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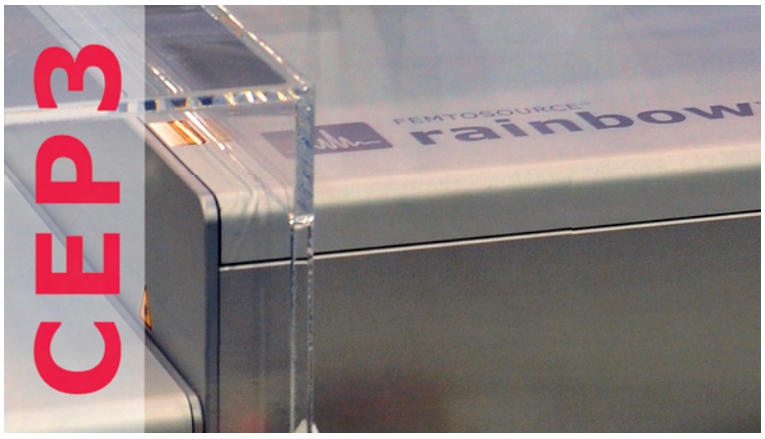
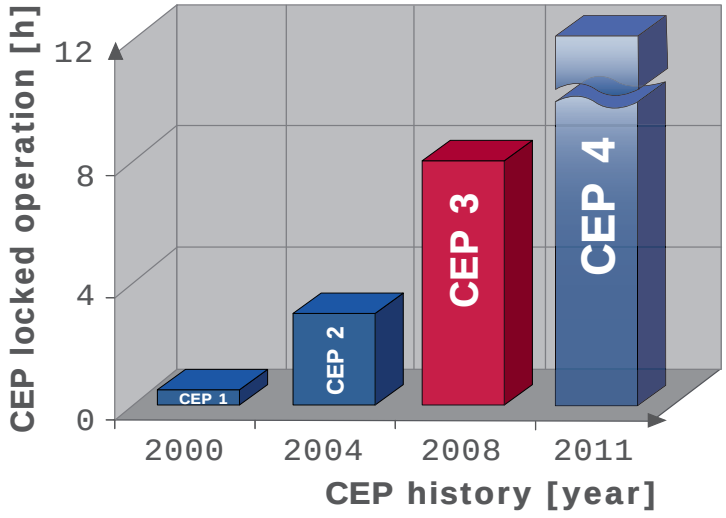
FEMTOLASERS` CE-Phase stabilized ultrafast laser systems

Setting the world´s new standards™



A decade ago, FEMTOLASERS made the development of Carrier Envelope Phase (CEP) stabilized oscillators and amplifiers a key topic. In retrospect, the CEP decision was not just courageous, but also farsighted. By developing a family of ultrafast lasers with CEP stable output pulses, the company landed its biggest success story: the break through into the attosecond-era.

FEMTOLASERS´CEP generations



FEMTOLASERS is not only the indisputable leader in CEP stabilized ultrafast oscillators and amplifiers, but the only manufacturer capable of supplying reliable and high quality CEP stabilized ultrafast laser systems. Our pioneering spirit continuously boosts performance and reliability of the CEP stabilized ultrafast laser systems, demonstrated by the current **CEP3** technology (3rd CEP generation).

Products from alternative manufacturers still rely on CEP1 (1st generation) dating back to FEMTOLASERS early days in CEP, a decade ago.

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CEP1 | 2000 | CE-Phase locked on the 10s of minutes time scale

Spectral broadening & f-to-2f nonlinear interferometer

FEMTOLASERS produced the first commercially available CEP stabilized systems in the year 2000, shortly after the scientific community introduced the necessary fundamental concepts (*Reichert et al., Optics Communication 172, p. 59-68 (1999) | Telle et al., Applied Physics B 69, p. 327-332 (1999)*). This is what FEMTOLASERS defines as CEP1.

The ultrafast oscillator's spectrum was broadened to an octave spanning spectrum, and via a subsequent f-to-2f interferometer the necessary beat signal was generated for a feed-back loop to actively stabilize the CE-Phase. Using the FEMTOSOURCE™ compact PRO (sub-10 fs) ultrafast oscillator, the CEP1 generation delivered a pulse train with every fourth pulse exhibiting an identical electric field waveform, for periods of up to half an hour.

In 2003 the first fully CEP stabilized amplified ultrashort pulses were obtained at the Institute for Photonics, Technical University of Vienna, employing FEMTOLASERS' FEMTOPOWER™ compact PRO amplifier. Here, the (slow) CE-Phase drift of the amplifier output was measured by means of a second f-to-2f interferometer. The resulting correction signal was then added to the single (fast) feed-back loop (*Baltuska et al., Nature 421, p. 611-615 (2003)*).

CEP2 | 2004 | CE-Phase locked on the few hours time scale

FEMTOSOURCE™ rainbow™ & monolithic DFG scheme

By 2004, FEMTOLASERS had already introduced the 2nd generation of CE-Phase stabilized systems. A real break-through in reliability, CEP2 opened the way to even more demanding and sophisticated research experiments. FEMTOLASERS´ CEP2 generation came as a result of two innovative technological steps yielding a major improvement in performance while radically reducing the number of optical components.

One was the now world renowned FEMTOSOURCE™ rainbow™ ultrafast oscillator. Drawing on FEMTOLASERS´ patented proprietary dispersion management and exceptional design, the FS rainbow™ delivers pulses with guaranteed durations of less than 7 fs and spectral bandwidth greater than 300 nm. Its outstanding performance immediately proved spectral broadening in a fragile nonlinear fibre obsolete for CEP stabilization.

On the other hand, we put to work the newly discovered FEMTOLASERS´ proprietary (*Fuji et al., Optics Letters 29, Issue 6, p. 632-634 (2004)*) monolithic Difference Frequency Generation (DFG) approach for CEP stabilization. With efficient design and elegant implementation, the DFG method offered a more user-friendly and straight-forward technique, replacing the very sensitive f-to-2f interferometer. The exceptionally broad spectrum delivered by the FS rainbow™ undergoes a collinear DFG process which provides outstanding beat signal quality for CEP stabilization of the pulse train. This allowed the CEP stability to break the two hour barrier.

Always in pace with new research fields, FEMTOLASERS was and is committed to respond to the most demanding requirements posed by the attosecond scientific community. Both CEP1 and CEP2 generations already allowed CEP stable output of the FEMTOPOWER™ ultrafast amplifier system. At the time, this was accomplished by applying the sum of both slow and fast CEP correction signals to the seed oscillator. This combined loop CEP stabilization approach was nevertheless soon outrun by scientific demands in terms of general performance, especially long term stability and noise.

CEP3 | 2008 | CE-Phase locked over a full working day

CEP2 & independent CEP loops of seed oscillator and amplifier

In 2008, FEMTOLASERS revealed its exclusive CEP3 generation of ultrafast laser systems. The concept behind CEP3 is based on independent CE-Phase stabilization of both the FS rainbow™ seed oscillator and the FEMTOPOWER™ amplifier (*LaserFocusWorld, April 2008; FEMTOLASERS exclusive technology*).

Integral part of the CEP3 is the CEP O-Clock™. This singular FEMTOLASERS´module constantly monitors and finely manages the fast rainbow™ feedback loop, maintaining its optimum working point for time periods longer than a day. The FEMTOPOWER™ ultrafast amplifiers are based on unique design elements in a multipass configuration delivering down to sub-20 fs pulses with energies in the multi mJ regime. Its unsurpassed performance fulfils the sine qua non condition for a solid CEP control: the complete system benefits from outstanding active and passive stability. The excellent stability of the FEMTOPOWER™ system allows strongly decreased dependence on the environmental conditions in the user's research laboratory, resulting in prime performance every day.

The CEP3 generation offers, to this day, the world's most advanced commercial CEP stabilization scheme. Employing the new FP rainbow™ 2010 version, the amplified pulses can be CEP stabilized for more than a full working day, with a CE Phase drift of less than 200 mrad (rms). The CEP stable pulses can be even further compressed to only few optical cycles, by using a hollow fiber and dispersive mirror compressor as FEMTOLASERS´ KALEIDOSCOPE™. This unique product on the market provides the user with sub-7 fs pulses with energies of up to 2 mJ per pulse, when used with the award winning FEMTOPOWER™ V CEP booster amplifier (*Anderson et al., Proc. of SPIE 7578, 75781T, 2010*).

CEP4 | 2011 to come | CE-Phase locked over an unlimited time period

Self-referenced feed-forward approach allows stabilization of any oscillator output with arbitrary chosen phase slip

Already the leader in the field of CE-Phase stabilization, FEMTOLASERS is committed to remain a pioneer at the forefront of the ultrafast laser community. With this in mind, we are already developing tomorrow's CE-Phase stabilization scheme.

Although CEP3 is the best active feed-back CE-Phase stabilization approach to date, we are currently undergoing research on a new and very promising path: CEP4 – the direct feed-forward approach. This new method does not affect the laser performance, requires no complicated locking electronics, and has already been demonstrated with sub-12 attoseconds residual timing jitter, below the atomic unit of time (*S. Koke et al., Nature Photonics 4, p. 462-465 (2010) | FEMTOLASERS patent*). CEP4 is a revolutionary step forward, for the first time the CE-Phase stabilization does not call for a feedback loop! The CE-Phase drift is corrected on-the-fly, after the free-running oscillator.

CEP4 will improve the behaviour of currently used feedback schemes by more than one order of magnitude. Furthermore, combs with arbitrary offset frequencies can be synthesized, with the most important case of a comb with zero offset being most easily obtained. The performance of CEP4 is limited only by the shot noise, where residual phase noise of 45 mrad (rms) has already been measured.

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2010 CLEO/Laser Focus World Innovation Award

Honorable mention for few-cycle pulse generation

FEMTOPOWER™ V CEP

FEMTOLASERS is the proud receiver of the 2010 CLEO/Laser Focus World Innovation Award Honorable Mention for "the FEMTOPOWER™ V carrier-envelope-phase (CEP)-stabilized booster amplifier that generates high-power, few-cycle laser pulses critical to the attosecond science community".

The FEMTOPOWER™ V CEP offers over 5 mJ pulse energy and sub-25 fs pulse duration with an extremely low CEP drift over an extended period of time (190 mrad rms over 7.5 hours demonstrated). It encompasses the ultra broadband FEMTOSOURCE™ rainbow™ seed oscil-lator with the proprietary compact and robust Difference Frequency Genera-tion approach (DFG) for CEP stabilization.

In conjunction with the unique KALEIDOSCOPE™ hollow fiber and dispersive mirror compressor, the system delivers sub-7 fs CEP stable pulses with 2 mJ energies. This is the highest CEP stabilized few cycle pulse energy achieved with a commercial system. The FEMTOPOWER™ V CEP and KALEIDOSCOPE™ system is ideal for high intensity physics in the realm of atto-science.

The FEMTOPOWER™ V CEP ultrafast amplifier system offers the shortest commercially available optical pulses with unprecedented stability and inherent lowest CEP noise. It guarantees the best solution for ongoing demands of the scientific community and provides the technological excellence needed for state of the art experiments.

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