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CEP Stabilization
MEDEA Webinar

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2016-03-16

Outline

1. The Carrier-Envelope Phase and its Changes
   - Time/Frequency picture
2. f_{ceo} – Measuring CEP Change
   - Linear method
   - Self-referencing
   - Interferometer types
3. From Random Change to Stable Change: Stabilizing f_{ceo}
   - What handle to turn?
   - Some less obvious handles
   - A word on residual noise characterization
4. From nJ to mJ – CEP stabilization in Amplifiers
   - Measuring the CEP of a single pulse
   - Nyquist's curse and how to live with it
5. Outlook
   - Current 'hot topics' in CEP
   - How good is good enough?

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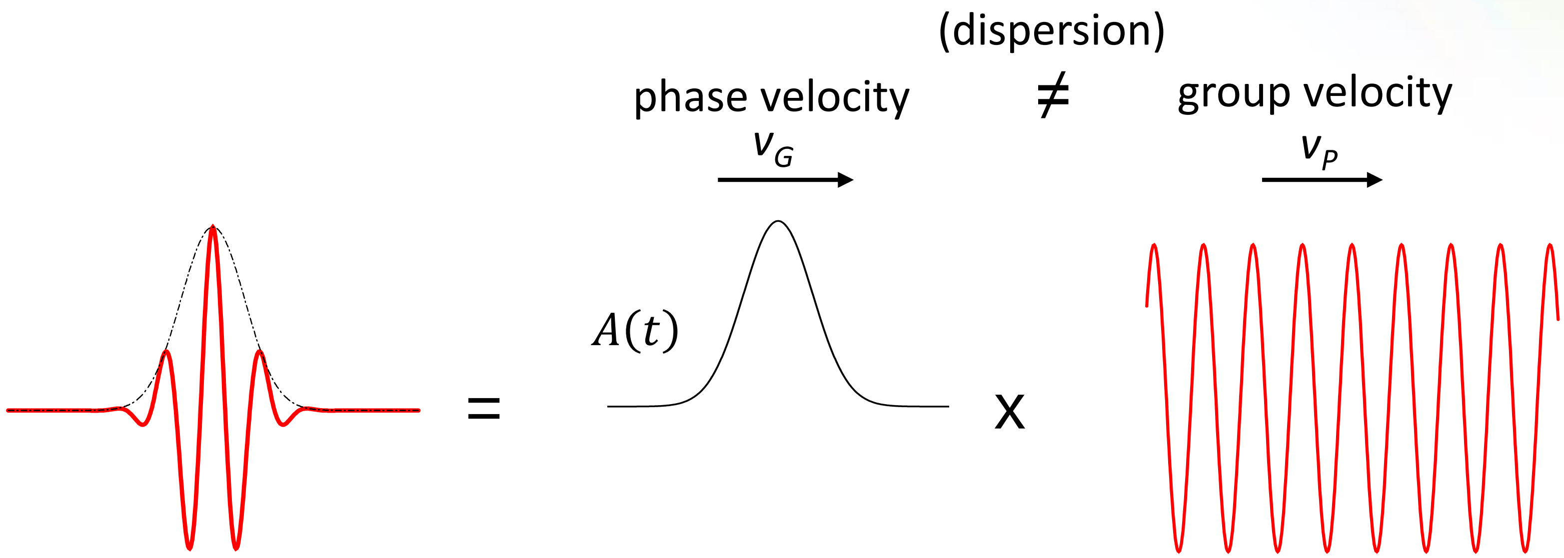
Introduction

THE CEP AND ITS CHANGES

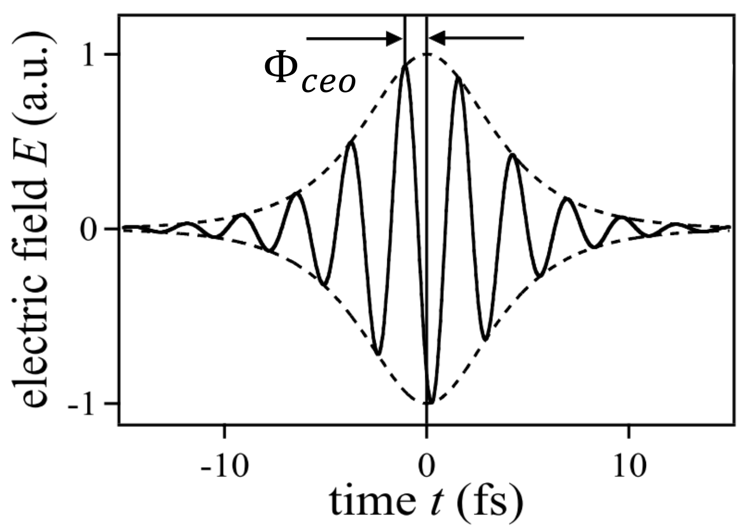
The Carrier-Envelope Phase



The CEP, Φ_{ceo} is

- the property of a **single pulse**
- unambiguous within $[0, 2\pi]$
- a function of time through
    - Dispersion
    - Nonlinearity
    - Geometry
    - …

$$E(t) = A(t)\exp(i\omega_0 t + i\Phi_{\text{ceo}})$$



Telle et al., *Appl. Phys. B* **69**, 327 (1999)

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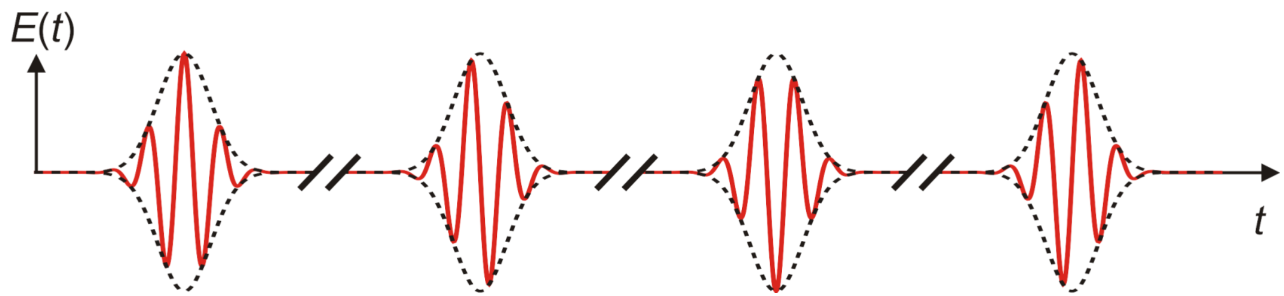
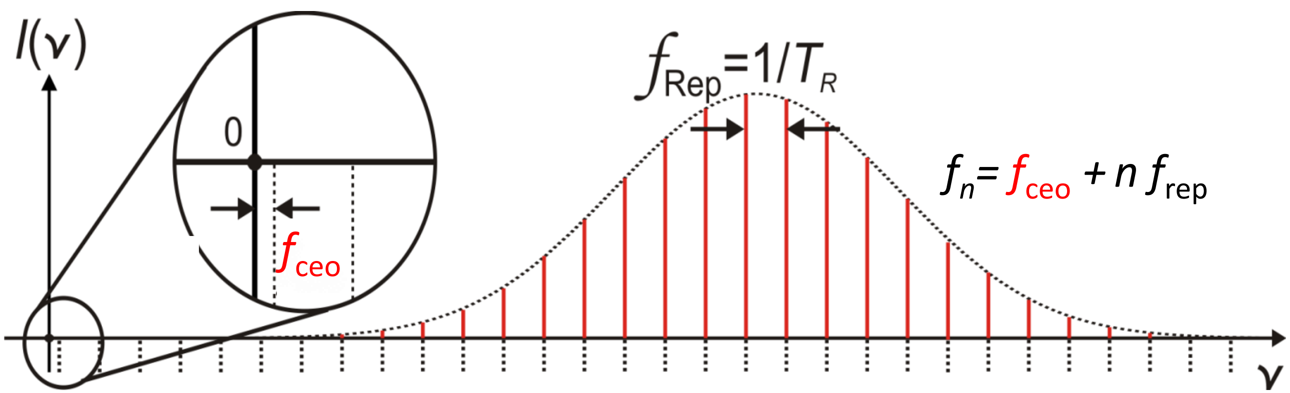
Output of a mode-locked oscillator



$\Phi_{ceo} = 0$ $\Phi_{ceo} = \pi/2$ $\Phi_{ceo} = \pi$ $\Phi_{ceo} = 3\pi/2$

$$T_{rt} = 1/f_{rep};\ \Delta\Phi_{ceo} = 2\pi\frac{f_{ceo}}{f_{rep}}$$

Fourier transform



Time domain: ΔΦ

- ns pulse spacing T_{rt}
- Intracavity effects (dispersion, nonlin…) determine **roundtrip phase change $\Delta\Phi_{ceo}$**
- Can't measure Φ_{ceo}

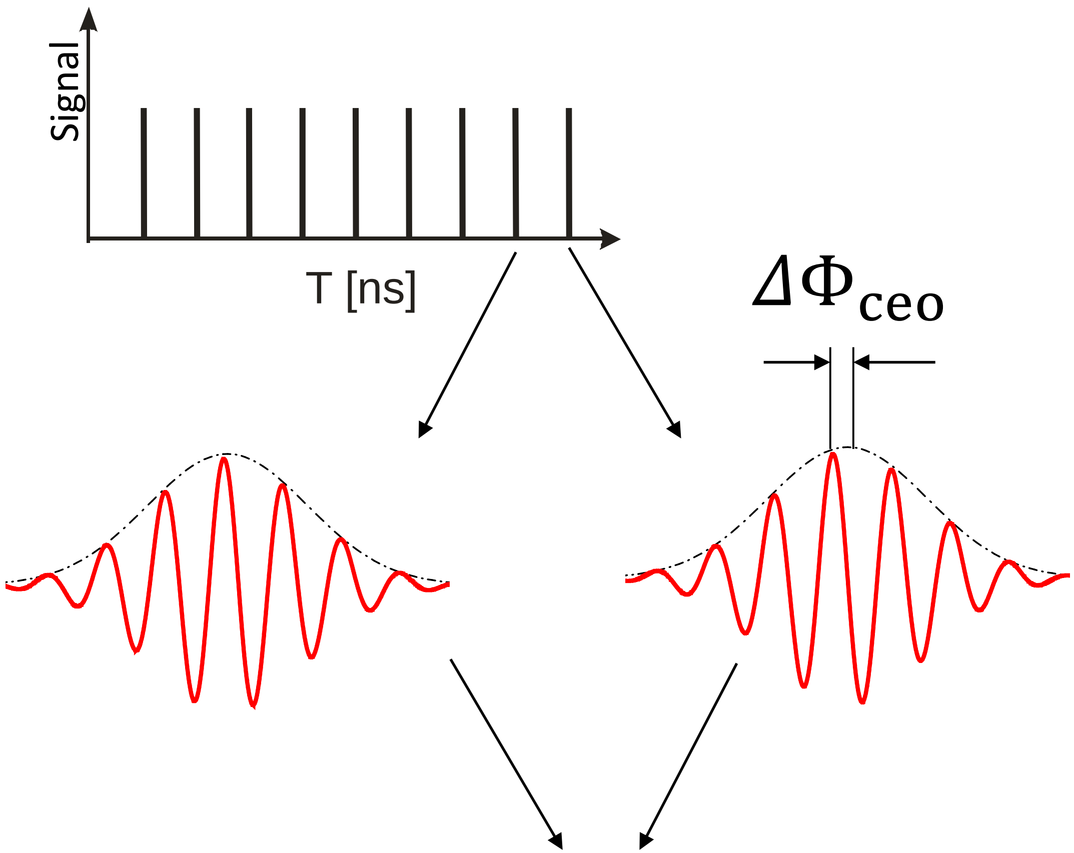
Frequency domain: f_{ceo}

- Frequency comb, determined by two parameters:
- **Repetition rate f_{rep}**
- **Comb offset f_{ceo}**
- Optical frequency of each line in spectrum $f_n = nf_{rep} + f_{ceo}$

Getting hold of the comb offset: Different flavors of self-referencing

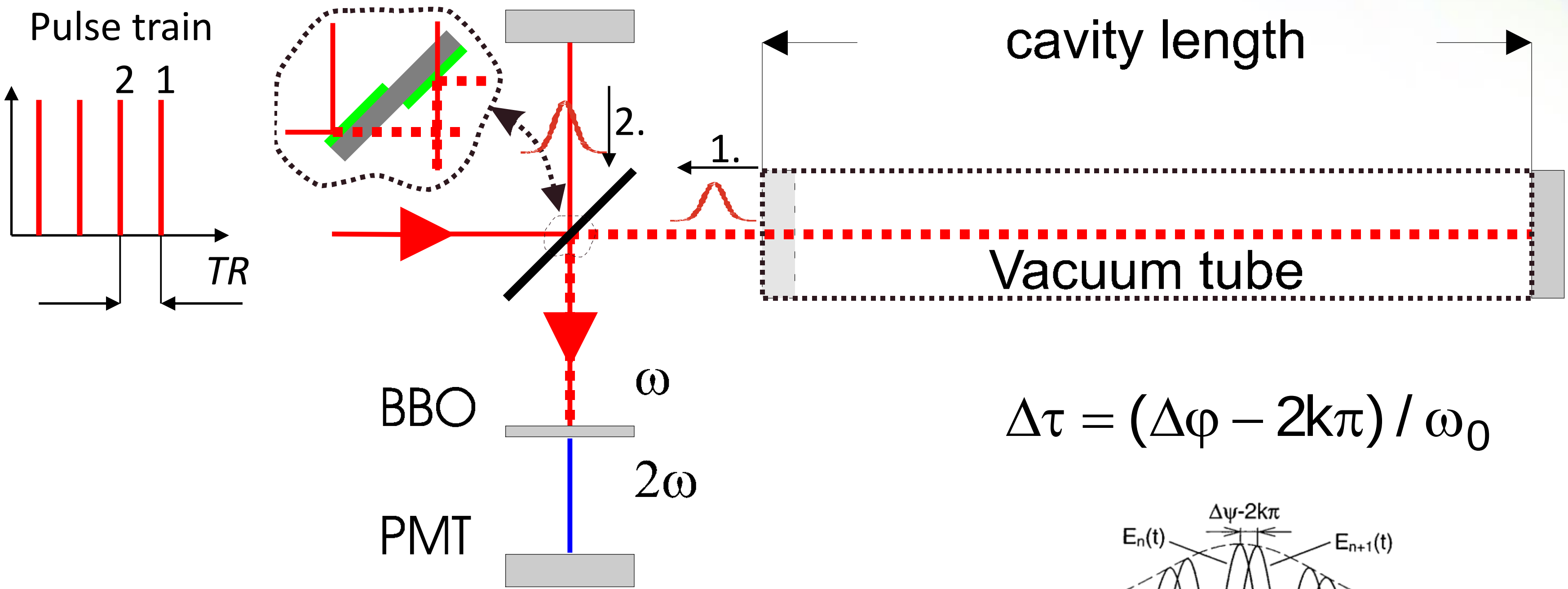
MEASURING CEP CHANGE

Can we measure the CEP change by linear means?

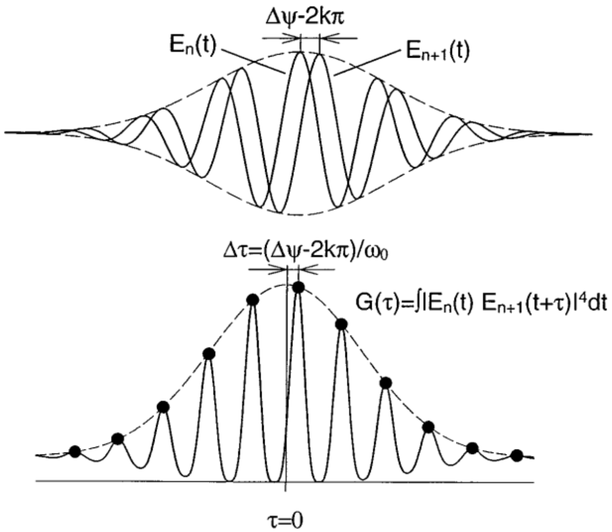


Cross-Correlation (SHG)
of two consecutive pulses?

Earliest measurement (1996) did just this…



$$\Delta\tau = (\Delta\varphi - 2k\pi) / \omega_0$$



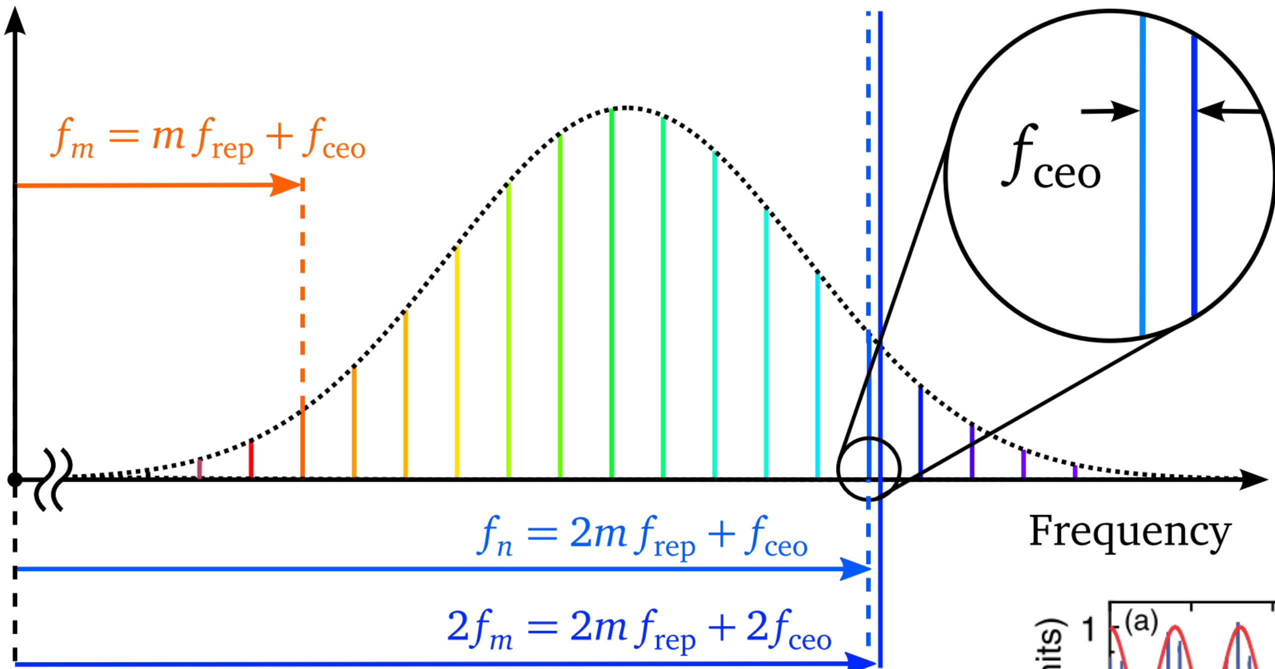
Results of this measurement:

- Value averaged over many (>10^5) pulses
- Showed dependency of $\Delta\Phi_{ceo}$ on
  - Intracavity dispersion
  - Pump power
- Low accuracy of only $\pi/10$

L. Xu *et al.*, Opt. Lett. **21**, 2008 (1996)

Self-referencing scheme („f-to-2f“)

E. Reichert et al., Opt. Commun. **172**,59 (1999)
H. R. Telle et al., Appl. Phys. B **69**, 327 (1999)
D. J. Jones et al., Science **288**, 635 (2000)
A. Apolonski et al., Phys. Rev. Lett. **85**, 740 (2000)

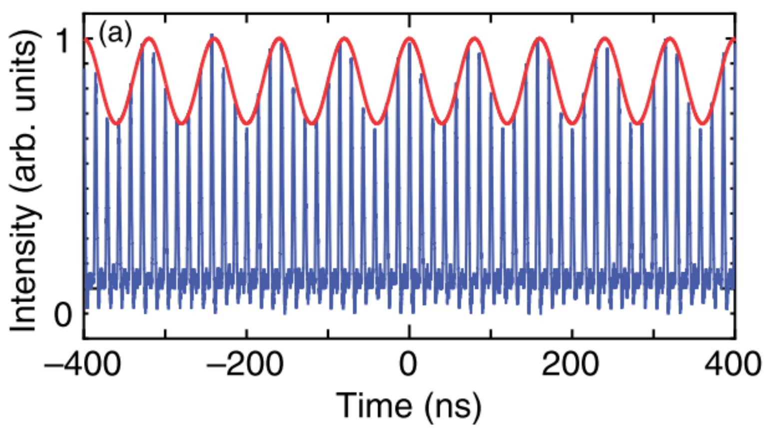


Beat at spectral overlap:
$(f_n - 2f_m) \bmod f_{rep} = f_{ceo}$

Pre-requisite:
Octave-spanning spectrum

Interference of fundamental and SHG lines results in ‘beating’ at the difference frequency:

$$(f_n - 2f_m) \bmod f_{rep} = f_{ceo}$$



Photodiode signal on oscilloscope

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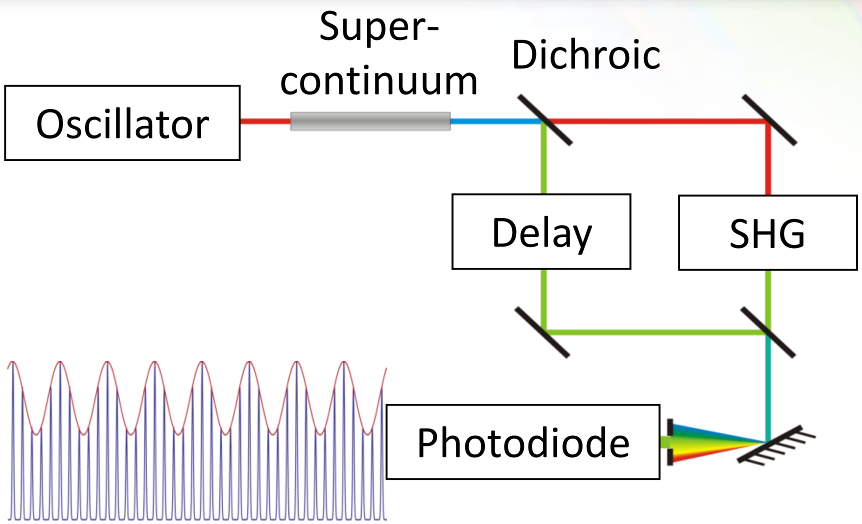
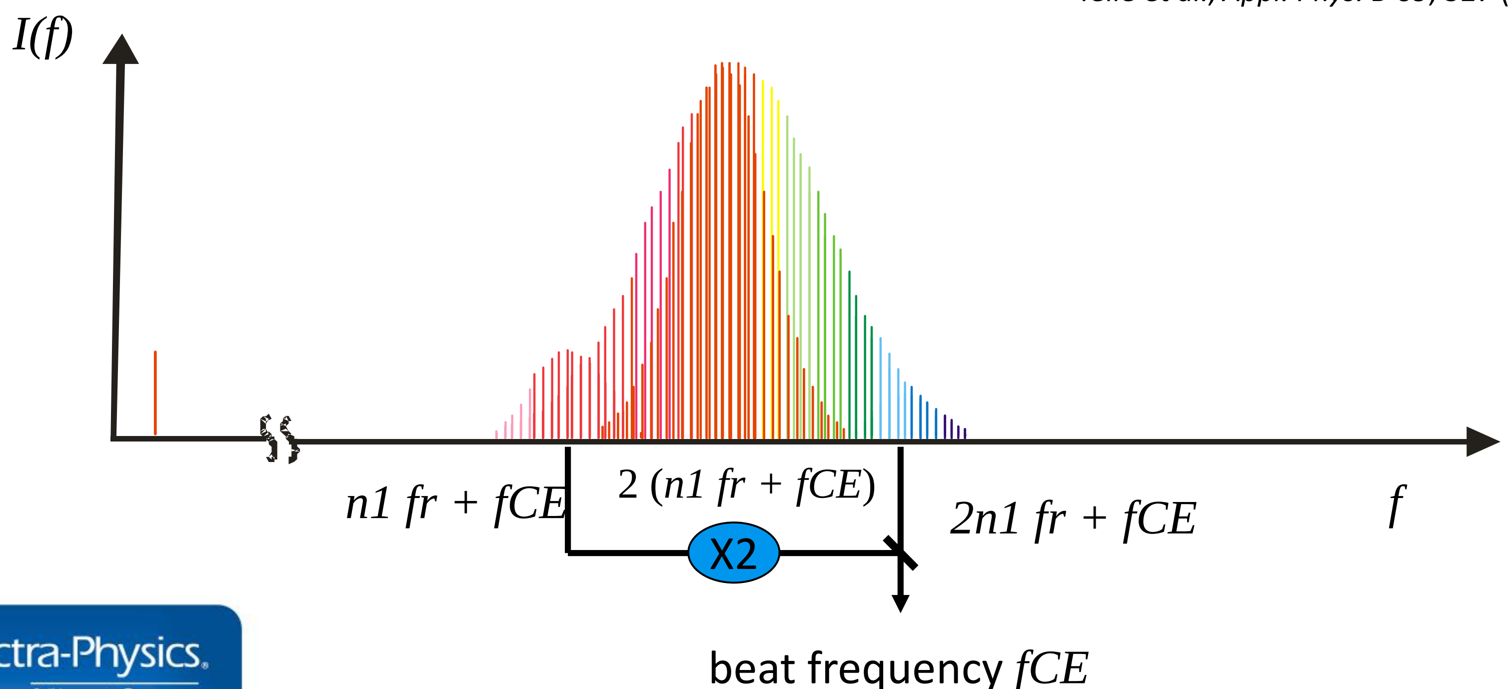
Mach-Zehnder "f-to-2f" type

Split-path "f-to-2f" interferometer (Michelson, Mach-Zehnder...)

- + Applicable to long (<80 fs) pulses
- – Various noise sources:
  - Non-common paths
  - Environment drifts
  - Sensitive fiber coupling



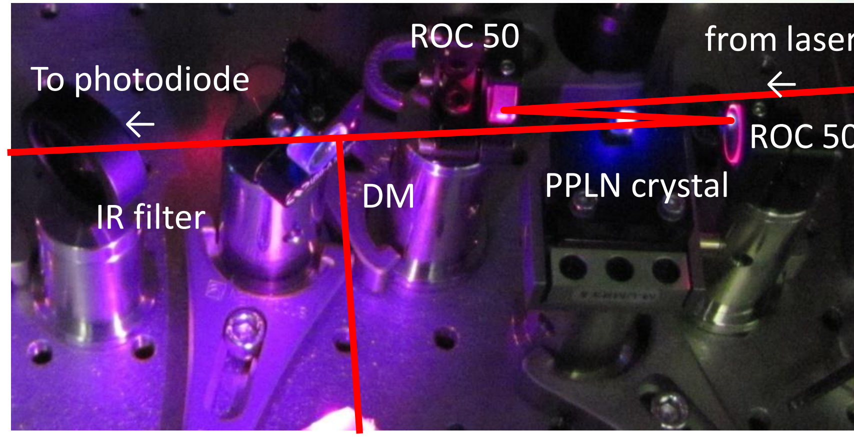
Telle et al., *Appl. Phys. B* **69**, 327 (1999)

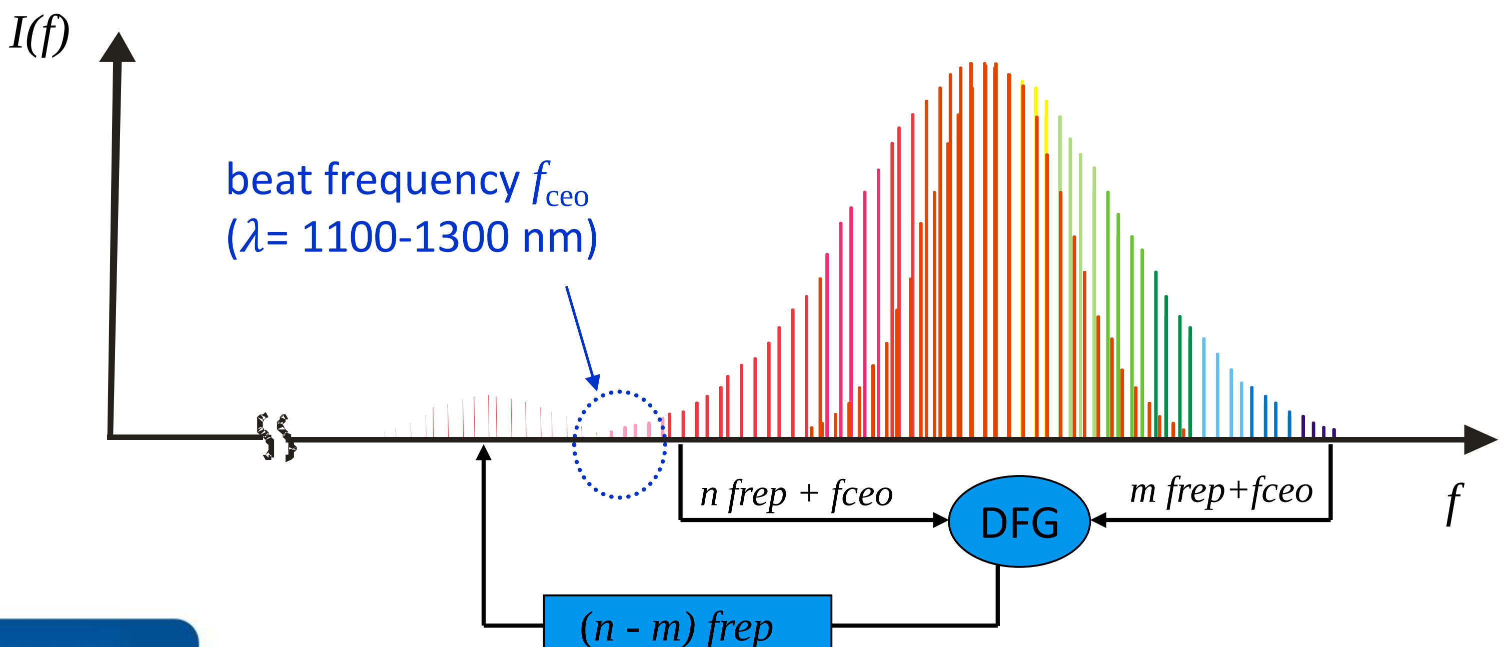


Monolithic DFG "0-to-f" type

Monolithic "DFG" or "0-to-f" type

- + Robust and simple
- + Perfectly common-path
- + Set-and-forget device
- + Up to 45 dB S/N ratio
- + Insensitive to beam drift
- – Requires compressed pulses with (almost) octave bandwidth





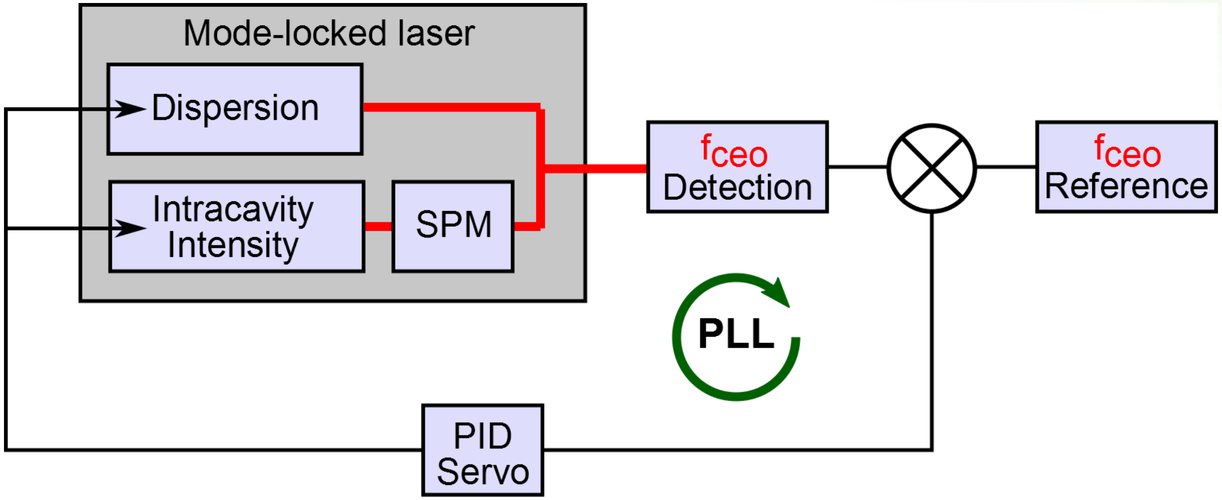
Fuji et al., *Opt. Lett.* **29**, 633 (2004)
Fuji et al., *Opt. Lett.* **30**, 332 (2005)

From random change to stable change: Fixing the comb offset

OSCILLATOR STABILIZATION

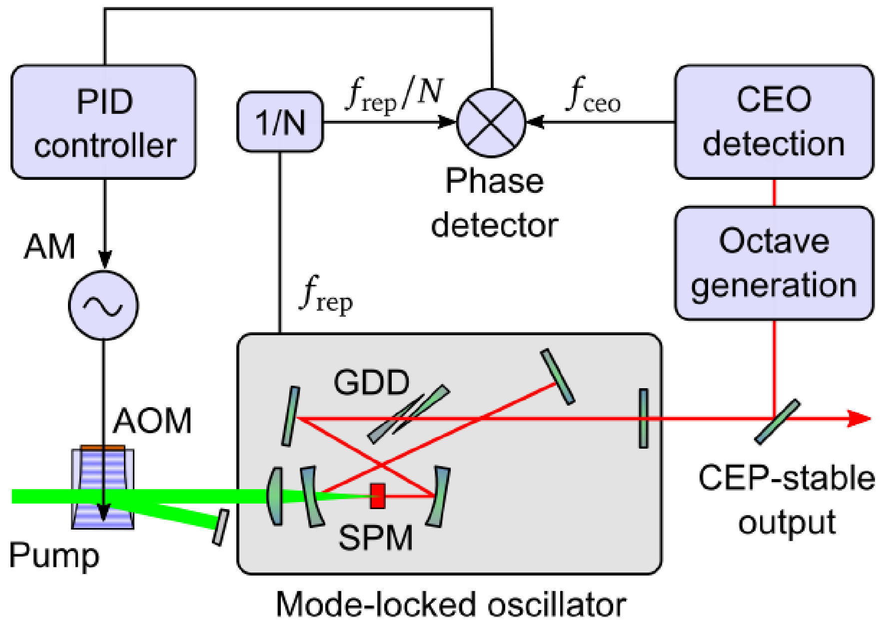
What handle to turn…?

…to change the pulse-to-pulse CEP change according to our wishes?



- Dispersion
  - Intracavity wedge insertion
  - End mirror tilting (beam path change through prisms)
  - Temperature changes in gain medium
- Intracavity intensity
  - End mirror tilt (also has impact on cavity Q)
  - Modulate gain (diode current, AOM in pump beam…)
  - Modulate loss (scattering AOM, graphene modulator, stimulated depletion…)
  - Polarization-dependent loss (EOM in fiber lasers, mostly)
- Frequency (center frequency directly linked to f_{ceo}!)

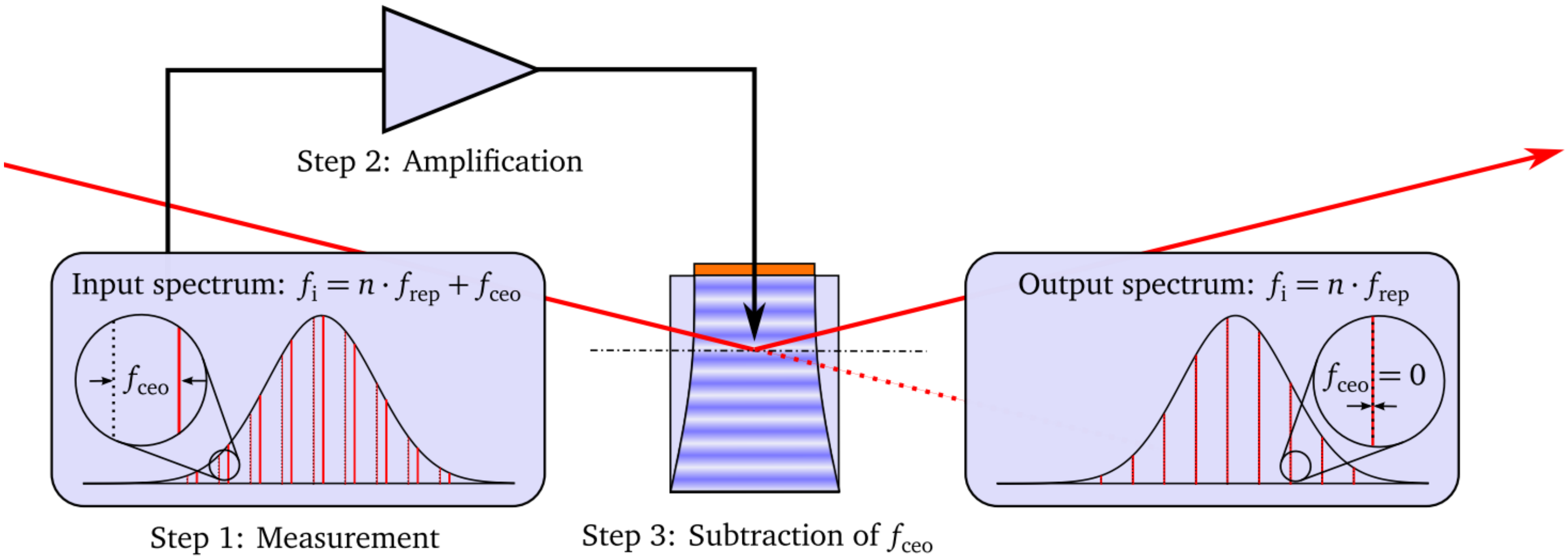
Ti:sa standard: Feed-back to pump power



- Earliest commercial approach for CEP stabilization
- Hours of CEP-stable operation when optimized for reliability
- Typical residual noise in Ti:sa oscillators: 90-180 mrad (optimized)
- Inherent drawbacks:
  - **Phase-lock loop trade-off:** Performance vs. Reliability
  - **Low correction bandwidth** (<100 kHz, typically 10-20 kHz)
  - $f_{ceo} = 0$ **impossible** with low-drift interferometers

Feed-forward* stabilization (CEP4)

Idea: Shift the comb center frequency by just the right amount!



+ Never loses phase relation
+ Arbitrary CEO (simplest: $f_{ceo}=0$)
+ Control bandwidth >300 kHz independent of oscillator
+ Out-of-loop specs only

Complications solved:
– Linear spatial chirp (use prism)
– AOFS dispersion (use GDD mirrors)
– Diffraction efficiency

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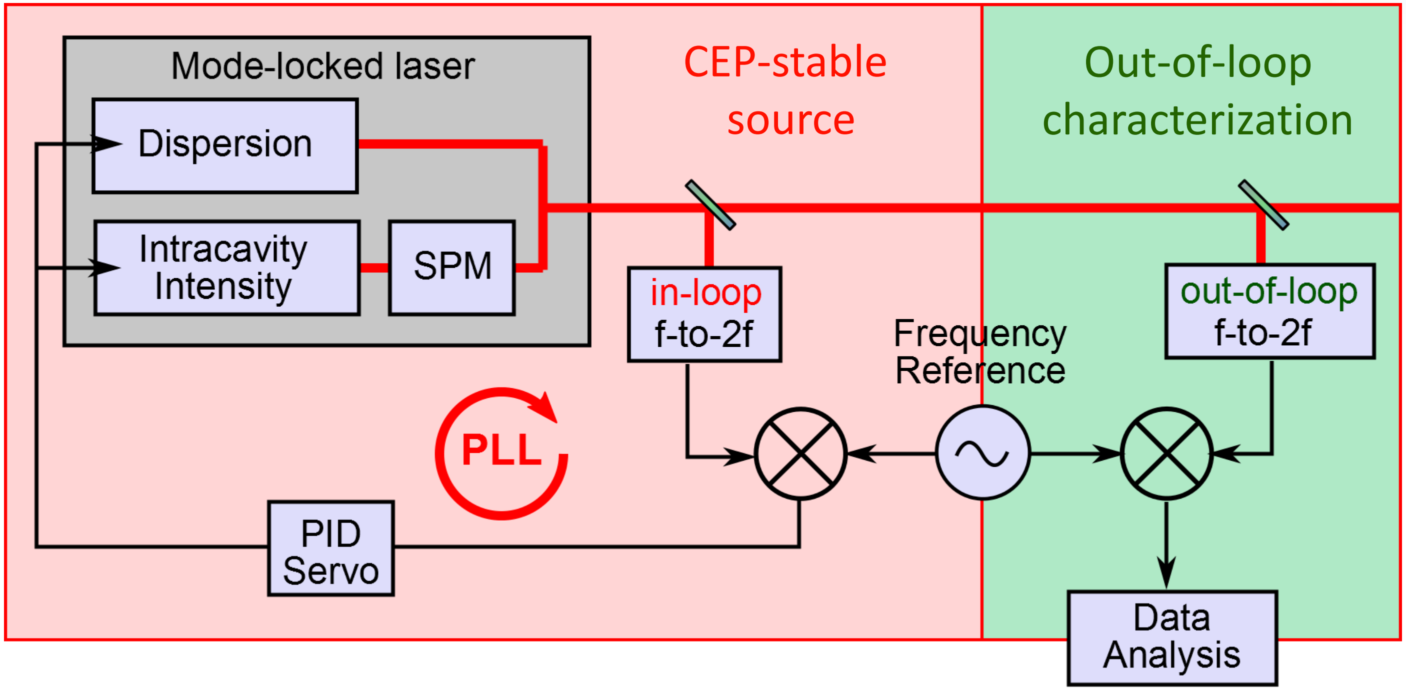
*Forward: Control does not affect the measurement! Not needed, because the action of the AOFS is precisely known. Does not imply correction of future pulses or even those used in the measurement…

Koke et al., *Nature Photonics* **4**, 462 (2010); Lücking et al., *Optics Letters* **37**, 2076 (2012)

Characterizing oscillator CEP properties



Any in-loop signal (e.g., the PID error signal) underestimates CEP noise!

Proper method to measure the CEP performance of oscillators:

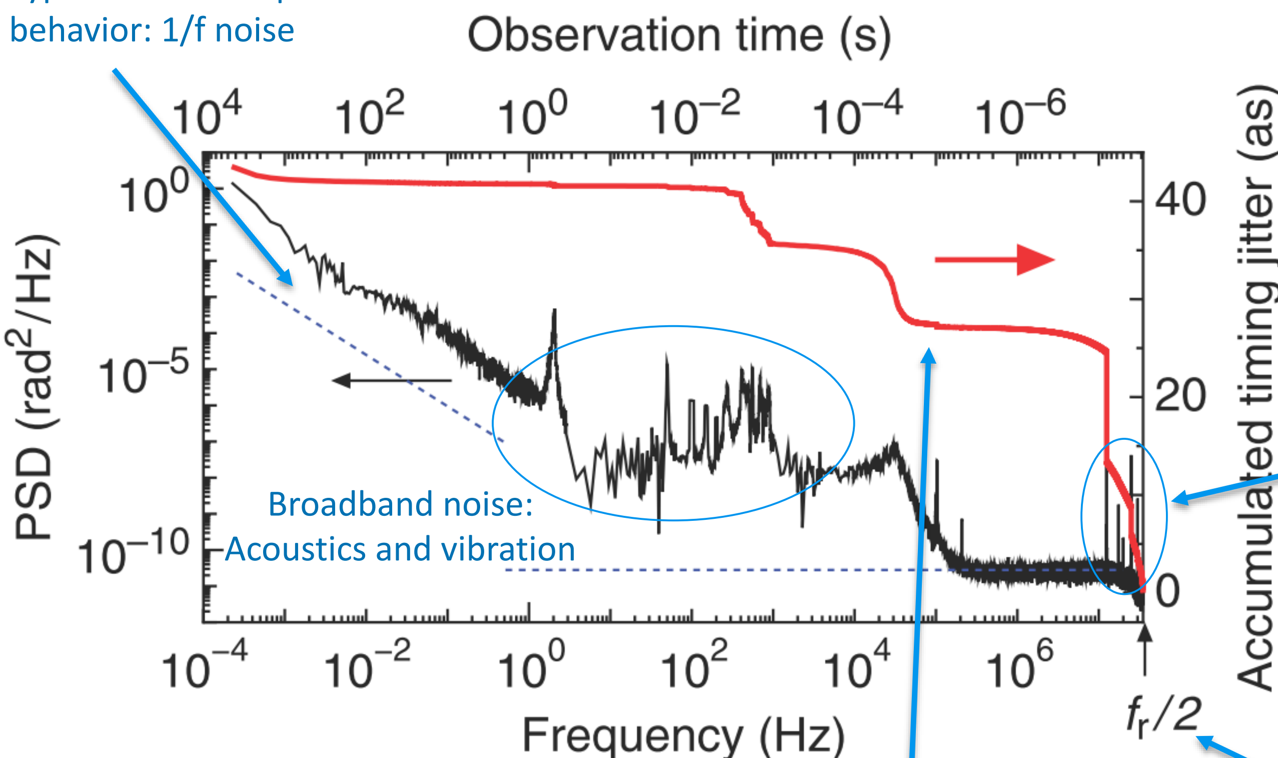
1. Lock f_{ceo} to a common reference (by whatever means)
2. Make a second (so-called out-of-loop) measurement of the stabilized output (f_{out})
3. Perform a phase comparison between the reference at f_{ref} and f_{out}
4. Record the suitably filtered signal and analyze…

Reading frequency-resolved noise plots

- Result of the measurement is the **phase error between f_{ref} and f_{out}**
- If this is properly sampled and calibrated, a Fourier transform leads to the plot below
- If f_{ceo} were set to 0, the phase noise figures here would correspond to the actual CEP

Typical out-of-loop behavior: 1/f noise

More common, but equivalent: Integrated phase noise (IPN). Answers “what noise to expect up to a defined measurement time“



Broadband noise: Acoustics and vibration

Narrowband noise >100 kHz: Electronics and RF noise

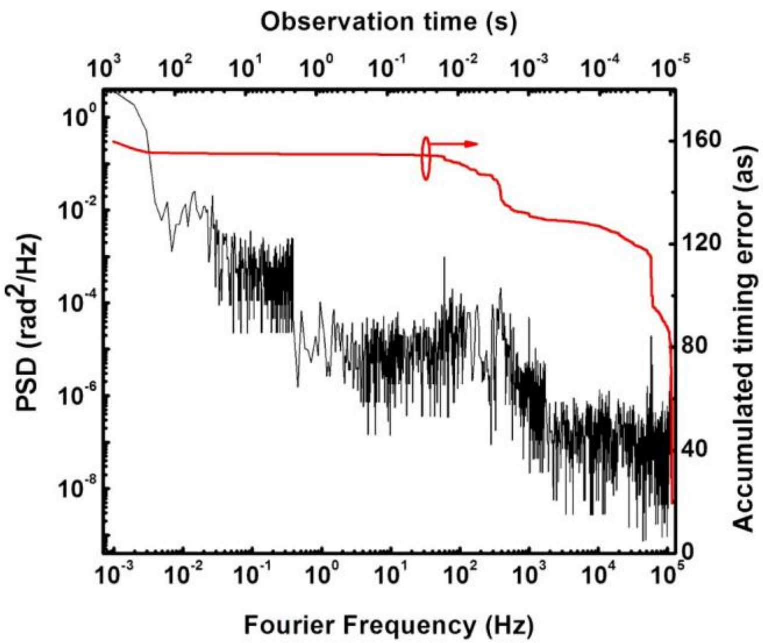
ATJ or IPN rises **monotonously** with decreasing frequency/increasing time
Steps denote major noise contributions

Half the sampling frequency is the upper limit in a Fourier transform (here: the repetition rate)

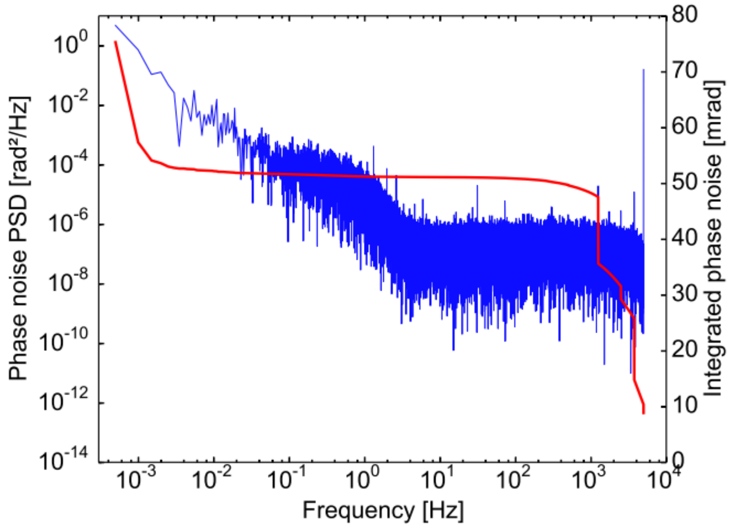
Some typical Ti:sa oscillator results

- Feed-back to pump power via AOM
- In-loop error signal
- 370 mrad (1 mHz – 102 kHz)

- Feed-forward to AOFS
- Out-of-loop measurement
- 80 mrad (0.5 mHz – 5 kHz)



Yun al., *Applied Optics* **48**, 5127 (2009)



Lücking et al., *Optics Letters* **37**, 2076 (2012)

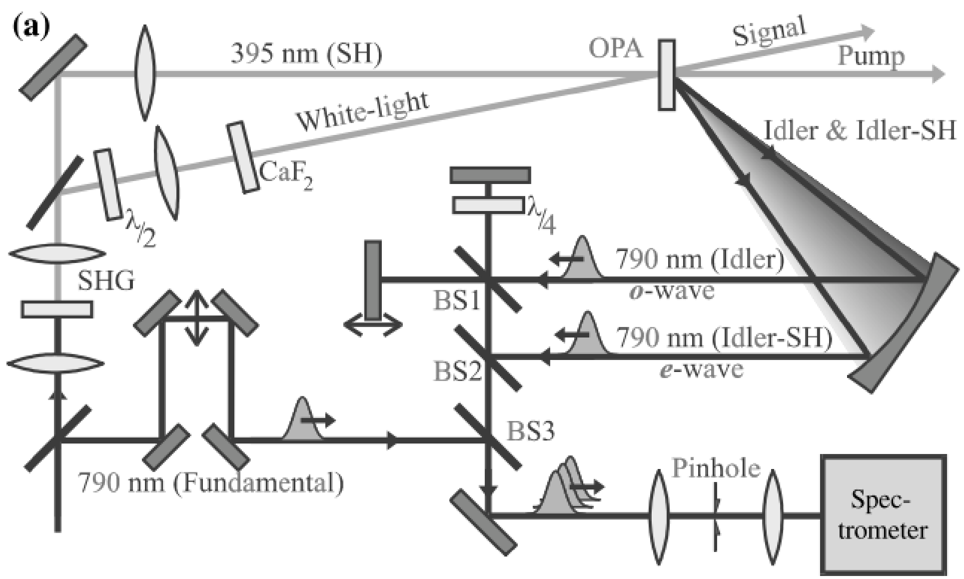
Passive stabilization via DFG

- During DFG/OPA, the idler carries the phase difference between pump and signal waves
- If those two are derived from the same source, the idler is "passively" CEP-stable

TABLE I. Phase properties of various OPA designs.

OPA configuration	A	B	C
Pump frequency, ω_P	ω_0	$2\omega_0$	$2\omega_0$
Central frequency of white light	ω_0	ω_0	$2\omega_0$
Phase offset of pump, ψ_P	ψ	$2\psi + \pi/2$	$2\psi + \pi/2$
Phase offset of signal, ψ_S	$\psi + \pi/2$	$\psi + \pi/2$	$2\psi + \pi$
Phase offset of idler, ψ_I	$-\pi$	$\psi - \pi/2$	$-\pi$
Self-stabilization of ψ_I?	Yes	No	Yes

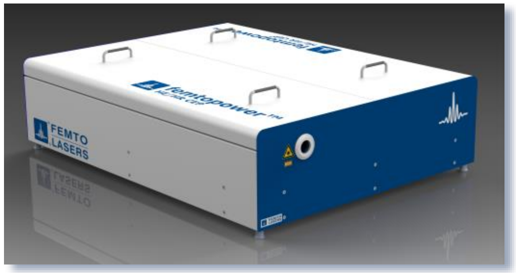
Baltuska et al., *Phys. Rev. Lett.* 88, 133901 (2002)

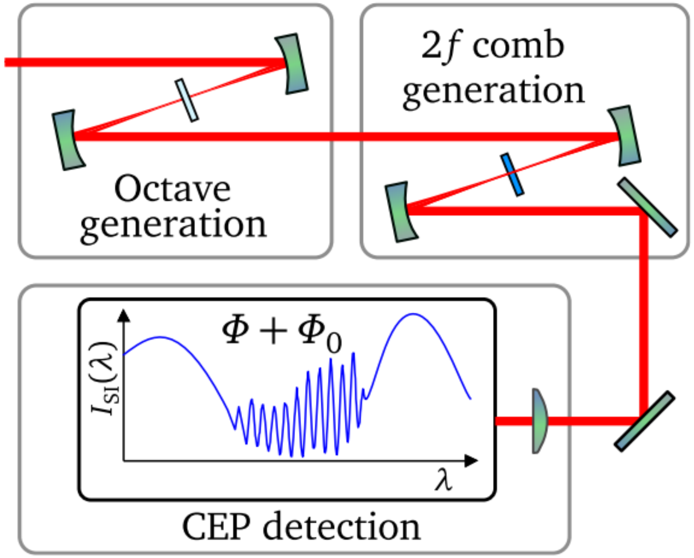


From nanojoule to millijoule

CEP STABILIZATION IN AMPLIFIERS

Single-pulse CEP from spectral interferometry



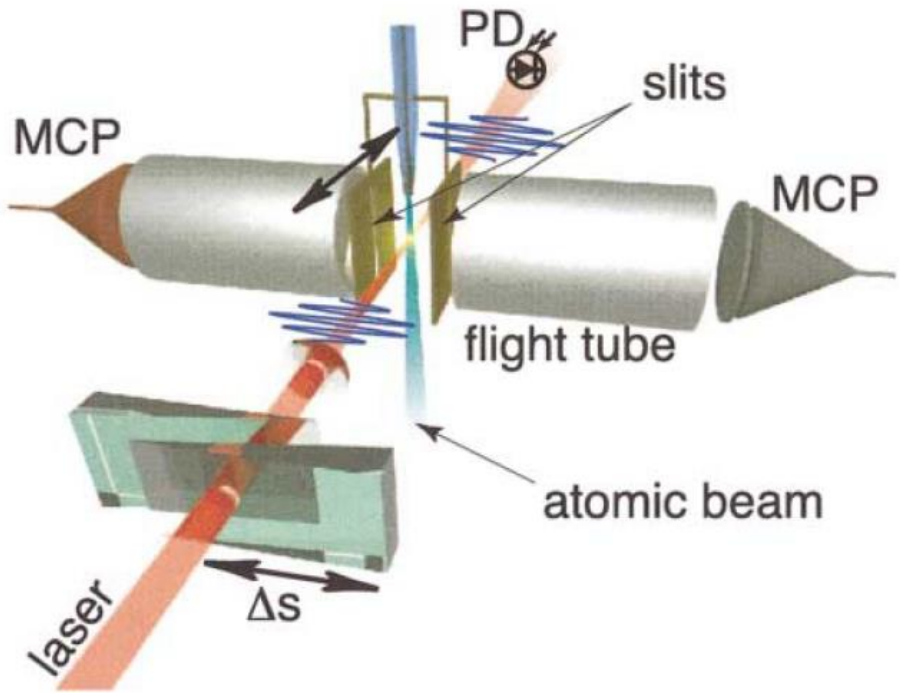


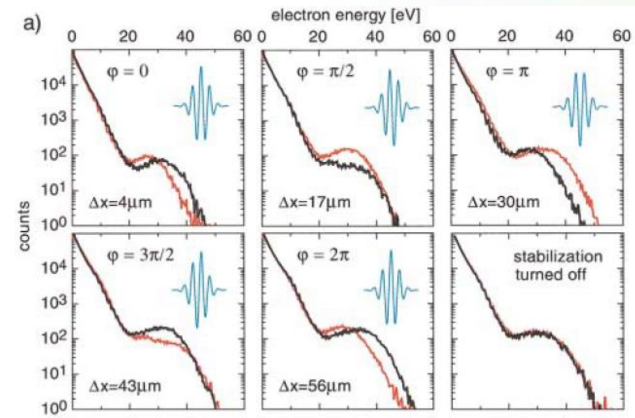
In-line ("collinear") f-to-2f interferometer

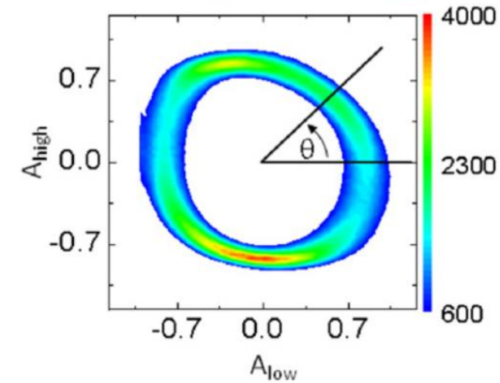
- Self-referencing: Octave-spanning spectrum + SHG = Interference
- Interference fringes detected in spectral domain (using spectrometer)
- Fringe spacing corresponds to temporal delay between fundamental and SHG
- Fringe phase identical to CEP (+ unknown constant offset)
- Precision depends on energy noise, but typically 50-150 mrad
- Input energy: <10 µJ
- Caution! Spectrometer must be set to acquire only single pulses!
  To compare N-pulse averaging: Rms noise goes with $1/\sqrt{N}$…

Proposal: Kakehata *et al.*, *Optics Letters* **26**, 1436 (2001)

Absolute CEP measurement with Stereo ATI







Stereo ATI, "CE Phase Meter"

- CEP is encoded in the energy spectra of left/right emitted ATI photoelectrons
- By choosing suitable energy ranges, the respective signal levels become parameters for a roughly spherical plot (PAP, "phase potato")
- Analog detection complex, but can be made fast (>10 kHz)
- Precision depends on pulse duration: <5 fs: 120 mrad, >12 fs: >350 mrad
- Required input energy between 35 and 175 μJ

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G. Paulus *et al*., *Nature* **414**, 182 (2001)
T. Rathje *et al*., *J. Phys. B* **45,** 074003 (2012)

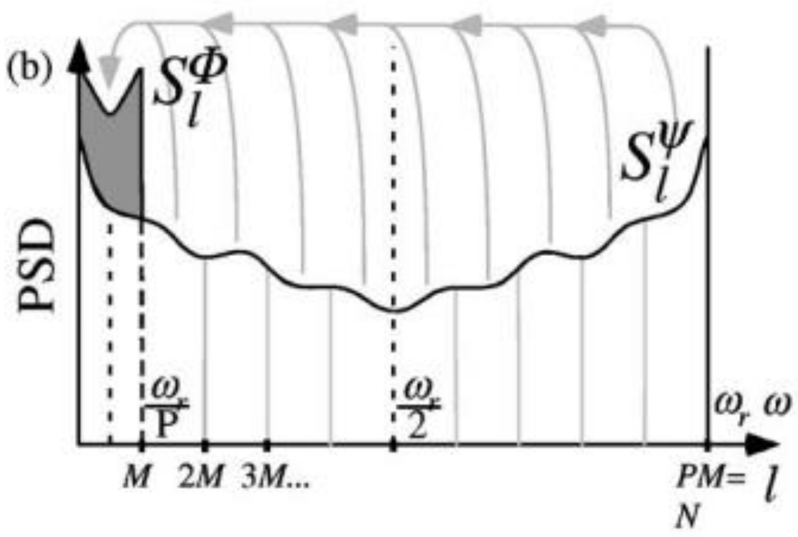
"Nyquist's curse"

Nyquist frequency f_{Ny}: Half the sampling rate of a discrete-time system, $f_{\mathrm{Ny}} = f_{\mathrm{sa}}/2$

Shannon-Nyquist theorem:

"If a function $x(t)$ contains no frequencies higher than f_{Ny}, it is completely determined by giving its ordinates at a series of points spaced $1/(2f_{\mathrm{Ny}})$ apart".

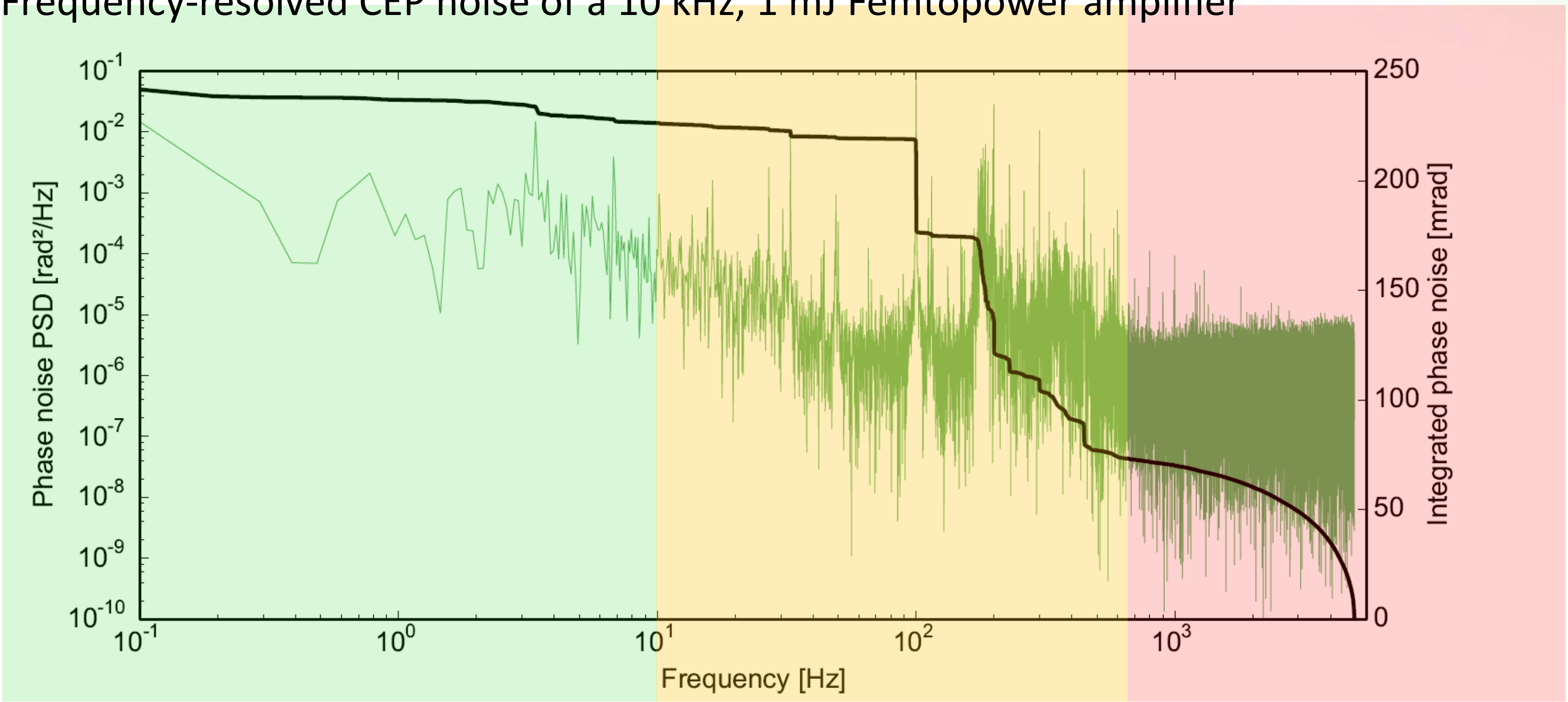
- Sampling CEP noise: Contributions can only be identified unambiguously when they occur at or below the Nyquist frequency.
- Start with a stabilized oscillator
  – repetition rate in the 10s of MHz range
- Amplifier sampling rate in the kHz range
  – subsampling by several 10^4
- What happens between to amplifier shots?



1. Whatever CEP noise accumulates between amplifier shots can never be corrected!
   - So start off with as low noise from the oscillator as possible
2. Correction of CEP noise from the amplifier cannot be faster than half the sampling rate
   - So measure as fast as possible – every single shot, at best!

CEP noise sources in amplifiers

Frequency-resolved CEP noise of a 10 kHz, 1 mJ Femtopower amplifier



Hz range and below:
Environmental drift
→ easily corrected

10 Hz – 1 kHz:
Acoustic range
→ biggest contribution!

> 1kHz:
f-to-2f noise floor
→ no correction possible

Keeping CEP noise low in amplifiers

f range	CEP noise sources in amplifiers:	Possible mitigations:
10–1000 Hz	• Mechanical vibrations of large components ▪ Stretcher/Compressor (important!) ▪ Mirror mounts	❑ Avoid vibrations ❑ Use bulk stretcher ❑ Low stretching factor ❑ **CEP detection >1 kHz and fast feed-back**
>1000 Hz	• Pump laser energy noise ▪ Stochastic (cannot cancel)	❑ Low-noise pump laser ❑ Saturate amplification
<10 Hz	• Beam pointing drift, causing dispersion changes in stretcher/compressor	❑ Stabilize separately

Lessons to learn from this…

1. Most noise comes from the acoustic range
2. Correction is difficult as it requires both a fast measurement and a fast actuator
3. Passive stability is paramount

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CEP feed-back actuators in amplifiers

Offset in oscillator CEP locking loop (to pump power) Nature 421, 611 (2003); JSTQE 9, 972 (2003)

- ❑ Fast
- ❑ Two loops in comparable frequency ranges, same actuator: Unstable!

Introducing dispersion in some way

- Wedges/prisms in beam path Opt. Lett. 31, 3113 (2006)
  - ❑ Slow (<100 Hz)
- Compressor grating separation or angle Appl. Phys. Lett. 92, 191114 (2008)
  - ❑ Very slow (<10 Hz)
  - ❑ Beam pointing impact
- ❑ All these: Dispersion impact on pulse duration

Acousto-optic devices

- AOPDF (“Dazzler”) Opt. Lett. 34, 1333 (2009)
  - Fast (10 kHz)
- CEP4 AOFS grating phase Opt. Lett. 39, 3884 (2014)
  - Simple add-on, no impact on any other parameter
  - Even faster (100 kHz)
- ❑ All these: No impact on pulse duration

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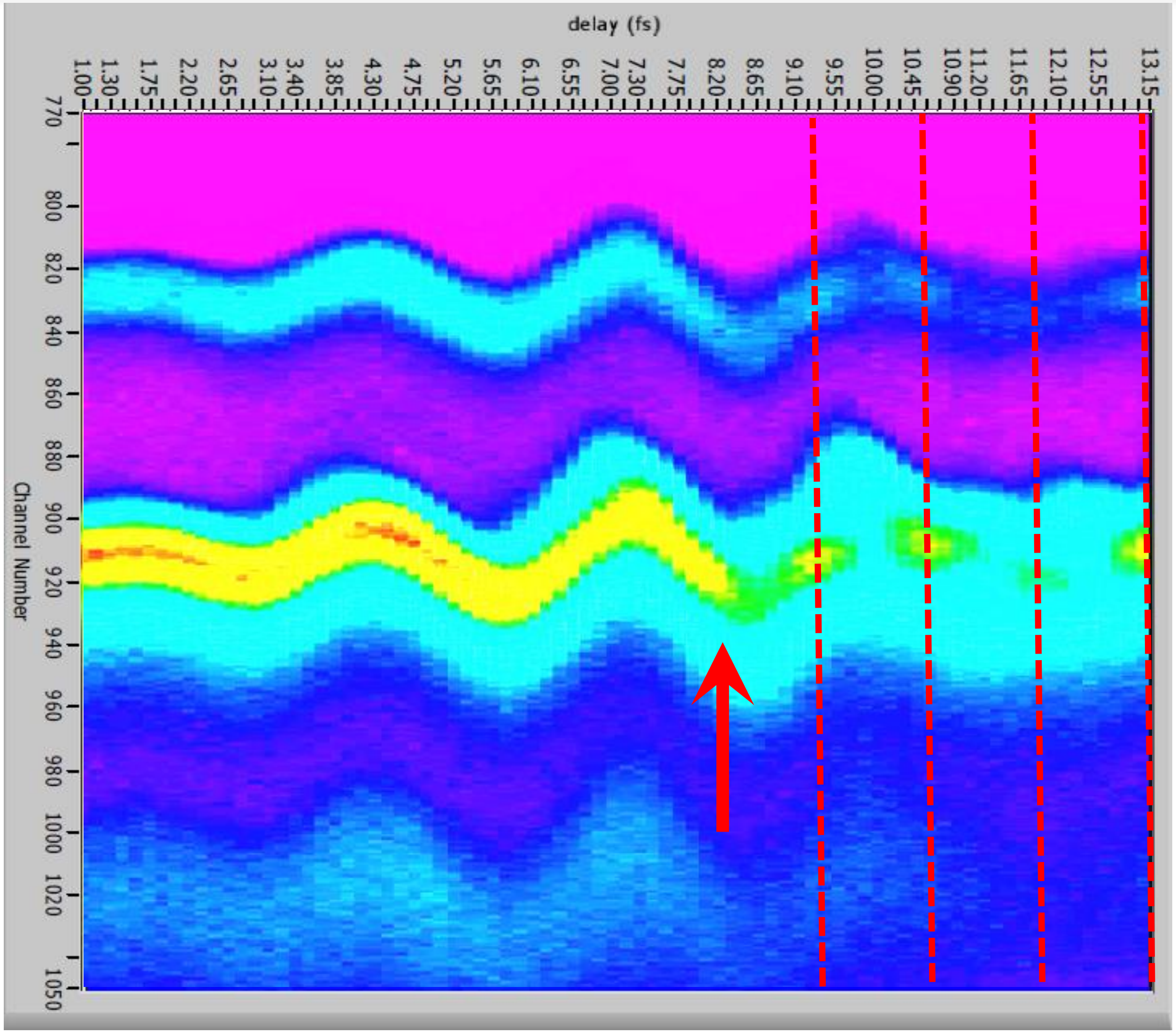
How good is good enough?

HOT TOPICS AND CURRENT RESEARCH

CEP lock failure



PLL loses oscillator CEP lock around 8.2 fs delay:

Re-lock possible, but **fixed phase relation is lost**

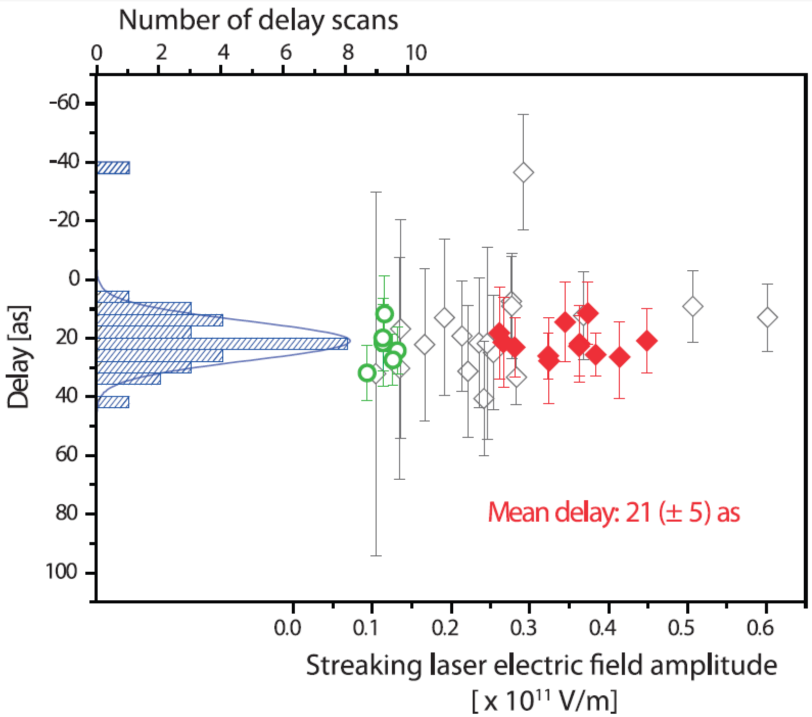
Random waveform drives attosecond pulse formation

Satellite pulses produce modulation of electron spectra

Caution:
f-to-2f interferometers might not even notice...

Image courtesy of the Kienberger group, TU Munich

Challenges to CEP stabilization



"Delay in Photoemission", Schultze et al., Science 328 (2010)

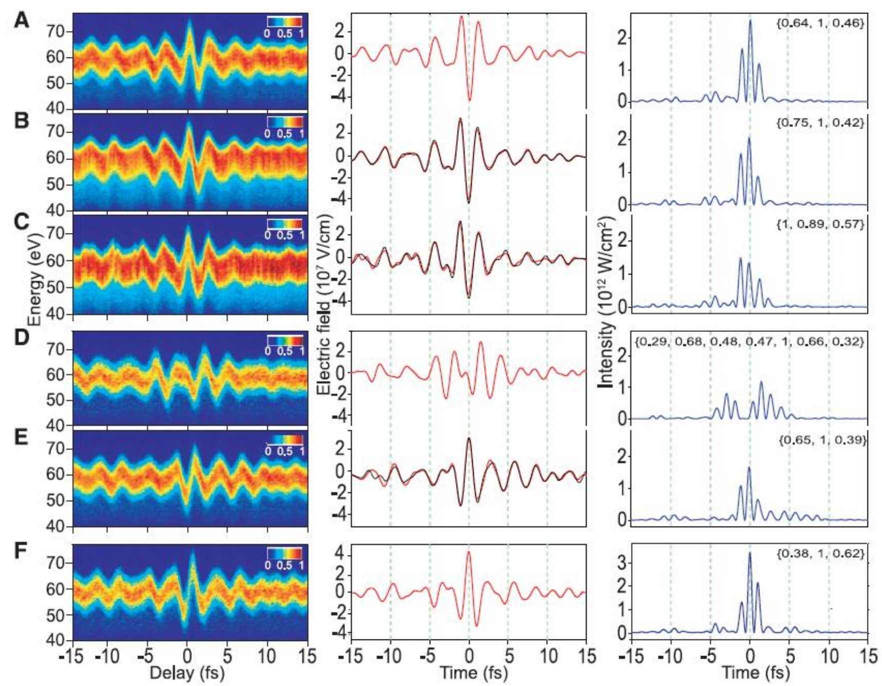
Required tens of streaking spectrograms for dependable statistics – no lock failures
– no satellite pulses

→ **Challenge #1: Reliability**

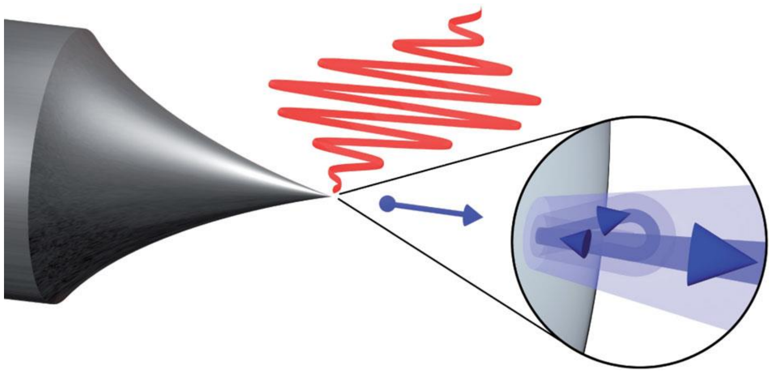
"Synthesized Light Transients", Wirth et al., Science 334 (2011):

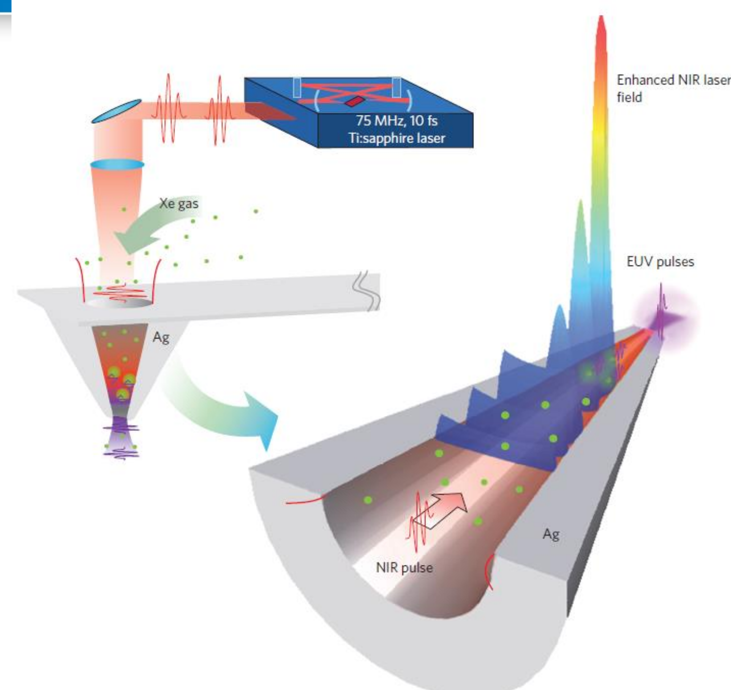
Sub-cycle NIR pulses as driving field for attosecond pulse generation

→ **Challenge #2: Precision**



Zero offset





Direct use of oscillators in attosecond science
Made possible by field enhancement, e.g.,

- At nanoscale metal tips [1], producing photocurrent modulation
- Using plasmonic waves on a conical surface [2] for high harmonic generation

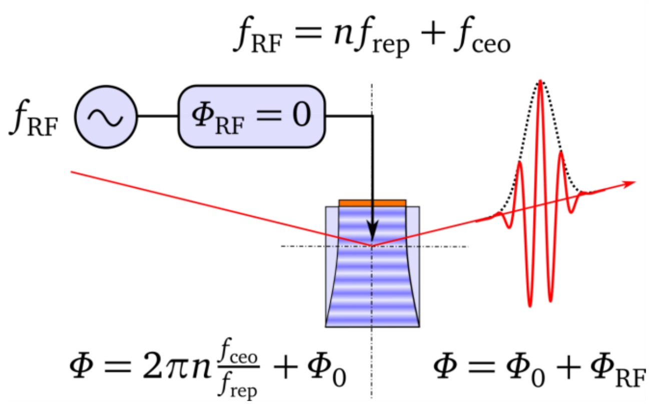
Experiments require a train of **identical pulses at the full repetition rate**

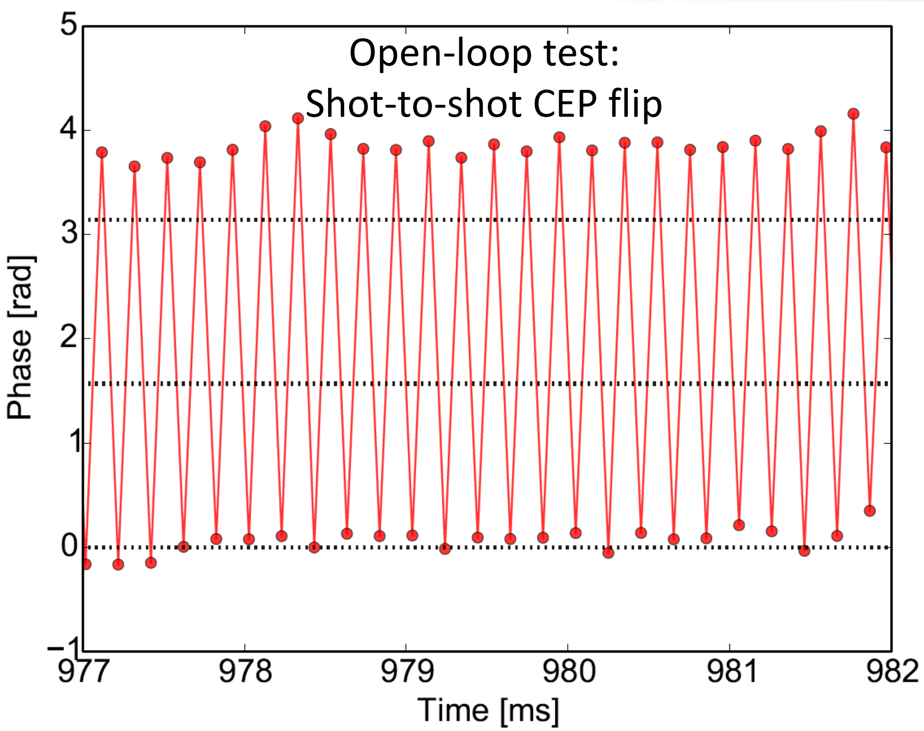
- **f_{ceo} = 0** – Hard to get with traditional stabilization
- **Seamless f_{ceo} scanning** – even harder...

→ **Challenge #3: Versatility**

[1] Krüger *et al.*, *Nature* **475**, 462 (2010)
[2] Park *et al.*, *Nature Photonics* **5**, 678 (2011)

Fast amplifier CEP correction using CEP4 phase





Frequency shifter: RF frequency → $\Delta\phi$ (CEP slip rate, set to zero)
RF phase → ϕ (CEP itself)

- Acoustic grating phase is a free parameter in CEP4 stabilization
- Dispersion-independent, fast, easily added to existing systems
- > 100 kHz BW: Arbitrary CEP from shot to shot

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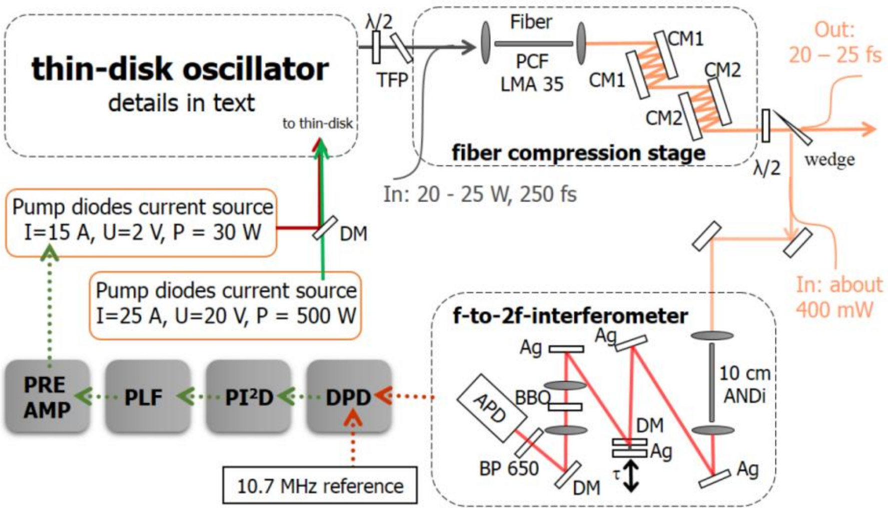
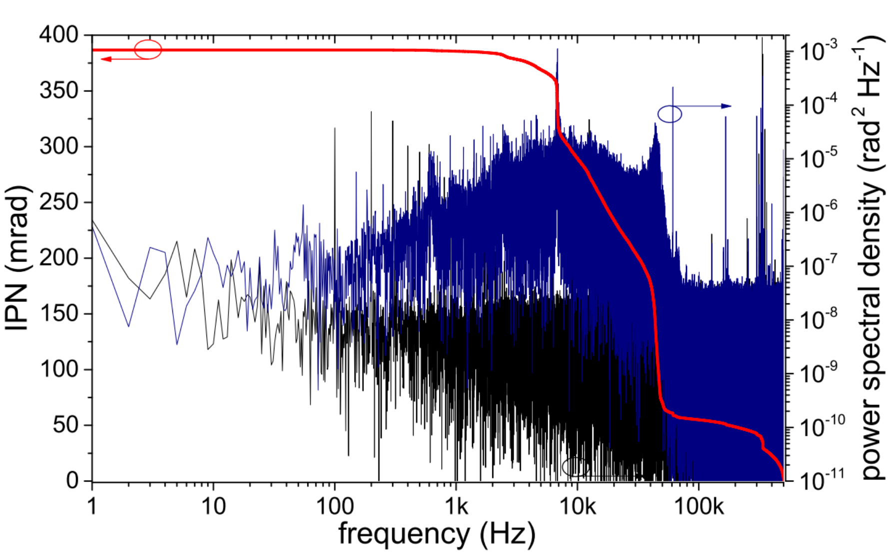
Lücking et al., Opt. Lett. 39, 3884 (2014)

Power scaling CEP-stable oscillators





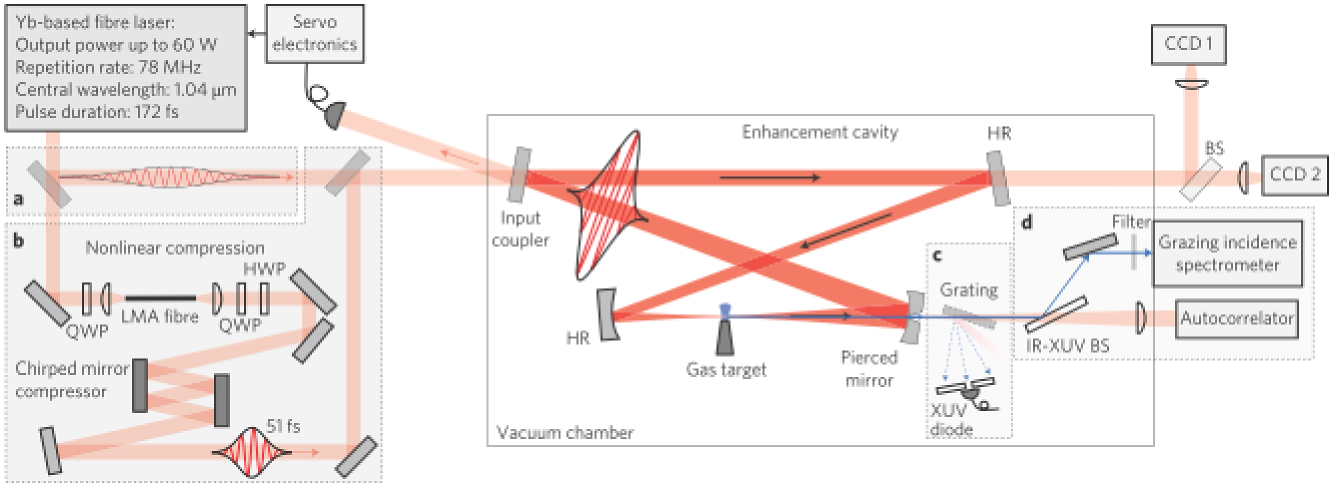
- Yb:YAG thin-disk hard to CEP-stabilize due to SBR issues
  - Overcome using hard-aperture Kerr lens mode-locking
- Compress pulses down to 10-20 fs
- CEP-stabilize using either scattering AOM [1] or second pump diode [2]
  - CEP noise comparable to early Ti:sa oscillators

[1] Pronin et al., "High-power multi-megahertz source of waveform-stabilized few-cycle light," Nature Communications 6, 6988 (2015)

[2] Seidel et al., "Carrier-envelope-phase stabilization via dual wavelength pumping," Opt. Lett. (in print, 2016)

Enhancement cavities

- HHG with its low efficiency lends itself to cavity enhancement
- Groups at Munich (bulk/fiber hybrid) and Jena (fibers) are pushing in this direction
- Enhancement of <30 fs pulses requires full frequency comb stabilization



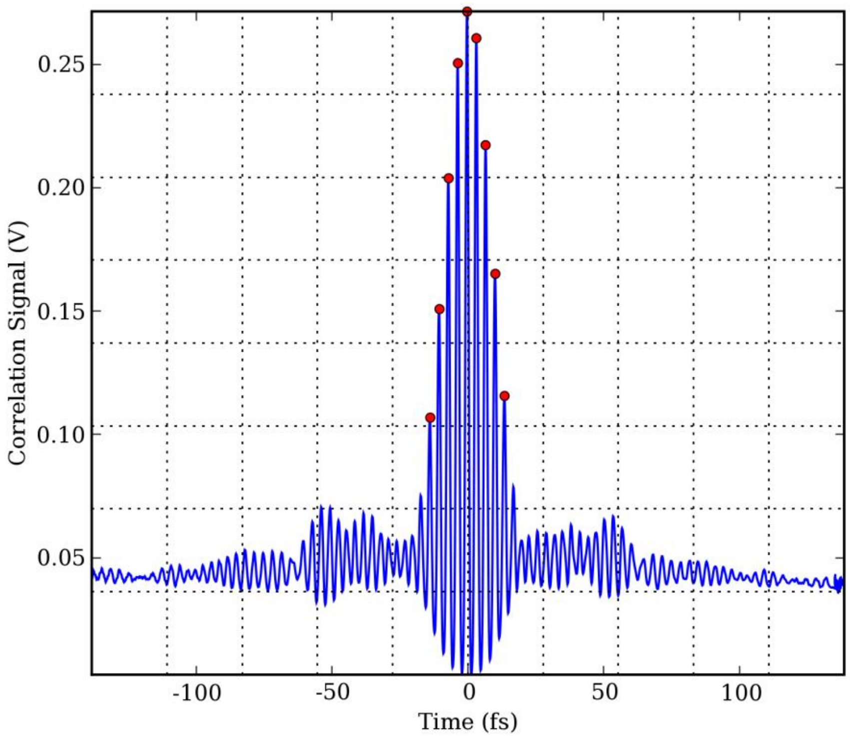
Pupeza et al., Nature Photonics 7, 608 (2013)
Holzberger et at., Opt. Lett. 40, 2165 (2015)
Breitkopf et al., Light: Sci. and Appl. 3, e211 (2014)

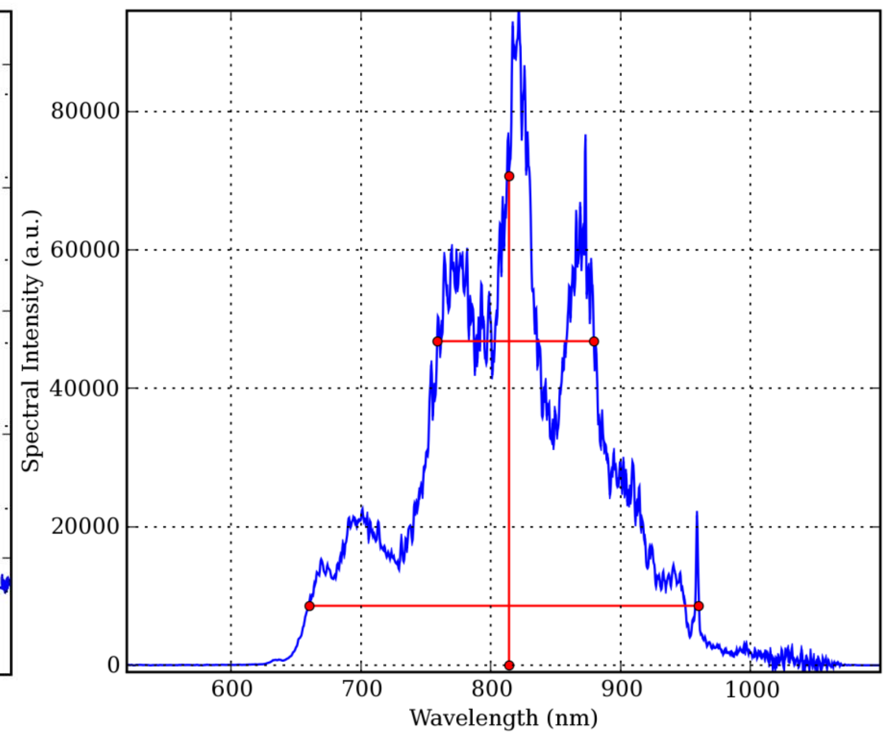
Thank you for your attention!

QUESTIONS?

ADDITIONAL MATERIAL

CEP 4: Autocorrelation after AOFS and wedge





- Measured after wedge and collimating mirror in -1st order
- Fringe-resolved SHG autocorrelation yields 9.8 fs pulse duration
- Fourier limit: <7 fs
- Recompression limited by mirrors: Better TOD match possible

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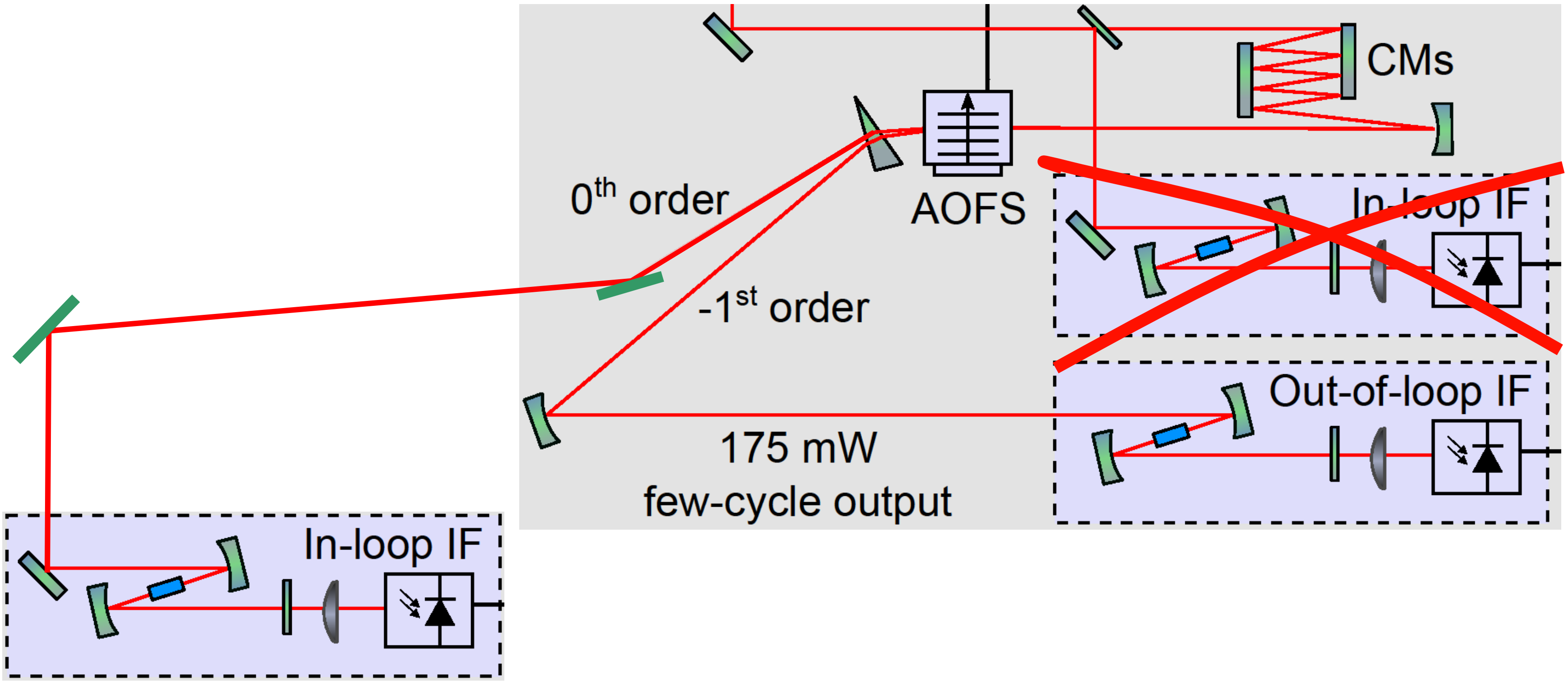
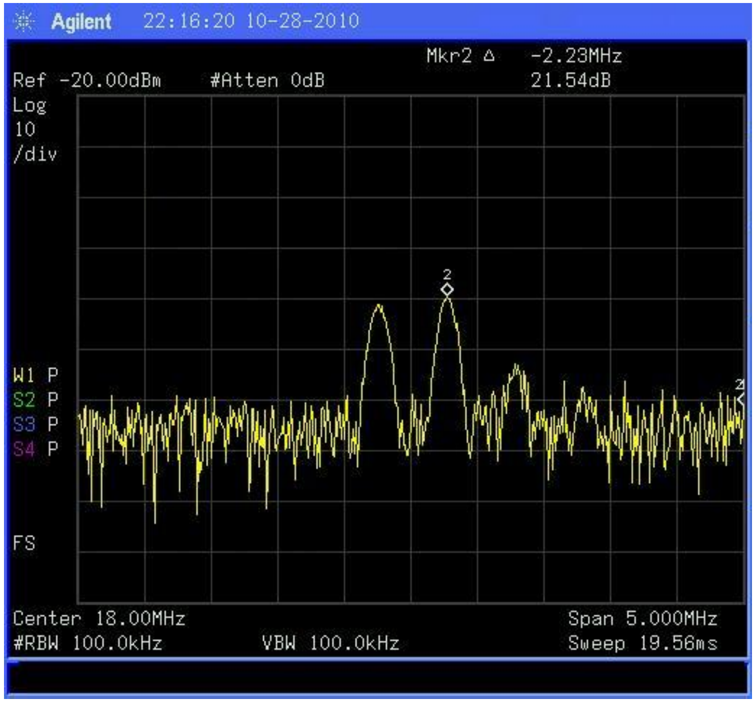
0^{th} order in-loop detection

- Why not use 0^{th} order power for in-loop measurement?
- Worked fine in fiber-based experiment…



0^{th} order in-loop detection



But: In-loop f_{CE} signal behaves strange:

- FF loop open: f_{CE} signal fine
- FF loop gradually closing: Sidebands appear in RF spectrum
- Sidebands are equidistant at some 300-900 kHz, depending on AOFS alignment…

- Problem: SNR in monolithic 0-to-f is extremely power-dependent
- We introduced a feedback loop that oscillates at its resonance…

Measured “by accident”:

Control bandwidth of FF scheme: >300 kHz

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f-noise to Φ-noise

$$\frac{\Delta\varphi}{T}$$: f_{CE} phase error over measurement time T

$$f_{CE,lin} = f_{CE} + \frac{\Delta\varphi}{2\pi T}$$: Corresponding frequency shift over measurement time

$$\Delta\Phi = 2\pi \frac{f_{CE}}{f_{rep}}$$: Pulse-to-pulse CEP shift

$$\Delta\Phi(t) = 2\pi \frac{f_{CE}}{f_{rep}} \cdot \frac{t}{T_{RT}} = 2\pi t f_{CE}$$: Accumulated CEP over time t assuming no error

$$= 2\pi t \left(f_{CE} + \frac{\Delta\varphi}{2\pi T} \right)$$: Accumulated CEP over time t with linearized error

$$= \frac{\Delta\varphi}{T} t$$: Accumulated CEP over time t with f_{CE} =0

$$\Delta\Phi = \Delta\varphi$$: Accumulated CEP over measurement time with f_{CE} =0