Quantum Beam Engineering E 量子ビーム発生工学特論E

Kenichi Ishikawa (石川顕一) downloadable from ITC-LMS, NEM google drive, and http://ishiken.free.fr/english/lecture.html http://www.atto.t.u-tokyo.ac.jp ishiken@n.t.u-tokyo.ac.jp



高次高調波発生と アト秒レーザーパルス high-order harmonic generation & attosecond laser pulse

© Johan Jarnestad/The Royal Swedish Academy of Sciences



-物理の分野における革新的な発明 THE ROYAL SWEDISH ACADEMY OF SCIENCES

Optical tweezers 光ピンセット

method of generating high-intensity, ultra-short optical pulses

高強度超短光パルスを発生する方法

Scientific Background on the Nobel Prize in Physics 2018 https://www.nobelprize.org/uploads/2018/10/advanced-physicsprize2018.pdf

— Applications

- Strong-field physics and attosecond science 高強度場物理とアト秒科学 This week (May 20) Advanced Laser and Photon Science
- Laser-plasma acceleration
 レーザープラズマ加速
 July 8 by Dr. Kondo

High-intensity lasers in industry and medicine 産業・医療用高強度レーザー Last week (May 13)



©Johan Jarnestad/The Royal Swedish Academy of Sciences

© Johan Jarnestad/The Royal Swedish Academy of Sciences



High-harmonic generation 高次高調波発生

more details at Advanced Laser and Photon Science on May 27, 2020



Chat your student ID number and full name.

References 参考文献

- * The lecture material is downloadable from: http://ishiken.free.fr/english/lecture.html
- * M. Protopapas, C.H. Keitel and P.L. Knight, "Atomic physics with super-high intensity lasers", Rep. Prog. Phys. 60, 389– 486 (1997)
- * F. Krausz and M. Ivanov, "Attosecond Physics", Rev. Mod. Phys. 81, 163-234 (2009)
- K. L. Ishikawa, High-harmonic generation, in Advances in Solid-State Lasers, ed. by M. Grishin (INTEH, 2010), pp. 439-464
- * 大森賢治編「アト秒科学: 1京分の1秒スケールの超高速現象 を光で観測・制御する」(化学同人、2015/8/10)

高調波発生 (Harmonic generation)



高次高調波発生 High-harmonic generation (HHG)

discovered in 1987



Highly nonlinear optical process in which the frequency of laser light is converted into its integer multiples. Harmonics of very high orders are generated.

> 新しい極端紫外・軟エックス線光源として注目される。 New extreme ultraviolet (XUV) and soft X-ray source

Plateau (プラトー) - remarkable feature of high-harmonic generation



プラトー(plateau): Efficiency does NOT decrease with increasing harmonic order. 次数が上がっても強度が落ちない。

カットオフ(cutoff): Maximum energy of harmonic photons $E_c \approx I_p + 3U_p$ $U_p(eV) = \frac{e^2 E_0^2}{4m\omega^2} = 9.3 \times 10^{-14} I(W/cm^2)\lambda^2(\mu m)$ ponderomotive energy 摂動論では解釈できない(non-perturbative)

高次高調波発生のメカニズム = 3 step model Mechanism of HHG = 3 step model



Paul B. Corkum, Phys. Rev. Lett. 71, 1994 (1993)

高次高調波発生のメカニズム = 3 step model Mechanism of HHG = 3 step model





高次高調波発生の3ステップモデル 3-step model of HHG

Paul B. Corkum, Phys. Rev. Lett. 71, 1994 (1993) K. C. Kulander, K. J. Schafer, and J. L. Krause, in Super-Intense Laser-Atom Physics, NATO ASI, Ser. B, 316, 95 (1993)

> Ionization at $\omega t_0 = \phi_0$ $z = \frac{E_0}{\omega^2} \left[(\cos \phi - \cos \phi_0) + (\phi - \phi_0) \sin \phi_0 \right]$ $E_{\text{kin}} = 2U_p (\sin \phi - \sin \phi_0)^2$

Recombination at $\phi = \phi_{\mathrm{ret}}(\phi_0)$, which satisfies z = 0



https://photonics.uottawa.ca/en/ people/corkum-paul



高次高調波発生の3ステップモデル 3-step model of HHG



Quantum Beam Engineering (Kenichi ISHIKAWA) for internal use only (Univ. of Tokyo) http://ishiken.free.fr/english/lecture.html This lecture is recorded for possible on-demand streaming. Chat your student ID number and full name.

Even up to 1.6 keV, > 5000 orders (almost) x-ray!



Popmintchev et al., Science 336, 1287 (2012)

a new type of laser-based radiation source

レーザーをベースにした新しいタイプの放射線源



What happens if the fundamental laser pulse is very short? では、超短パルスレーザ ーによる高次高調波はどんな感じ? Hentschel et al. Nature 414, 509, (2001)





Quantum Beam Engineering (Kenichi ISHIKAWA) for internal use only (Univ. of Tokyo) Chat your student ID number and full name.

How to generate an isolated attosecond pulse (IAP)





Quantum Beam Engineering (Kenichi ISHIKAWA) for internal use only (Univ. of Tokyo) Chat your student ID number and full name.



Quantum Beam Engineering (Kenichi ISHIKAWA) for internal use only (Univ. of Tokyo) Chat your student ID number and full name.

IONIZATION SHUTTER HHG is suppressed when neutral atoms are depleted



Isolated sub-fs pulse generation from a ~ 10 fs pulse Sekikawa et al., Nature 432, 605 (2004) 20

Quantum Beam Engineering (Kenichi ISHIKAWA) for internal use only (Univ. of Tokyo) Chat your student ID number and full name.

and Marchara

HHG is suppressed when circular polarization is used

counter-rotating circularly polarized pulses with a delay Sansone et al., Science

POLARIZATION GAT





С HHG bursts Laser field 1.0- Ar = 0.8 µm EUV intensity 0.6-0.7-0.7-0.7-Phase (rad) 0 200 400 -200 Time (as) **Bi-colour** field with shaped polarization Single HHG burst

IAP generation from a > 20 fs pulse without need of carrierenvelope stabilization

Gilbertson et al., PRL 105, 093902 (201 Gilbertson et al., PRA 81, 043810 (201

23

Quantum Beam Engineering (Kenichi ISHIKAWA) for internal use only (Univ. of Tokyo) Chat your student ID number and full name.

INFRARED TWO-COLOR SYNTHESIS

800 nm + 1300 nm two-color driving field



High-energy (I.3 micro J), high-power (2.6 GW) IAP

more than 100 times more energetic than previously reported

FROM FEMTOSECOND TO ATTOSECOND



25

Quantum Beam Engineering (Kenichi ISHIKAWA) for internal use only (Univ. of Tokyo) Chat your student ID number and full name.

Quest for higher photon energy (shorter wavelength)

cutoff $E_c = I_p + 3.17U_p$

$$U_p(\text{eV}) = \frac{e^2 E_0^2}{4m\omega^2} = 9.3 \times 10^{-14} I(\text{W/cm}^2) \lambda^2(\mu\text{m})$$

Longer fundamental wavelength is advantageous

Optical parametric chirped-pulse amplification (OPCPA)

WATER-WINDOW HHG

spectral range between the K-absorption edges of C (284 eV) and O (543 eV)

absorbed by biological samples but not by water

attractive for high-contrast biological imaging



Quantum Beam Engineering (Kenichi ISHIKAWA) for internal use only (Univ. of Tokyo) Chat your student ID number and full name.

keV HHG Even up to 1.6 keV, > 5000 orders almost x-ray!



Popmintchev et al., Science 336, 1287 (2012)

a new type of laser-based radiation source

Quantum Beam Engineering (Kenichi ISHIKAWA) for internal use only (Univ. of Tokyo) Chat your student ID number and full name.

Report Assignment

Summarize the Physics Nobel Prize 2018 including,

- Who won it for what.
- Its significance
- Applications
- Your own opinion on it