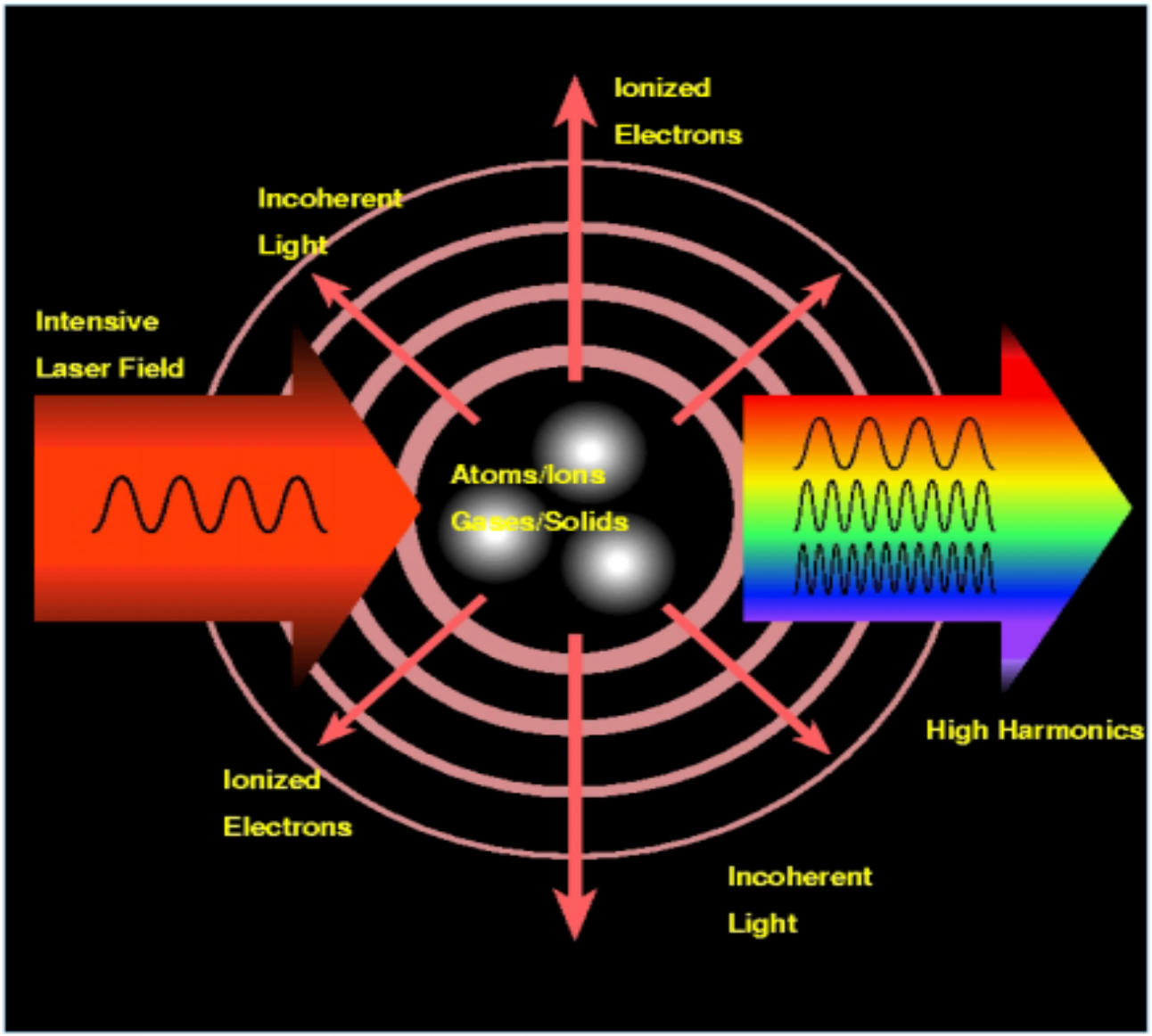
Relativistic quantum dynamics of multiply charged ions in very intense laser pulses



Christoph H Keitel
SFB Nachwuchsgruppe
University of Freiburg
Germany

Outline

Introduction into relativistic Laser-Atom Interaction:
Free Electrons, Ionization and the Lorentz Force

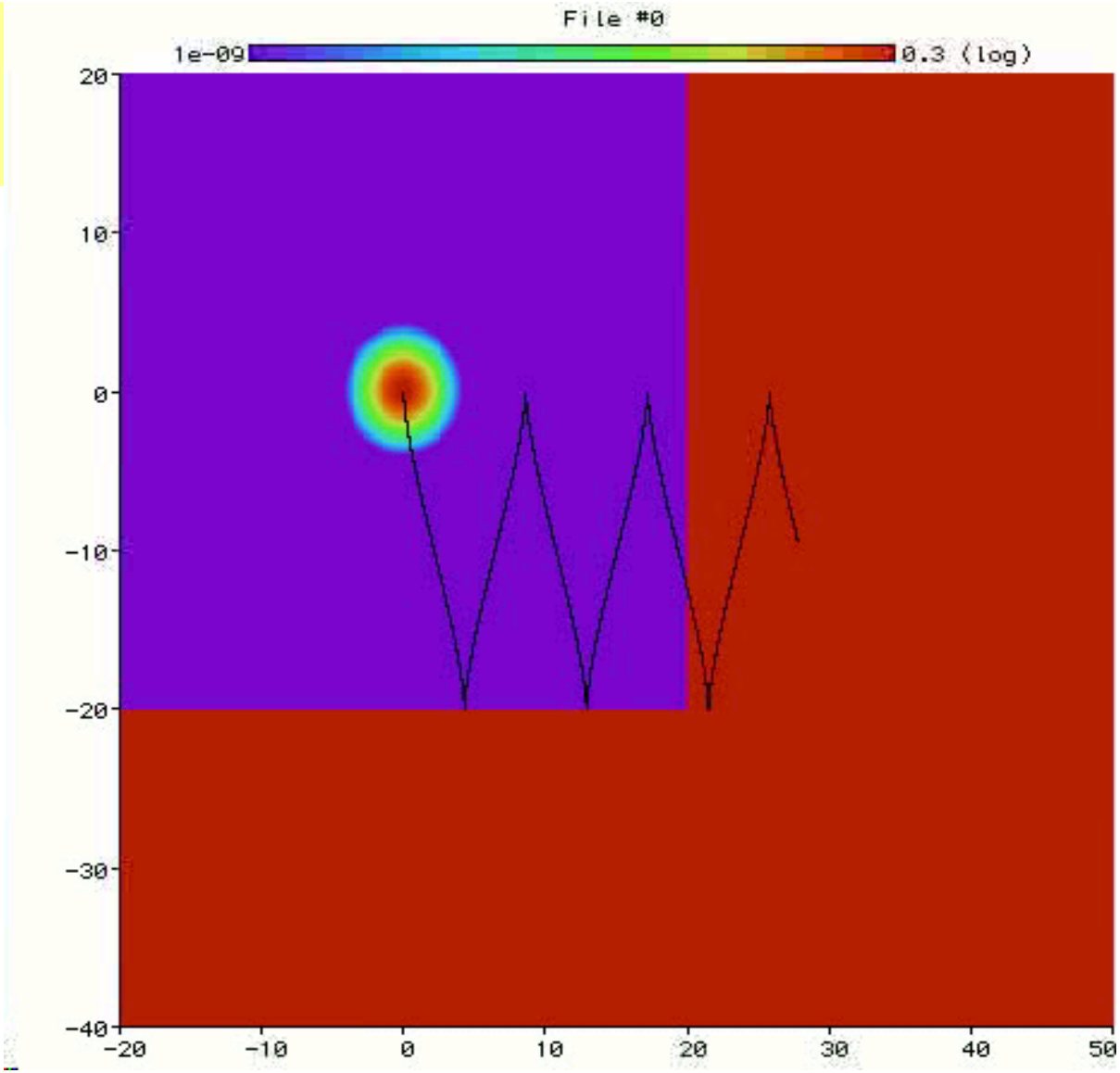
Relativistic Laser-Single Ion Interaction

Quantum Features: Interferences and Spin
High Energy Acceleration and X-Ray Emission

Interaction with vacuum and its control

Dirac Dynamics in strong Laser Fields

Free Electron



Analytical for planes waves Volkov 1932

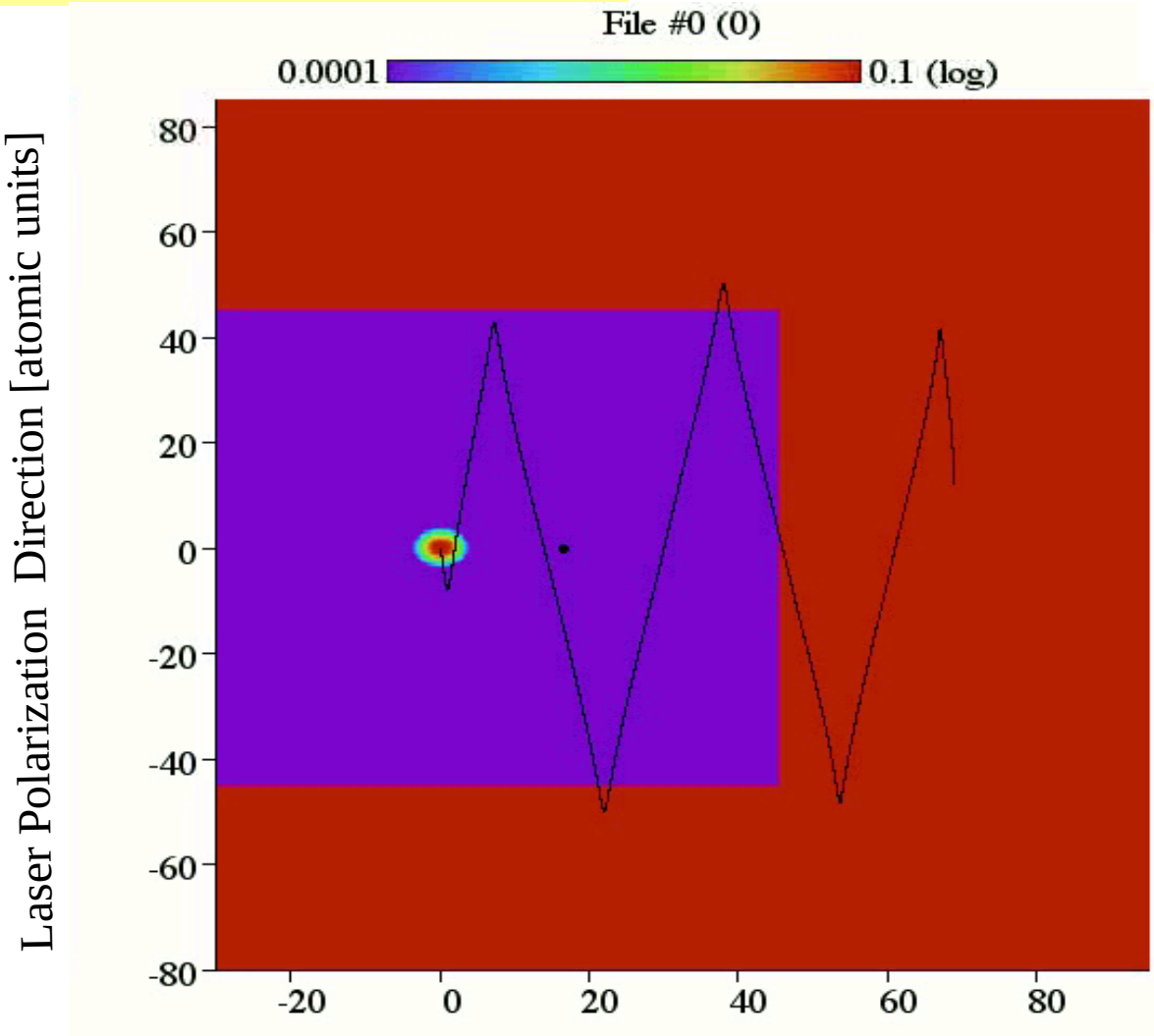
E= 640 a.u., w= 8 a.u., kin Energie ca. 40 keV

Movie G. Mocken

Mott Scattering in strong Laser Fields

Scattering at naked Uranium

$$ih\partial_t\Psi = \left\{c\boldsymbol{\alpha}\cdot\left[\mathbf{p}+\frac{e}{c}\mathbf{A}\right]+\beta mc^2+V\right\}\Psi$$

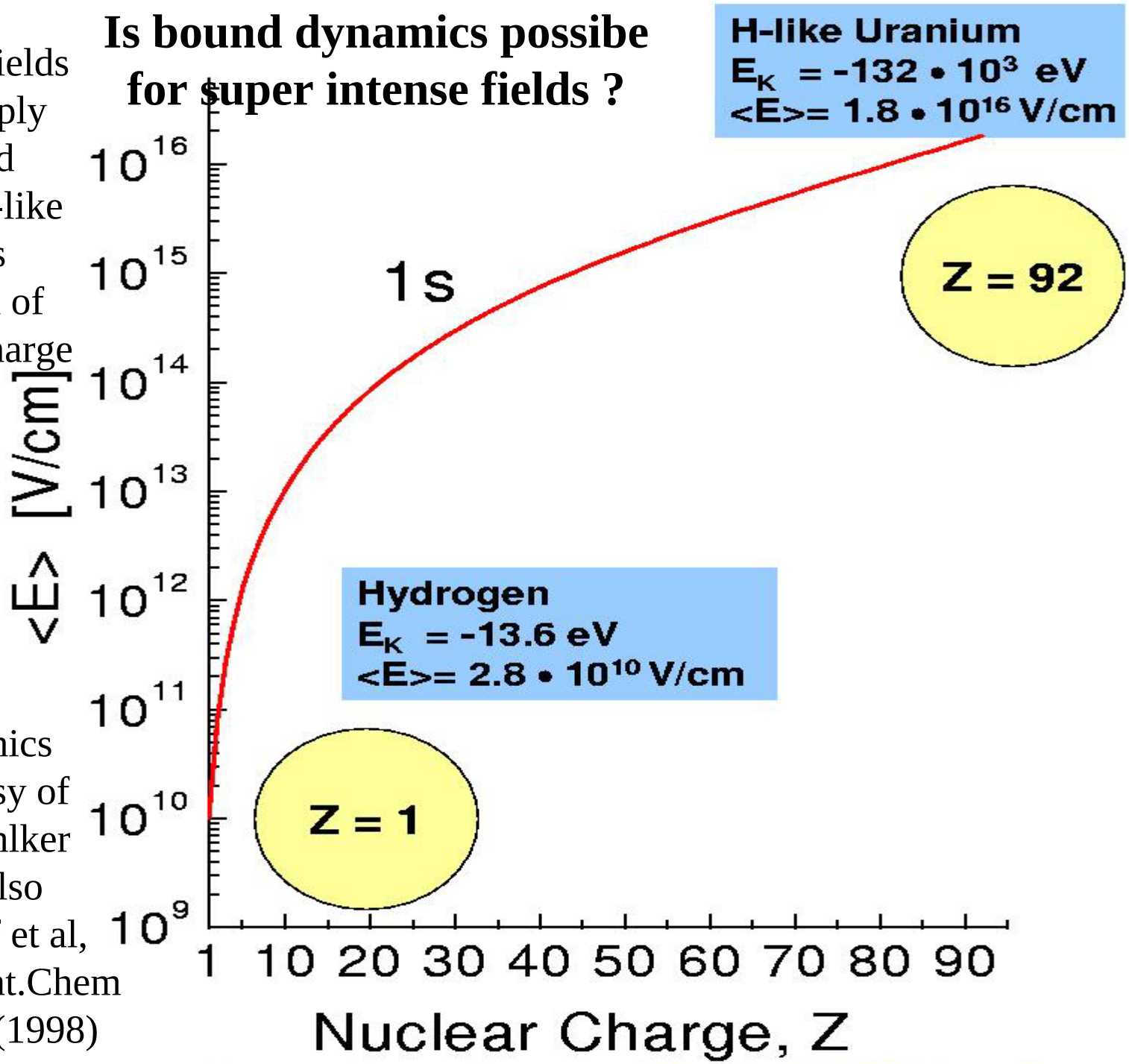


see also earlier
analytical work by
Mott, Proc. R. Soc. 1932;
Bunkin&Fedorov Z.Ek.Teo.F.
1965, Denisov&Fedorov,
Zh.Eksp.Teor.Fiz. 1967;
C. Szymanowski et.al,PRA 97

E= 50 a.u., w= 1 a.u., kin Energie ca. 30 keV Movie PhD student G. Mocken

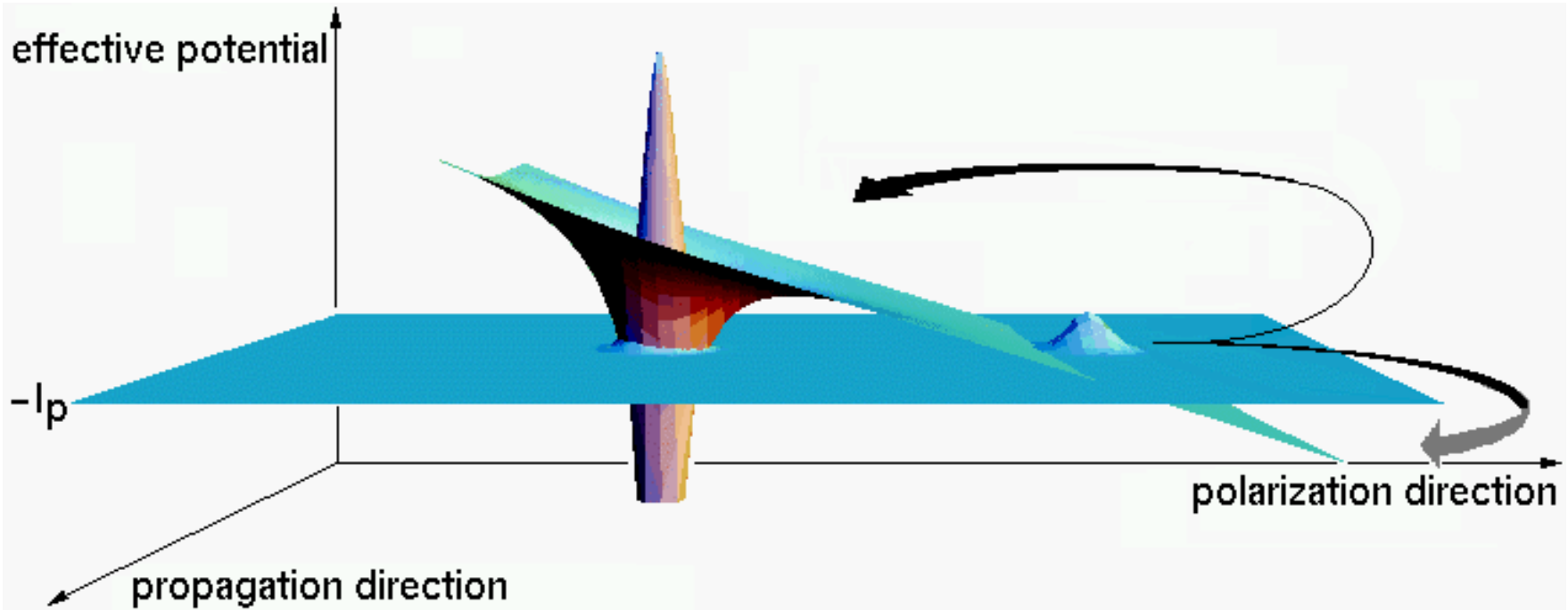
Is bound dynamics possibe for super intense fields ?

Mean E-fields for multiply charged hydrogen-like ions as function of nuclear charge



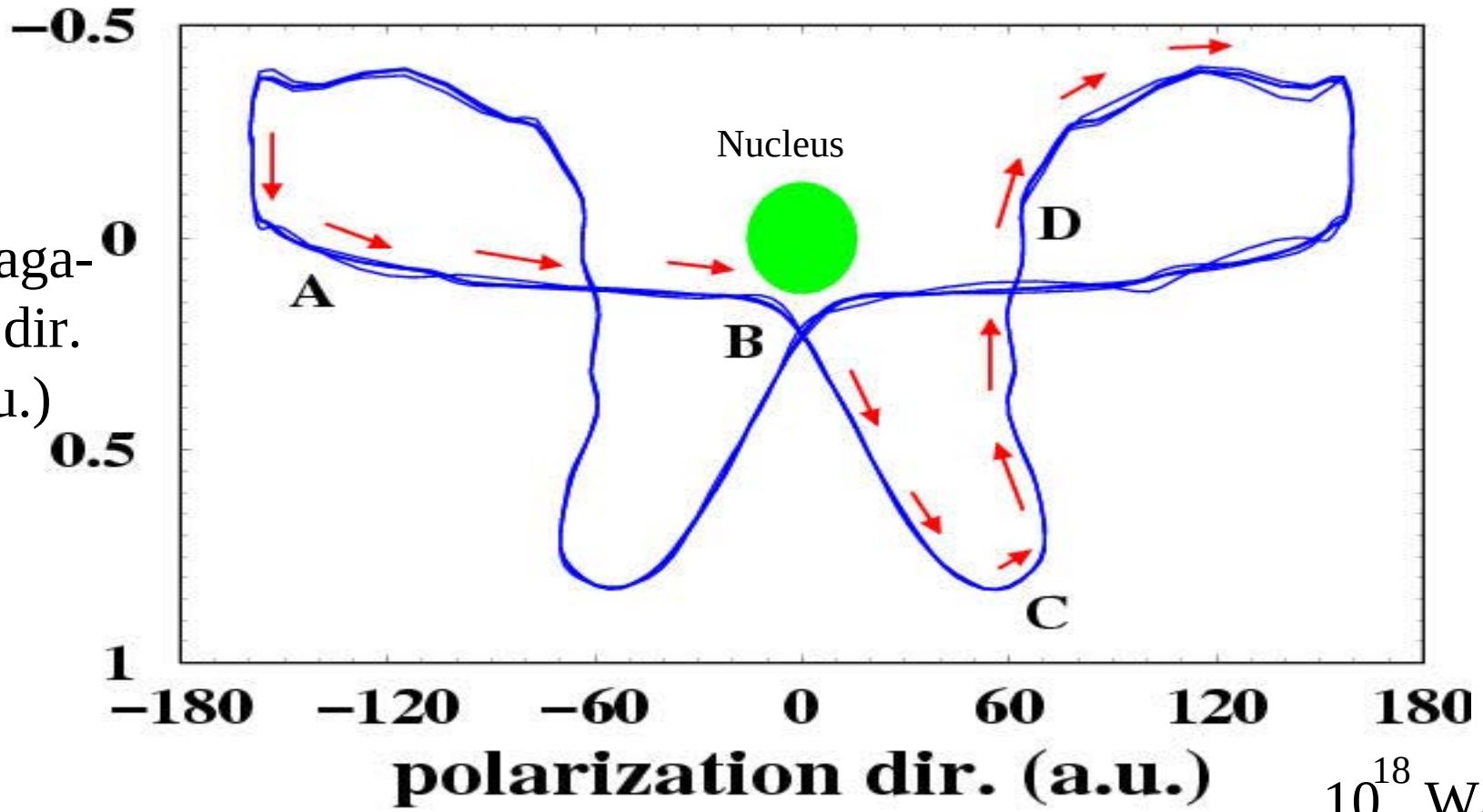
Graphics courtesy of T. Stöhlker see also G. Soff et al, Adv.Quant.Chem 30, 125 (1998)

Laser-induced tunneling for multiply charged ions



Competition between Lorentz Force and Coulomb Attraction

Tunnel-Recollision Dynamics for Multiply Charged Ions

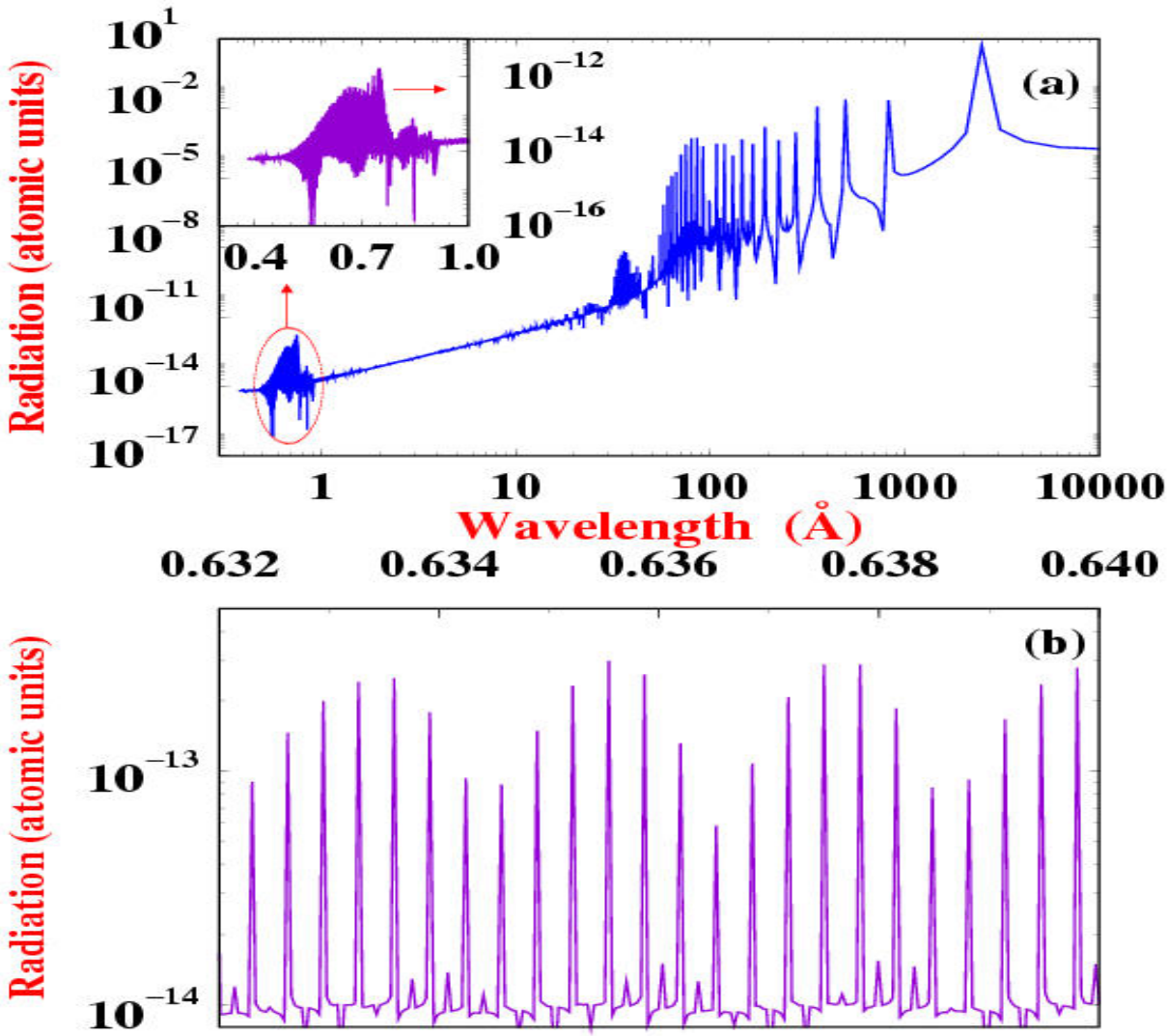


10^{18} W/cm^2

248 nm N^{6+}

Center of Mass Motion of the Tunneled Wave Packet

Sub-Angstrom Harmonics



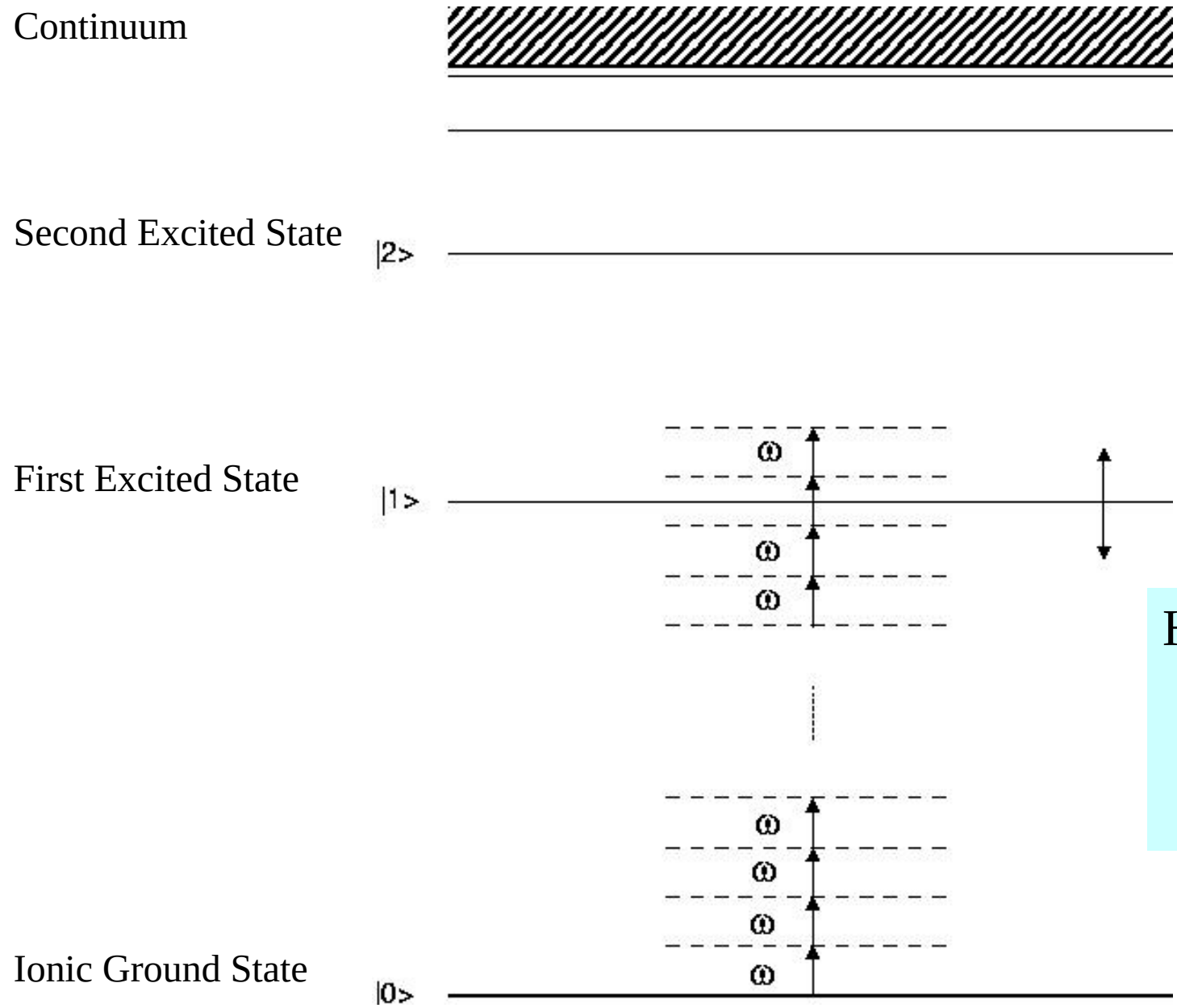
10^{18} W/cm^2

248 nm (KrF)

N^{6+} Ions

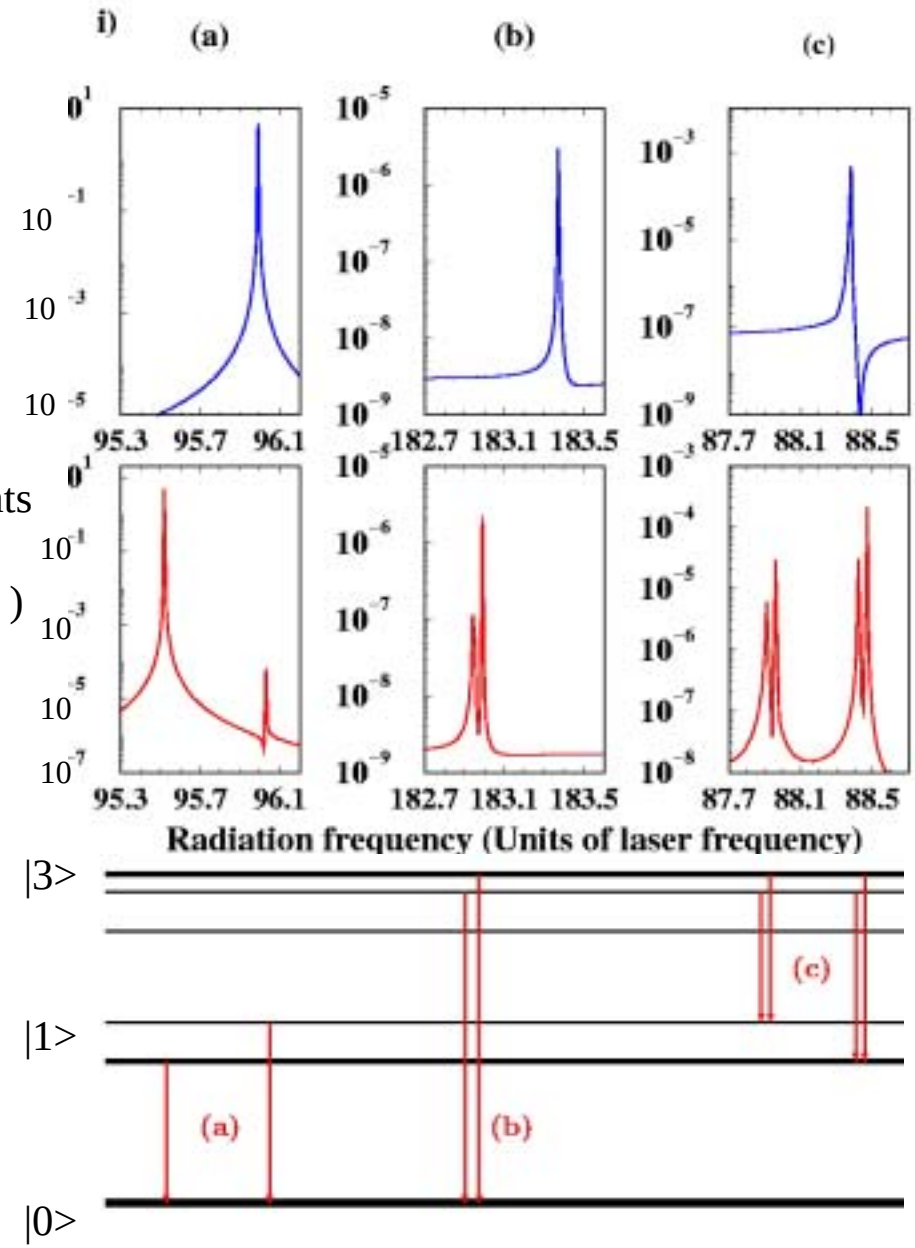
CHK, S Hu, APL 80, 541 (02), see also DB Milocevic et al, PRA (01), NJ Kylstra et al ,JPB (01), MW Walser et al, PRL (00)

Resonant Multiphoton X-Ray Optics with Multiply/Highly Charged Ions



High-Frequency Laser Light soon possible With TESLA

Multiply Charged Ions



Via Pauli Equation

Via Expansion of Dirac Equation to Second Order

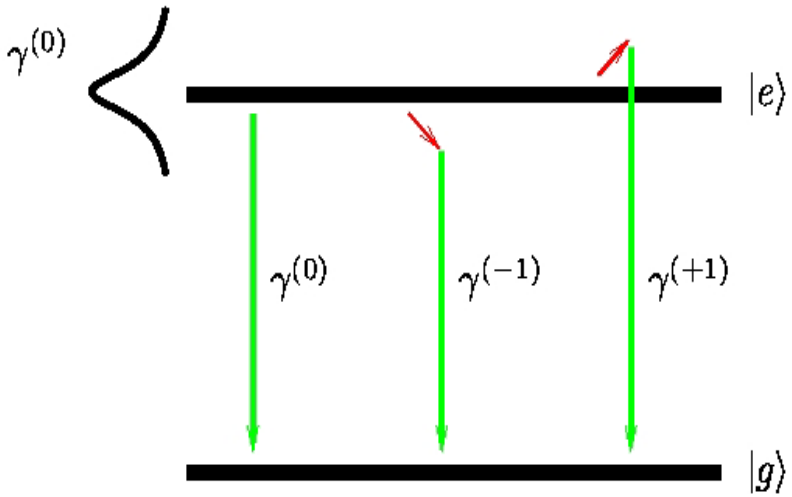
Al^{12+} Ions

$7\ 10^{16}$ W/cm^2

800 nm

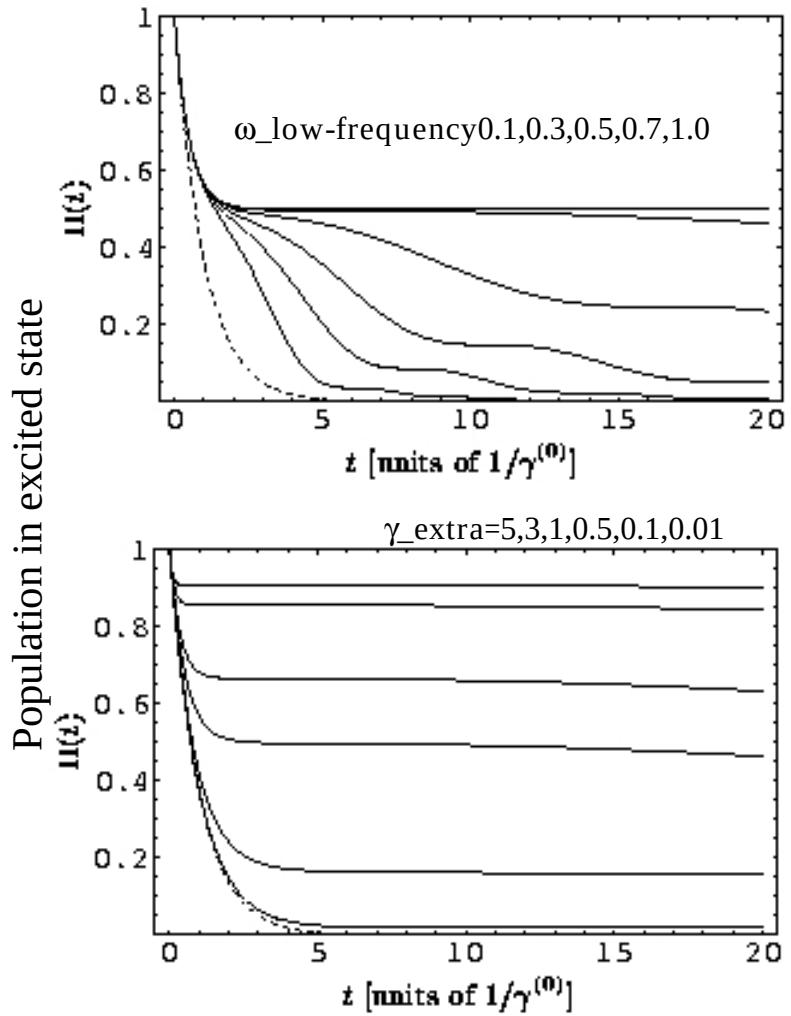
S X Hu, CHK, PRL(99)& PRA(01)

The role of the vacuum and spontaneous emission suppression via quantum interference



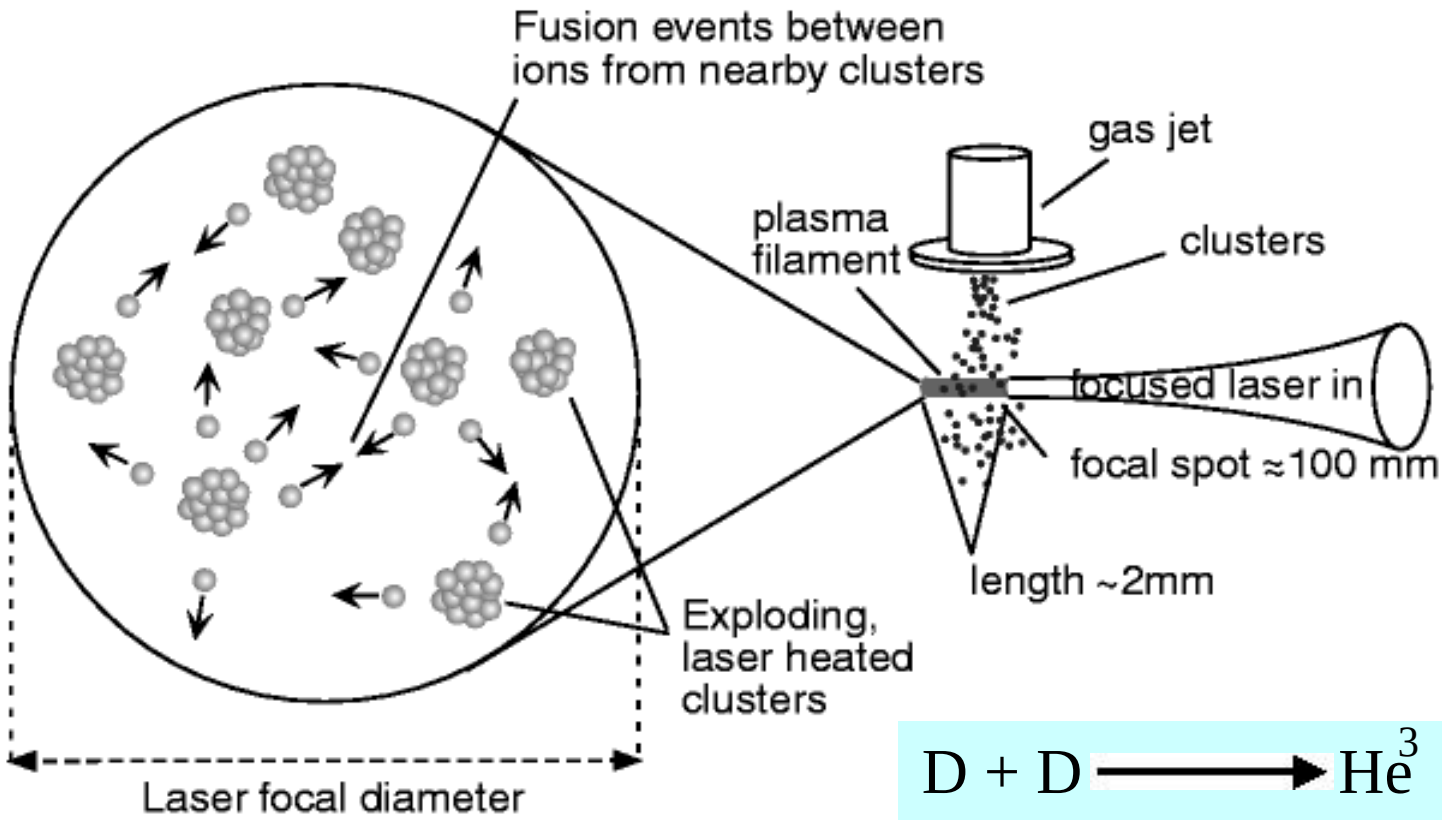
Interferences via additional low-frequency field

First results for nonrelativistic atom/laser parameters: Jörg Evers & CHK, Phys. Rev. Lett. 89, 163601 (2002)



Time dependent decay as a function of frequency and additional decay rates

Nuclear Physics: Fusion & Neutrons



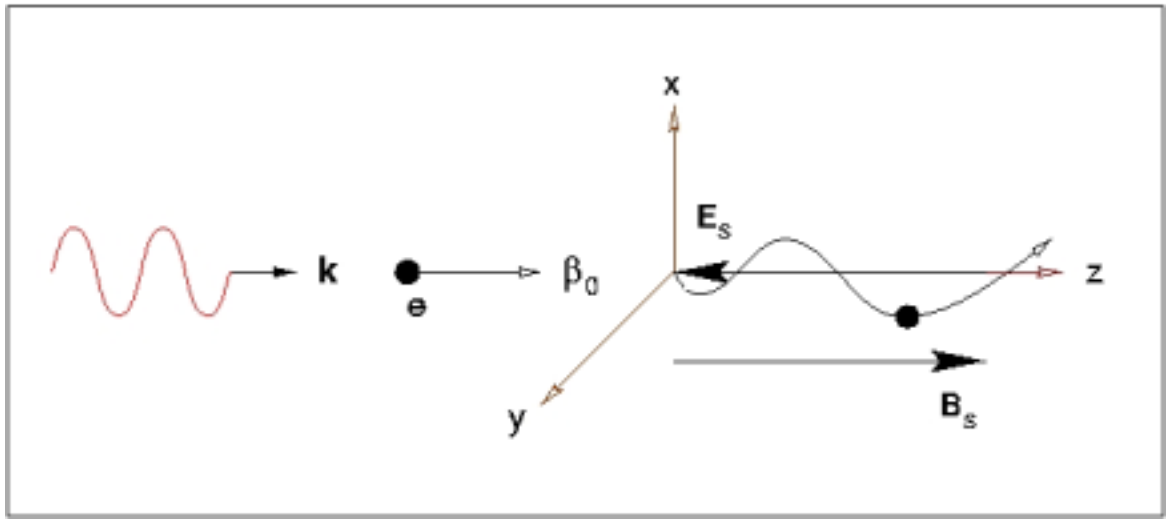
$$D + D \longrightarrow He^{3} + n$$

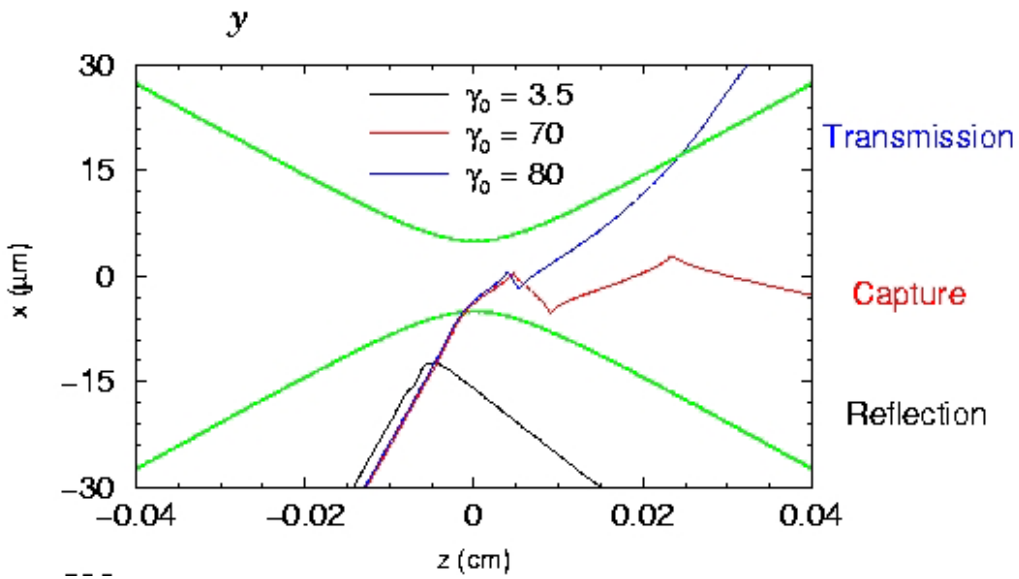
Neutron with 2.45 MeV

from T. Ditmire et al, Nature 398, 489 (1999); further photonuclear neutrons by G. Pretzler et al., PRE 58, 1165 (1998), K. Ledingham et al., PRL (2000), D. Hilscher et al., PRE (2001), N. Izuma PRE (2002), G. Grillon et al PRL (2002)

High energy physics via GeV acceleration

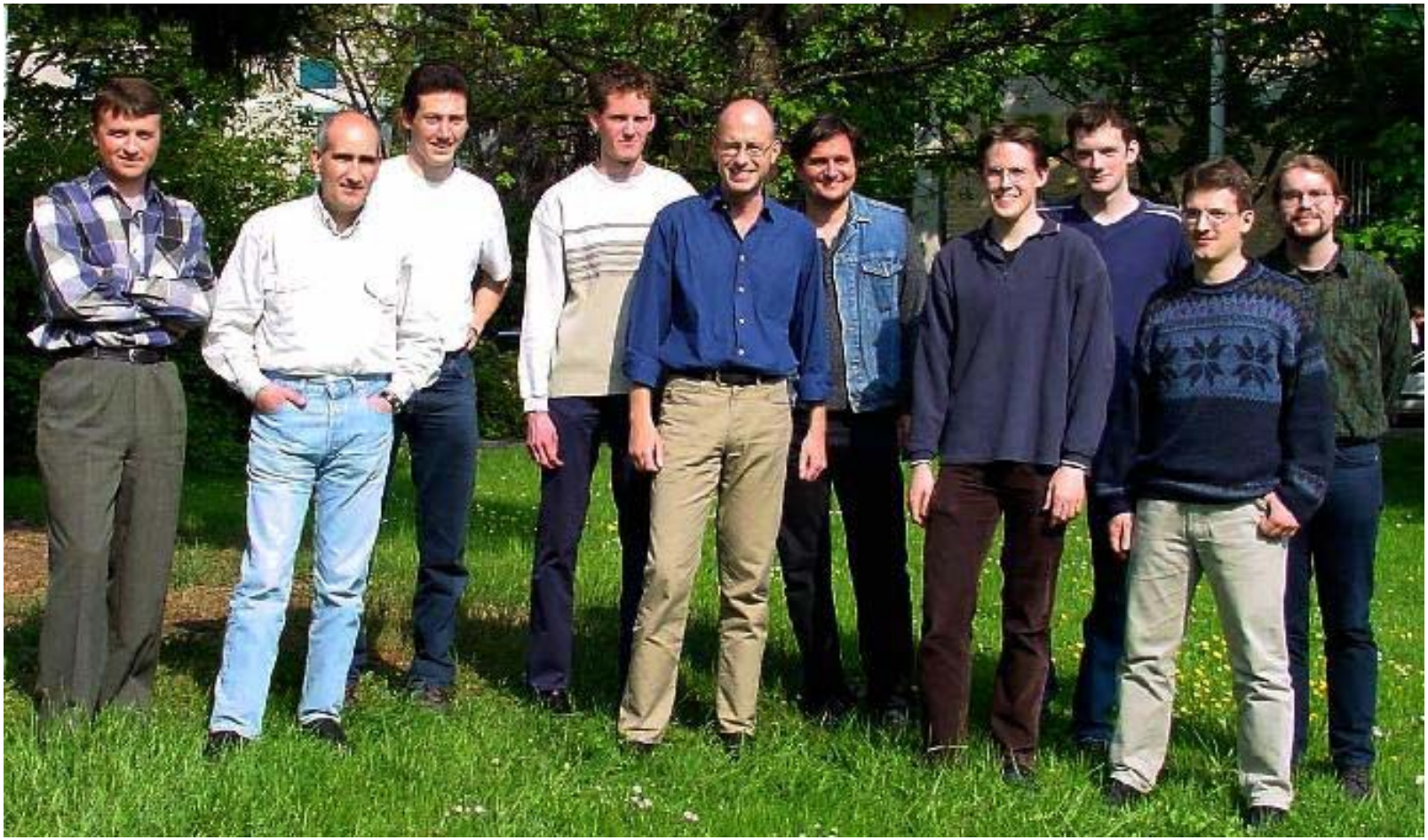
Short Laser Pulses, Static Magnetic Fields, Crossed Beams



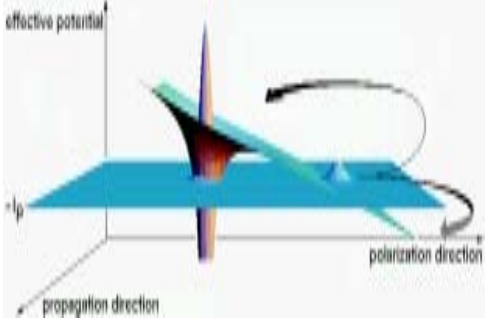


GeV energies for single & crossed laser pulses
Y.I. Salamin, CHK, APL 77, 1082 (2000) & PRL 88, 095005(2002);
from highly charged ions:
S.X. Hu, A. F. Starace, PRL 88, 245003(2002)

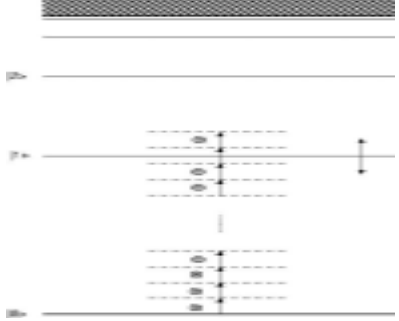
Group members



Left to right: M. Macovei, K. Hatsagortsyan, G. Mocken, B. Henrich, CHK, U. Jentschura, J. Evers, D. Bullock, M. Haas, A. Staudt



Conclusions



Free and scattered electron quantum dynamics

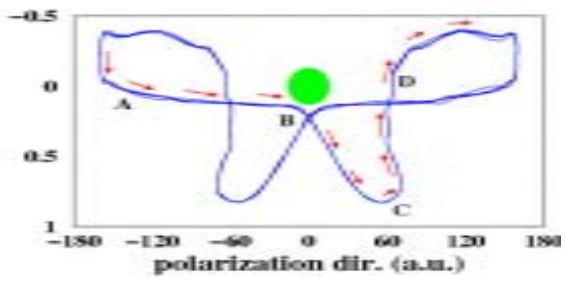
Relativistic Laser-Ion Interaction:

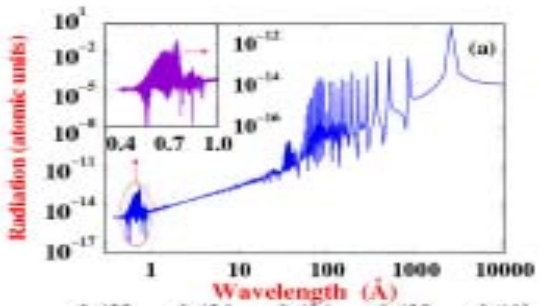
Tunnel Regime & Multi-Photon Resonances

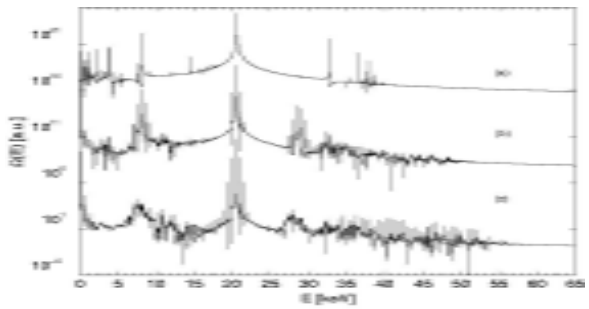
=> Generation of coherent hard X-ray pulses

Spontaneous emission control via quantum interference

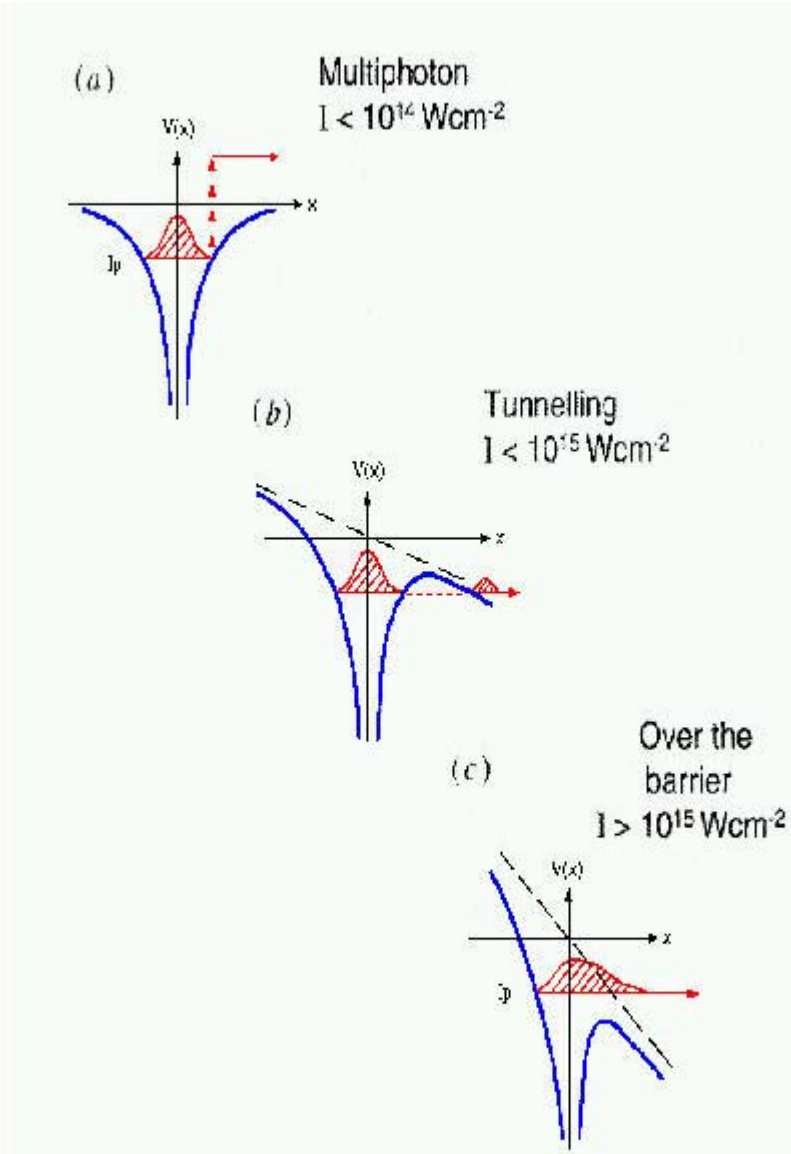
GeV laser acceleration towards high engery physics







Atoms in Intense Laser Fields



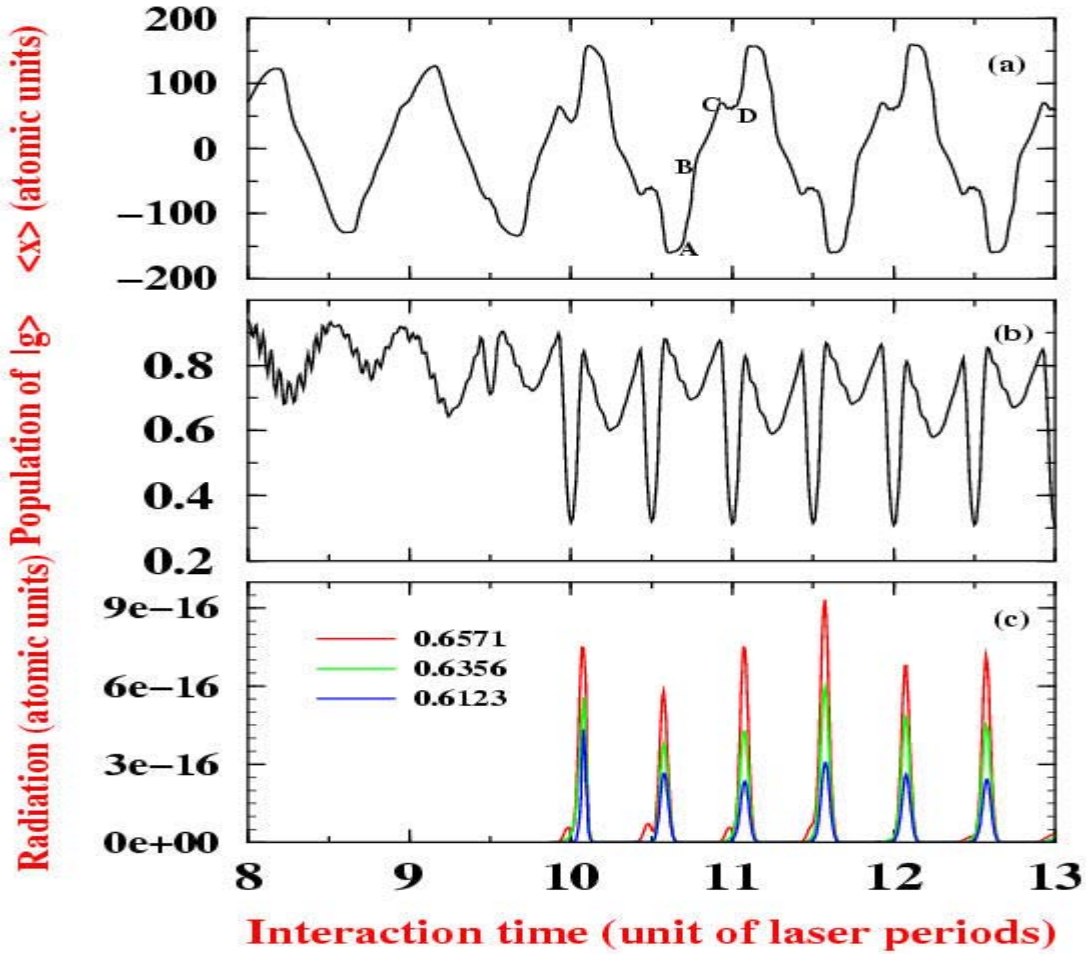
Multi-Photon Regime
Eigenstates Important

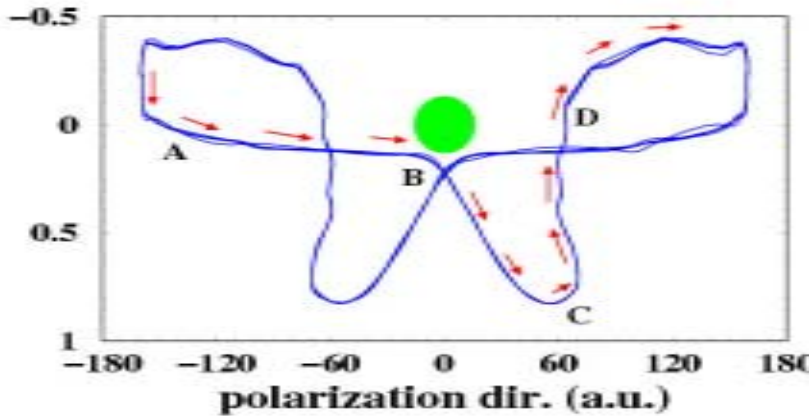
Tunnel-Recollision Regime
ATI (Paulus/Walther)
High-Harmonic Generation
(Krausz/Kapteyn)

Over-the-Barrier Regime
Immediate Ionization

Quantum Multi-Photon and Tunnel Regime possible for much higher laser intensities ?

Sub-Angstrom Harmonics: Mechanism





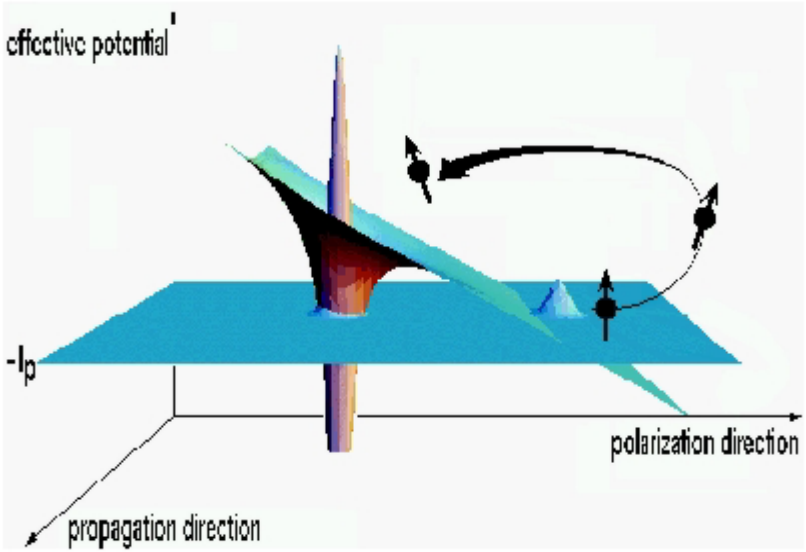
10^{18} W/cm^2

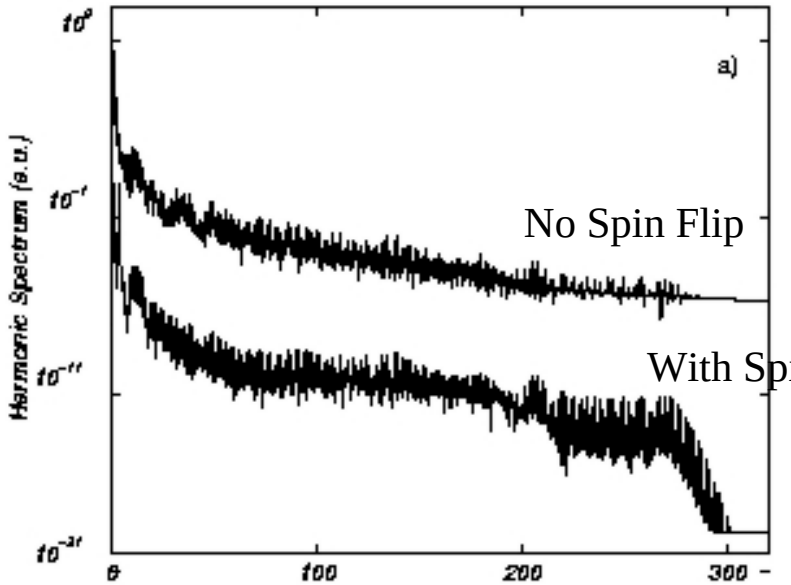
248 nm (KrF)

N^{6+} Ions

CHK, S Hu, APL 80, 541 (02), see also without Coulomb attraction DB Milocevic et al, PRA (01), M Walser et al, PRL (00)

Spin Signatures for Tunneling Harmonics





Harmonic Order

$$i\hbar\dot{\Psi}_+(\mathbf{x},t) \approx \frac{[\mathbf{p}-(e/c)\mathbf{A}(\mathbf{x},t)]^2}{2m}\Psi_+(\mathbf{x},t) + V(\mathbf{x})\Psi_+(\mathbf{x},t),$$

$$i\hbar\dot{\Psi}_-(\mathbf{x},t) \approx -\frac{ie\hbar}{2mc}\mathbf{B}(\mathbf{x},t)\Psi_+(\mathbf{x},t).$$

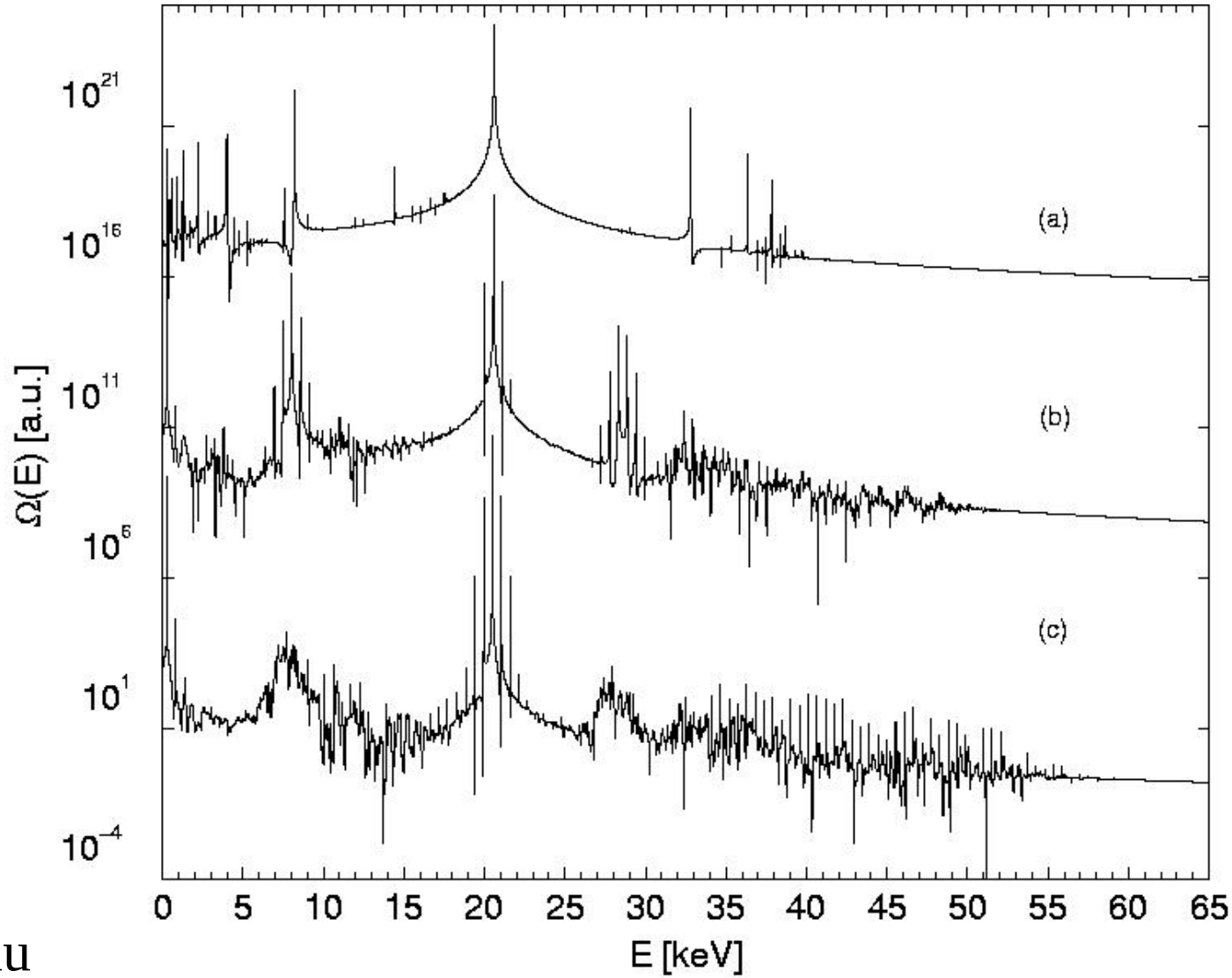
$6\ 10^{16}\ \mathrm{W/cm^2}$

248 nm (KrF)

Be^{3+} Ions

M W Walser, CHK, Opt. Comm. 199, 447 (2001)

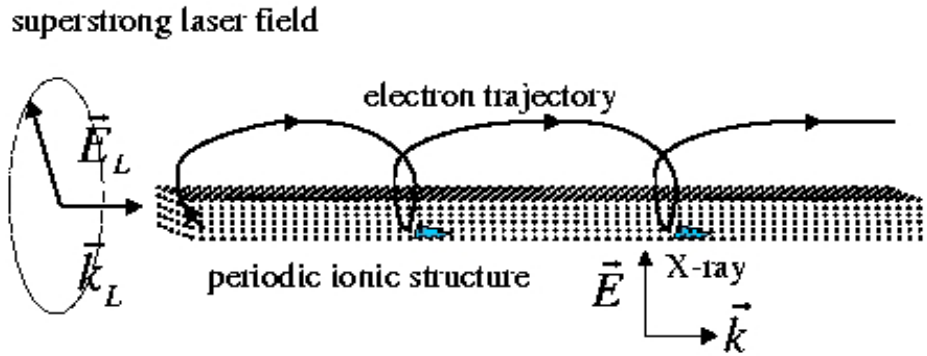
Spectra of Laser-Driven Hydrogen-like Xenon

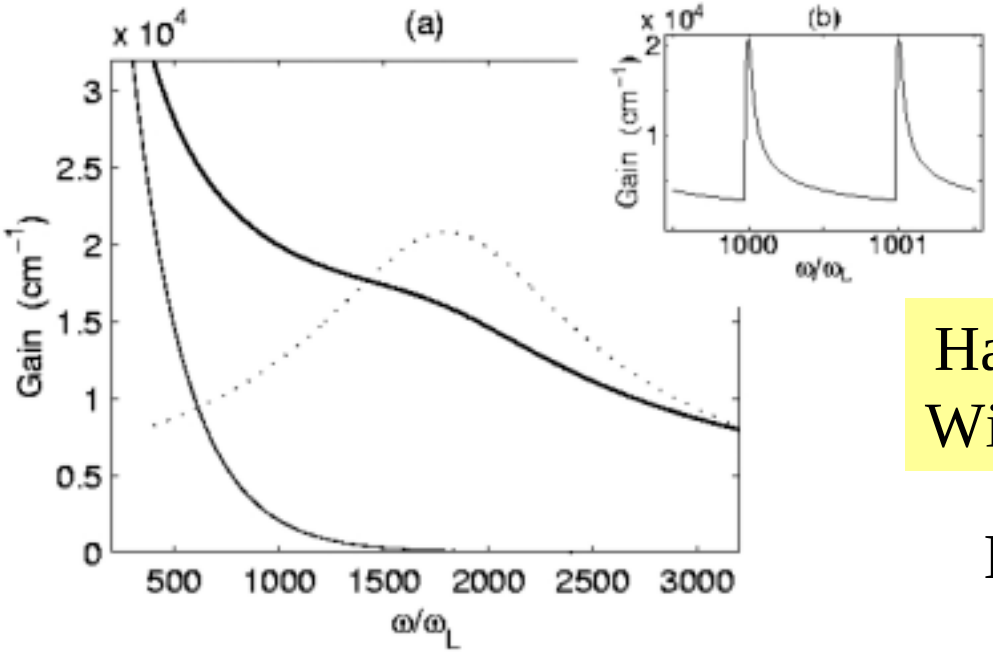


ω=10au
E=10,600,1000au (a,b,c)

M Casu and CHK, Europhys Lett 58, 496 (2002)

Thin Crystals in Intense Laser Pulses



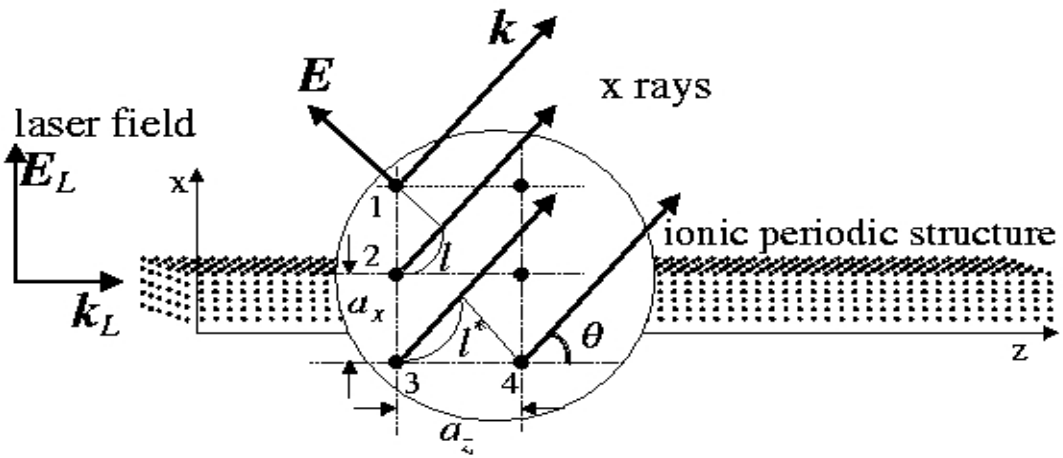


$I = 10^{21} W/cm^2$
μm dimensions
10 fs pulse

Harmonic x-ray amplification
With short intense laser pulses

Karen Hatsagortsyan, CHK,
PRL 86, 2277 (2001)

Phase Matched Harmonics from Crystals in the Tunneling Regime



"Transverse" phase matching, i.e. between ion 1 and 2:

$\omega t_1 - kl = 2\pi s_1$ with $l = a_x \sin\theta$, $t_1 = 0$ and integer number s_1

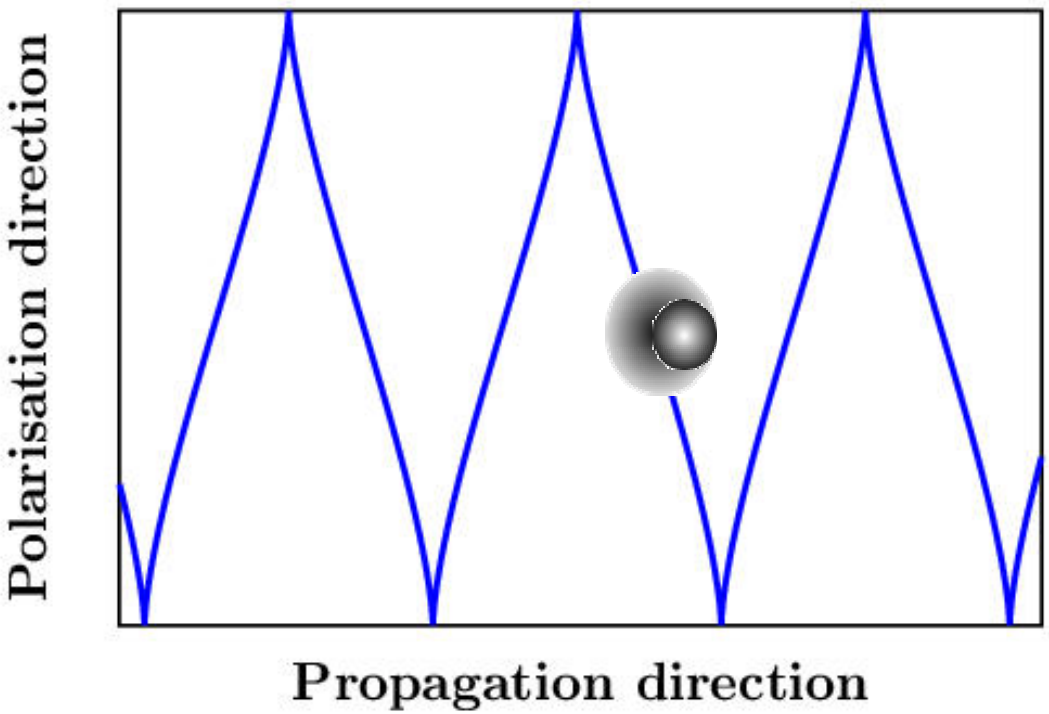
"Longitudinal" phase matching, i.e. between ions 3 and 4:

$\omega t_2 - kl^* = 2\pi s_2$ with $l^* = a_z \cos\theta$, time delay $t_2 = a_z n_L / c$ and integer s_2.

θ: angle between the propagation direction and $\mathbf{k}$.

K. Hatsagortsyan, CHK, J. Phys B35, L175 (2002)

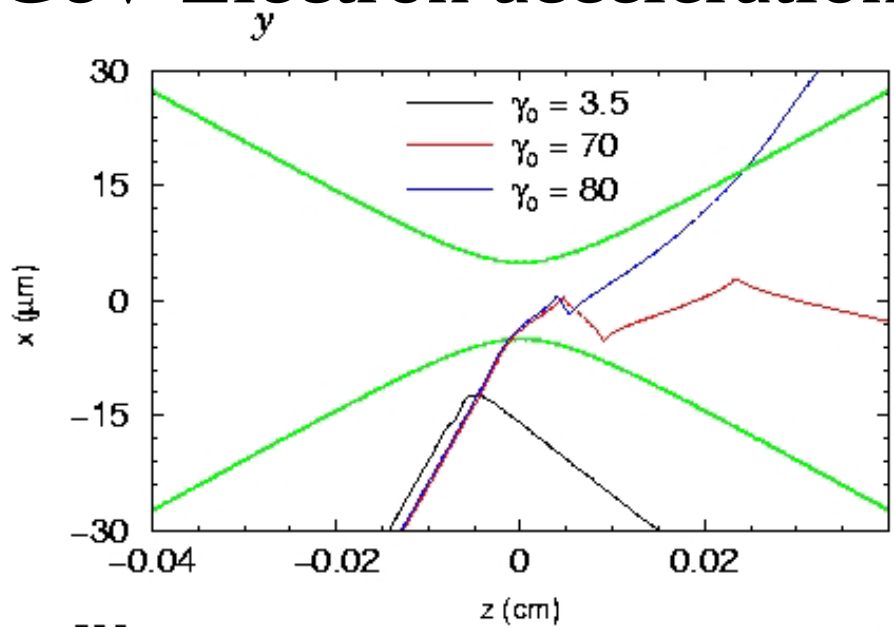
Radiative Reaction / QED Effects



Reabsorption of
Initially Emitted
Light alters Dynamics

C. Bula ... DD Meyerhofer, PRL 76, 3116 (1996);
CHK, C Szymanowski, PL Knight, A Maquet, JPB 31, L75 (1998)

GeV Electron acceleration in Tighly Focussed Beams

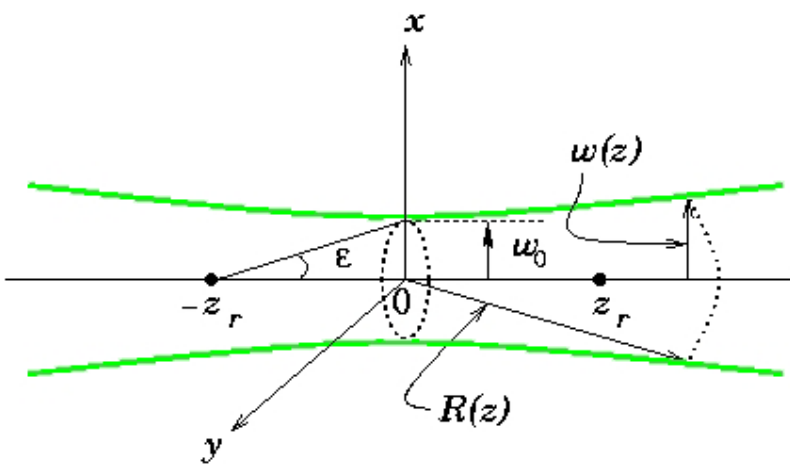


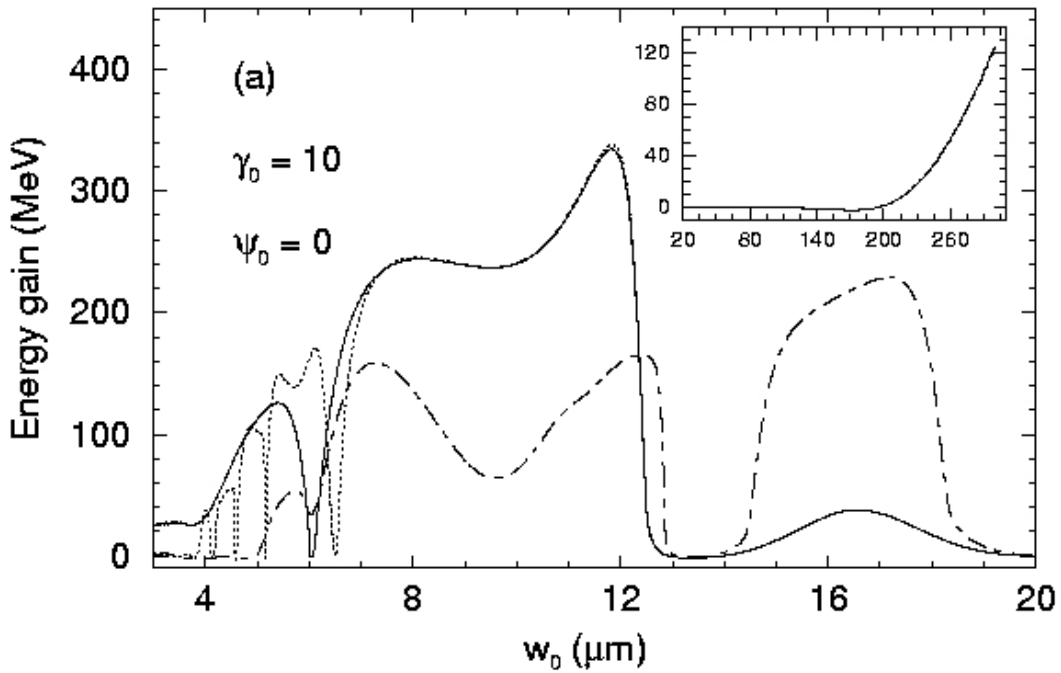
Transmission

Capture

Reflection

Inclusion 5th order terms in the diffraction angle for beams below 5 micron meter width
YI Salamin and CHK, PRL 88, 095005 (02)





Electron GeV Acceleration also from Ions: see S.X .Hu, A.F. Starace, PRL 88, 245003 (2002)