13th International Beam Instrumentation Conference (IBIC2024)

Cost-effective time-stretch Terahertz electro-optic recorders, by using 1550 nm laser probes

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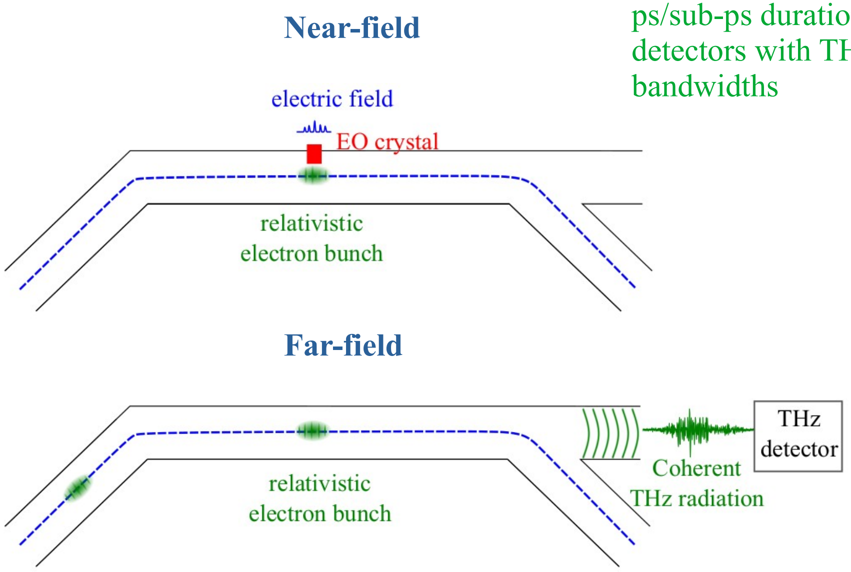
Longitudinal electro-optic (EO) diagnostics in accelerators-based light sources

Longitudinal diagnostic tools needed in free-electron lasers and storage rings:

- ❒ to measure and obtain information on electron bunches shapes (shape, envelope, carrier, ...)
- ❒ study the dynamics of the electron bunches



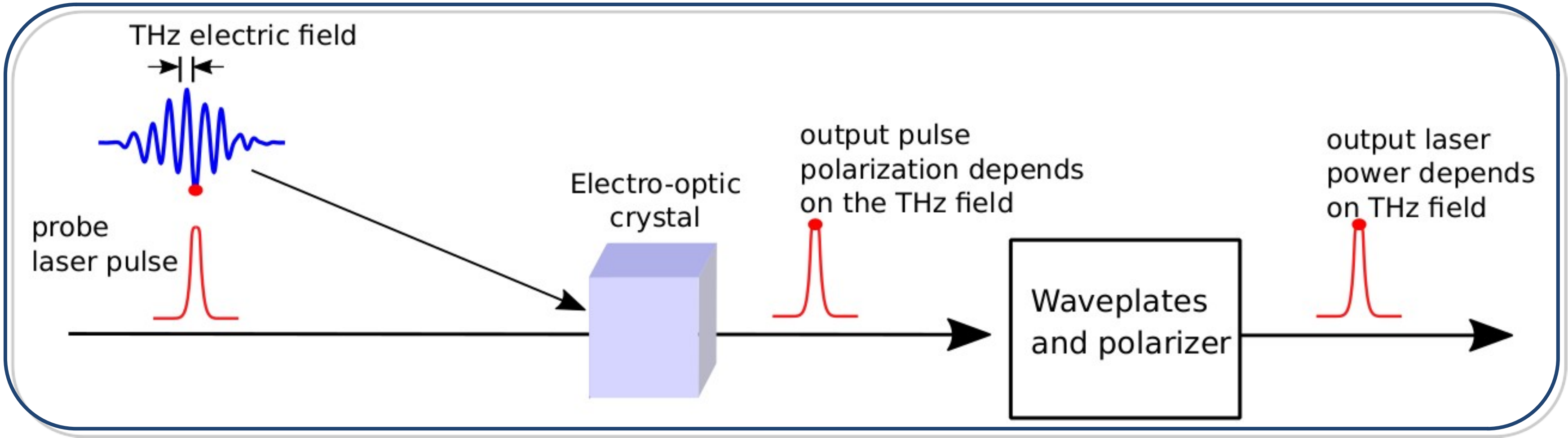
Electron bunches with ps/sub-ps duration requiring detectors with THz bandwidths

Requirements and challenges:

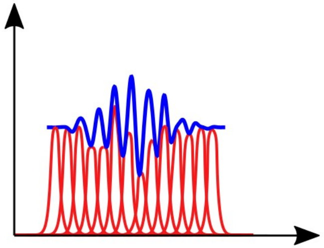
- Single-shot measurements
- High repetition rates (MHz+) for a range of machines, e.g., EU-XFEL, SOLEIL, KARA, ELBE
- ps/sub-ps temporal resolution
- Long THz signals

Main upgrade: Reduce the cost of high repetition rates single-shot THz detectors

Classical THz detection based on electro-optic sampling: scanning technique



- ➢ The electric field modifies the birefringence of a crystal.
- ➢ The THz field-induced birefringence is probed using a laser pulse.
- ➢ Varying the optical path between pump and probe pulses.
- ➢ Serial **scanning acquisition technique**.

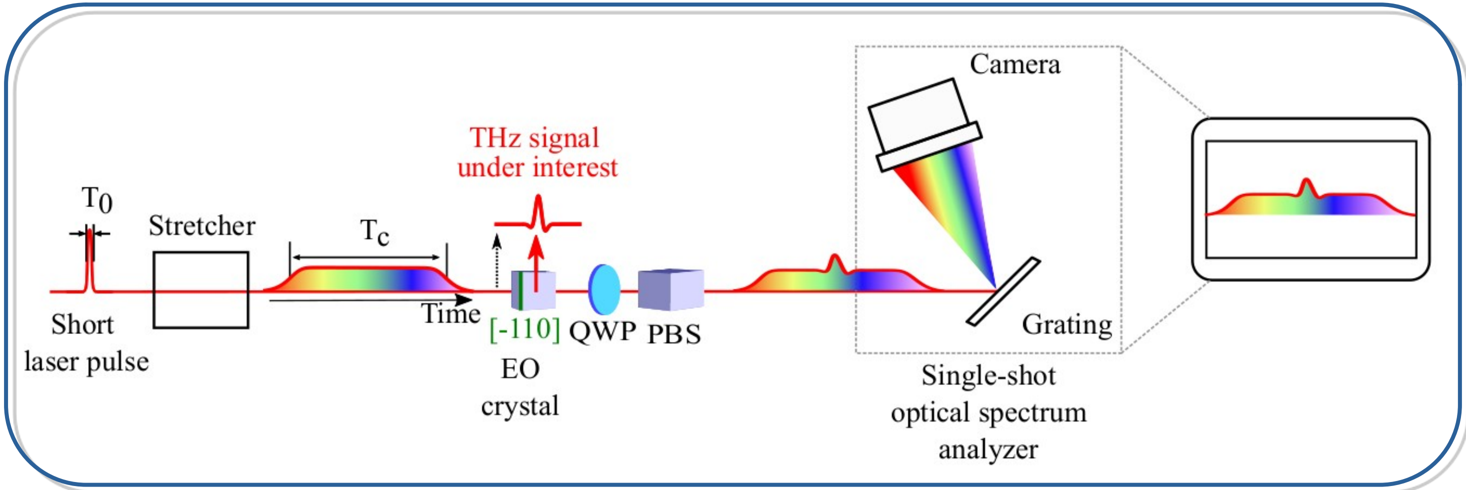


Popular since the 80s: Near-field measurements Valdmanis, Mourou, Gabel, APL 41, 211, (1982)

THz single-shot detection technique capable of high repetition rates

Main idea: Achieve single-shot THz measurements using single-shot electro-optic sampling or spectral-encoding

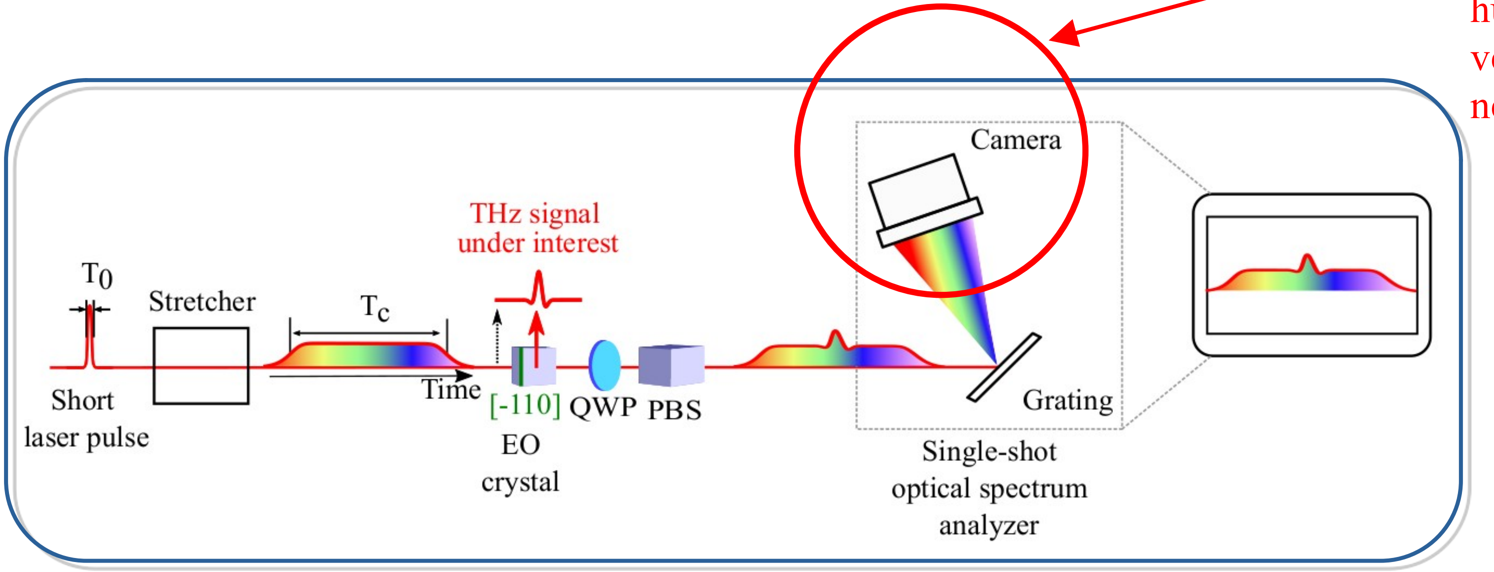
→ **with the use of chirped laser pulses**



- Chirp ~ linear ramp of frequency versus time
- The full THz waveform is imprinted on a single optical probe pulse
- Measurement of the modulated signal using a spectrometer (grating +camera)

First demonstration for THz pulses (table-top exp.): Jiang and Zhang, Appl. Phys. Lett. 72, 1945 (1998)
First demonstration in the accelerator context: bunch shapes at FELIX [Wilke et al., PRL 88, 124801 (2002)]
Novel design for speed (<200 fs) and sensitivity (fibered system): [Bernd Steffen et al., Proc. DIPAC09 TUPB42 (2009), RSI 91, 045123 (2020)]

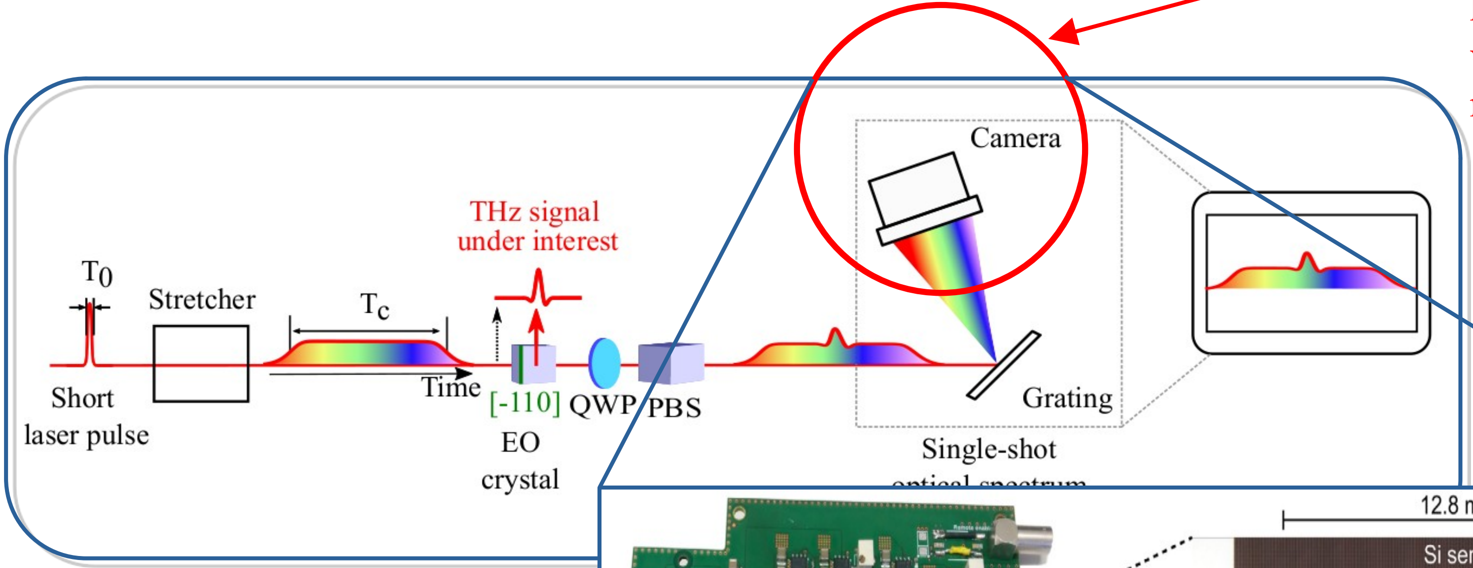
Single-shot electro-optic sampling using chirped laser pulses : spectral encoding and the acquisition rate challenge

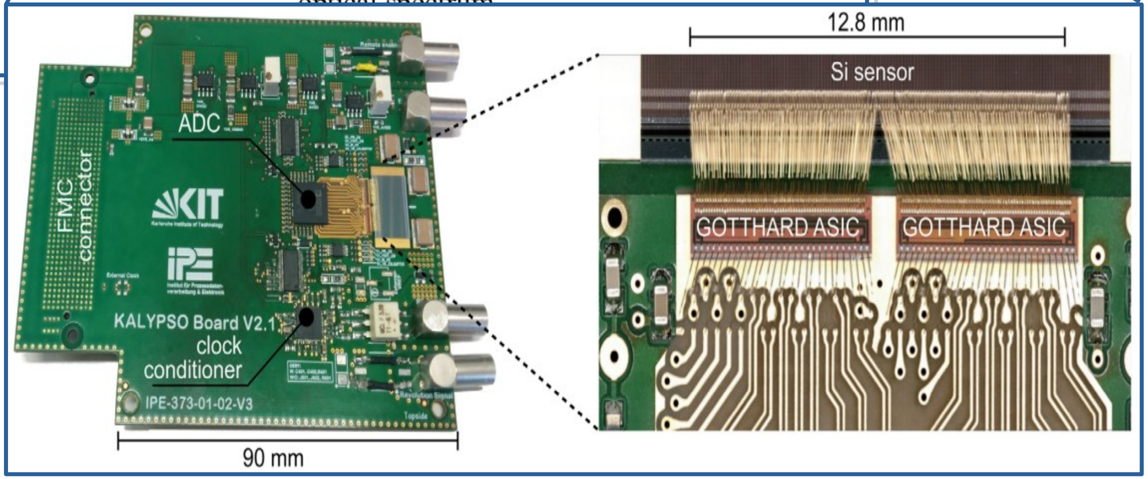


Speed of commercial cameras limited to few hundreds of kHz, versus several MHz needed for accelerators

Single-shot electro-optic sampling using chirped laser pulses : spectral encoding and the acquisition rate challenge

Speed of commercial cameras limited to few hundreds of kHz, versus several MHz needed for accelerators



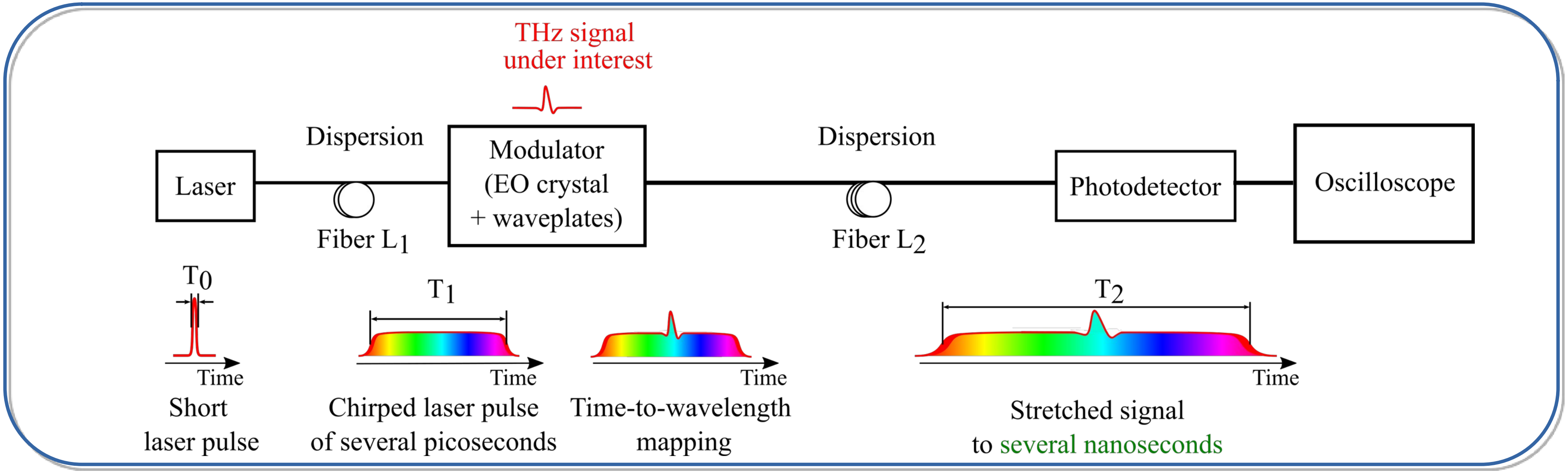


Option 1: ultrafast cameras such as KALYPSO project at KIT. Currently 4 Mf/s over 512 pixels.

[Rota, L., et al. NIMA 936 (2019): 10-13 https://doi.org/10.1016/j.nima.2018.10.093]

Alternative option: Single-shot electro-optic sampling with **photonic time-stretch for high repetition rates**

Main idea: Associate single-shot EO sampling with photonic time-stretch to reach MHz+ repetition rates
[B. Jalali team, Electronics Letters 34, 1081 (1998)]



On the oscilloscope: replica of the THz pulse that is "temporally stretched" by a factor $M = 1+L_2/L_1$

For example, when L_1 = 16 m and L_2 = 4 km → $M \approx 250$.

➔ 4 GHz on the oscilloscope corresponds to 1 THz at the input.

Technique adapted for high repetition rates

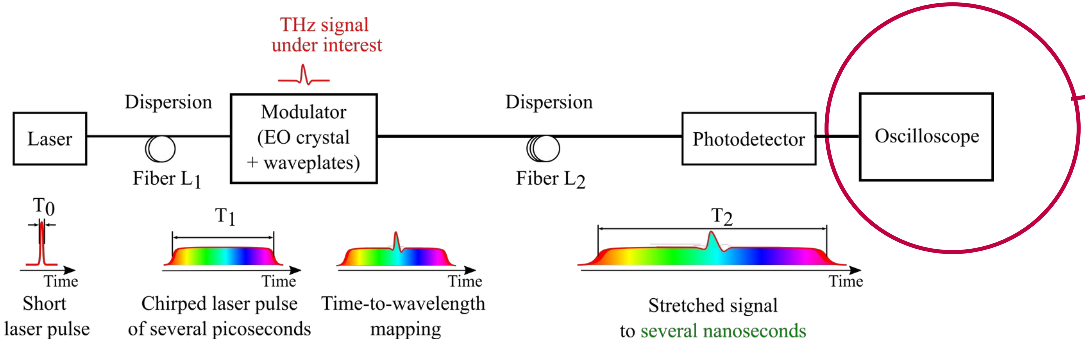
First demonstration of THz time-stretch EO: [(PhLAM-SOLEIL coll.) Roussel et al. Sci. Rep. 5, 10330, 2015]
KARA@KIT: Bielawski, S., Blomley, E., Brosi, M. et al. Scientific Reports 9, 10391 (2019). https://doi.org/10.1038/s41598-019-45024-2
(ANR-DFG collaboration projet between PhLAM, SOLEIL and KIT)

Limitation of photonic time-stretch electro-optic detection

- ✔ Single-shot measurements
- ✔ Easily reach MHz repetition rates (1MHz @ SOLEIL, 2.7 MHz @ KARA)
- ✔ Allows to stretch **up to few ns (2-6 ns)** → use of an oscilloscope with a 8-20 GHz bandwidth

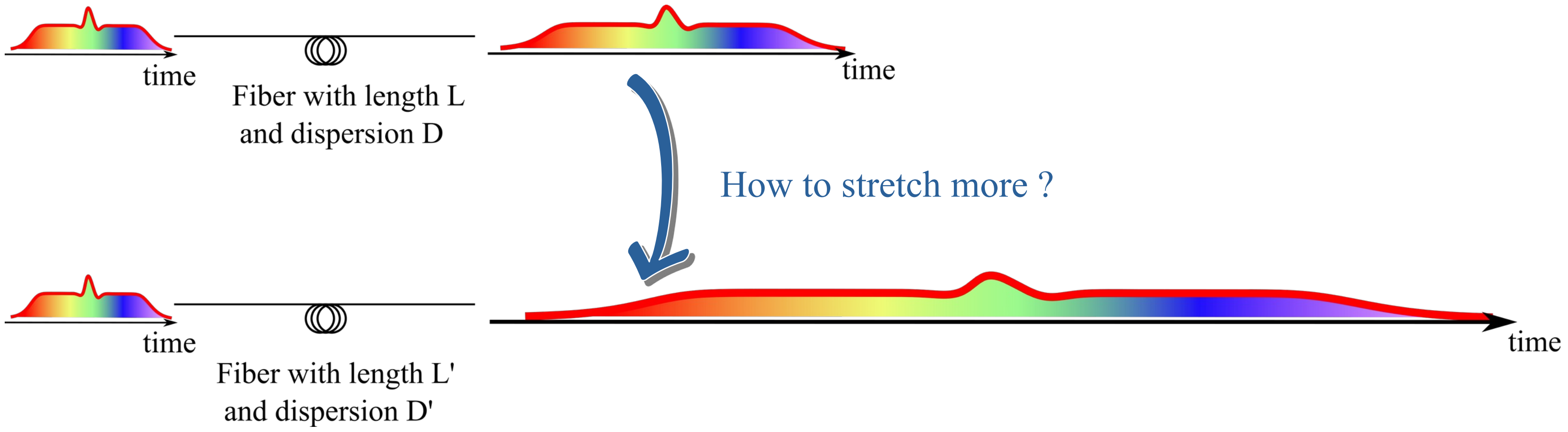
Photonic time-stretch has been an expensive technique so far:

- ➢ Typically requires a fast oscilloscope **(usually 8-20 GHz bandwidth) → ~ 100 - 200 k€**
- ➢ **Oscilloscope BW (or budget) directly determines the number of samples per THz waveform**



Strategies for stretching more ? Decreasing costs and increasing record duration

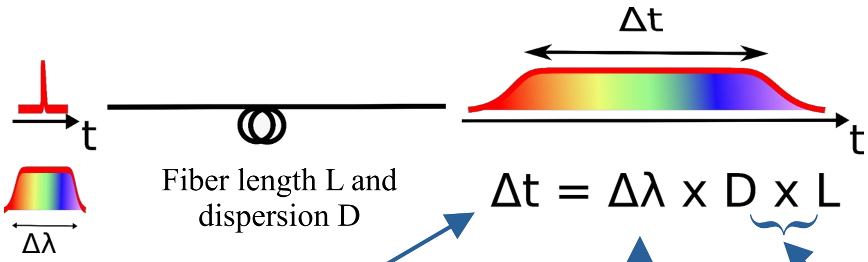
More dispersion → more stretch → less required detection bandwidth (reduced cost)



Solutions for more dispersion:

- **Longer fiber ? (limited by losses)** (in practice, trade-off = dispersion giving ~3-6 dB loss)
- Increase laser bandwidth (nonlinear amp., etc.) [N. Couture, et al. Nat Commun 14, 2595 (2023)]
- Compensate losses using **Raman amplification** [D. Solli, et al. Nature Photon 2, 48–51 (2008)]
- Replace the fiber by **long Bragg gratings** (10 m) [M. Kobayashi, et al. Opt. Lett. 44, 163-166 (2019)]

Strategies for stretching more ? Maximal stretch crucially depends on wavelength

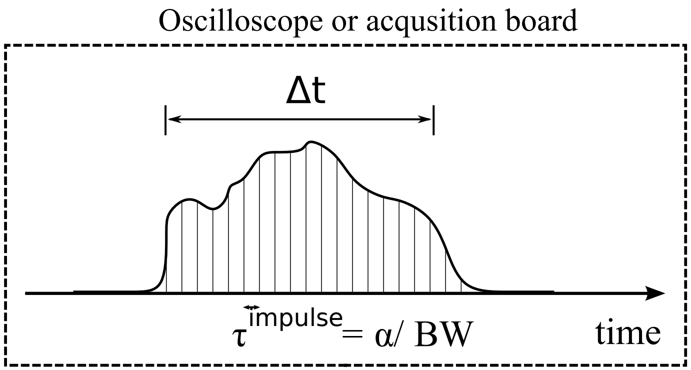


$$\Delta t = \Delta\lambda \times D \times L$$

Amount of stretch achieved

Laser spectral width

Parameters of the fibers related to the laser wavelength



Effective number of points

$N_{eff1} = \Delta t \times BW$ with $\alpha \sim 1$

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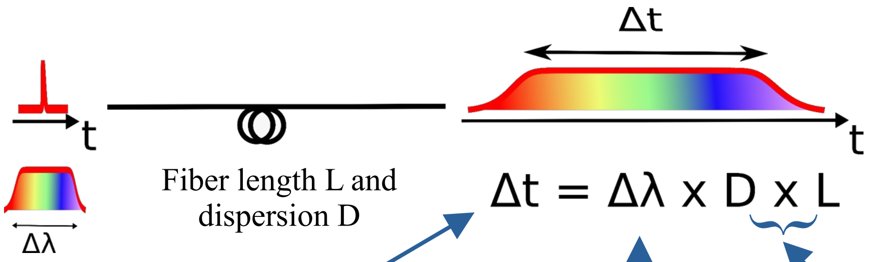

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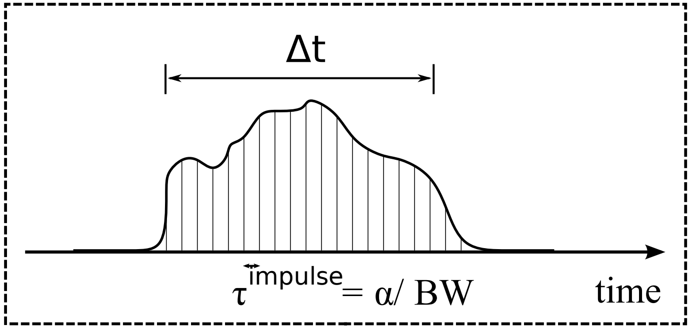
Oscilloscope or acqusition board



Effective number of points

$N_{eff1} = \Delta t \times BW$ with $\alpha \sim 1$

			For 6 dB loss			
					Effective "Nb. of points" N_{eff1} recorded with bandwidth	
Wavelength (nm)	Spectral width $\Delta\lambda$ (nm)	Fiber	Fiber length L	Final stretch for a typical laser	1 GHz	20 GHz
1030	35	HI1060	4 km	6 ns	6	120
1550	68.2	SMF28	33 km	48 ns	48	960
		DCM	Equivalent to 80 km of SMF28	108.8 ns	108	2160

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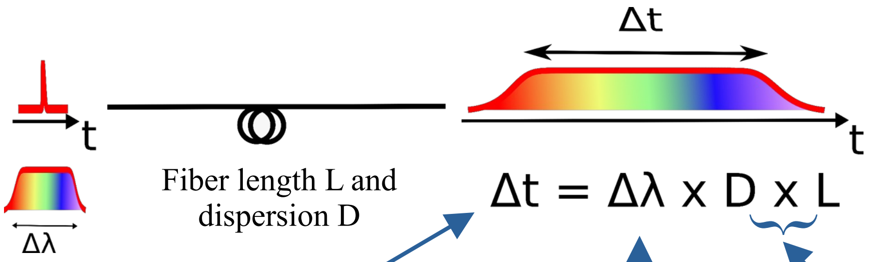

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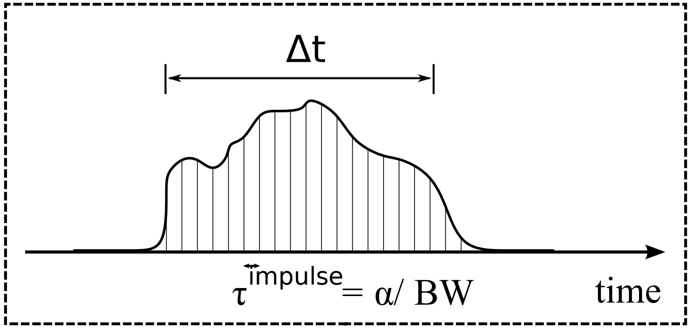

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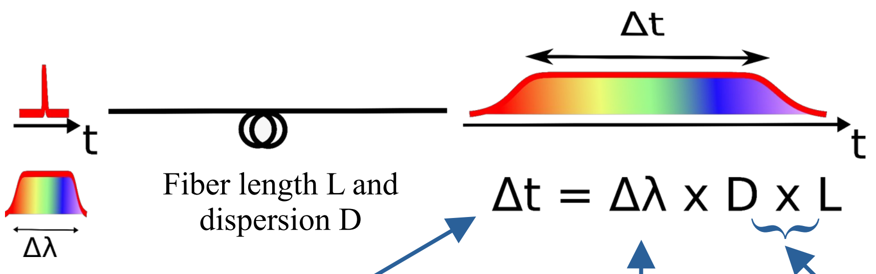

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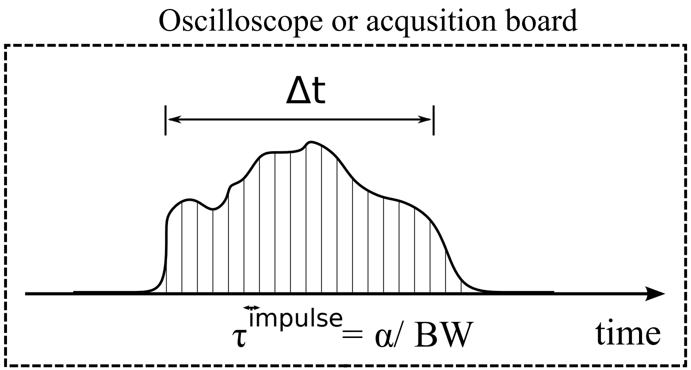

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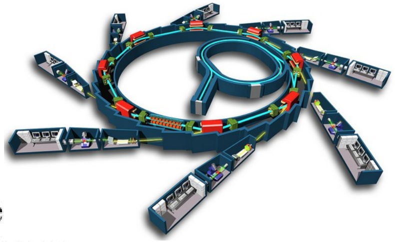
		DCM	Equivalent to 80 km of SMF28	**108.8 ns**	**108**	**2160**

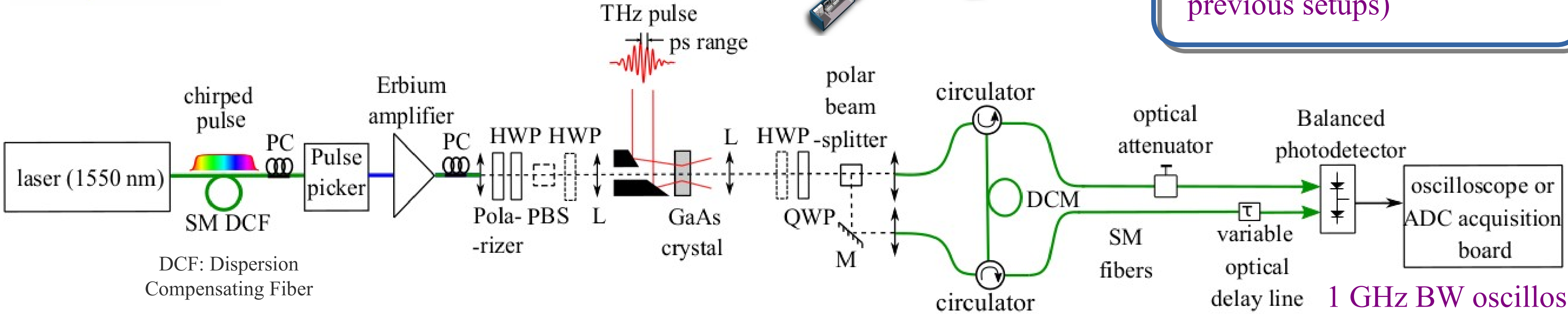
Use of a **commercial** DCM80 Km: Dispersion compensation module with 5.8 dB losses and -1360 ps/nm

Experimental setup for monitoring coherent THz pulses at the SOLEIL synchrotron radiation facility

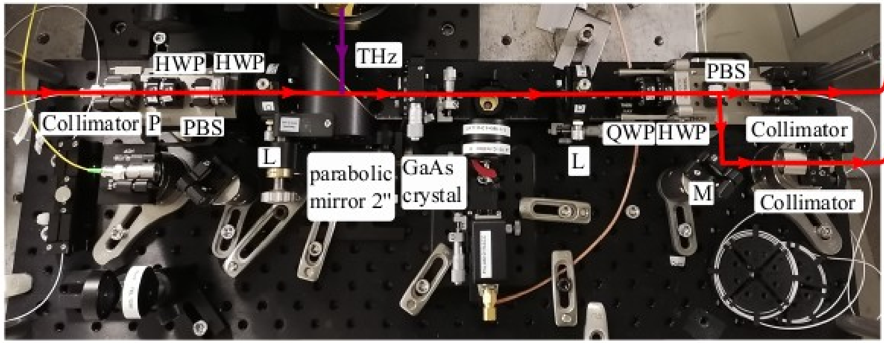
SOLEIL SYNCHROTRON



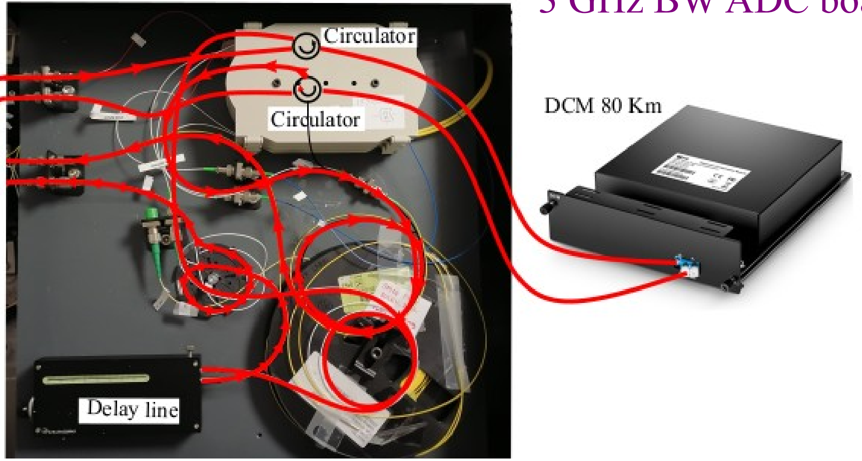
Readout ADC (3 GHz) cost: 15k€ (instead of >100 k€ in previous setups)



1 GHz BW oscilloscope
3 GHz BW ADC board

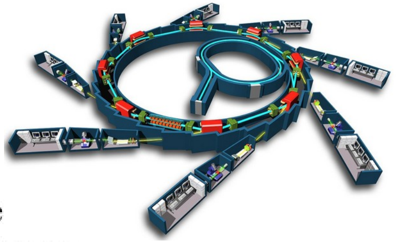


20 cm × 60 cm breadboard



19” rack

Experimental setup for monitoring coherent THz pulses at the SOLEIL synchrotron radiation facility



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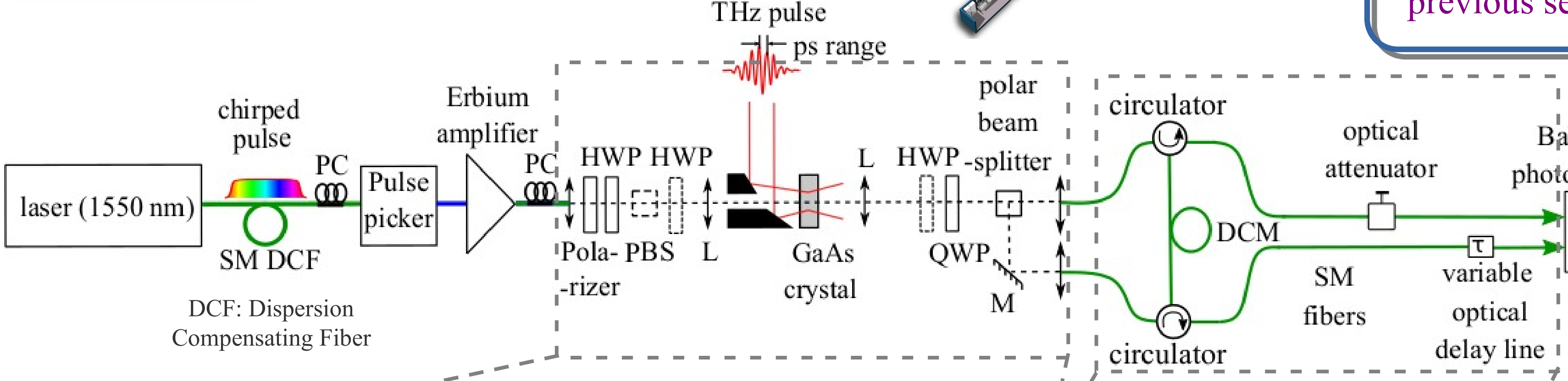
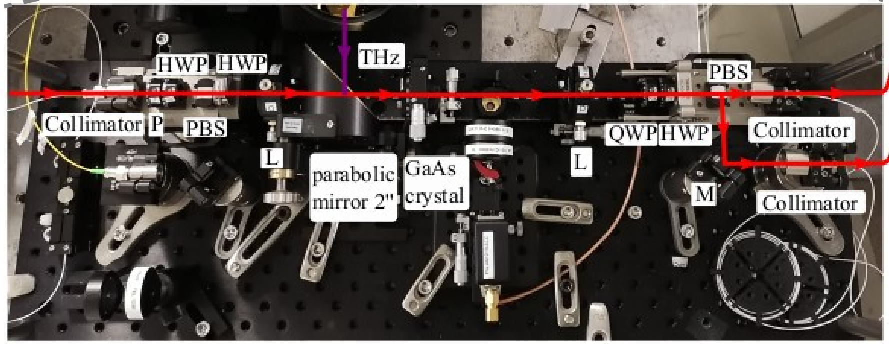


DCF: Dispersion Compensating Fiber

1 GHz BW oscilloscope
3 GHz BW ADC board



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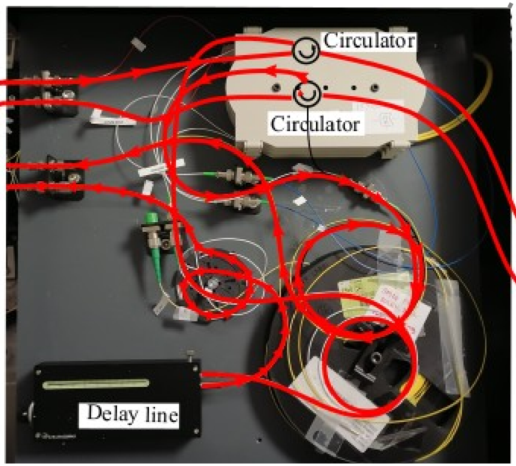
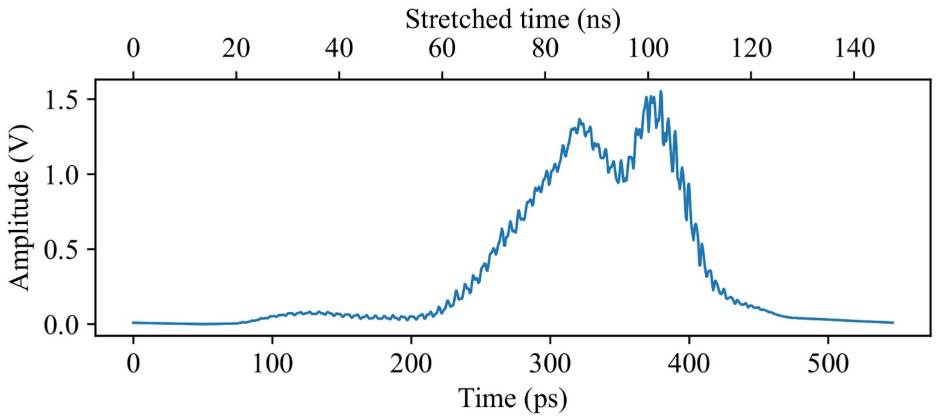
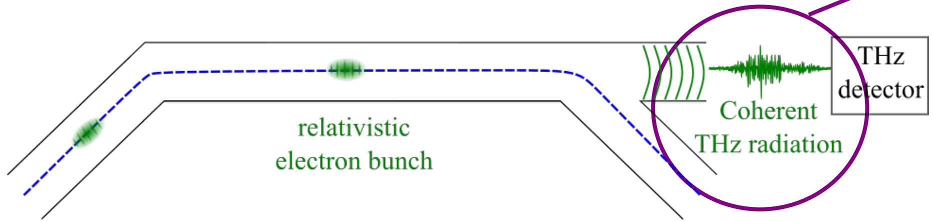


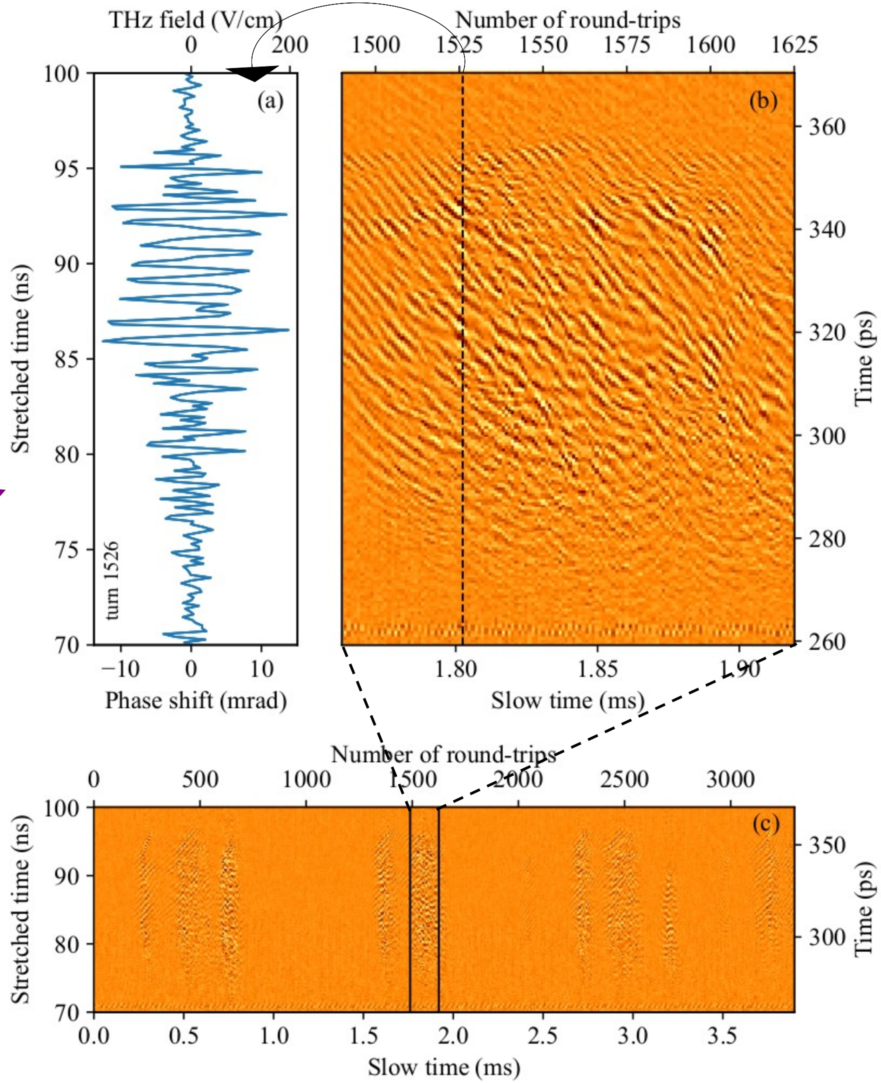
19” rack

THz coherent synchrotron radiation (CSR) pulses emitted at SOLEIL



- Recording using 1500 nm-based time-stretch ADC
- Stretched laser pulse **up to 35 ns**, corresponding to 130 ps
- Measurements in classical balanced detection configuration





Recorded CSR pulses versus the number of round-trips in the storage ring at I = 15 mA

Measurement of the microbunching instability at SOLEIL storage ring

EO recordings using 1550 nm vs 1030 nm probes for the same THz source

In 2015: 1030 nm mode-locked laser probe (40 nm BW)

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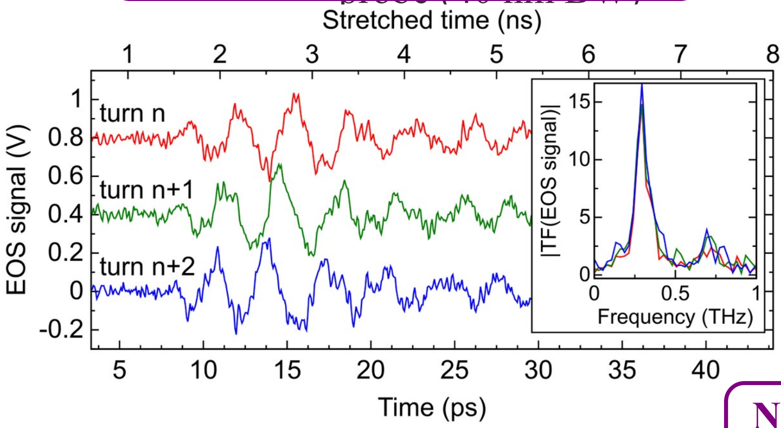

[Roussel, E., et al. *Scientific reports* 5.1 (2015): 10330.]

In 2016: Amplified 1030 nm probe (40→20 nm BW after amplification)

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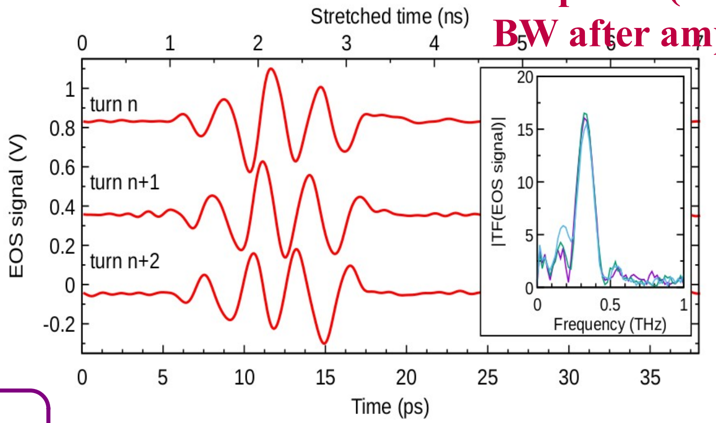
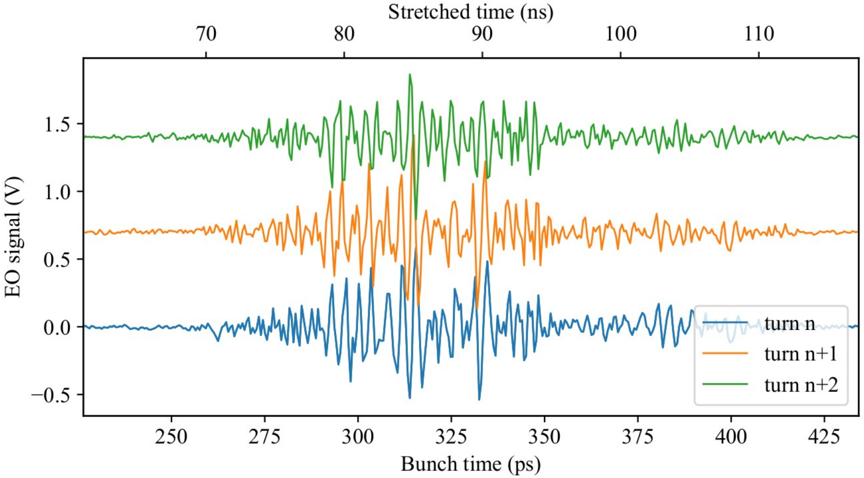


[Evain, C., et al. *JACoW Pub* (2017): 121-124.]

Now: Amplified 1550 nm probe (70→35 nm BW)



Single-shot EO signals of the **complete CSR THz pulses** at each round-trip

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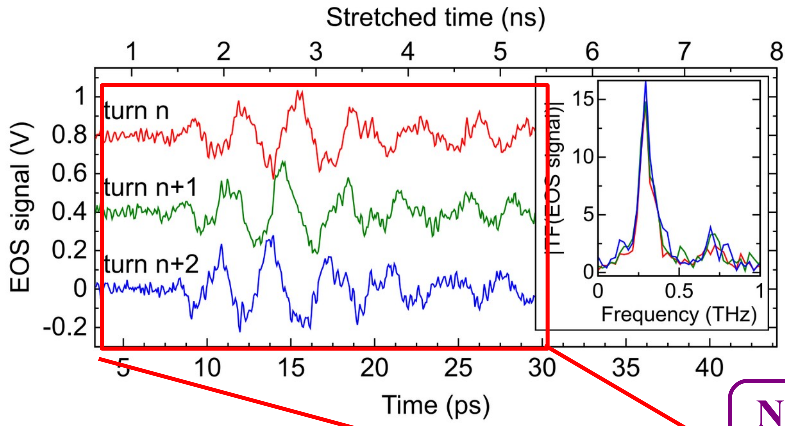
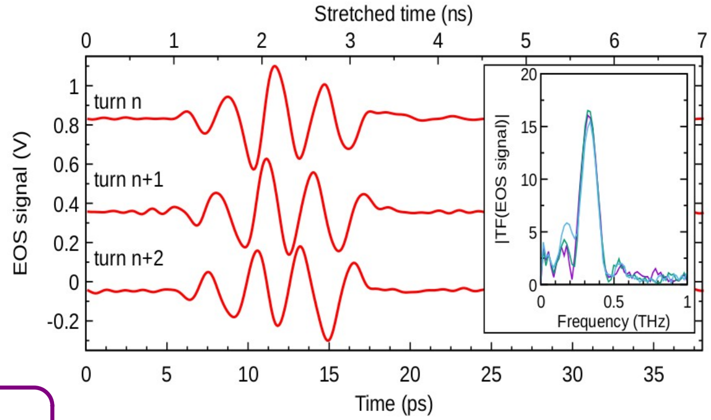


[Roussel, E., et al. *Scientific reports* 5.1 (2015): 10330.]

In 2016: Amplified 1030 nm probe (40→20 nm BW after amplification)



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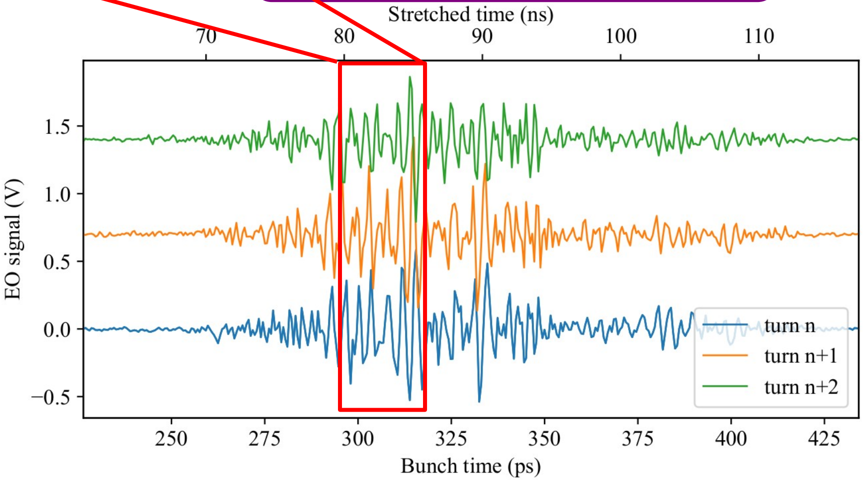


!!! Previously only a part of the THz pulse was recorded due to the limited stretch up to 4.5 ns

Single-shot EO signals of the **complete CSR THz pulses** at each round-trip

Sensitivity of the EO detection setup

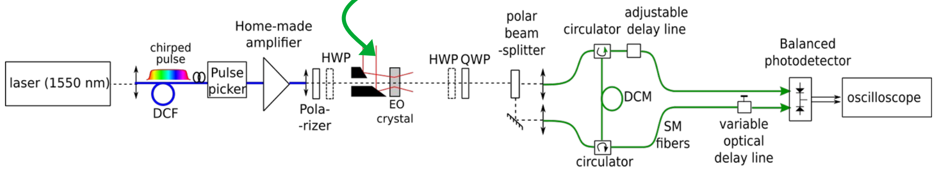
Sensitivity of the EO setup **at 1550 nm** wavelength is relatively **similar** to the setup **at 1030 nm** considering the bandwidth of the oscilloscope (same number of effective points).

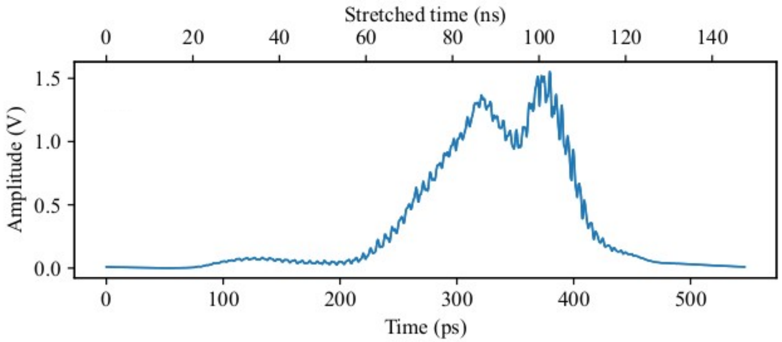
Sensitivity of the EO setup at 1550 nm = 6.5 V/cm (or eq. ~5e-4 rad) with a 2.5 GHz BW ADC board

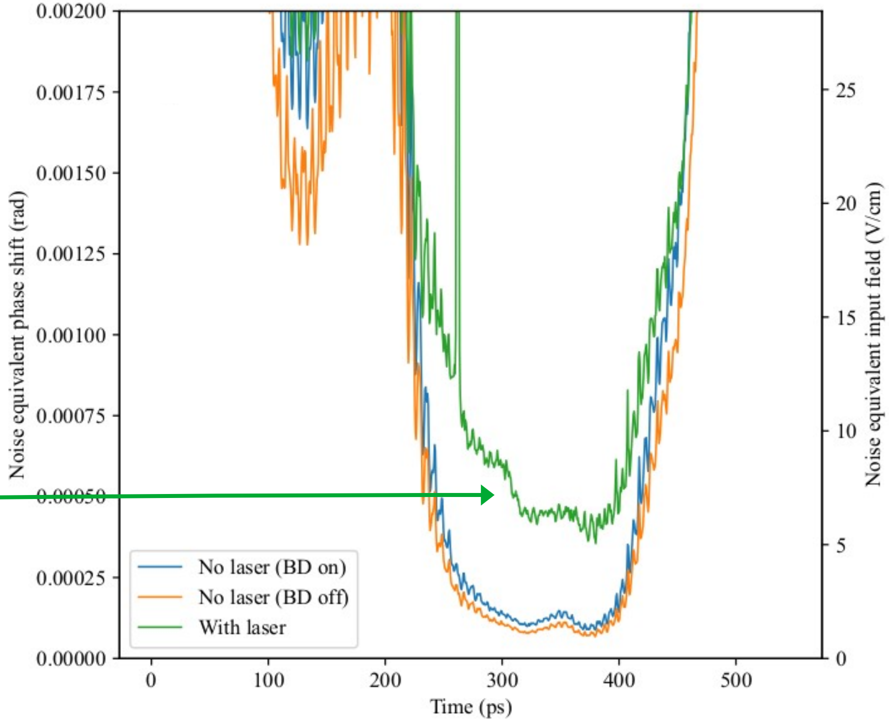
*Sensitivity defined as the input THz signal at the crystal, that would correspond to the detector noise.

** Sensitivity scales as (rule of thumb)~1/sqrt(number of points), i.e., sqrt(oscilloscope BW)

Noise-equivalent input THz signal

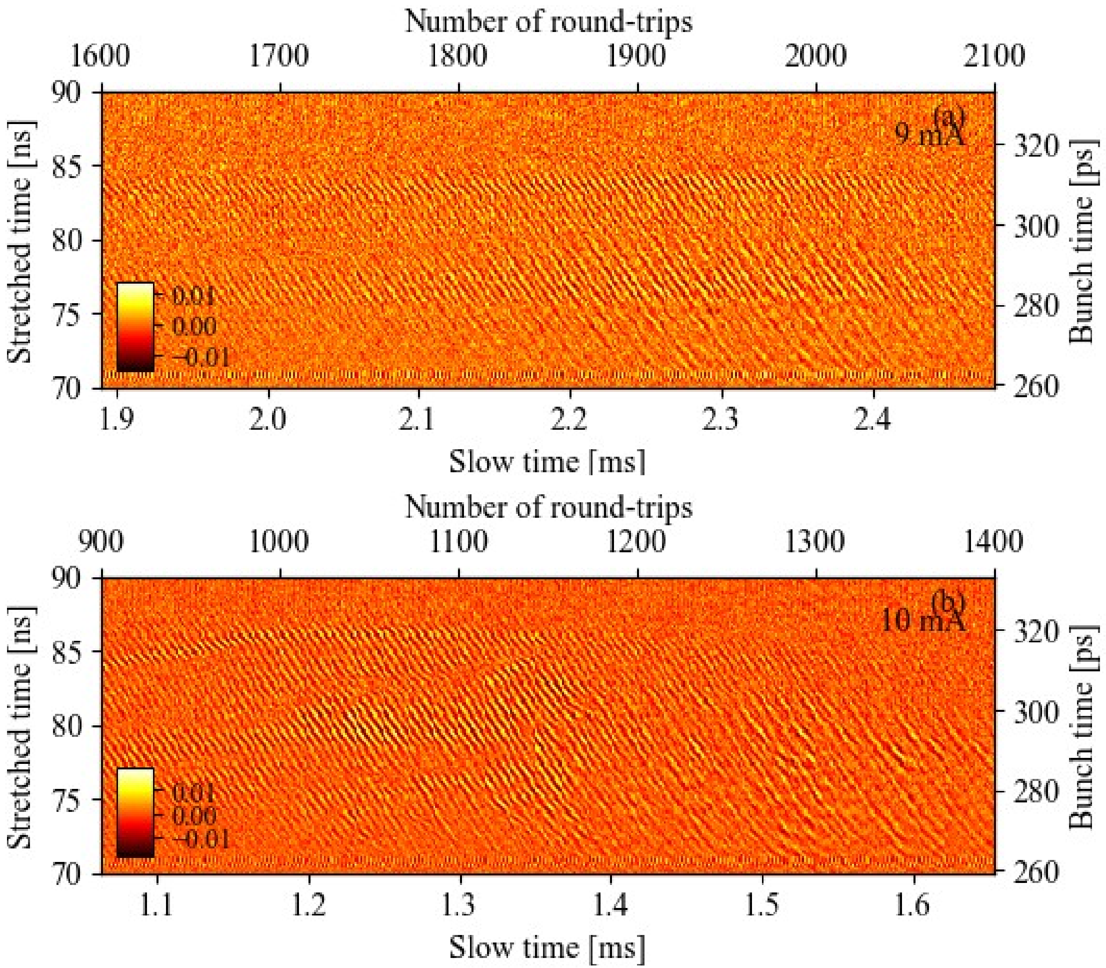






Machine study

Performed a systematic series of measurements over the beam current



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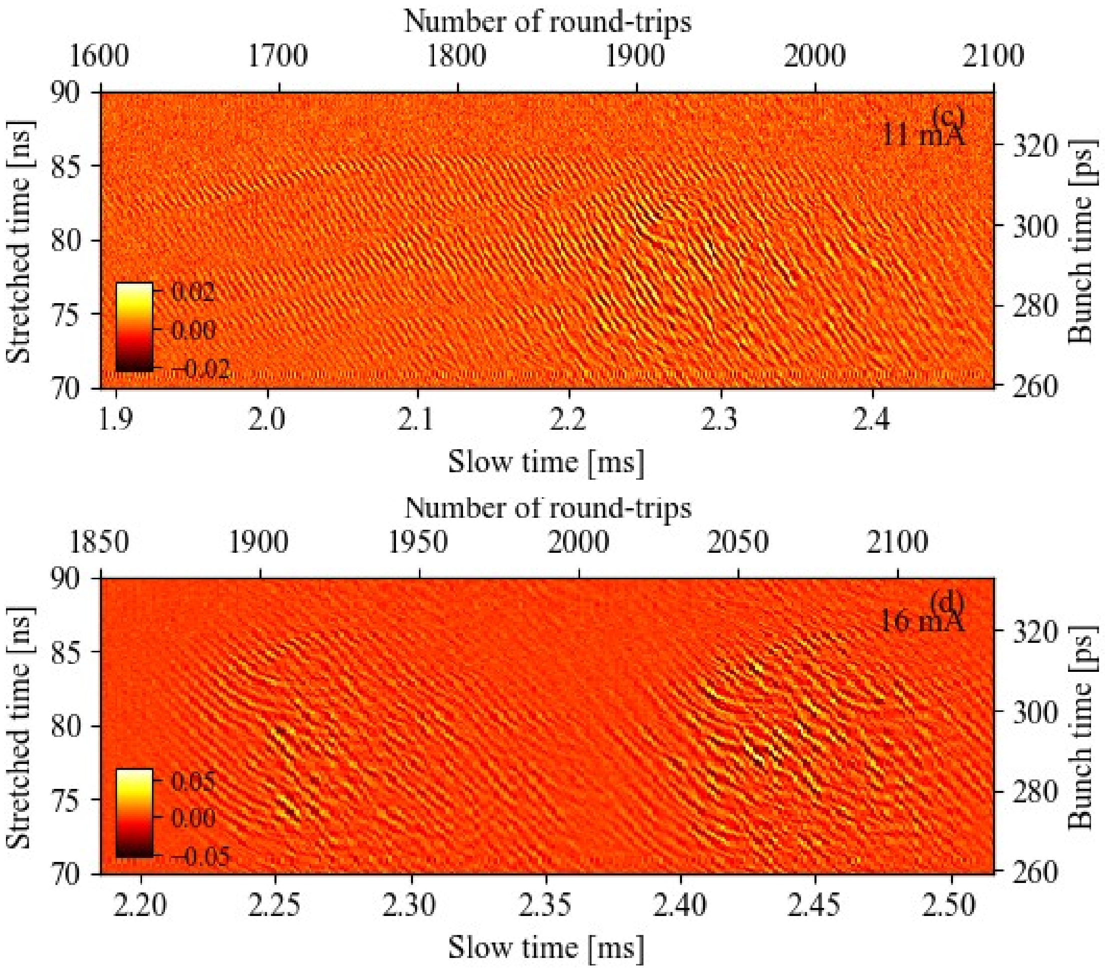
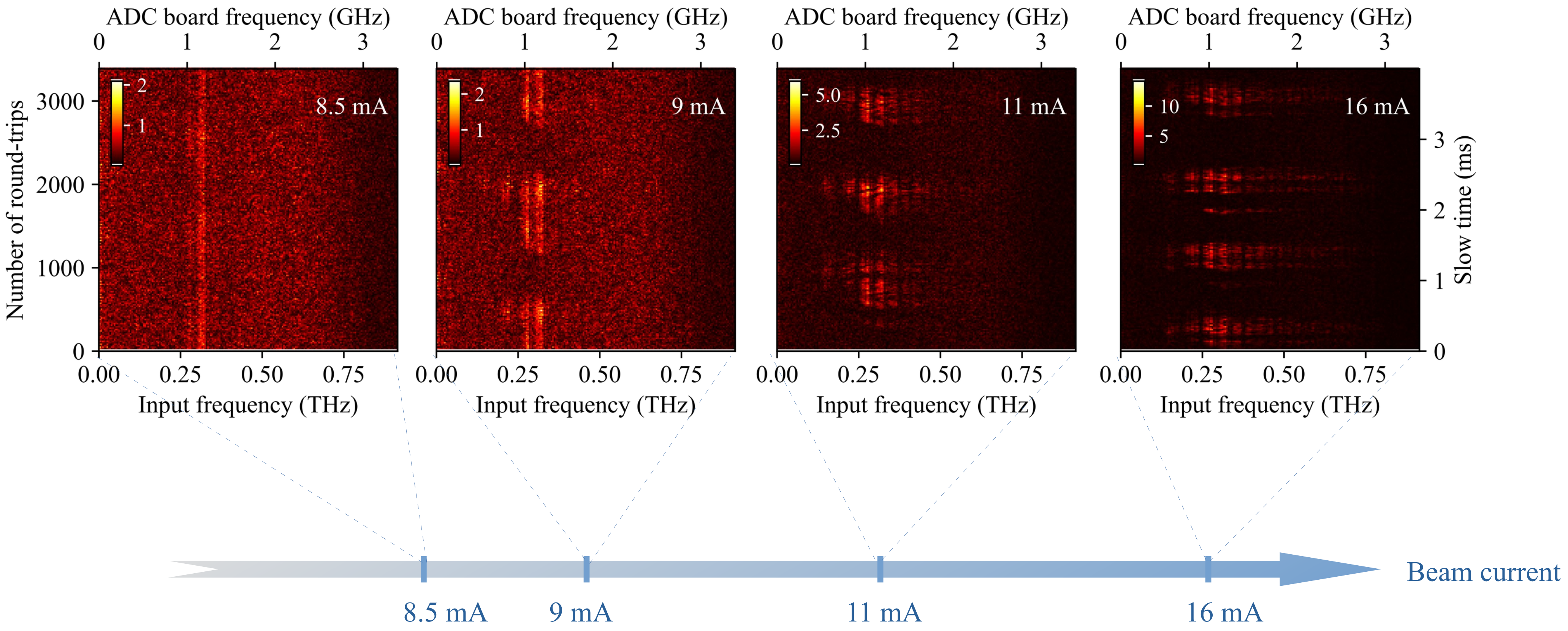


CSR spectra: Study versus the current

Performed a systematic series of spectra measurements over the beam current



Conclusion

Development of a **time-stretch electro-optic setup at 1550 nm** at a considerably cost-affordable budget:

- Stretch up to 35 ns and measurements of THz signals with a **1 GHz BW oscilloscope**
- With a cost reduction from > 100 k€ (in previous setups) to ~15 k€ (for a 3 GHz ADC board)

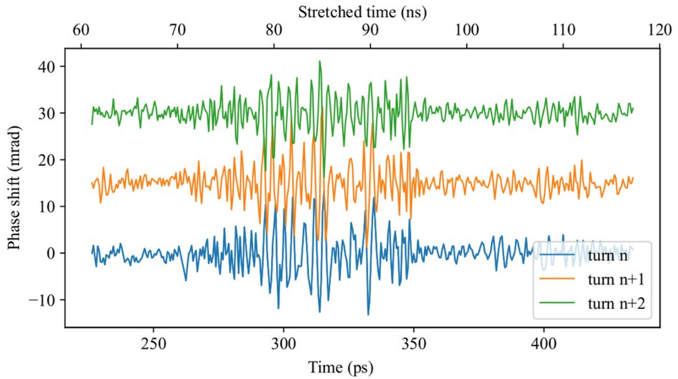
→ Allowing table-top experiments for time-domain THz spectroscopy **at lower costs** using **commercial devices** and **off-the shelf components**

Successful experiment at SOLEIL storage ring:

- Single-shot measurements of the **complete microbunching instability coherent synchrotron radiation**

- Performed **series of measurements at different beam currents,** over ~200e3 turns (200 ms), that can be now **compared with theory** and simulations

++ Many facilities routinely use a 1550 nm fs laser **"clock"** for synchronizing various equipments



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