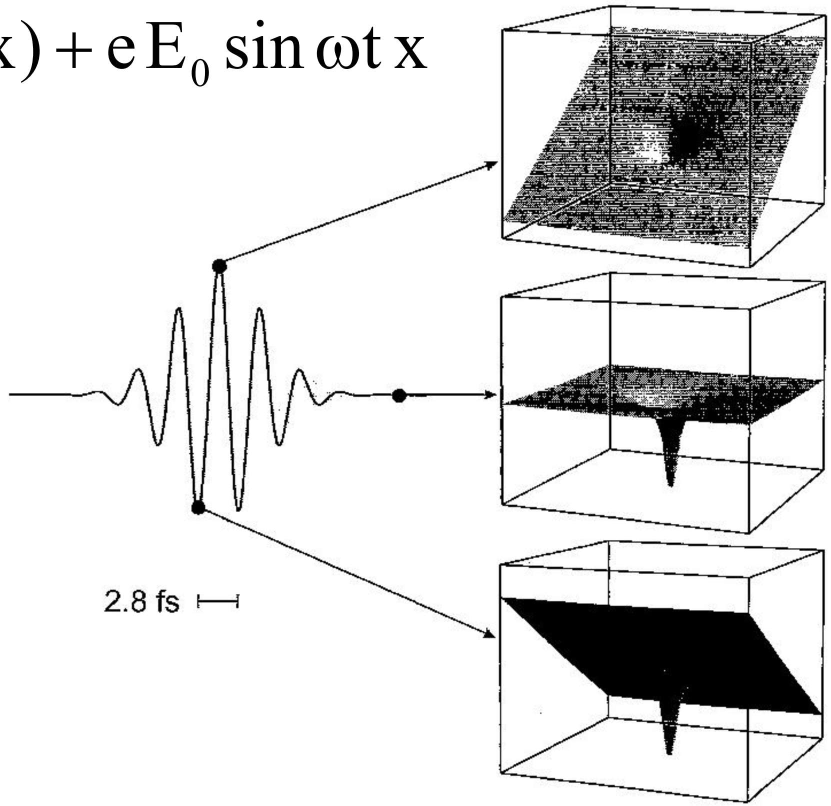
(2) Short pulse

$I = 7.2\times10^{12} W/cm^2$

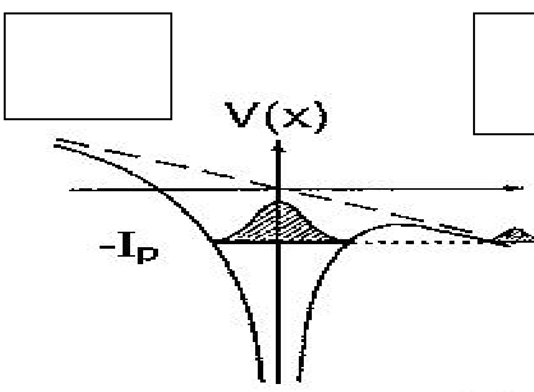


Tunnel Ionisation

$$U(x) = V(x) + eE_0 \sin\omega t\, x$$



Time dependent Barrie



Maximum of Ionisation when $\omega t = \frac{\pi}{2}[\pi]$

Tunnel Ionisation: Keldysh parameter

$$\gamma = \frac{\text{time needed to escape}}{\text{optical period}} \qquad \gamma = \sqrt{\frac{E_{ion}}{2U_P}}$$

$$\gamma < 1 \rightarrow \text{Tunneling}$$

$$\gamma > 1 \rightarrow \text{Multiphoton Ionisation}$$

onis. rate in the quasi-static regime (Amnosov, Delone, Krainov formula)

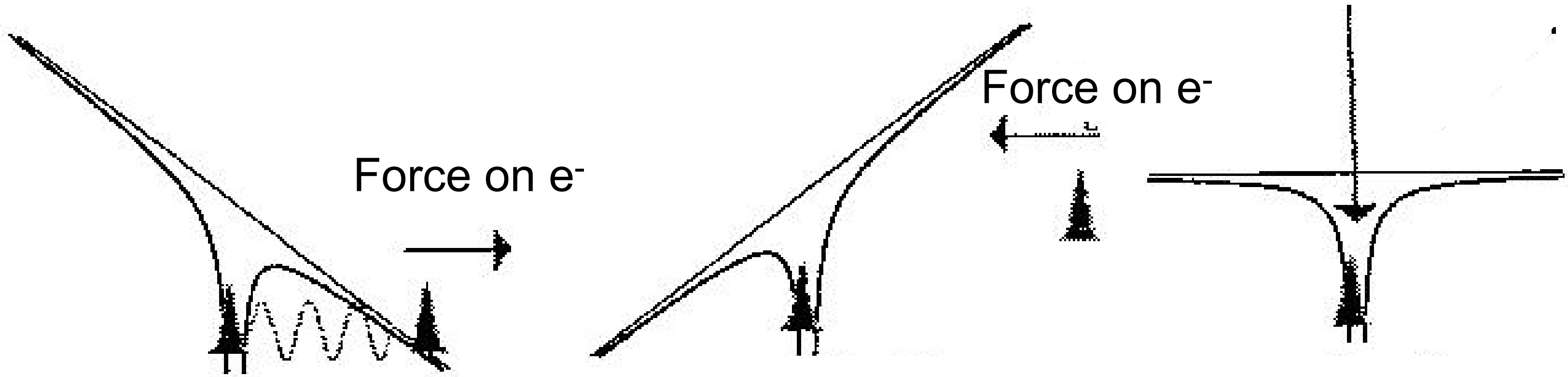
$$\text{itially electron } |n^*, l, m\rangle; l^* = n^* - 1; m = Z(2E_{ion})^{1/2} \qquad m_e = \hbar = c =$$

$$\Gamma_{ion} = \sqrt{\frac{3E_0}{\pi(2E_{ion})^{3/2}}} |C_{n^*l^*}|^2 f(l,m) E_{ion} \left(\frac{2(2E_{ion})^{3/2}}{E_0} \right)^{\left(\frac{2Z}{\sqrt{2E_{ion}}} - |m| - 1\right)} e^{-\frac{2}{3E_0}(2E_{ion}}$$

$$f(l,m) = \frac{(2l+1)(1+|m|)}{2^{|m|}|m|!(1-|m|)!} \qquad |C_{n^*l^*}|^2 = \frac{2^{ln^*}}{n^*\Gamma(n^*+l^*+1)\Gamma(m^*-l^*)}$$

Tunnel Ionisation: cut-off energies

Three-step model $E = E_0 \sin \omega t$



① Tunneling ionization | ② Oscillation in the laser field | ③ Re-collision

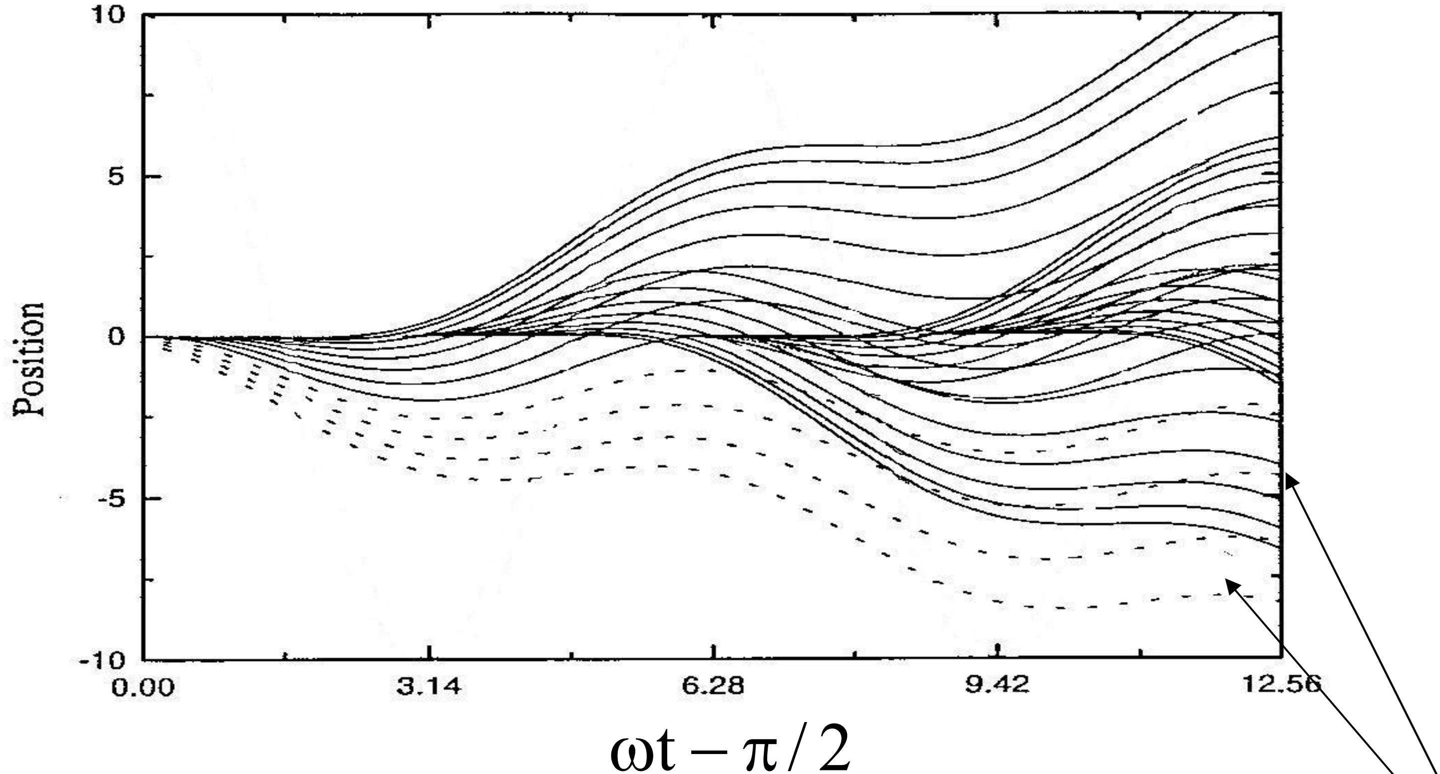
$$t = t_0$$

$$\omega t_0 \simeq \frac{\pi}{2}[\pi]$$

$$x = \frac{-eE_0}{m\omega^2}\left(\sin \omega t - \sin \omega t_0\right) + \frac{eE_0}{m\omega^2}\left(\omega t - \omega t_0\right)$$

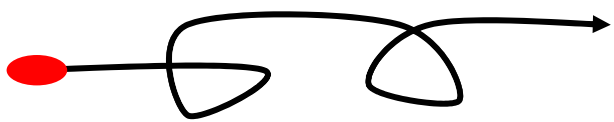
$$t = t_1(t_0)$$

TRAJECTORIES



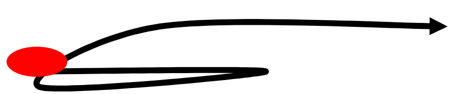
Several t_0

…. : No return



$$0 \le \omega t_0 \le \frac{\pi}{2} \quad [\pi]$$

—— : Return



$$\frac{\pi}{2} \le \omega t_0 \le \pi \quad [\pi]$$

Recombinaison → HHG plateau

$$t = t_1 \qquad x(t_1) = 0$$

$$\langle E_{kin} \rangle = \frac{e^2 E_0^2}{2m\omega^2}\left(\cos\omega t_1 - \cos\omega t_0\right)^2$$

$$\text{max when } \omega t_0 \simeq 108^0 \rightarrow \omega t_1 \simeq 342^0 \rightarrow \langle E_{kin} \rangle = 3.17U$$

$$\rightarrow N_{max}\hbar\omega = E_{ion} + 3.17U_P$$

e-collision:

Diffusion → ATI Plateau

$$t = t_1^{\,+} \qquad \dot{x}(t_1^{\,+}) = -\dot{x}(t_1)\,(\text{best situation})$$

$$E_{drift} = \frac{eE_0^2}{2m\omega^2}\left(2\cos\omega t_1 - \cos\omega t_0\right)^2$$

$$\text{max when } \omega t_0 \simeq 105^0 \rightarrow \omega t_1 \simeq 351.7^0 \rightarrow E_{drift} = 10U$$

PERIOD T/2 → 2ω

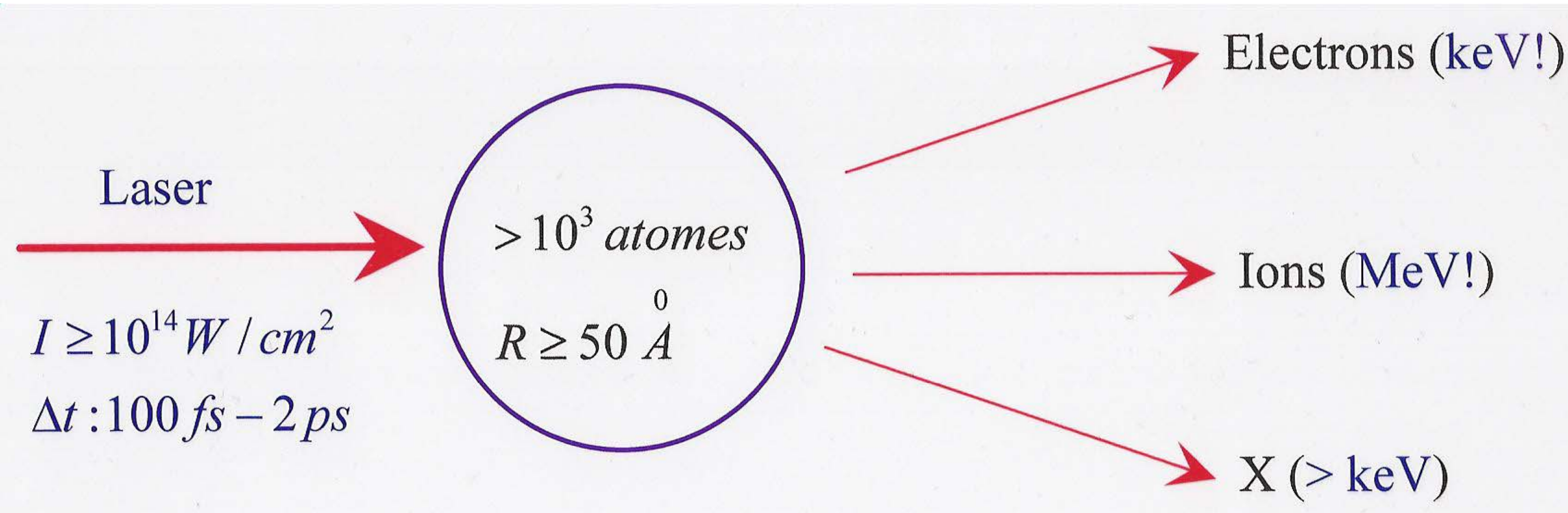
FURTHER DEVELOMENTS

- Attosecond pulse generation (mode locking of HH)
- Coherent sources in the VUV and XUV
- Cluster explosion :

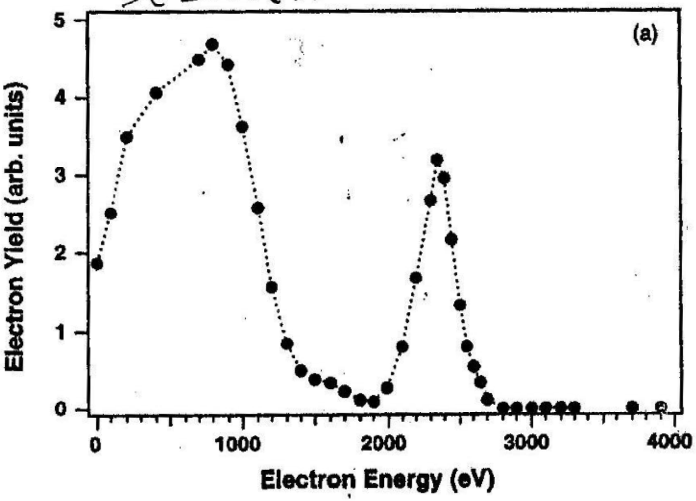
  neutron sources

  Highly energetic particles

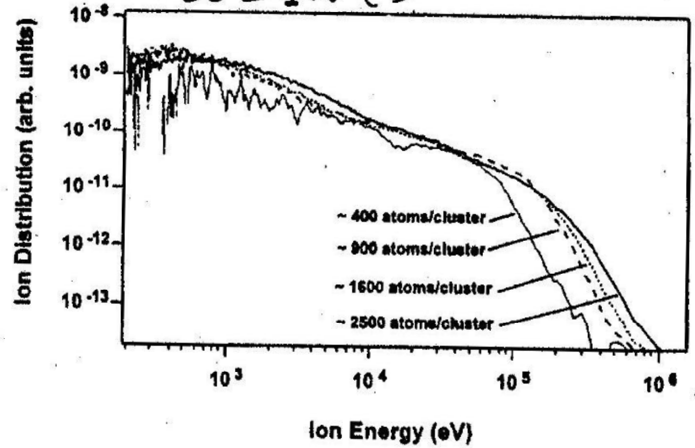
CLUSTER EXPLOSION



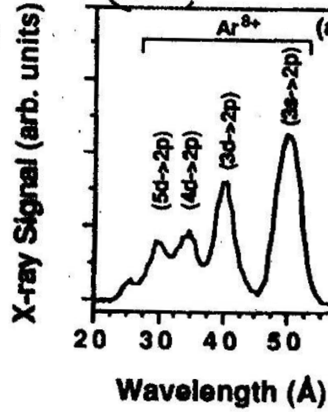
(Xe)
$I = 10^{16}$ W/cm^2
$\Delta t \simeq 150$ fs.



(Xe)
$I = 2\ 10^{16}$ W/cm^2
$\Delta t \simeq 150$ fs



$I = 8\ 10^{15}$ W/cm^2
$\Delta t = 130$ fs
$(Ar)^n$



DITMIRE et al.
(NATURE, 8 Avril 99)

FUSION!