

# Quantum Ultra fast lasers

← [Quantum](#)

- [Femtosecond lasers](#) ( $10^{-15}$  s)
- [Attosecond lasers](#) ( $10^{-18}$  s)
- [Zeptosecond lasers](#) ( $10^{-21}$  s)
- [Yoctosecond timescales](#) ( $10^{-24}$  s)
- [Rontosecond timescales](#) ( $10^{-27}$  s)

Ultrafast lasers represent a new frontier in photonics and quantum optics, enabling the generation of light pulses with durations spanning from femtoseconds ( $10^{-15}$  seconds) down to theoretical yoctoseconds ( $10^{-24}$  seconds). These brief bursts of coherent light allow researchers to "freeze" and investigate ultrafast phenomena that occur on atomic, electronic, and even subnuclear timescales, processes that are too fast for traditional observation methods. From capturing the movement of electrons in atoms to probing the inner workings of quark-gluon plasmas, ultrafast lasers have transformed our understanding of matter, energy, and time itself.

The evolution of ultrafast laser technology traces back to the 1960s with mode-locking for picosecond pulses, through the femtosecond era in the 1980s and 1990s, and reaching attosecond capabilities in the early 2000s. Key innovations, such as chirped pulse amplification (CPA), recognized with the 2018 Nobel Prize in Physics for Donna Strickland and Gérard Mourou, and high-harmonic generation (HHG), honored in the 2023 Nobel for Pierre Agostini, Ferenc Krausz, and Anne L'Huillier, brought this field forward. Recent advancements, including zeptosecond measurements in 2020 and experimental attosecond X-ray lasers by 2025, continue to push boundaries, with yoctosecond pulses emerging as a theoretical horizon for exploring quantum chromodynamics and beyond.

This learning project explores the principles, generation methods, historical milestones, and applications of ultrafast lasers across progressively shorter timescales. Through detailed explanations, diagrams, and quizzes, this resource aims to demystify these complex technologies for students, researchers, and enthusiasts. Whether you're studying quantum mechanics or exploring practical applications in medicine and computing, ultrafast lasers illuminate the unseen universe.

Ultrafast time-resolved X-ray probes as tools in solid-state physics and Chemistry applied in research. This type of work will lead to a deeper understanding of how light induced processes alter the structure of matter. The dynamic behaviour of solids is closely linked to the motion of their atoms, with the critical timescale being that of a typical atomic vibration, roughly 100 femtoseconds ( $10^{-13}$  seconds). This is exactly the window in which molecular motions, chemical reactions and solid-state phase transitions take place.

Unlike today's femtosecond laser-based probes, X-rays have wavelengths comparable to the spacing between atoms themselves. That match lets us image atomic displacements directly. For this reason, X-ray diffraction is the obvious and most powerful method for tracking how atomic structures evolve in real time.


Ever since their discovery, X-rays have remained the gold-standard tool for determining atomic arrangements. The development of time-resolved X-ray diffraction probes with sub-picosecond resolution will unlock transformative new science by showing rapidly changing structures as they happen. At present, advancing this work through international collaborations that gives access to the femtosecond X-ray sources already available worldwide.


## Femtosecond Pulse Lasers


### What Are Femtosecond Pulse Lasers?


Femtosecond pulse lasers produce extremely short bursts of light, with durations on the order of femtoseconds (1 femtosecond =  $10^{-15}$  seconds, or one quadrillionth of a second). This is about a thousand times longer than attosecond pulses but still incredibly brief, comparable to the timescale of molecular vibrations or electron movements in chemical bonds. These pulses allow for precise control over energy delivery, minimizing heat transfer to surrounding materials, which makes them ideal for applications requiring high accuracy without thermal damage.

Unlike continuous-wave lasers or longer-pulse (nanosecond) lasers, femtosecond pulses achieve high peak intensities (often in the gigawatt to terawatt range) while keeping average power low, enabling nonlinear optical effects like multiphoton absorption without melting or ablating unintended areas.

 **Attribution:** this resource was created by [Harold Foppele](#).

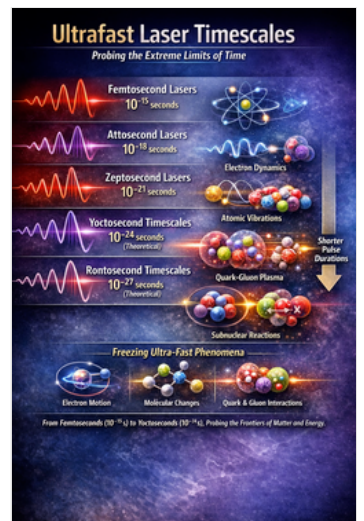
 **Subject classification:** this is a [physics](#) resource.

 **Type classification:** this is a [quiz](#) resource.

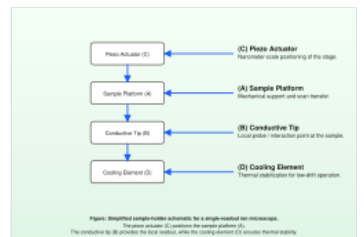
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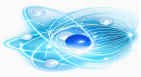
Artistic impression of an atom 10



An infographic illustrates ultrafast laser pulses



Ion microscope



Femtosecond pulses are primarily generated using **passive mode-locking** in solid-state lasers, such as titanium-sapphire (Ti:sapphire) lasers. Mode-locking synchronizes the phases of multiple longitudinal modes in the laser cavity, causing them to interfere constructively and produce short pulses. Key techniques include:

- **Kerr Lens Mode-Locking (KLM):** The laser medium (e.g., Ti:sapphire crystal) acts as a Kerr medium, where intense light induces a refractive index change, creating a self-focusing effect that favors pulsed operation over continuous wave.
- **Chirped Pulse Amplification (CPA):** To boost power without damaging optics, pulses are stretched (chirped) in time, amplified, and then compressed back to femtosecond durations. This is crucial for high-energy applications.<sup>[1]</sup>
- **Dispersion Control:** Prisms, gratings, or chirped mirrors compensate for group velocity dispersion in the cavity to maintain short pulse widths.

Typical setups use a pump laser (e.g., green diode-pumped solid-state laser) to excite the Ti:sapphire crystal, producing pulses around 800 nm with durations from 5 fs to hundreds of fs.

Here's a diagram illustrating femtosecond laser pulse generation:

For X-ray femtosecond pulses, methods like high-harmonic generation or free-electron lasers are used, building on optical femtosecond drivers.

## Attosecond Pulse Lasers

### What Are Attosecond Pulse Lasers?

Attosecond pulse lasers produce extremely short bursts of light lasting on the order of attoseconds (1 attosecond =  $10^{-18}$  seconds, or one quintillionth of a second). To put that in perspective, there are as many attoseconds in one second as there are seconds in the age of the universe. These pulses are so brief that they allow scientists to capture and study ultrafast processes at the atomic and subatomic levels, such as the motion of electrons within atoms.

Unlike longer-pulse lasers (e.g., femtoseconds at  $10^{-15}$  seconds), attosecond pulses "freeze-frame" electron dynamics, revealing behaviors that unfold too quickly for other tools to observe. This capability stems from advances in nonlinear optics, where intense laser light interacts with matter in ways that defy simple linear predictions.

### How Are Attosecond Pulses Generated?

The primary method for creating attosecond pulses is **high harmonic generation (HHG)**, a nonlinear process where an intense infrared laser pulse (often from a titanium-sapphire laser) interacts with a noble gas like argon or neon in a vacuum. Here's a step-by-step breakdown based on the "three-step model" developed by physicist Paul Corkum:<sup>[2]</sup>

1. **Ionization:** The strong electric field of the driving laser pulse strips an electron from an atom, freeing it into a continuum state.
2. **Acceleration:** The freed electron is accelerated away from the atom by the oscillating laser field, gaining kinetic energy.
3. **Recollision and Recombination:** As the laser field reverses, the electron is driven back toward the atom. Upon recolliding, it recombines with the ion, releasing its excess energy as a high-energy photon in the extreme ultraviolet (EUV) or soft X-ray range. This burst is the attosecond pulse.

This process repeats with each half-cycle of the driving laser, but techniques like chirped pulse amplification (CPA), spectral broadening, and carrier-envelope phase stabilization help isolate single attosecond pulses as short as 60-100 attoseconds.

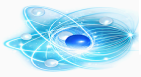
Other sources include free-electron lasers (FELs), but HHG is more common for tabletop setups. Recent breakthroughs have extended this to X-ray wavelengths, creating attosecond atomic X-ray lasers by focusing high-power X-ray pulses onto metal targets like copper or manganese, triggering stimulated emission.<sup>[3]</sup>

Here's a diagram illustrating the HHG process:

### History and Key Milestones

The field of attosecond science emerged in the early 2000s, building on femtosecond laser technology from the 1980s and '90s. Key enablers included:

- **1986:** Development of broadband Ti:sapphire lasers.
- **1988:** Chirped pulse amplification for high-intensity pulses.
- **1994:** Chirped mirrors for dispersion control.
- **2000:** Carrier-envelope offset stabilization.
- **2004-2006:** First isolated attosecond pulses via HHG.



By 2025, researchers at SLAC National Accelerator Laboratory and the University of Wisconsin-Madison created the first attosecond atomic X-ray laser, pushing pulse durations below 100 attoseconds in hard X-rays.<sup>[5]</sup>

## Applications

Attosecond pulses open windows into fundamental physics and chemistry:

- **Electron Dynamics:** Track electrons orbiting atoms or being ejected during ionization, providing insights into quantum mechanics.
- **Molecular Processes:** Observe bond formation/breaking in real time, aiding drug design and photochemistry.
- **Material Science:** Probe phase transitions or superconductivity at atomic scales.
- **Advanced Imaging:** Measure atomic sizes more precisely or image electron wavefunctions.
- **Future Tech:** Potential for ultrafast electronics, petahertz computing, or precision metrology in optical clocks.

These tools are unique because no other method can resolve events on attosecond timescales—femtoseconds are too slow for electron-level details.

For a visual of pulse isolation in few-cycle driving fields:

## Zeptosecond Pulse Lasers and Measurements

Generating pulses at the  $10^{-21}$  s scale remains elusive experimentally due to fundamental limits in laser technology, such as the need for extreme phase control, high intensities, and longer-wavelength driving lasers to push harmonics into shorter durations.

## History

The development of zeptosecond pulse lasers represents the latest milestone in the ongoing quest to generate and measure ever-shorter laser pulses, enabling scientists to probe ultrafast phenomena at atomic and subatomic scales. This journey builds on decades of advancements in laser technology, starting from the invention of the laser itself.

- **Early Foundations (1960s–1970s)** The laser was first demonstrated in 1960 by Theodore Maiman using a ruby crystal, producing coherent light in millisecond pulses. Initial lasers operated in continuous-wave mode, but techniques like Q-switching (developed in the early 1960s) soon allowed for nanosecond pulses, useful for high-power applications. In 1964, mode-locking was invented, enabling picosecond ( $10^{-12}$  seconds) pulses by synchronizing laser cavity modes. By the 1970s, dye lasers refined these methods, pushing pulse durations into the sub-picosecond range and laying groundwork for ultrafast science.
- **Femtosecond Era (1980s–1990s)** The 1980s marked the advent of femtosecond ( $10^{-15}$  seconds) lasers, primarily through colliding-pulse mode-locked dye lasers and titanium-sapphire (Ti:sapphire) lasers, which became dominant by the late 1980s. A pivotal breakthrough was chirped pulse amplification (CPA) in 1985 by Gérard Mourou and Donna Strickland, allowing amplification of ultrashort pulses to high energies without damaging optics, this earned them the 2018 Nobel Prize in Physics. Femtosecond pulses enabled femtochemistry, pioneered by Ahmed Zewail, who used them to observe molecular reactions in real time. Zewail received the 1999 Nobel Prize in Chemistry for this work.
- **Attosecond Advances (2000s)** By the early 2000s, high-harmonic generation (HHG) in gases driven by intense femtosecond lasers produced attosecond ( $10^{-18}$  seconds) pulses in the extreme ultraviolet (EUV) and soft X-ray regimes. The first isolated attosecond pulses were generated around 2001, opening attosecond science for studying electron dynamics. Facilities like free-electron lasers (FELs) and advancements in CPA further intensified these pulses, reaching petawatt powers by the 2010s.
- **Zeptosecond Breakthroughs (2010s–Present)** Zeptosecond ( $10^{-21}$  seconds) pulses, a thousand times shorter than attoseconds, emerged as theoretical concepts in the early 2010s. In 2013, researchers proposed methods using mid-infrared lasers and HHG with multiple electron rescatterings to generate zeptosecond X-ray waveforms. Another approach involved relativistic plasma mirrors for compressing pulses to zeptosecond durations. The first experimental measurement of a zeptosecond timescale occurred in 2020 at Goethe University Frankfurt and DESY, where scientists recorded 247 zeptoseconds, the time for a photon to traverse a hydrogen molecule, using X-ray pulses from the PETRA III accelerator. This built on attosecond techniques and marked a new record in time resolution.

**Dimitar popmintchev** is a physicist at TU Wien's Photonics Institute, specializing in high-harmonic generation (HHG) for coherent EUV/soft X-ray sources.

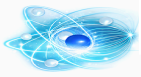
### Key contributions:

- Efficient soft X-ray HHG in ionized plasmas (*Science*, 2015).<sup>[6]</sup>
- Resonant attosecond dynamics (*Phys. Rev. Research*, 2025).<sup>[7]</sup>
- Tabletop zeptosecond X-ray sources (Popmintchev LABS).<sup>[8]</sup>

Ongoing research focuses on generating stable zeptosecond pulses for applications like nuclear dynamics and quantum vacuum studies, with proposals for even shorter yoctosecond ( $10^{-24}$  seconds) pulses on the horizon. The field continues to evolve, driven by facilities like the European XFEL and Extreme Light Infrastructure (ELI).

## Theoretical and Proposed Zeptosecond Pulses

Theoretical work has outlined paths to zeptosecond-scale X-ray pulses (around a few hundred to 800 zeptoseconds) using advanced HHG techniques.<sup>[9]</sup>



pulse into a train of zeptosecond bursts (e.g.,  $\sim 800$  zs each). Longer-wavelength infrared drivers are key, as they enable higher-energy harmonics and shorter output pulses, though developing such lasers is a major challenge.



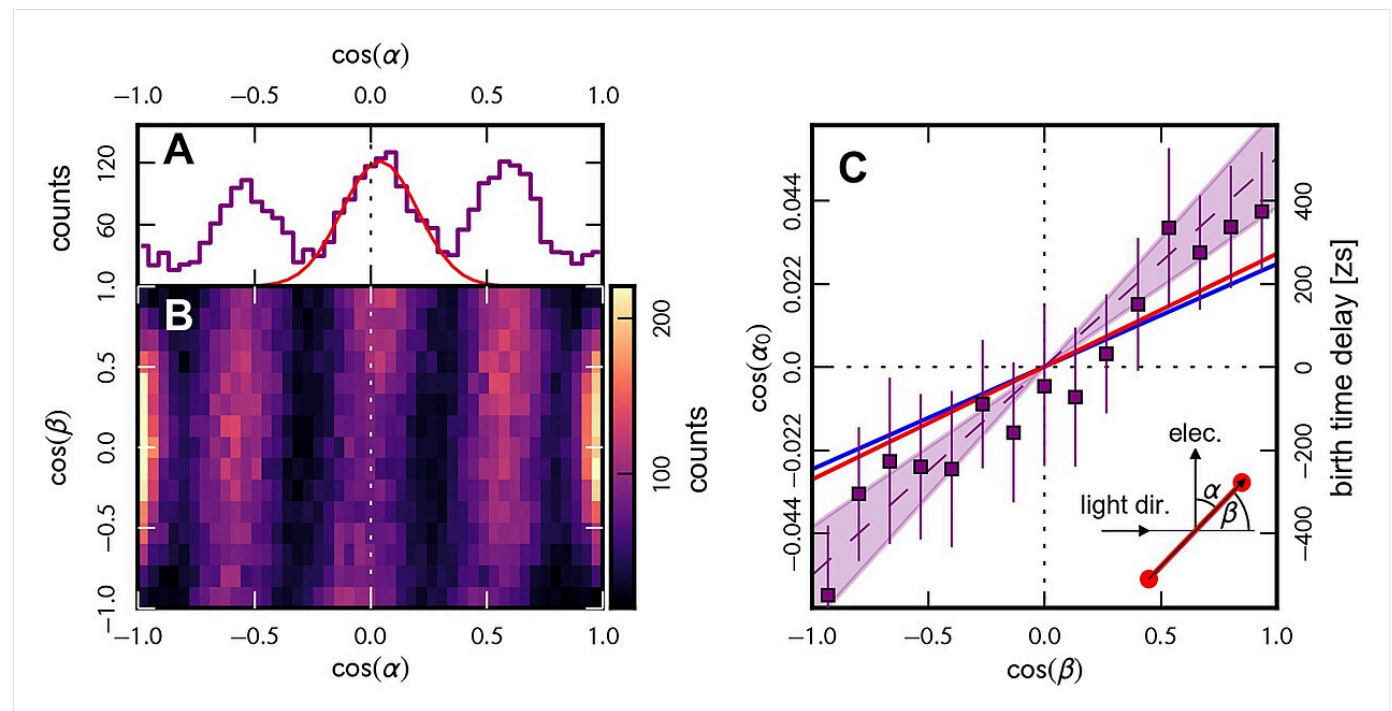
Ultrashort Ti:sapphire pulse amplifier ODIN

Another theoretical study predicts zeptosecond keV X-ray waveforms from mid-infrared laser-driven HHG, leveraging quantum diffusion of electron wavefunctions to produce isolated or sequenced pulses as short as a few hundred zeptoseconds. These could probe nuclear processes like fission or fusion.

Visions for future lasers include zeptosecond durations at zettawatt ( $10^{21}$  W) powers, building on Nobel Prize-winning chirped pulse amplification (CPA) techniques.

These proposals rely on compressing petawatt-class lasers to near-single-cycle durations, opening applications in attosecond/zeptosecond science for studying electron-nuclear interactions.

## Zeptosecond Measurements Achieved with Lasers

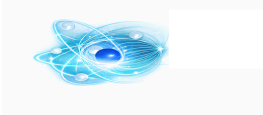


Zeptosecond Birth Time Delay in Molecular Photoionization

FIG. 1: Concept of birth time delay measurement. (A) Intensity distribution on a screen in the far field behind the double slit in panel B. (B) A plane wave impinges on a double slit. The phase shift  $[\Delta\phi]$  in the right slit causes a tilt of the interference pattern. (C,D) Emission of a photoelectron wave from two indistinguishable atoms of a homonuclear diatomic molecule mimics the double-slit setup in panel B. Here, the angle  $\alpha$  is enclosed by the electron momentum vector and the molecular axis. A time delay  $[\Delta t]$  between the emission from one of the two centers, e.g., originating from the travel time of the photon impinging from the left side in panel D, leads to a shift of the interference fringes in panel C. The ratio of slit distance [molecular bond length  $R$ , respectively] to wavelength is 1.65 in both cases (B,D). In panel B the right-hand part of the wave is delayed by  $\Delta\phi = \pi/2$ , whereas in panel D a birth time delay of 247 zeptoseconds causes  $\Delta\phi \cong \pi/11$  for  $R = 0.74 \text{ \AA}$ .

Photoionization is a fundamental quantum process that has become a powerful tool to study atoms, molecules, liquids, and solids. Facilitated by the advent of attosecond technology, nowadays it can even be addressed in the time domain. Timing in photoionization usually refers to the time it takes for an electron to escape to the continuum after absorption of the photon. In a recent work, is uncovered another intriguing aspect of timing in photoionization: The electron is not launched at the same time across a molecular orbital. Rather, the birth time depends on the travel time of the photon across the molecule, which is up to 247 zeptoseconds for the average bond length of molecular hydrogen. To measure the birth time delay, it has utilized the close analogy between the double-slit experiment and electron emission from the two atoms of a homonuclear diatomic molecule (FIG. 1). The irradiated hydrogen molecules with 800 eV photons and measured the interference pattern of fast electrons in the molecular frame of reference (FIG. 2). Finally, the orientation is varied of the molecular frame of reference with respect to the photon propagation direction and observed changes in the electron interference pattern (FIG. 3). From the shifted position of the central interference maximum we calculated the birth time delay.

FIG. 2: Interference pattern of fast electrons [ $E = 735 \text{ eV}$ ] from one-photon double ionization of  $H_2$  by 800 eV circularly polarized photons for the average internuclear distance of  $R = 0.74 \text{ \AA}$  [purple line] in panel A and as function of  $R$  in panel B. The blue line in panel A models a double-slit interference pattern for a slit distance of  $R = 0.74 \text{ \AA}$  and a wavelength of  $\lambda = 0.45 \text{ \AA}$ , which is the average de Broglie wavelength of the fast electron. The subset  $S$  of the data is used for panel A and for the subsequent analysis of the birth time delay. FIG. 3: Birth time delay of fast electrons [ $E = 735 \text{ eV}$ ] from one-photon



distribution in the molecular frame of reference as function of  $\cos(\beta)$ . Dashed line: perpendicular to molecular axis, i.e., location of the zeroth-order maximum in the absence of birth time delays. (C) Location of the maxima of the zeroth-order interference fringe as function of  $\cos(\beta)$ . The maxima are obtained using Gaussian fits as indicated by the red line in panel A. The error bars include statistical and systematic errors and the purple-shaded error range indicates the systematical error. Left axis:  $\cos(\alpha_0)$ , right axis: birth time delay. The blue line resembles a birth time delay given by the travel time of light across the molecule. Red line: prediction combining atomic nondipole effects and the travel time of the photon.

Publication:

- **Zeptosecond Birth Time Delay in Molecular Photoionization.** Sven Grundmann, Daniel Trabert, Kilian Fehre, Nico Strenger, Andreas Pier, Leon Kaiser, Max Kircher, Miriam Weller, Sebastian Eckart, Lothar Ph. H. Schmidt, Florian Trinter, Till Jahnke, Markus S. Schöffler, Reinhard Dörner. *Science* 16 Oct 2020: Vol. 370, Issue 6514, pp. 339-341 DOI: 10.1126/science.abb9318

While direct zeptosecond pulse generation isn't realized, lasers have enabled measurements on this timescale:

In 2020, physicists at Goethe University Frankfurt used ultrashort X-ray flashes from the PETRA III synchrotron (acting as a free-electron laser) to measure the time a photon takes to cross a hydrogen molecule: an average of 247 zeptoseconds.<sup>[10]</sup> This was done via photoionization, where an X-ray photon ejects electrons from the molecule, creating interfering electron waves analyzed with a COLTRIMS reaction microscope. The finding revealed that light doesn't interact uniformly across a molecule but propagates at finite speed, causing tiny delays.

Earlier work in 2016 measured zeptosecond delays in helium electron ejection using laser-driven techniques.<sup>[11]</sup>

Such measurements highlight lasers' role in probing zeptosecond phenomena, even if the driving pulses are longer (femtosecond to attosecond).

## Implications and Challenges

Zeptosecond lasers or probes could revolutionize fields like quantum chemistry, allowing direct observation of nuclear motions or inner-shell electron dynamics. However, challenges include stabilizing phases over extreme bandwidths, managing quantum noise, and scaling laser power without damaging media. Progress in mid-infrared lasers and HHG efficiency is ongoing, with potential breakthroughs in facilities like DESY or LCLS.

## Physical Limitations

Applications include particle detectors (e.g., in high-energy physics experiments like those at CERN) to measure particle velocities and in medical imaging or astrophysics for detecting cosmic rays. The radiation's intensity and angle depend on the particle's speed and the medium's properties, following the formula for the emission angle:  $\cos \theta = \frac{c}{vn}$ , where  $v$  is the particle speed,  $n$  is the refractive index, and  $c/n$  is light's speed in the medium.<sup>[12]</sup>

# Future Developments

## Yoctosecond Pulse Lasers

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### Introduction

A yoctosecond pulse laser refers to a laser system capable of producing light pulses on the timescale of one yoctosecond, or  $10^{-24}$  seconds.<sup>[13]</sup> This duration is extreme brief, 1000 times shorter than the attosecond ( $10^{-18}$  s) pulses that represent the current frontier of experimental ultrafast optics.<sup>[14]</sup> Yoctosecond pulses are primarily theoretical or proposed in the context of high-energy physics, where they could probe phenomena at the subnuclear level, such as quark-gluon plasmas (QGP) or electron dynamics in extreme conditions.<sup>[15]</sup> At such timescales, the pulses approach the Planck time ( $5.39 \times 10^{-44}$  s), challenging fundamental limits of quantum mechanics and relativity.

Yoctosecond lasers differ from conventional ultrashort pulse lasers, which typically operate in the femtosecond ( $10^{-15}$  s) to attosecond range.<sup>[16]</sup>

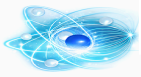
For comparison:

- Femtosecond lasers are used in applications like eye surgery and material processing.<sup>[17]</sup>
- Attosecond lasers enable real-time observation of electron movements in atoms and molecules.<sup>[18]</sup>
- Zeptosecond ( $10^{-21}$  s) and yoctosecond pulses extend this to nuclear and subnuclear processes, potentially revolutionizing fields like particle physics and quantum chromodynamics (QCD).<sup>[19]</sup>

### Generation Methods

Generating yoctosecond pulses requires extreme conditions beyond standard laser technology.<sup>[20]</sup> Proposed methods include:

- **Quark-Gluon Plasma Interactions:** In high-energy collisions, such as those in particle accelerators, QGPs can emit yoctosecond photon pulses. These arise from the thermal radiation or bremsstrahlung in the plasma, where the pulse duration is determined by the plasma's expansion time. Theoretical models suggest pulses as short as  $10^{-24}$  s with energies in the keV to MeV range.<sup>[21][22]</sup>



- **High-Harmonic Generation in Extreme Fields:** Extending attosecond techniques, yoctosecond pulses might be created through harmonic up-conversion in ultra-intense laser-plasma interactions. However, this remains speculative, as current lasers (e.g., petawatt-class systems) are limited to attoseconds.<sup>[24]</sup>

The spatiotemporal properties of these pulses, such as modulation and beam divergence, are critical for control. For instance, the pulse envelope can be described by the wave equation in relativistic contexts, where the duration  $\tau$  scales inversely with the driving field's intensity  $I$ :  $\tau \propto I^{-1/2}$ .<sup>[25]</sup>

## Applications and Challenges

Yoctosecond pulses could enable unprecedented temporal and spatial resolution:

- **Probing Subnuclear Dynamics:** Imaging quark and gluon interactions in real time, aiding in understanding QCD phase transitions.<sup>[26]</sup>
- **Thermal Processes in Plasmas:** Studying energy deposition and heating in QGPs, with implications for heavy-ion collision experiments like those at the LHC.<sup>[27]</sup>
- **Advanced Spectroscopy:** Resolving processes faster than nuclear vibrations, potentially in nuclear fusion or astrophysics.<sup>[28]</sup>

Challenges include:

- **Technical Feasibility:** No experimental yoctosecond lasers exist; current limits are around 43 attoseconds.<sup>[29][30]</sup>
- **Quantum Limits:** Heisenberg's uncertainty principle imposes bounds on pulse shortness versus energy spread:  $\Delta E \cdot \Delta t \geq \hbar/2$ .<sup>[31][32]</sup>
- **Detection:** Measuring such pulses requires detectors with yoctosecond resolution, which are not yet developed.<sup>[33]</sup>

## Rontosecond Pulse Lasers

The **rontosecond** (symbol: **rs**) is the SI-prefixed unit of time equal to **one octillionth of a second** ( $10^{-27}$  s). It is one of the smallest named units of time in the International System of Units (SI).

Compared to ronnaseconds/years: 31.69 quintillion years ( $10^{27}$  seconds)

### Official Adoption of the Prefix

The ronto prefix (r) was officially adopted on 18 November 2022 by the 27th General Conference on Weights and Measures (CGPM) alongside the quecto prefix (q =  $10^{-30}$ ).<sup>[34][35]</sup> The names were proposed by the UK's National Physical Laboratory (NPL). "Ronto" derives from the French word "ronde" (round/small), chosen for its phonetic similarity to "ronna" ( $10^{27}$ ).<sup>[34]</sup> This extension of SI prefixes addresses the growing need for smaller units in data science, quantum computing, and particle physics measurements.

### Natural Phenomena at Rontosecond Scales

- **Mean lifetime of  $W^\pm$  and  $Z^0$  bosons:** approximately **300 rontoseconds** ( $\approx 3 \times 10^{-25}$  s).<sup>[36][37]</sup>

The W boson has a measured lifetime of approximately  $3.08 \times 10^{-25}$  s ( $\approx 0.308$  yoctoseconds or 308 rontoseconds), consistent with the Standard Model prediction.

### Theoretical Research

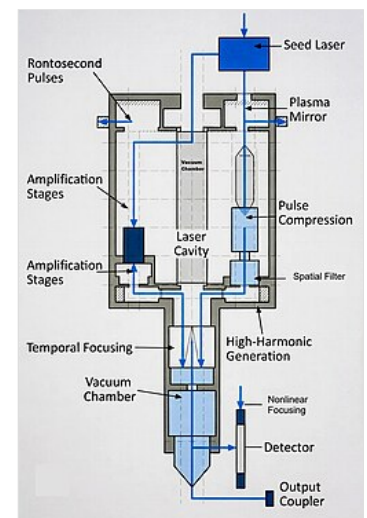
- **Gravitationally-induced wave function collapse** (Diósi–Penrose model): In the 2024 study published in *Physical Chemistry Chemical Physics*, researchers calculated collapse times for macroscopic superpositions. For a 1 kg iron or carbon object, the collapse time reaches the rontosecond regime ( $\approx 10^{-27}$  s).<sup>[38]</sup>

Smaller systems (e.g. isolated molecules) have collapse times of billions of years, while mesoscopic crystals collapse in days.

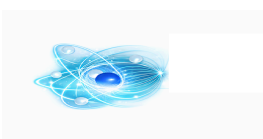
### Current Experimental Status

As of January 2026, **no experimental measurements or generation of rontosecond pulses/events** have been achieved.<sup>[36]</sup>

- **Shortest directly measured time interval: 247 zeptoseconds** ( $2.47 \times 10^{-21}$  s) - the time for a photon to cross a hydrogen molecule (Goethe University Frankfurt / PETRA III synchrotron experiment, 2020).<sup>[39]</sup>
- Yoctosecond ( $10^{-24}$  s) and rontosecond scales remain **theoretical** - observed indirectly via particle lifetimes (Higgs boson  $\approx 180$  yoctoseconds from ATLAS/CMS measurements) and proposed gravitational collapse models.<sup>[40]</sup>



Rontosecond pulse laser (Schematic)



## Future thought experiment

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**Quantum Ultrafast Lasers** (Written in 2082 – Historical and Contemporary Perspective)

### Introduction

By the late 21st century, quantum ultrafast lasers have evolved from laboratory curiosities into the primary tool for exploring the deepest timescales of the universe. What began with femtosecond pulses in the 1990s has now reached the **rontosecond regime** ( $10^{-27}$  s) and is rapidly approaching **quectosecond** ( $10^{-30}$  s) territory.

### Timeline of Ultrafast Laser Milestones

- 1990s–2000s: Femtosecond lasers become widespread (Ti:sapphire, fiber lasers)
- 2001–2023: Attosecond science emerges (Nobel Prize 2023)
- 2038: First isolated **zeptosecond** ( $10^{-21}$  s) pulses achieved using relativistic plasma mirrors
- 2051: **yoctosecond** ( $10^{-24}$  s) regime entered via coherent inverse Compton scattering in petawatt laser-plasma accelerators
- 2064: Breakthrough – first **rontosecond** ( $10^{-27}$  s) laser pulses generated at the International Quantum Timing Facility (Lunar Orbit)
- 2071: Routine rontosecond pump–probe experiments become standard at major research centers
- 2079: First demonstration of **quectosecond** ( $10^{-30}$  s) temporal resolution using entangled photon-pair compression



Rontosecond pulse laser (Futuristic)

### What Rontosecond Lasers Enabled Rontosecond lasers allow us to directly observe

- Real-time dynamics of **quark-gluon plasma** inside heavy-ion collisions
- Weak-force mediated particle decays (W and Z boson lifetimes ~250–300 rontoseconds)
- Gravitationally-induced wavefunction collapse events (testing Diósi–Penrose and related models)
- Nuclear fission/fusion processes at the attometer scale
- Early-universe analogue conditions in laboratory settings

### Applications in 2082

- **Quantum Gravity Research:** Direct measurement of spacetime foam fluctuations
- **Nuclear Engineering:** Ultrafast control of nuclear reactions for next-generation fusion reactors
- **Fundamental Metrology:** Redefinition of the second based on rontosecond optical transitions
- **Quantum Computing:** Coherent control of nuclear spins and quark-level qubits
- **Time-Resolved Particle Physics:** Watching individual quarks exchange gluons in real time

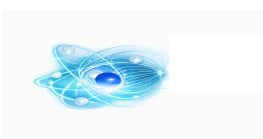
### Current Frontiers (2082)

The next frontier is the **quectosecond** ( $10^{-30}$  s) and **ronto-** prefix extensions. These timescales approach the Planck time ( $5.39 \times 10^{-44}$  s), where quantum gravity effects are expected to dominate and classical spacetime may break down.

## See also

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- [Yoctosecond](#)
- [Zeptosecond](#)
- [SI prefixes](#)
- [Orders of magnitude \(time\)](#)
- [Diósi–Penrose model](#)
- [Quantum](#)
- [Quantum A Matter Of Size](#)
- [Quantum A Spooky Action at a Distance](#)
- [Quantum: A Walk Through the Universe](#)
- [Number of independent spatial modes in a spherical volume](#)
- [Quantum Computing Algorithms in the NISQ Era](#)
- [Quantum Formulas Collection](#)
- [Quantum Matter Elements and Particles](#)
- [Quantum mechanics](#)
- [Quantum mechanics/Timeline](#)
- [Quantum mechanics measurements](#)
- [Quantum Noisy Qubits](#)

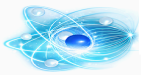


- [Template:Quantum optics operators](#)
- [Physical Sciences](#)

### Learning Activities

- **Simulation exercise:** Use computational tools (e.g., Python with NumPy/SciPy) to model pulse propagation in a plasma. Calculate the pulse duration for varying electron densities.
- **Discussion question:** How might yoctosecond lasers impact our understanding of the early universe, given their relevance to QGP states?
- **Further reading:** Explore attosecond physics as a prerequisite, then advance to papers on nonlinear Thomson scattering.
- **Research task:**
  - Who contributed to the Zeptosecond laser technology, name at least four.
  - What are the advantages of faster lasers

This section provides a foundational overview; for deeper study, consult high-energy physics textbooks or simulate basic pulse dynamics.



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