Optical Frequency Combs

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MSc Seminar

Your passion for Physics: what are you curious about?

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Introduction

Passion for precision

- With better measuring tools, one can look where no one has looked before.

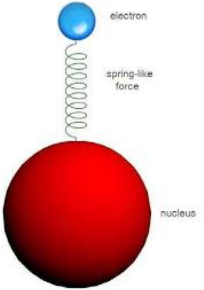
In this talk...

- Definition of Optical Frequency Combs (OFC).
- Description of a Mode-locking technique to create them.
- Determining the parameters of the OFC.
- Applications of Frequency Combs.

Measuring time I

What makes a good clock?

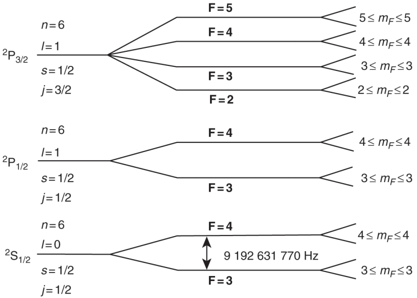
- Goal: increase the number of oscillations per unit time (ticks per second).



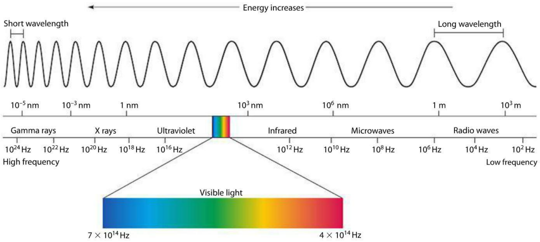
IS definition of the second

One second in the IS is measured as the time taken by 9,192,631,770 cycles of radiation from electrons moving between the ground-state hyperfine transition energy levels of the caesium-133 atom.

Measuring time II



Energy levels of Cs^{133} [1]



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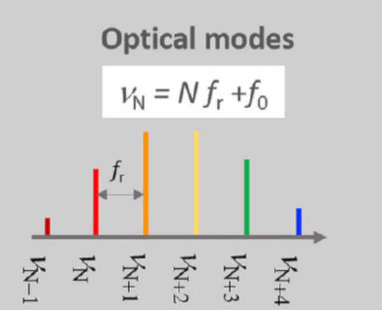
Optical Frequency Combs



Adapted from [2]

OFC = coherent addition of $10^5 - 10^6$ optical cavity modes, spanning up to 100 nm in the optical domain.

T.W. Hänsch and J.L.Hall

Photo: Sears.P.Studio
John L. Hall
Prize share: 1/4

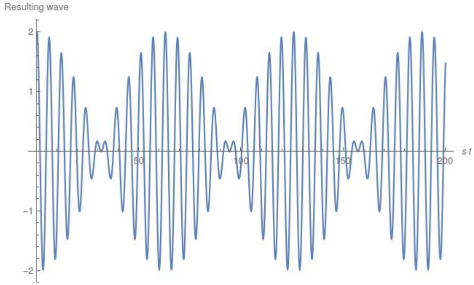
Photo: F.M. Schmidt
Theodor W. Hänsch
Prize share: 1/4

"For their contributions to the development of laser-based precision spectroscopy, including the optical frequency comb technique."

Addition of modes

Monochromatic wave (in time space): $\Psi_n(t) = A_n \cos(\omega n t + \phi)$

$\Psi_1(t) + \Psi_2(t)$



Fast oscillation $\rightarrow \frac{\omega_1+\omega_2}{2}$
Slow oscillation $\rightarrow \frac{\omega_1-\omega_2}{2}$

Addition of modes

Monochromatic wave (in time space): $\Psi_n(t) = A_n \cos(\omega n t + \phi)$

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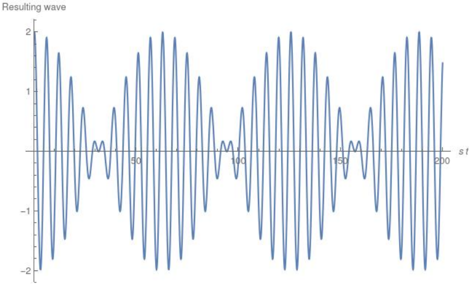
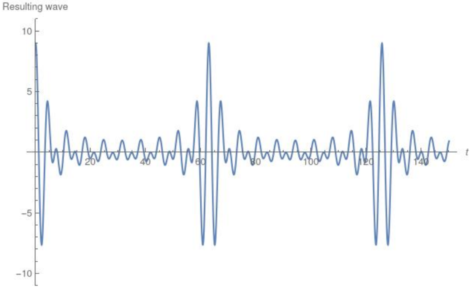
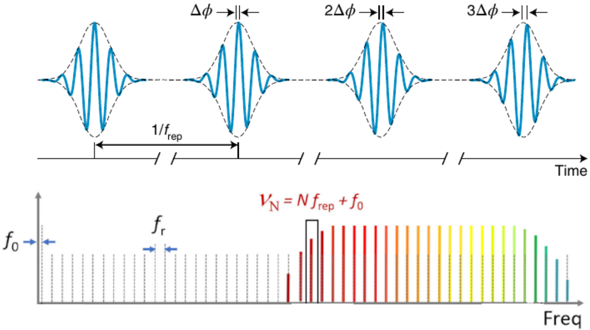


$\sum_{n=1}^{8} \Psi_n(t)$



Fast oscillation $\rightarrow \frac{\omega_1+\omega_2}{2}$
Slow oscillation $\rightarrow \frac{\omega_1-\omega_2}{2}$

Optical Frequency Combs in the time domain

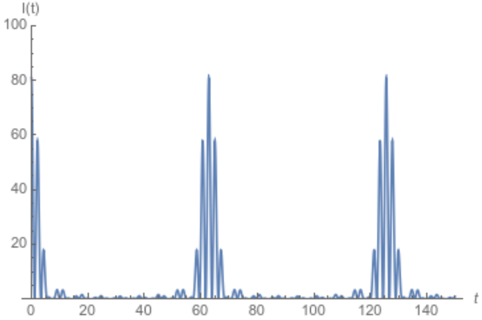


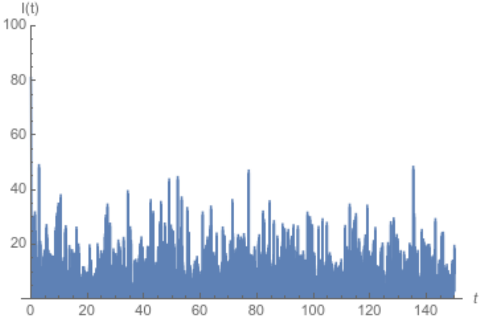
Adapted from [3]

- $\Delta\phi$ = phase shift of the carrier of the wave relative to the envelope of the pulses
- Induces the translation $f_0 = \frac{\Delta\phi}{2\pi}$ of all the lines in the spectrum from nf_r

Importance of the phase

$$\Psi_n(t) = A_n \cos(\omega n t + \phi)$$





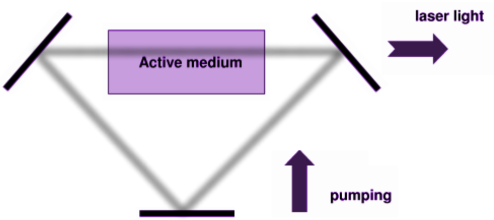
Interference of $N = 8$ modes in phase (a) and with random relative phases (b)

Contents

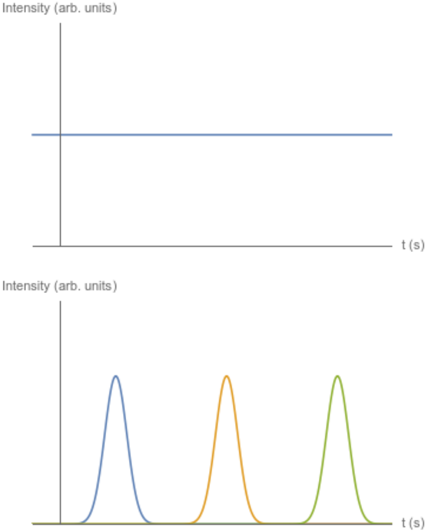
The laser

Elements of a laser:

- Cavity.
- Active medium.
- Pumping parameter.

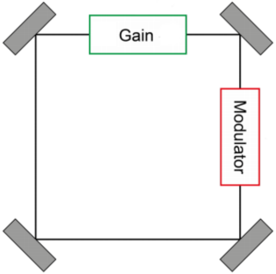


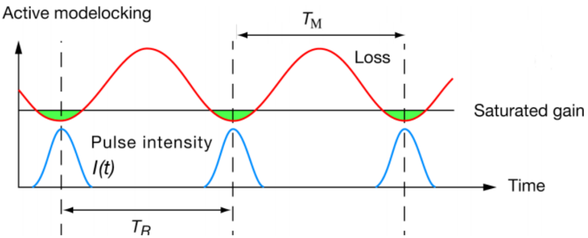
Adapted from [4]



Active mode locking

- A modulator is introduced in the cavity $T(t) = e^{M(t)}$.
- $M(t) = M(\cos(\Omega_M t) - 1)$,
  - $\Omega_M \rightarrow$ frequency of the modulator (s^{-1}),
  - $M \rightarrow$ amplitude of the modulator.





Cavity and evolution of the pulse when introducing the modulator. Adapted from [5]

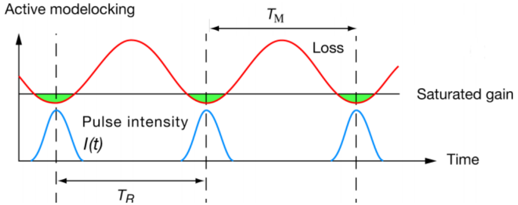
Creation of “locked” modes

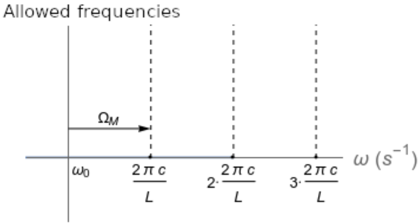
- Suppose initial monochromatic light $E^{in}(t) \propto e^{-i\omega_0 t}$

$$
\begin{aligned}
E^{out}(t) &= T(t)E^{in}(t) \propto e^{M(t)}e^{-i\omega_0 t}\\
&= e^{M(\cos(\Omega_M t)-1)}e^{-i\omega_0 t}\\
&\approx (1 + M(\cos(\Omega_M t) - 1))e^{-i\omega_0 t}\\
&= (1 - M)e^{-i\omega_0 t} + \frac{M}{2}e^{-i(\omega_0+\Omega_M)t} + \frac{M}{2}e^{-i(\omega_0-\Omega_M)t}.
\end{aligned}
$$

The period of the modulator must have

$$T_M = \frac{2\pi}{\Omega_M} = \frac{L}{c}.$$





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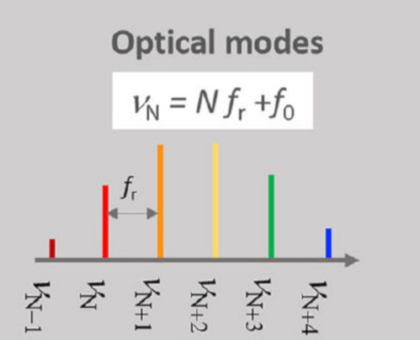
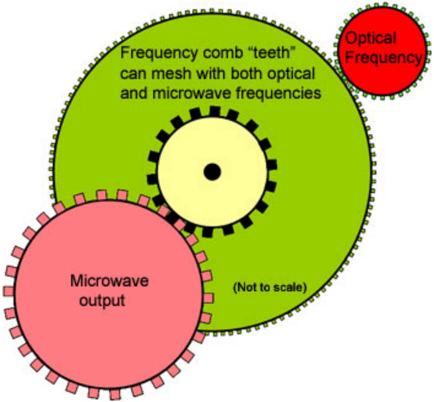
Optical Clocks

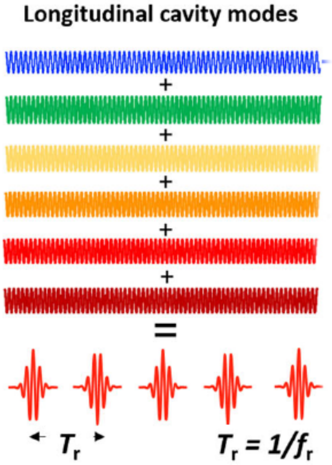


Adapted from [2]



From [6]

Determining f_r



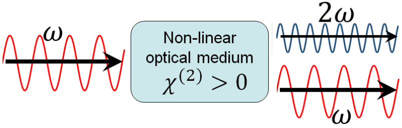
Adapted from [2]

Typical cavity lengths are between 30cm and 3m $\rightarrow f_r$ is in the microwave domain

The beatings offer information on phase differences.
$\rightarrow f_r$ can be observed
$\rightarrow$ no information on f_0 is available

$$\begin{aligned} f_N - f_M &= (N\, f_r + f_0) - (M\, f_r + f_0) \\ &= (N - M) f_r \end{aligned}$$

Determining f_0



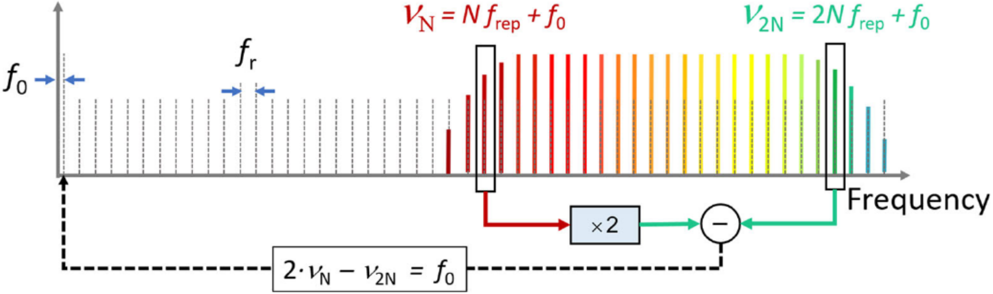
Second Harmonic Generation scheme. Source:wikipedia.

Generate a second OFC with double frequencies

If some of the lines of the original and the "doubled" OFC interfere, the beatings offer information on f_0

$$2f_N - f_{2N} = 2(Nf_r + f_0) - (2Nf_r - f_0) = f_0$$

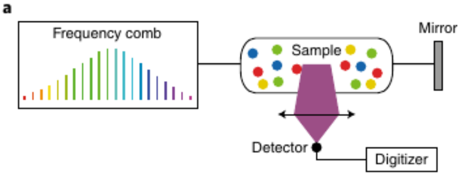
Determining f_0



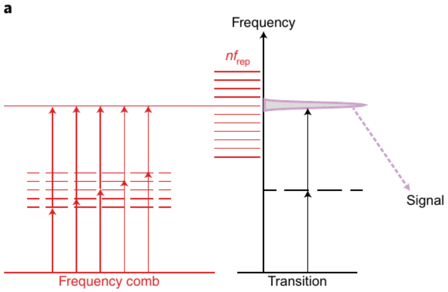
From [2]

Contents

Direct Spectroscopy I



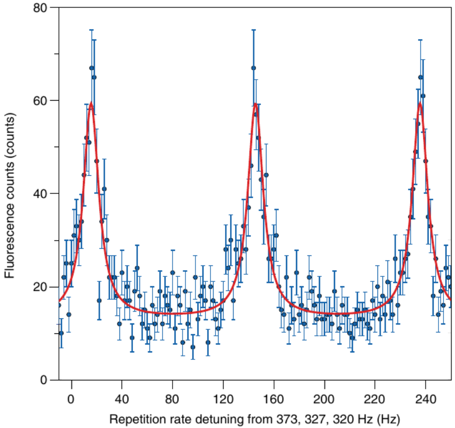
Figures from [3]



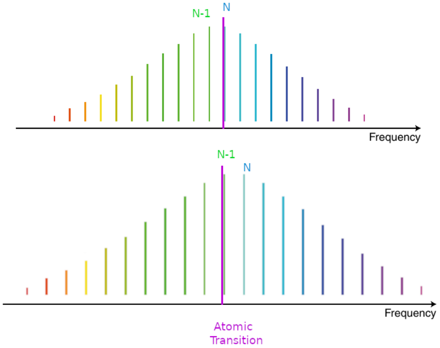
Ideally, line spacing > transition bandwidth

It can produce one- or two- photon excitation

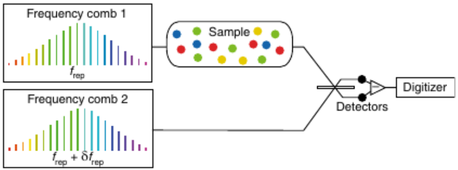
Direct Spectroscopy II



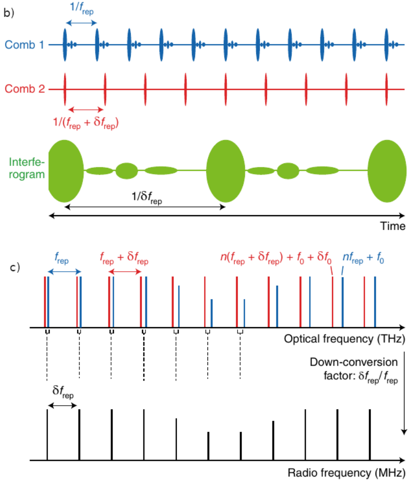
Direct frequency comb spectrum of the D2 line of a single Mg^+ ion around 280 nm (1,070 THz) observed through fluorescence. From [3]



Dual-Comb Spectroscopy

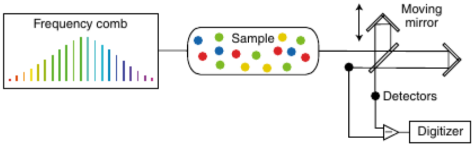


(a)



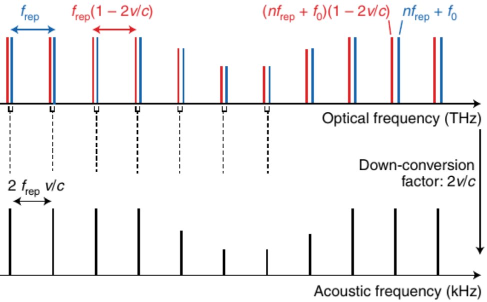
Schematic representation of Dual-Comb spectroscopy (a). Dual comb spectroscopy in the time domain (b) and in the frequency domain (c). From [2]

Michelson-based spectroscopy



a

b



Schematic representation of Michelson-based spectroscoper (a). Dual comb spectroscopy in the time and in the frequency domains (b) From [2]

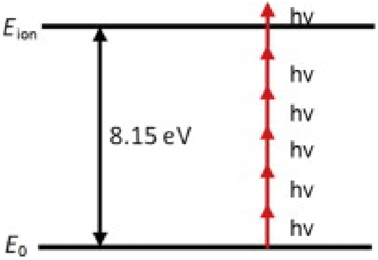
FC for the study of non-linear phenomena

- The experiments on non-linear phenomena (MPI, HHG*, ATI*...) are highly dependendent on the laser intensity (I)
- OFC could be new field of precision tests in nonlinear physics
- Higher repetition rates → lower acquisition times

The problem:

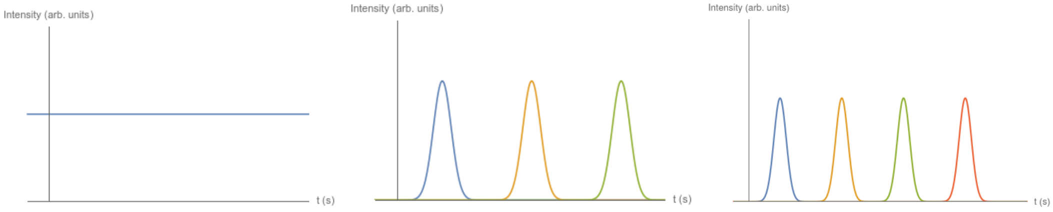
Increasing the repetition rate decreases laser I

HHG* = High-order Harmonic Generation
ATI* = Above Threshold Ionization



Multi-Photon ionization (MPI). Source: wikipedia.

Increasing the repetition rate decreases intensity



Constant and pulsed emission of a laser.

Velocity-map imaging of multi-photon ionization (MPI) in xenon

100 MHz frequency comb for low-intensity multi-photon studies: intra-cavity velocity-map imaging of xenon

J. NAUTA,[1,2,*] J.-H. OELMANN,[1,2] A. ACKERMANN,[1] P. KNAUER,[1] R. PAPPENBERGER,[1] A. BORODIN,[1] I. S. MUHAMMAD,[1] H. LEDWA,[1] T. PFEIFER,[1] AND J. R. CRESPO LÓPEZ-URRUTIA[1]

Multi-photon ionization in xenon: experimental set-up

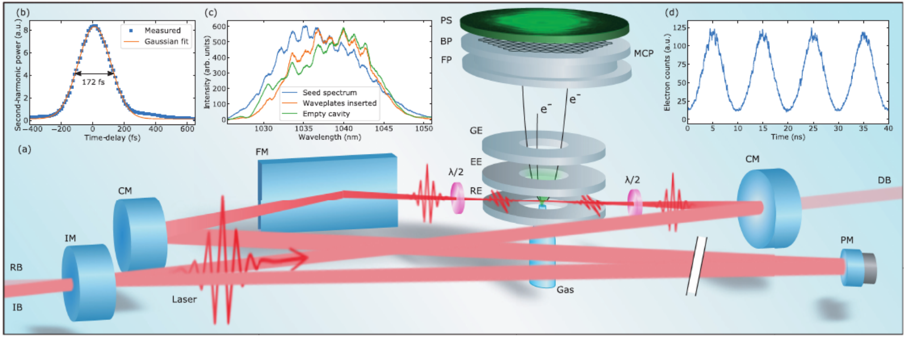
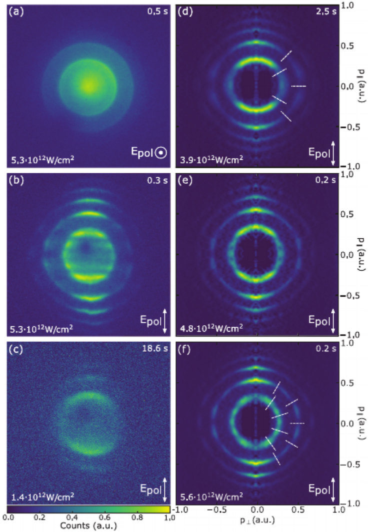
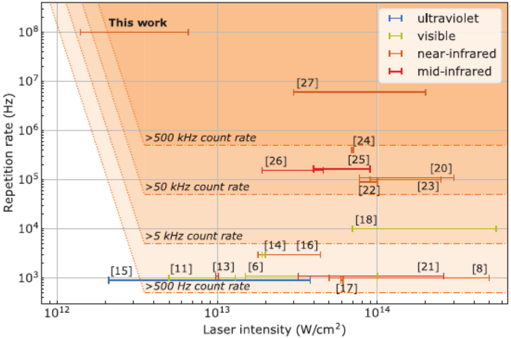


Fig. 1. Schematic overview of the experimental setup. (a) 100 MHz femtosecond pulses are fed into a resonant bow-tie cavity, where they are enhanced and focused on an effusive gas target. There, multi-photon ionization generates photoelectrons that are detected on a micro-channel plate (MCP) with its screen imaged by a camera. IB, incoming beam; RB, reflected beam; IM, input coupler mirror; CM, curved mirror; DB, diagnostic beam; FM, flat mirror; PM, piezo mirror; $\lambda/2$, half-wave plate; RE, repeller electrode; EE, extractor electrode; GE, ground electrode; FP, front plate; BP, back plate; PS, phosphor screen. (b) Auto-correlation measurement of the pulse length before entering the cavity, fitted assuming a Gaussian shape. (c) Comparison of the seed spectrum (blue) and intra-cavity spectrum with (orange) and without (green) half-wave plates inserted, showing no significant spectral narrowing due to the plates. (d) Arrival of electron bunches ionized by individual laser pulses, separated by 10 ns.

From [7]

Multi-photon ionization in xenon: experimental results





Photoelectron spectra for Xenon and contextualization of their work. Figures from [7].

FC for studying Highly Charged Ions (HCI)

Applications of HCI

- Improvement of atomic clocks.
- High sensitivity to the variation of fundamental constants (later).

The vast majority of electronic transitions in HCI are located in the extreme ultraviolet regime (XUV).

FC for studying Highly Charged Ions (HCI)

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- Improvement of atomic clocks.
- Advances in Quatum Computing.
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The vast majority of electronic transitions in HCI are located in the extreme ultraviolet regime (XUV).

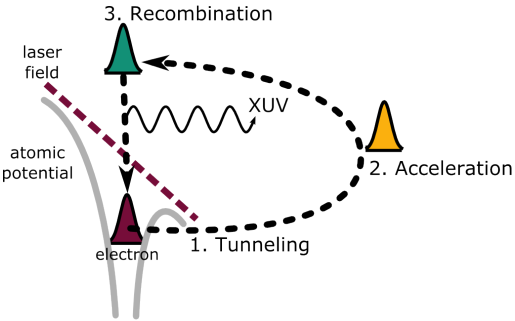
The challenge:

Create a Frequency Comb in the XUV regime using High-order Harmonic Generation (HHG).

Three-step model for High-order Harmonic Generation (HHG)

Process of HHG

1. An atom is exposed to a very intense Electric Field (∼ intraatomic Coulomb potential).
2. Tunnel ionization and propagation of the electron in the electric field.
3. Recollision with the parent ion → emission of High-order Harmonic of the original radiation.



Three-step model of HHG. Source: wikipedia

FC for studying Highly Charged Ions

Towards precision measurements on highly charged ions using a high harmonic generation frequency comb

Janko Nauta [a,*], Andrii Borodin [a], Hans B. Ledwa [c], Julian Stark [a], Maria Schwarz [a,b], Lisa Schmöger [a,b], Peter Micke [a,b], José R. Crespo López-Urrutia [a], Thomas Pfeifer [a]

Highly Charged Ions study: experimental set-up

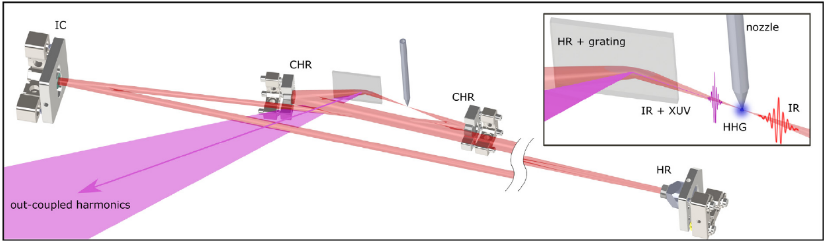
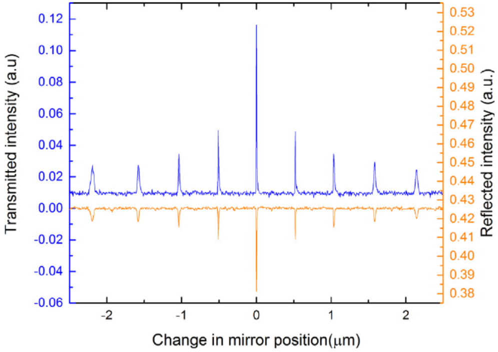


Fig. 1. Overview of the femtosecond enhancement cavity. Infrared (IR) pulses are coupled in through the in-coupling mirror (IC) and circulate in the cavity composed of four other high-reflective (HR) mirrors. In one of this mirrors, a shallow grating structure is etched. The inset shows high-order harmonic generation (HHG) inside the tight focus of the cavity, created by the two curved mirrors in the middle (CHR). The high-order harmonics (labeled XUV) propagate collinearly with the IR beam, and are coupled out of the cavity using the minus-first order diffraction of the grating.

From [8]

Highly Charged Ions study: results for the cavity



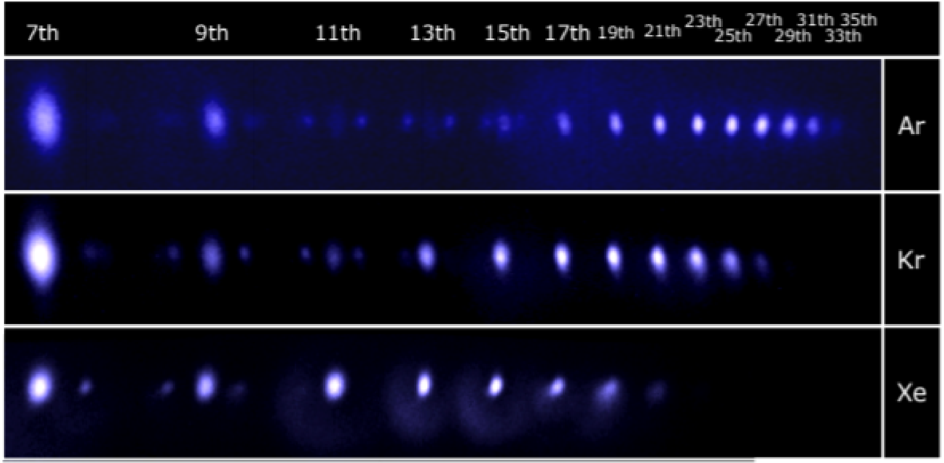
Transmitted and reflected intensities from the enhacement cavity w.r.t. changes in the cavity length (from L = 3m). From [8]

- The central ressonance corresponds to a cavity length of 3m.
- It matches exactly the repetition rates cycles of 100MHz used in the experiment

$$L = \frac{c}{100MHz} = 3m.$$

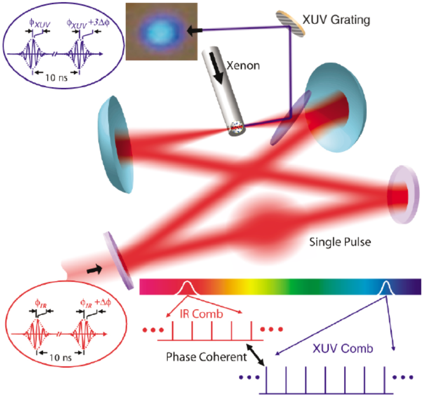
- Next step → working on the production of the HHG.

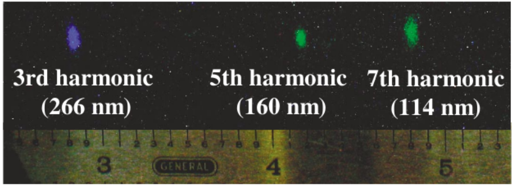
Results on High-order Harmonic Generation



Fluorescence (from sodium salicycate) by various harmonic orders for three different target gases. From [9]

Previous work on cavity-enhaced High-order Harmonic Generation





Work of R. Jones, K. Moll, M. Thorpe, J. Le in HHG (2005). From [10]

Other applications

More applications for frequency combs

- Applications of pulsed radiation with high intensity: Cornea laser operations, nuclear reactions...

  → Nobel prize 2018: Gérard Mourou and Donna Strickland "for their method of generating high-intensity, ultra-short optical pulses."

- Study of other non-linear phenomena (second harmonic generation, parametric down conversion...).

- Spectroscopy in Astronomy: observation of exoplanets. [11]

- Precision measurements of fundamental constants.

Are the fundamental constants really **constant**?

Contents

Conclusions

- Precision measurements are very important in science → look where no one has looked before!
- Frequency Combs are a powerful tool for measuring frequencies with previosly unreached resolution.
- They are key for:
  - atomic clocks
  - highly precise spectroscopy
  - experiments on non-linear phenomena
  - other series of experiments that need high precision in frequency measurements
- Mode-locking techniques are a tool to create ultrashort pulsed radiation that ranges from ps to fs.

Thanks for listening!
Any questions?

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2. Fortier, T. & Baumann, E. “20 years of developments in optical frequency comb technology and applications”. *Commun. Phys.* **2,** 153 (2019).
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8. Nauta, J. *et al.* "Towards precision measurements on highly charged ions using a high harmonic generation frequency comb". *Nucl. Instrum. Meth. Phys. Res. B* **408,** 285–288 (2017).

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10. Jones, R. J., Moll, K. D., Thorpe, M. J. & Ye, J. "Phase-Coherent Frequency Combs in the Vacuum Ultraviolet via High-Harmonic Generation inside a Femtosecond Enhancement Cavity". *Phys. Rev. Lett.* **94,** 193201 (19 May 2005).

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