Remote Sensing of Fast Beam Signals Using Electro-optical Modulators

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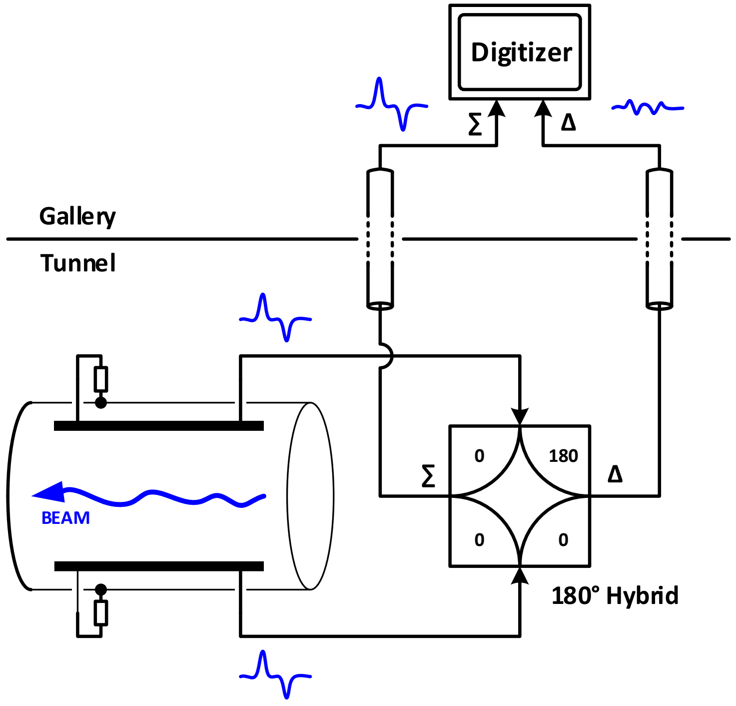
Fast Beam Signals

Current Setup at LHC

Wideband beam position monitor capable of measuring intra-bunch beam position

- Stripline PU’s + 180 hybrid for Δ and Σ
- Long cables to an fast oscilloscope located in non radioactive location
  - 10 GSa/s sampling rate
  - 4 GHz analog bandwidth
  - 10-bit ADCs

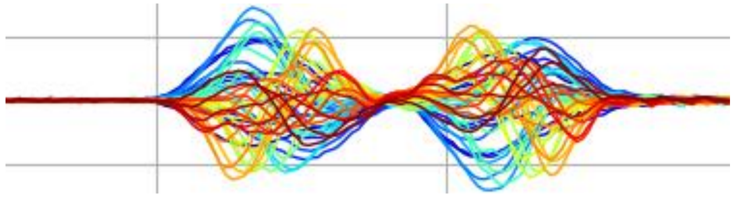


System improvement?

Development of a radio-over-fibre acquisition system

- > 20 GSa/s (@LHC, 1 sigma = 350 ps)
- > 10 GHz analogue bandwidth
- > 12-bit ADCs

Δ signal



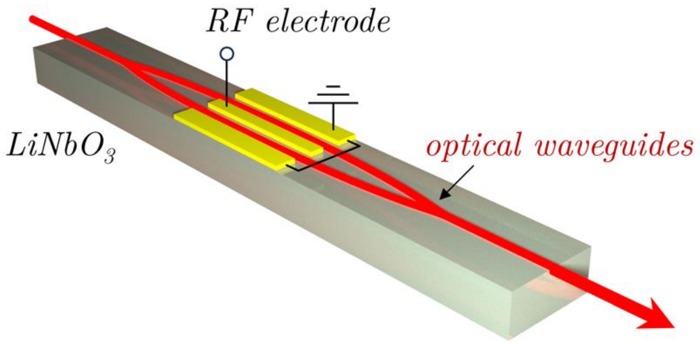
See: T.E. Levens, Head-Tail Measurements

Fast Beam Signals

"Fast" : broadband beam-induced signals in the order of **tens of GHz**

Why can this be difficult to measure?

- Signal transmission at high frequencies strongly affected by long transmission lines
- High-speed digitizer needs to be close to signal source
- Radiation hardness of high-frequency components



Could this be easier?

Development of a **radio-over-fibre** acquisition system to replace traditional read-out methods. Encoding and transport of RF signal using an optical carrier.

→ Set up and test prototype with various beam-induced signals

- Wall current monitor
- Coherent transition radiation
- Coherent Cherenkov diffraction radiation

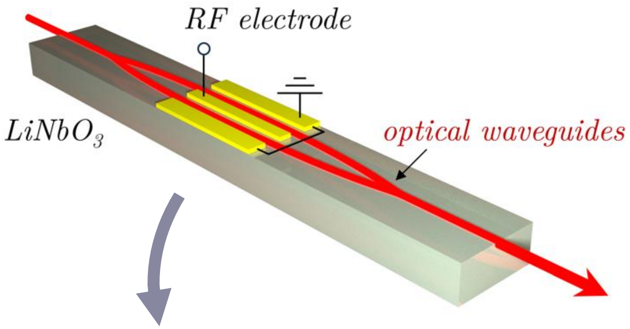
Radio-over-fibre with electro-optical modulators

Mach-Zehnder electro-optical modulator as an intensity modulator

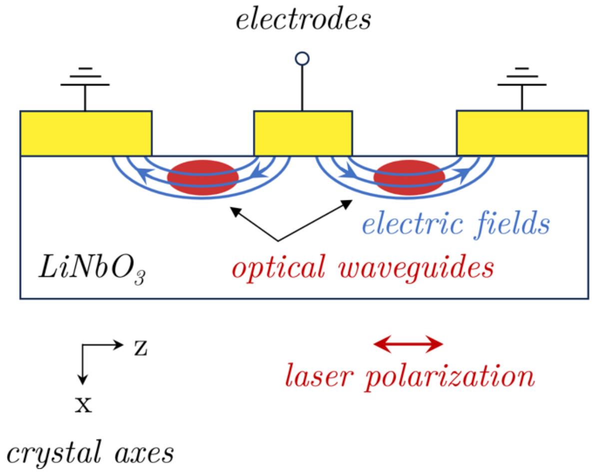
- **Modulation due to Pockels effect**
  - linear variation of refractive index in response to an applied electric field
  - would produce a phase offset proportional to the voltage applied (depeding on material, $V\pi$)

- **Electro-optic material**
  - Lithium niobate ($LiNbO_3$)
  - Gallium arsenide (GaAs)
  - Indium phosphide (InP)

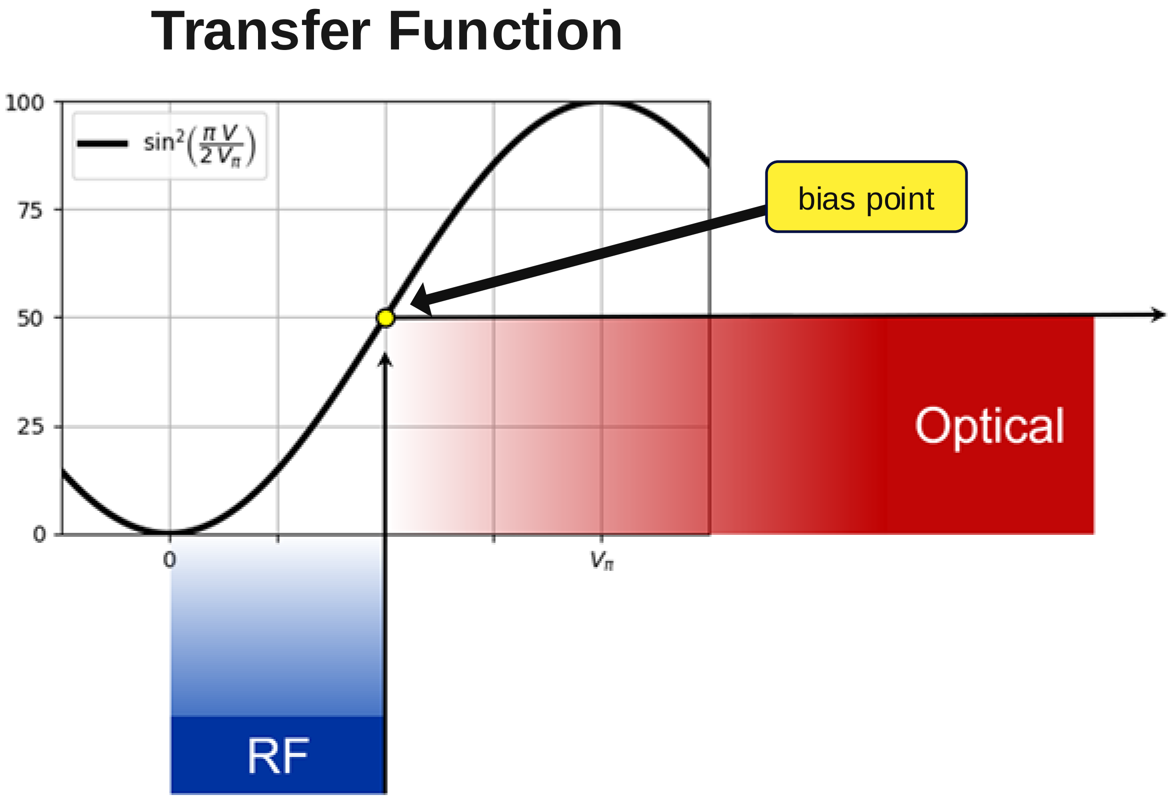
- **Interference-based modulation of light**
  - Interferometer to convert phase offset into an amplitude modulation
  - laser light splits into two arms, modulated, and recombined, resulting in constructive or destructive interferences, which would create a laser replica of the voltage applied.

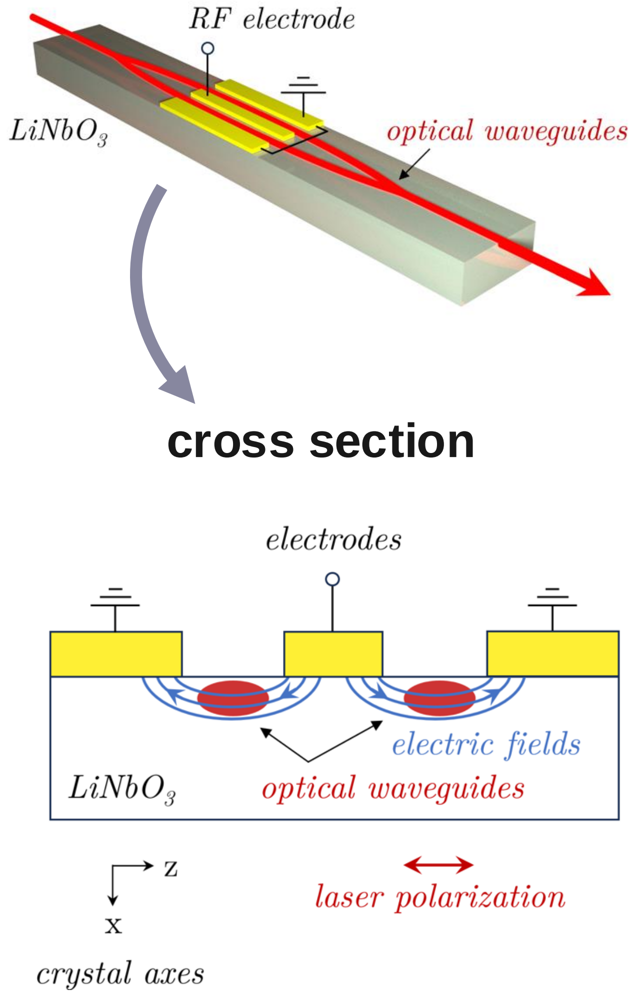


cross section

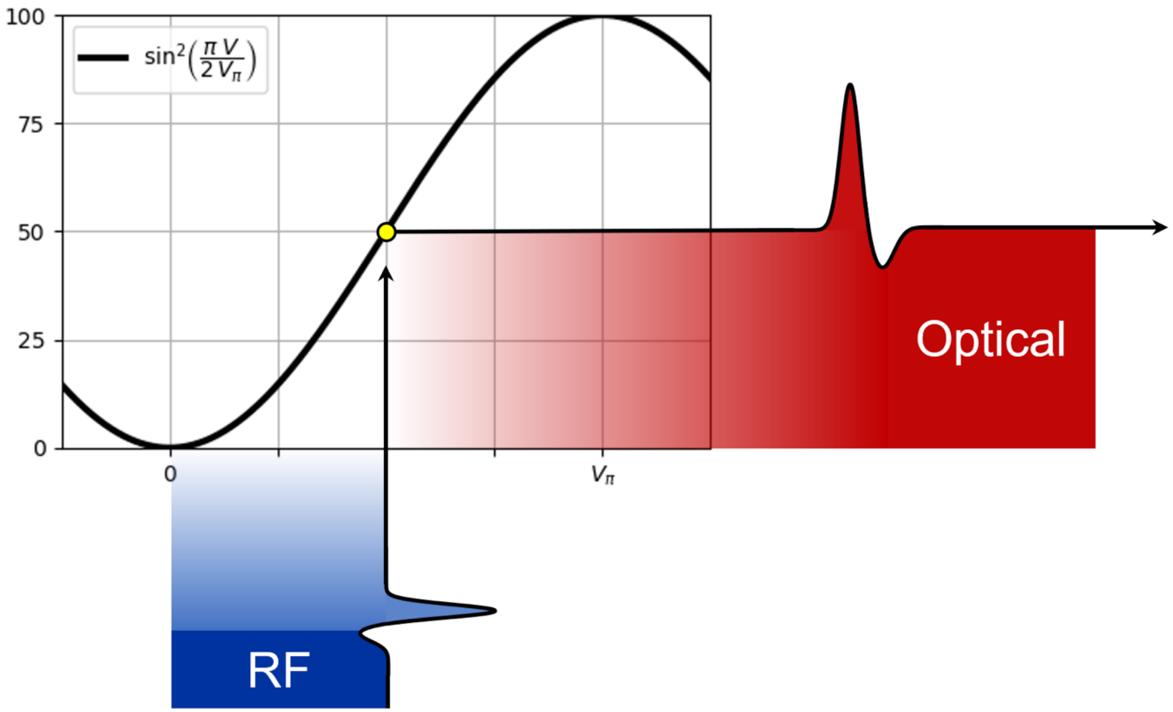


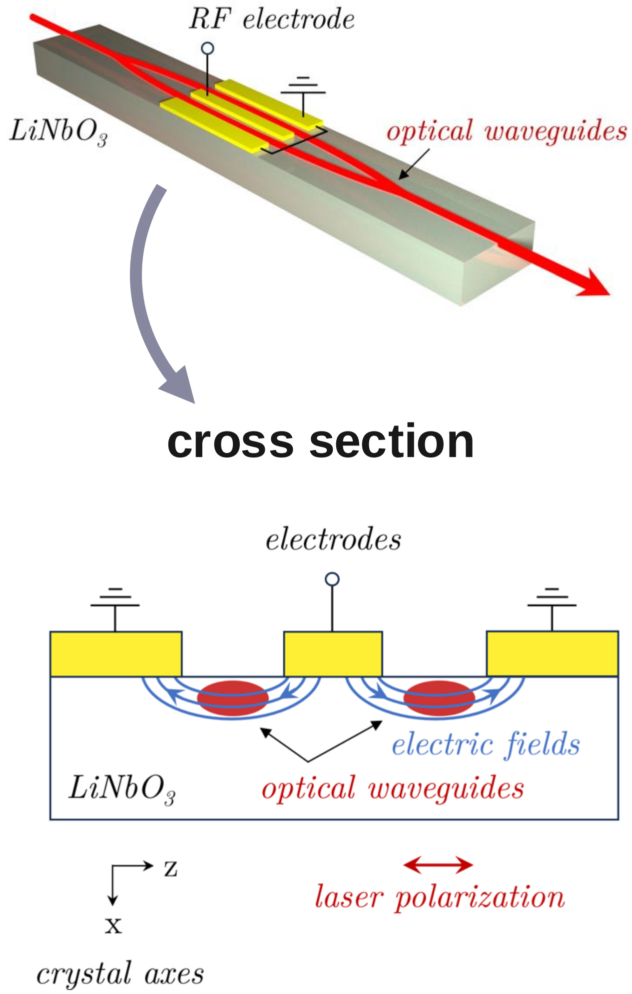
Radio-over-fibre with electro-optical modulators





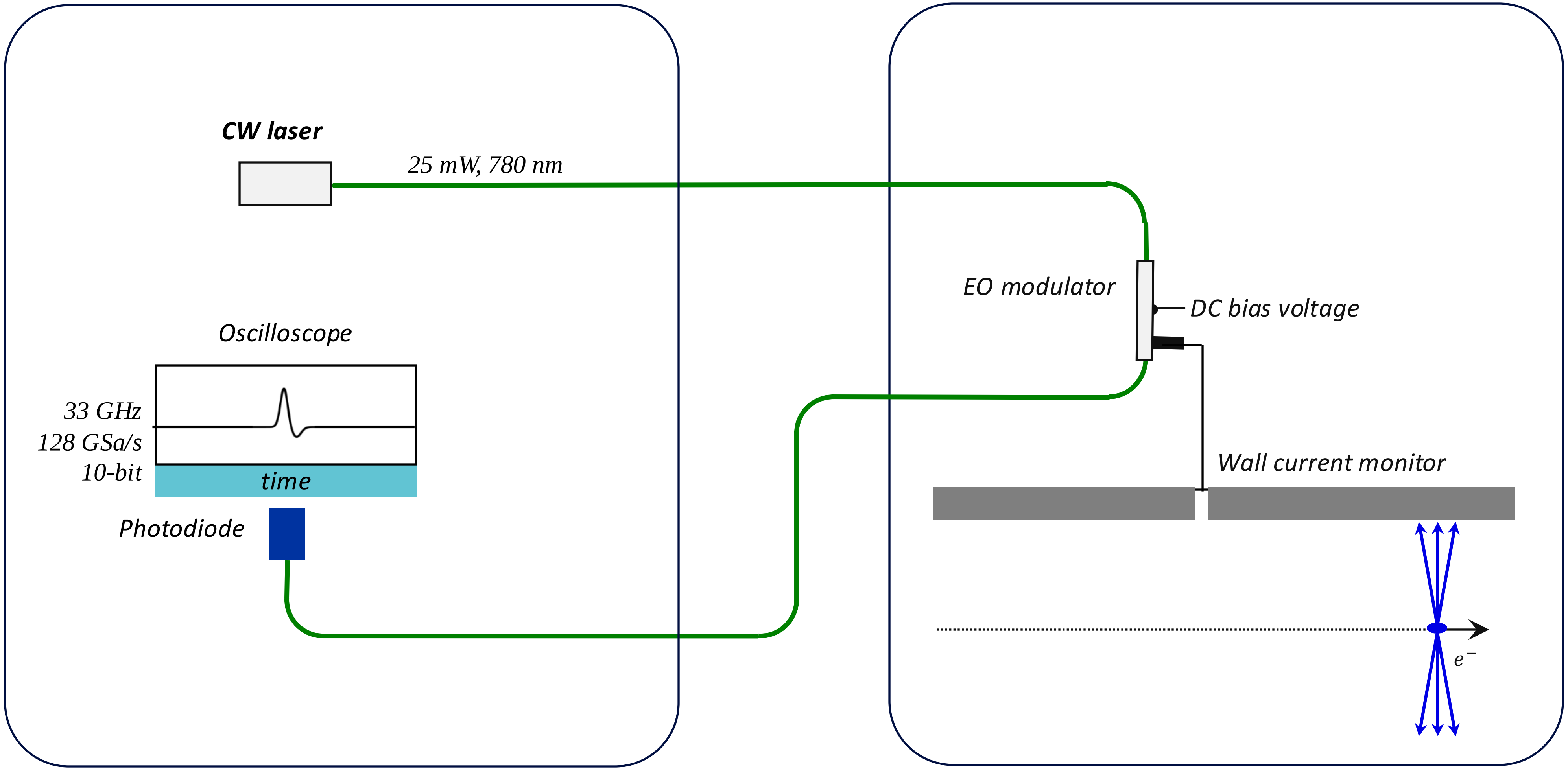
Radio-over-fibre with electro-optical modulators



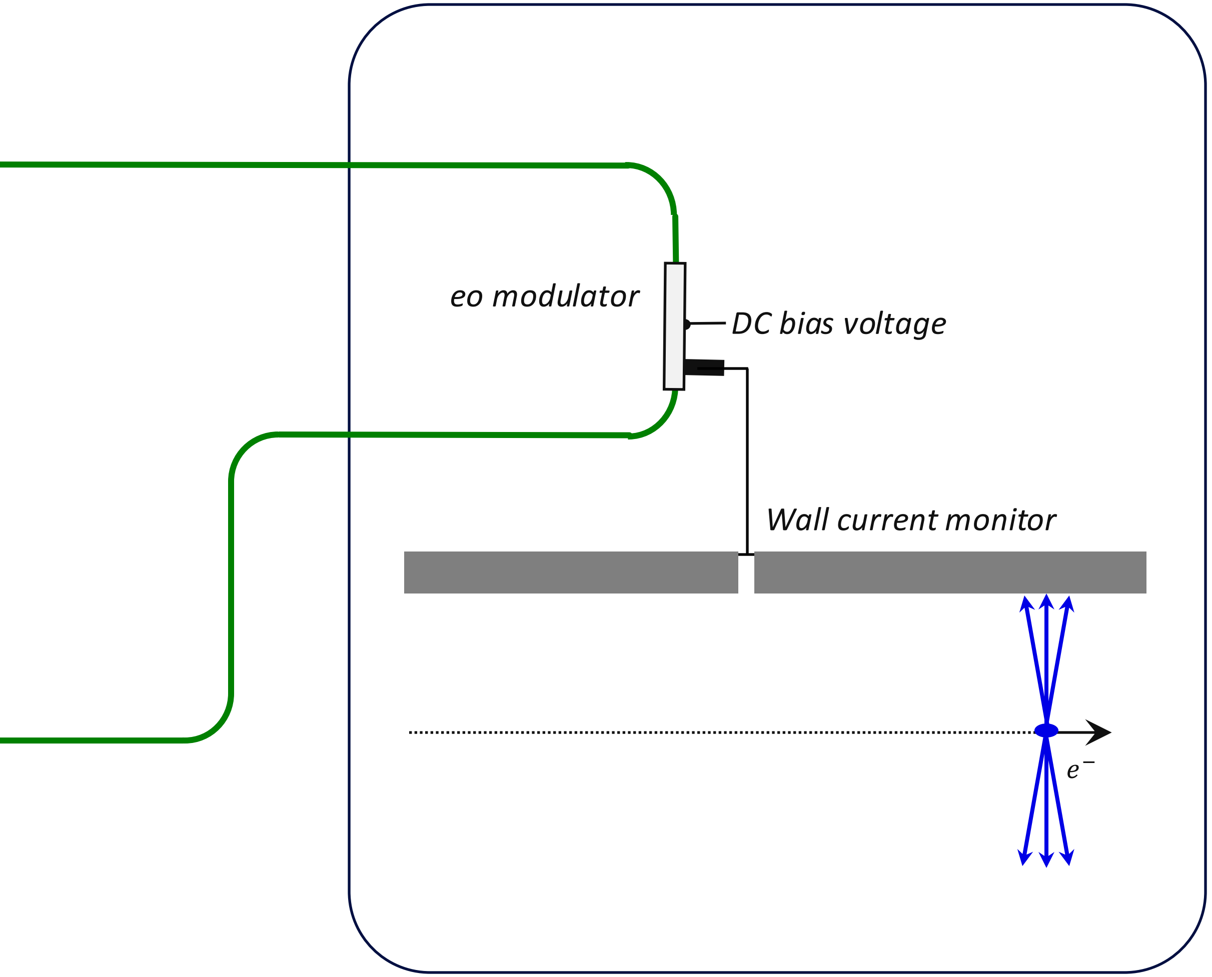


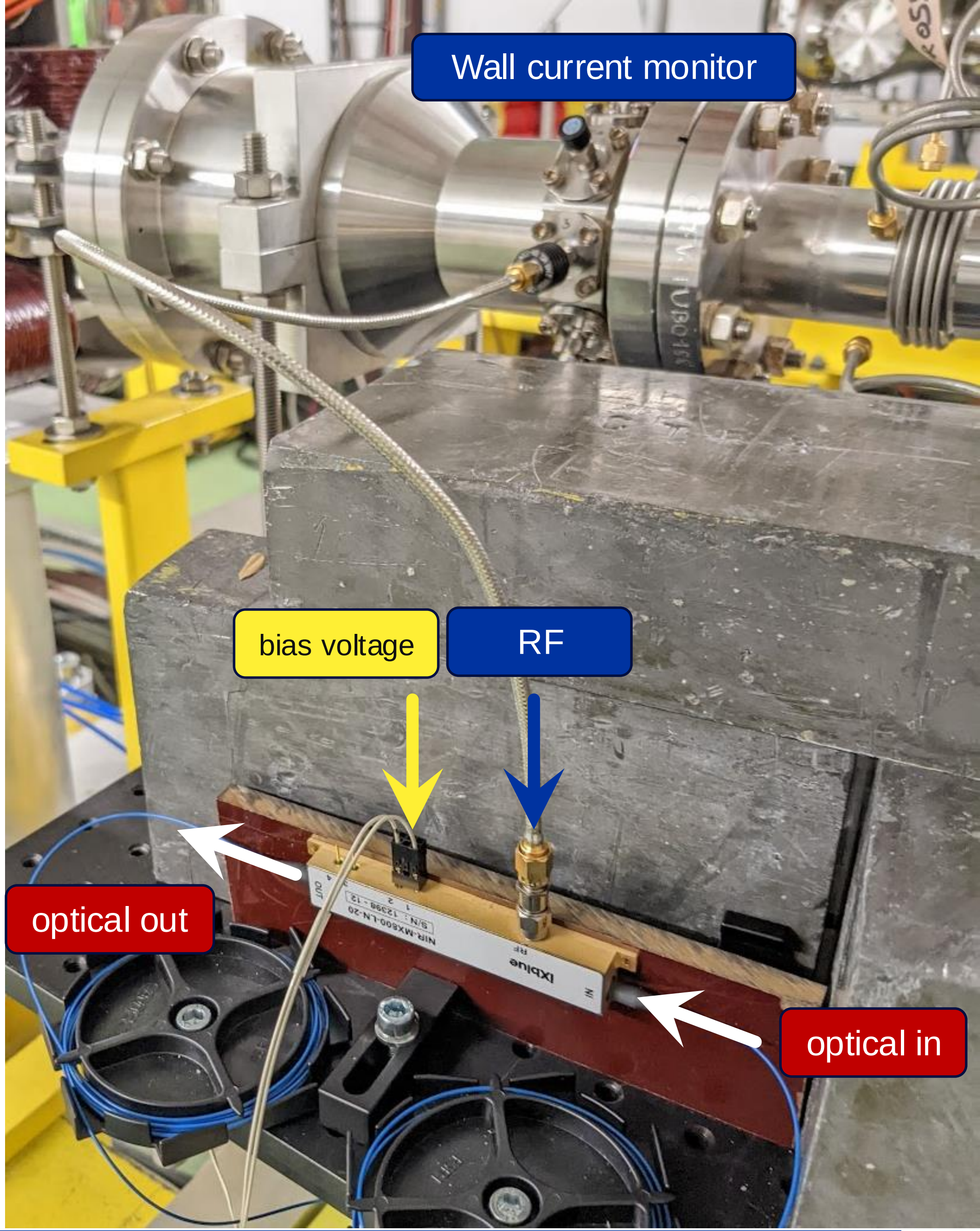
Continuous wave laser measurement

CW laser measurement



CW laser measurement

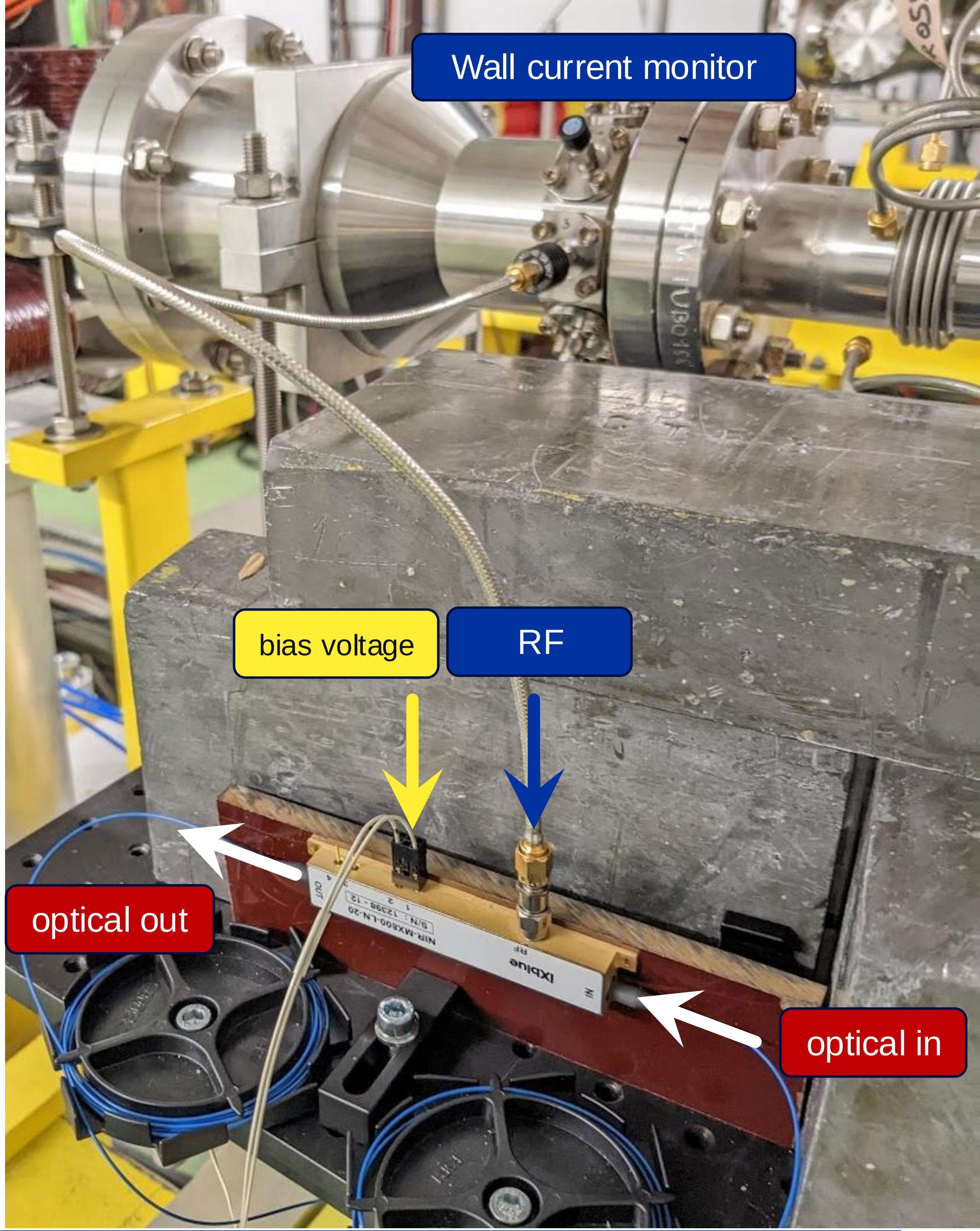




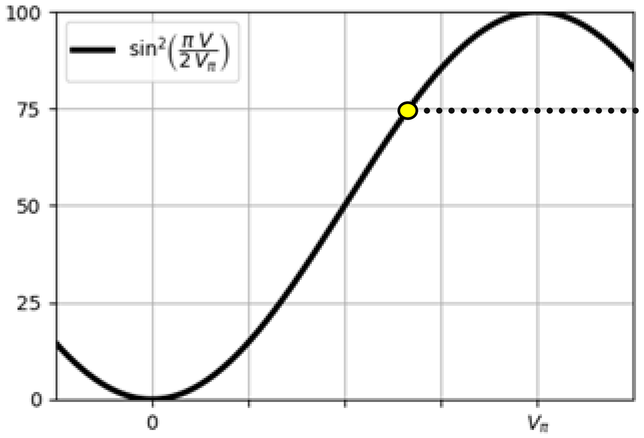
CW laser measurement

Signal		
Electron beam @ CLEAR		
	Energy	200 MeV
	Bunch length	5 ps (1σ)
	Bunch charge	100 pC
	Bunch spacing	667 ps
Wall Current Monitor		
	Low-frequency cutoff	10 kHz
	High-frequency cutoff	10 GHz

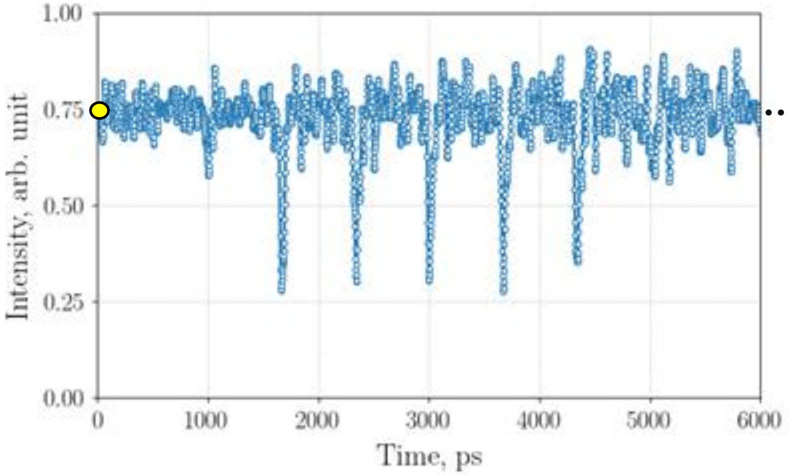
Modulator		
	Operating wavelength	780 – 850 nm
	Max. optical input power	25 mW
	Max. RF input power	28 dBm
	Connector type	2.92 mm (K)
	Electro optical bandwidth	> 25 GHz
	V_{π} RF @ 50 kHz	3.5 – 4.5 V



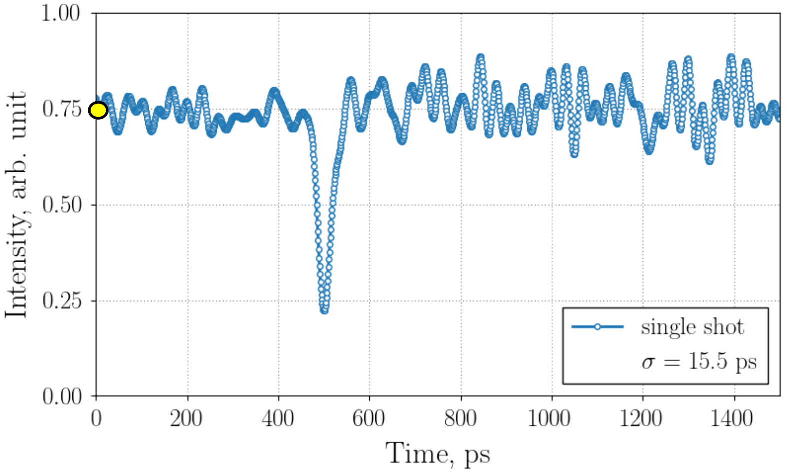
Wall Current Monitor



Train of 5 bunches



1 bunch

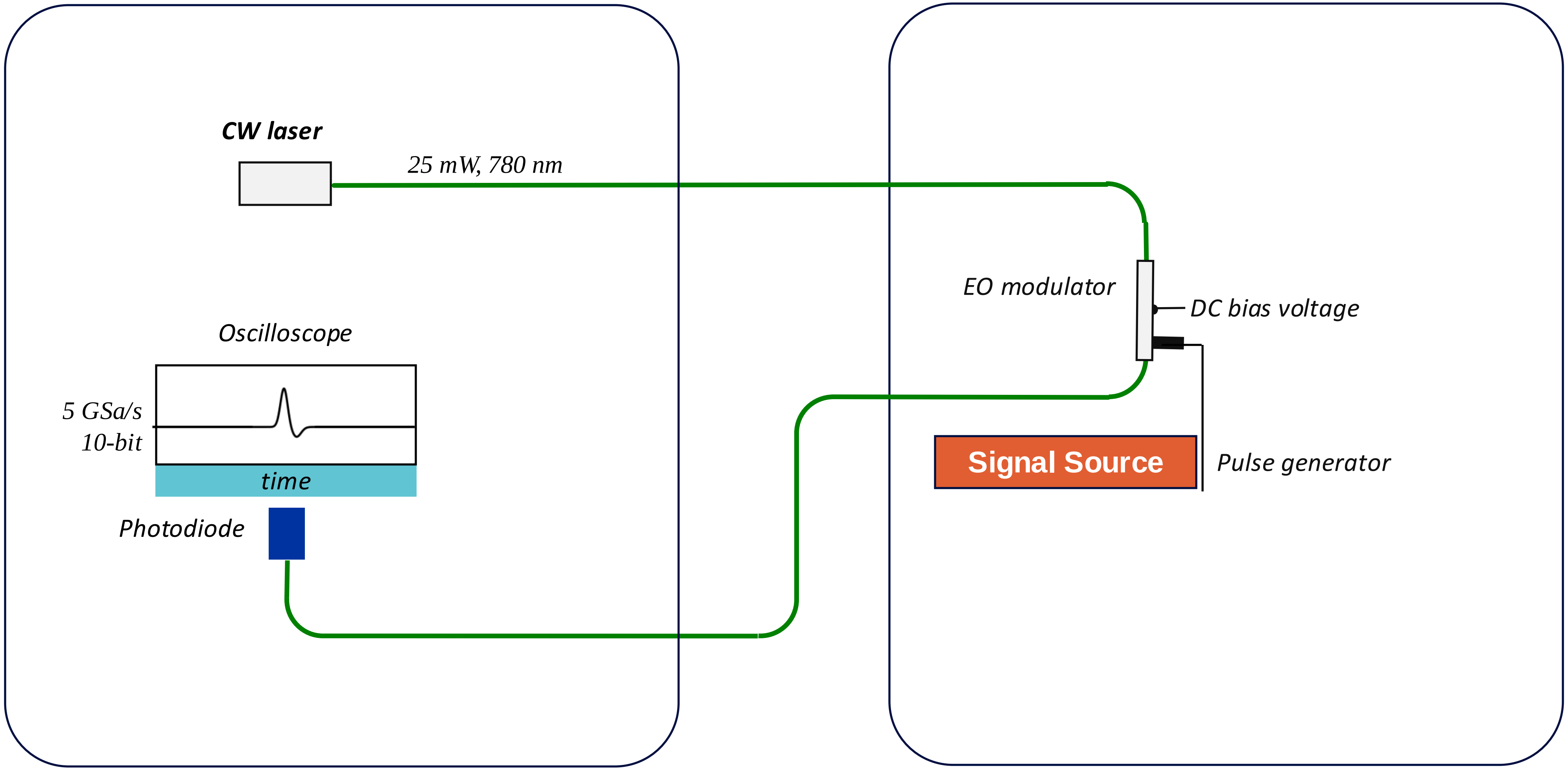


Single shot measurement:
σ = 16 ps (BW approx. 13 GHz)

- **fastest measurement**
  of this WCM in the past was approx. 5 GHz
- **13 GHz ≪ 25 GHz of modulator BW**

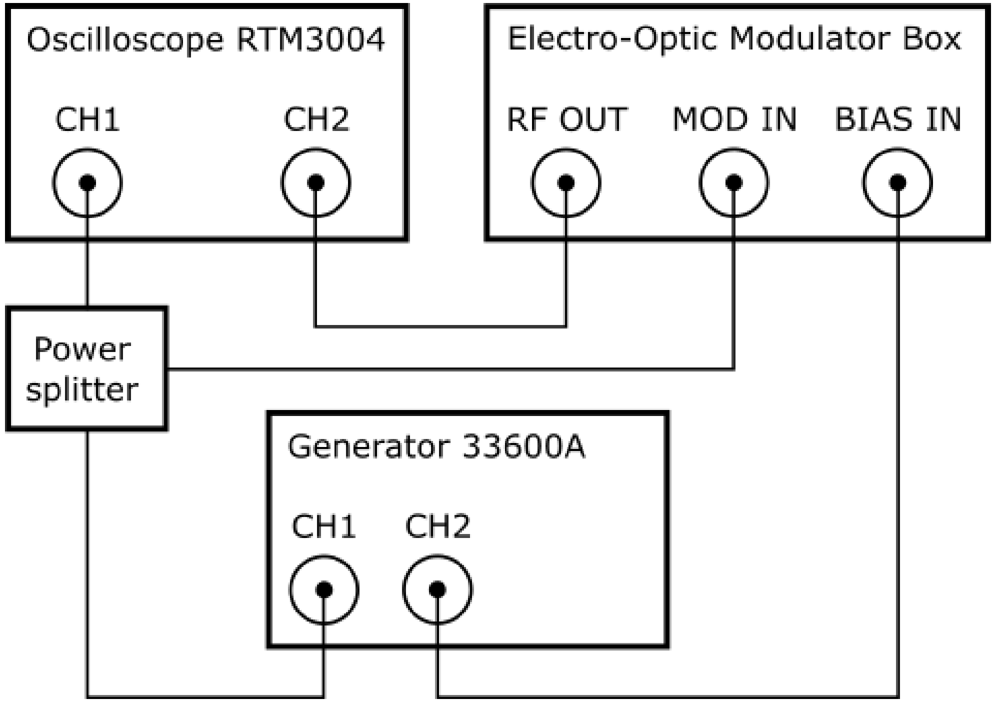
CAS setup – EO modulator

CAS EO modulator measurement concept

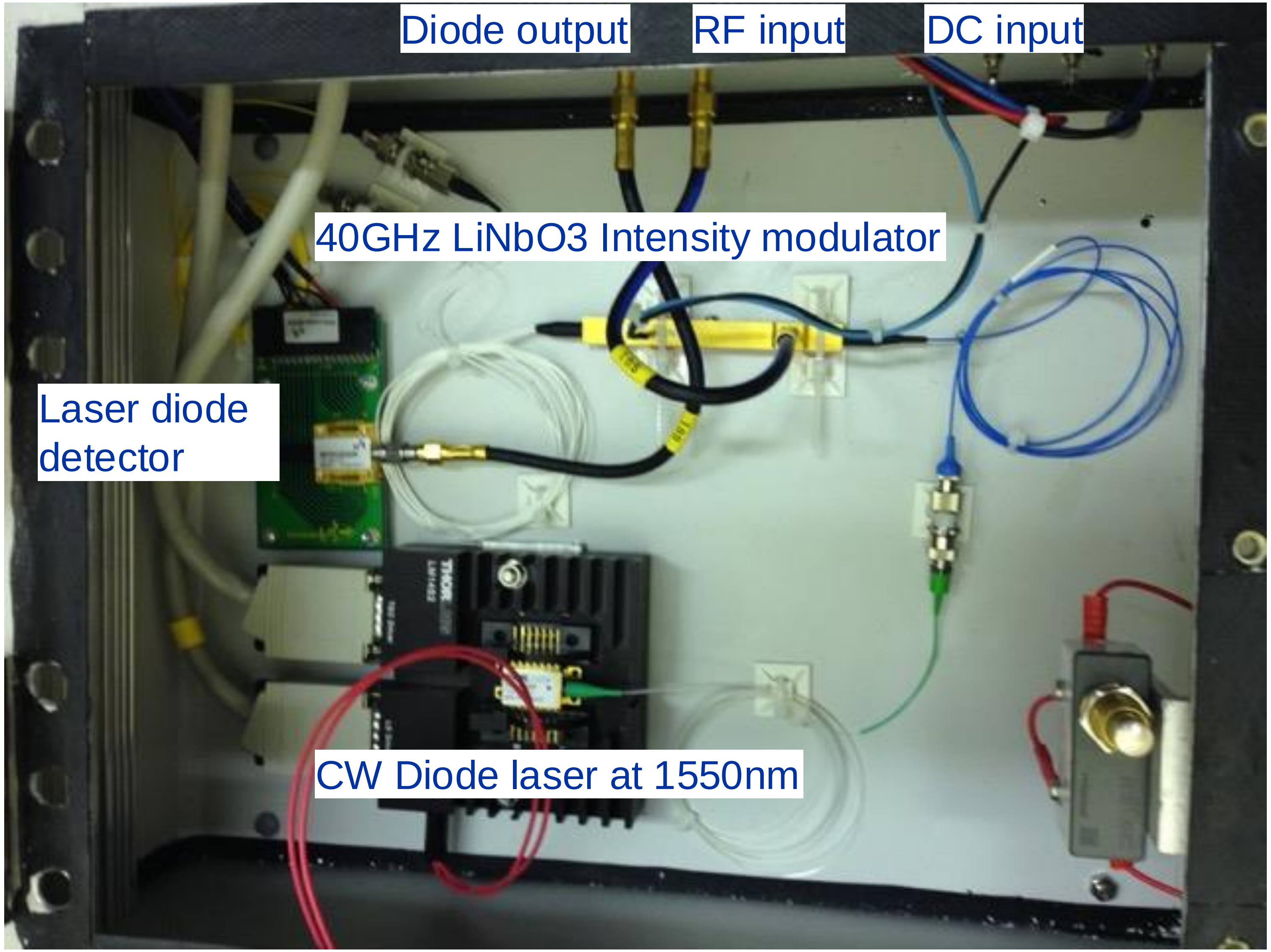


CAS EO modulator measurement set-up

CAS EO modulator measurement – electrical connections



CAS EO modulator measurement : inside the box



CAS EO modulator measurement : part 1

Detecting DC and Fast Pulses

• Apply a DC pulse (on RFin) across the EOmodulator, can you see it on the scope?

• Set the oscilloscope to measure both the input RFin and output RFout voltages simultaneously.

• Plot the evolution of the signal RFout as a function of the amplitude of the RFin DC signal. What shape does it have ? What is the electric-optical to electric conversion ratio of the present system in dB ? What is the dynamic range of the system ? Do you observe over rotation ?

• Apply now shorter or shorter pulse (RFin) across the pickup, can you see it on the scope? What is the minimum pulse length you can reproduce and measure efficiently ? What will be the corresponding bandwidth of the system

CAS EO modulator measurement : part 2

Turn on the bias voltage

- Scan the bias voltage by small step (i.e. 0.1volts) and plot the amplitude of the RFout signal as a function of the bias voltage. Find the best DC bias voltage that would provide the highest output voltage RFout.

- For a pulse length of your choice, increase the amplitude of the RFin signal and adjust the dc bias to keep the output voltage RFout constant. Plot then the curve RFin as function of DC bias for a constant output signal RFout. What do you conclude ?

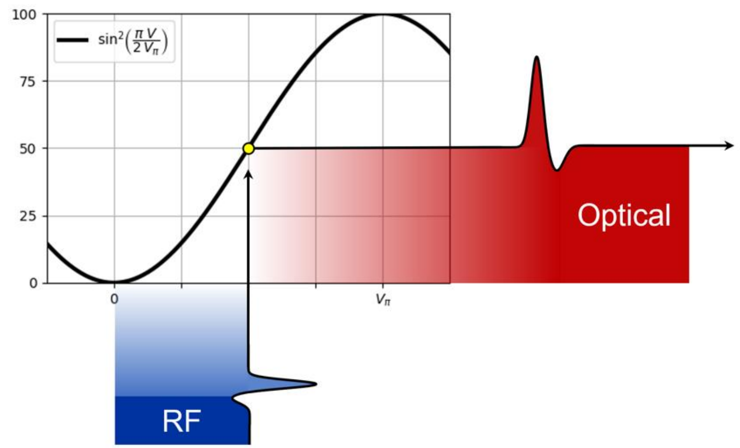
- Change the pulse length of RFin and redo the bias voltage scan. Do you find the same optimum as before ?

Spares slides

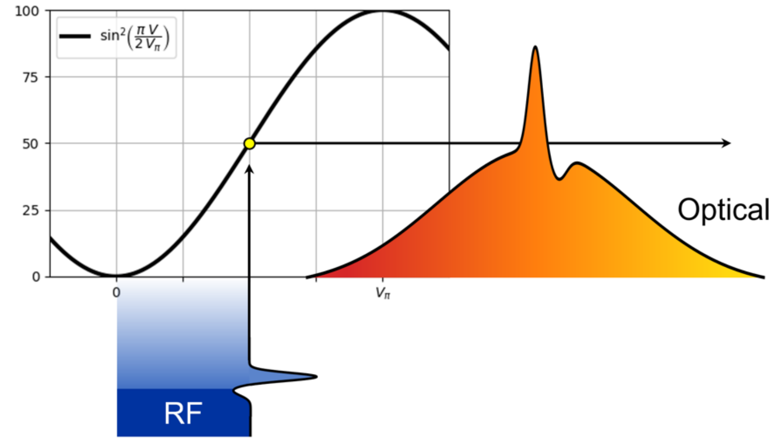
DAQ: Spectral Encoding

- ▶ **Use a chirped laser pulse instead of a continuous wave laser**
  - increase power density of the laser
- ▶ **Encode the signals on the laser spectrum**
  - possibility to use laser spectrum also for decoding
  - moving away from real-time sampling
- ▶ **Narrow optical spectrum**
  - keep reasonable performance of Mach-Zehnder interferometer

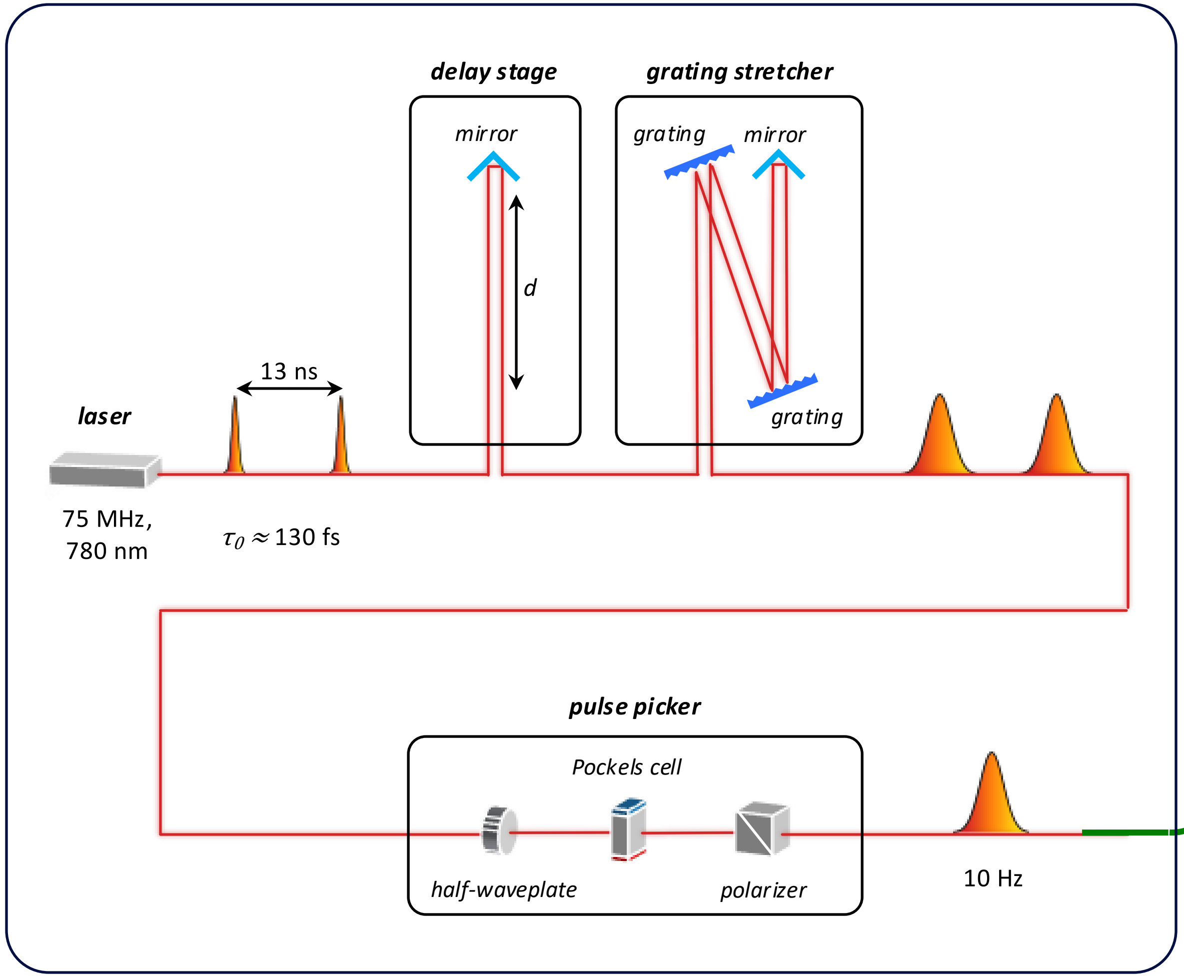
Continuous wave laser



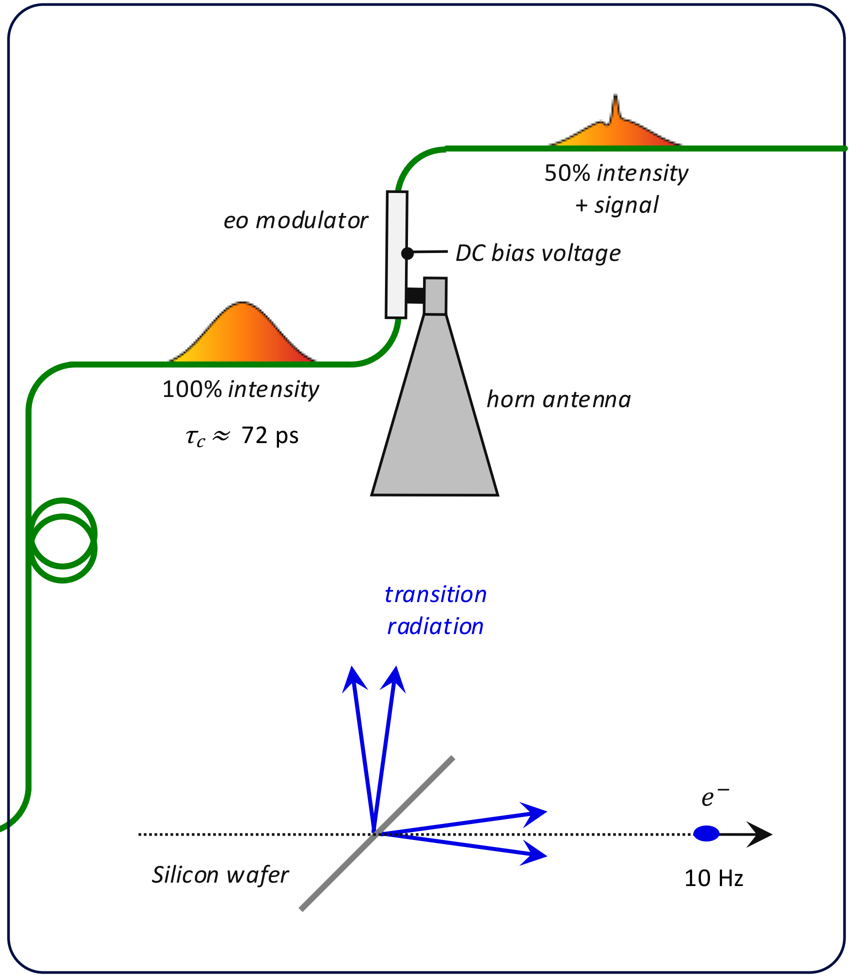
Chirped laser pulse



Preparing pulse



Encoding



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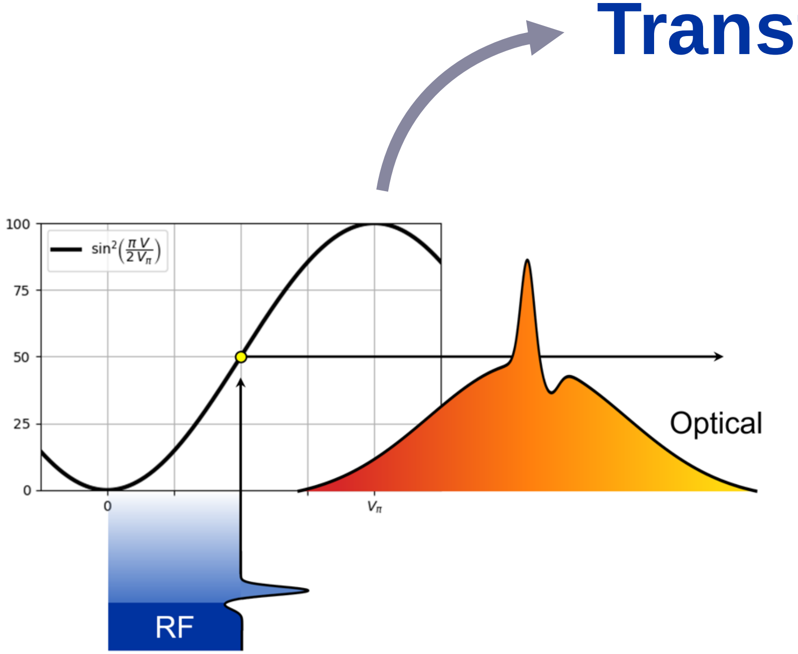
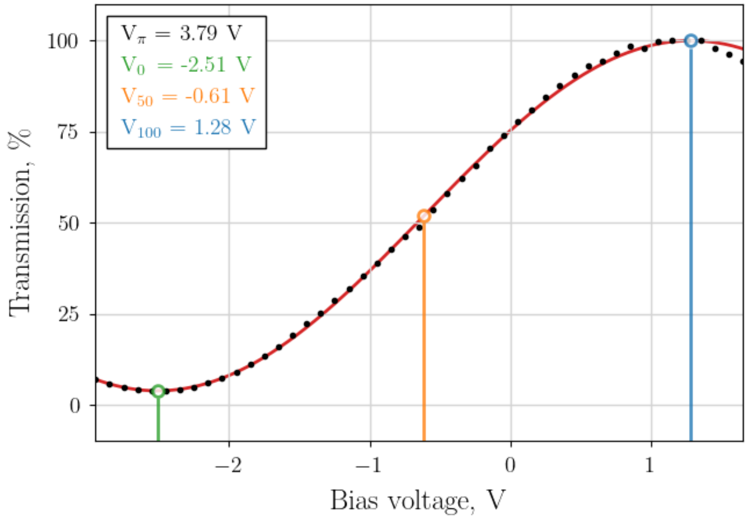
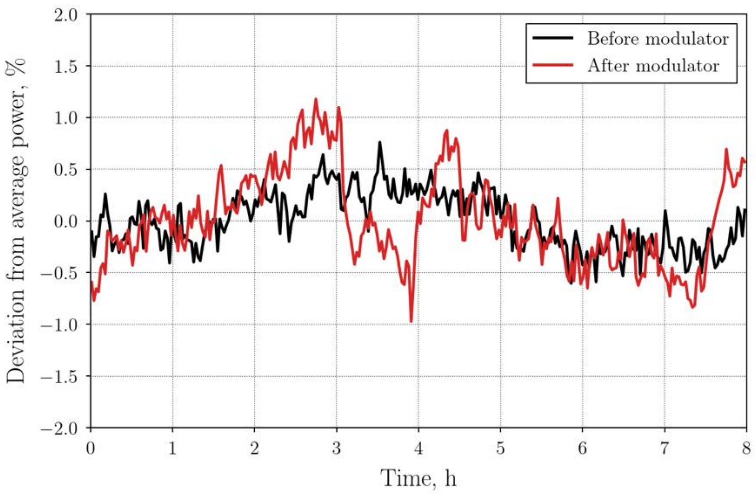


Transfer Function?

Transfer Function

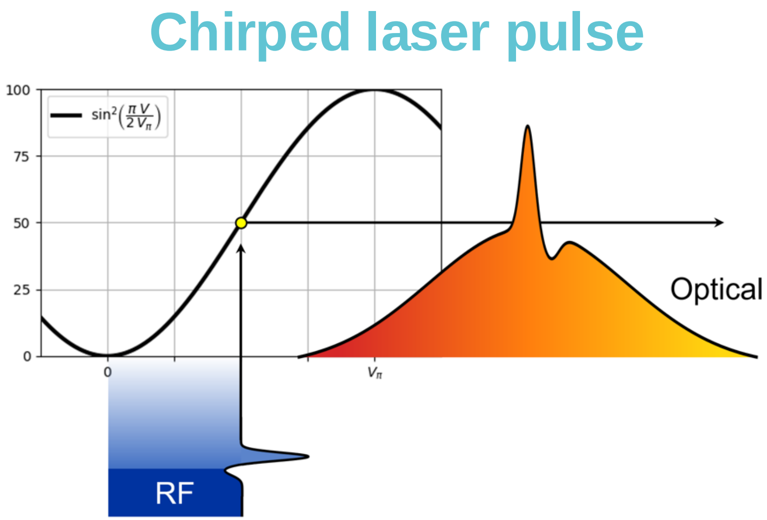




- **Single pulse transfer function**
- **DC extinction ratio**
  - Reduced due to optical bandwidth (7 nm FWHM)
  - > 20.0 dB for CW laser (data sheet)
    down to 15.8 dB for pulsed laser

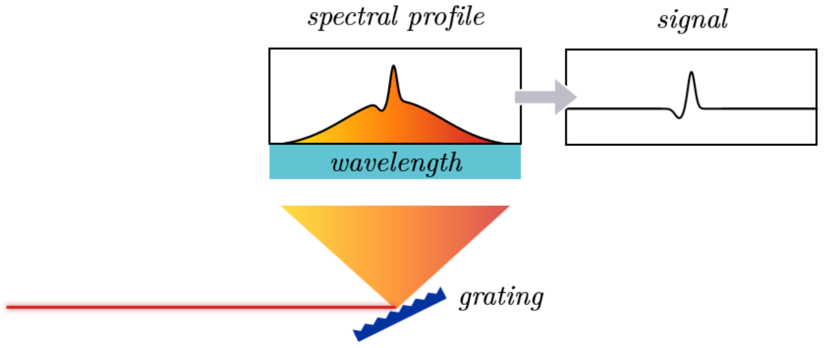
    → Lower modulation depth, less dynamic range
- **No DC bias feedback**
  - Modulator relaxed into quadrature bias point (50%)
  - Long term **stability over several hours**
  - Operational system would require bias feedback

Encoding ✓

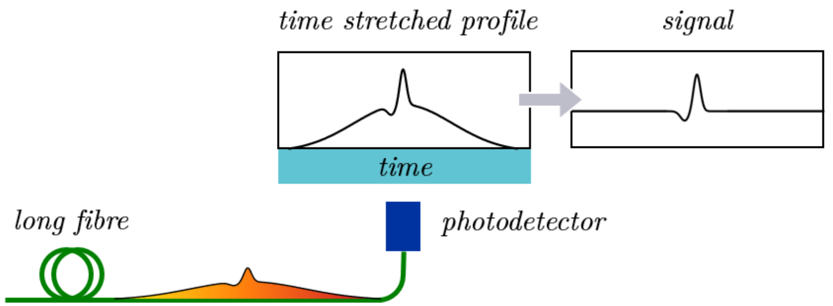


Decoding ?

1 Spectral Decoding

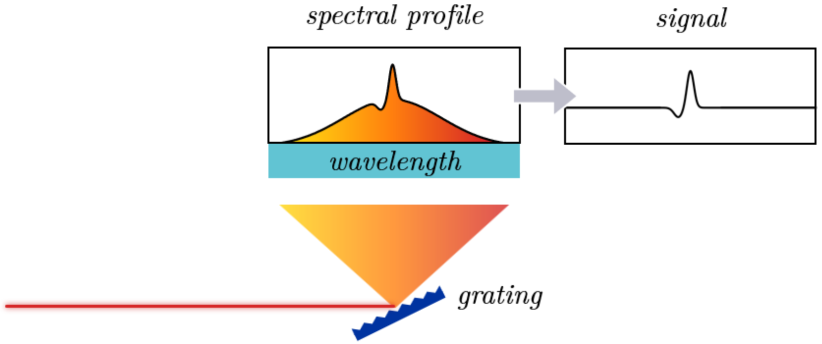


2 Photonic Time Stretch

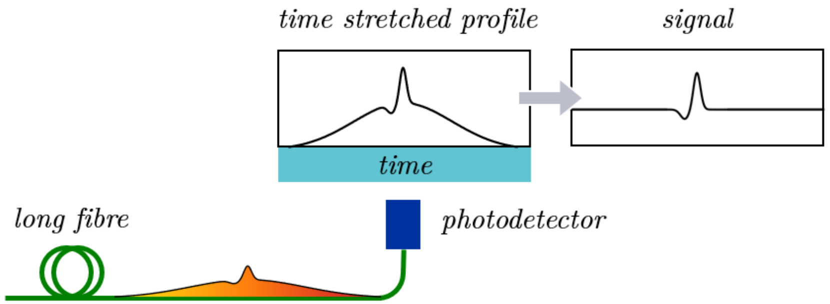


Decoding ?

1 **Spectral Decoding**



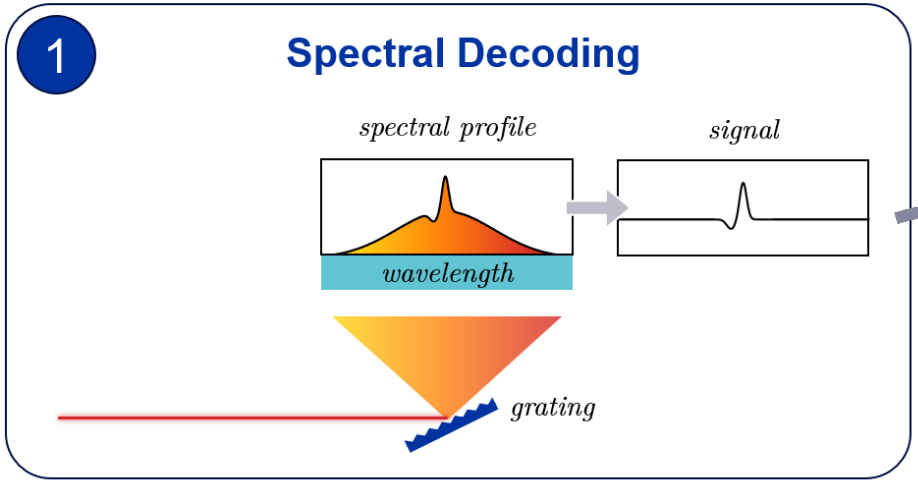
2 **Photonic Time Stretch**

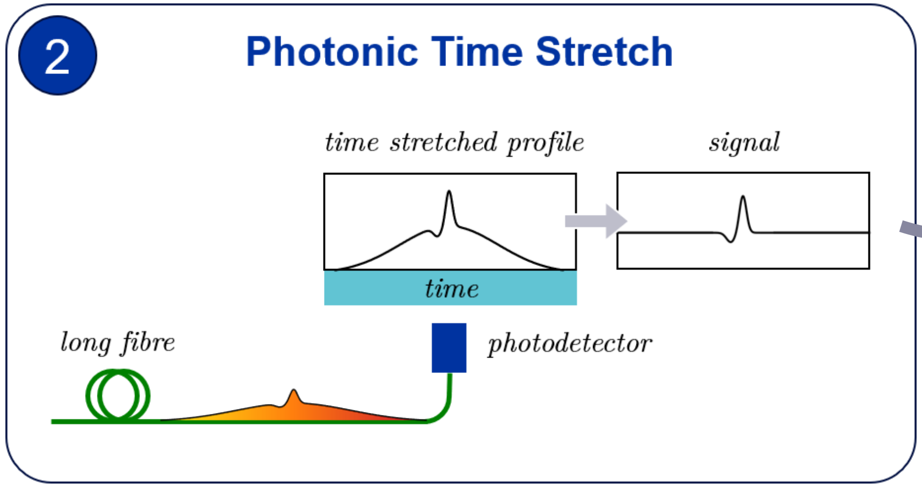


- **Jitter:**
  - no acquisition jitter present
  - only relative jitter between beam-induced signal and laser pulse remains
- **Temporal resolution:**
  - limited by spectrometer resolution
- **Setup:** more complicated
  - free space setup, alignment, intensified camera, …

- **Jitter:**
  - added acquisition jitter from acquisition trigger
- **Temporal resolution:**
  - limited by temporal stretching (available laser intensity)
- **Setup:** less complicated
  - long fibre + photodetector + oscilloscope

Decoding ✓



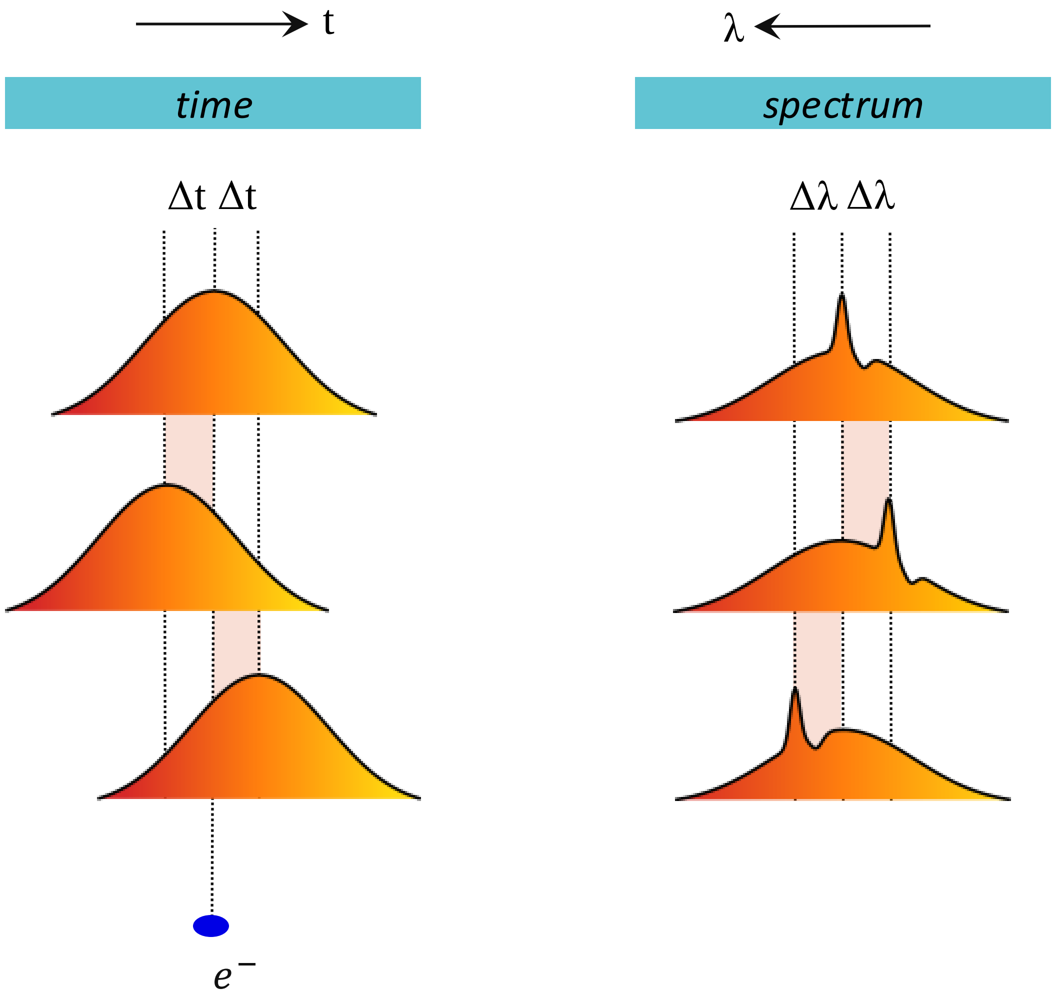


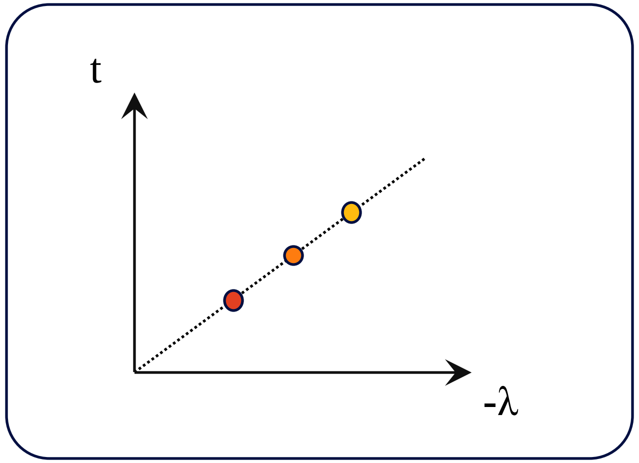
$\Delta\lambda \rightarrow \Delta t$

$\Delta\lambda \rightarrow \Delta t$

Time Conversion?

Time Conversion





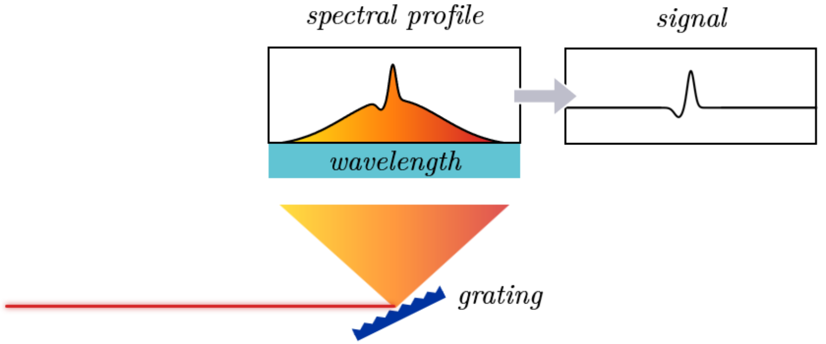
- Relationship between wavelength and time

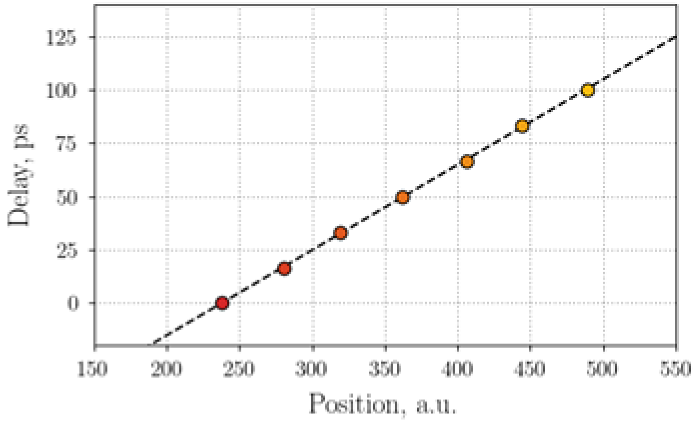
Decoding

Time Conversion

1

Spectral Decoding



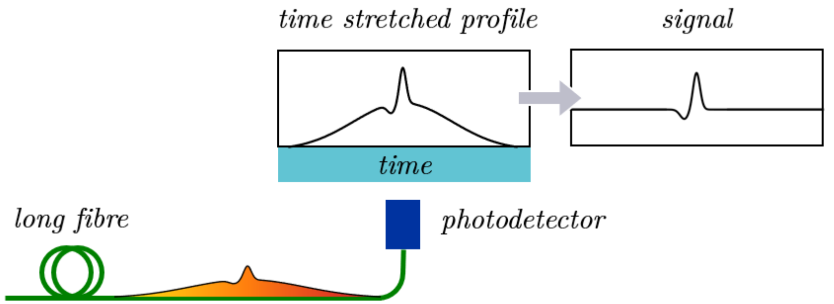


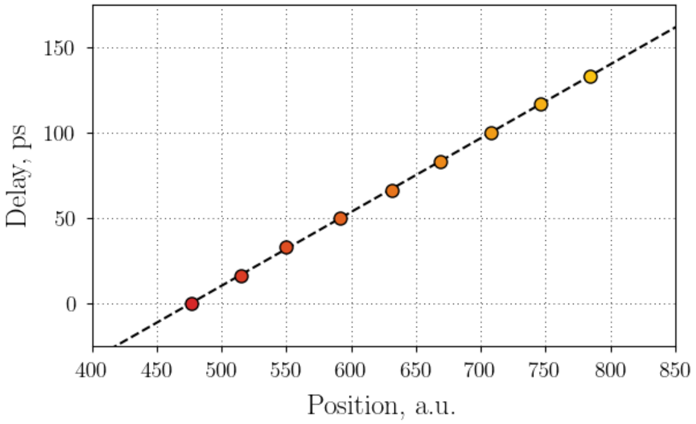
400 ± 3 fs/pos

~ 2500 GS/s

2

Photonic Time Stretch



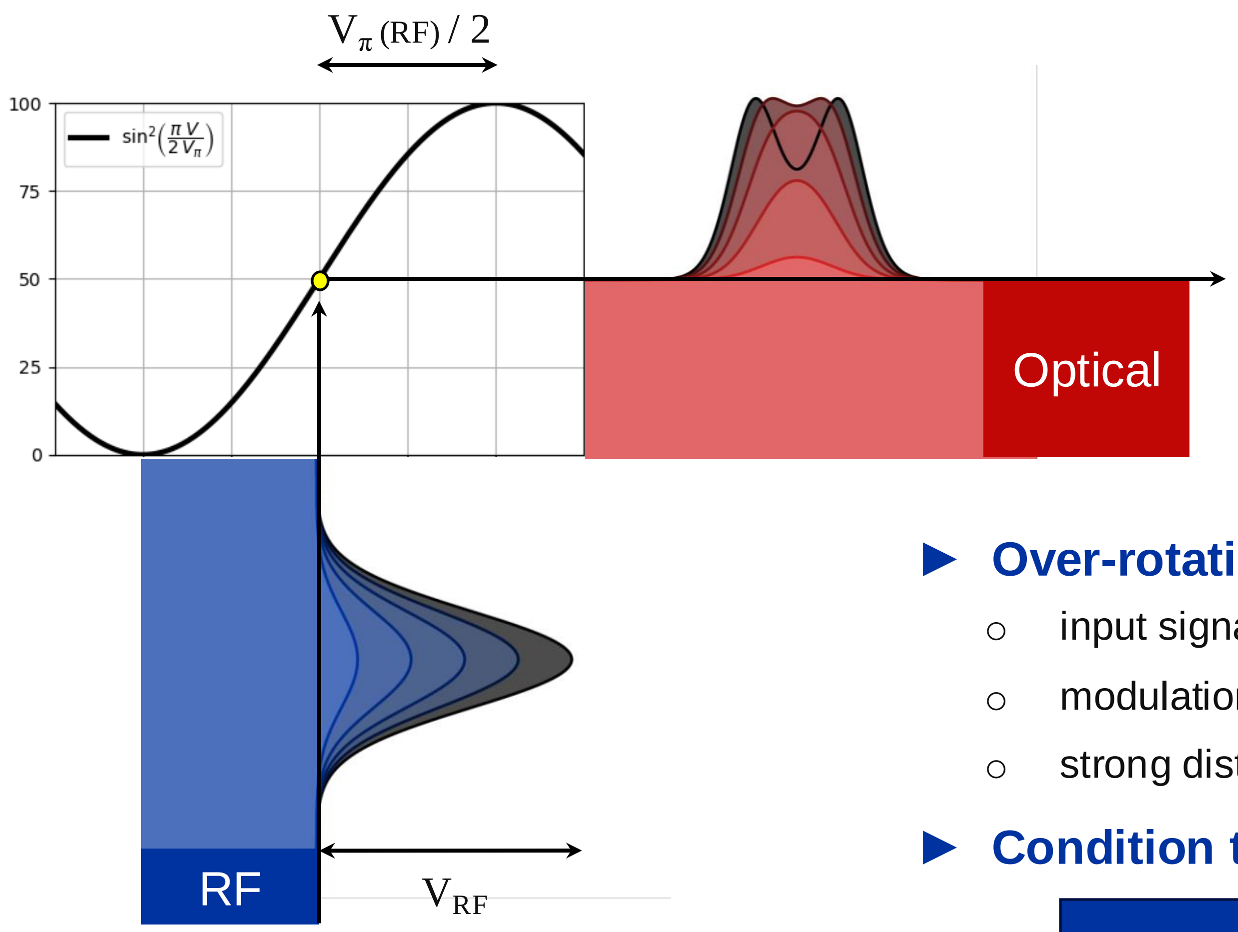


432 ± 2 fs/pos

~ 2315 GS/s

Pulsed laser measurement

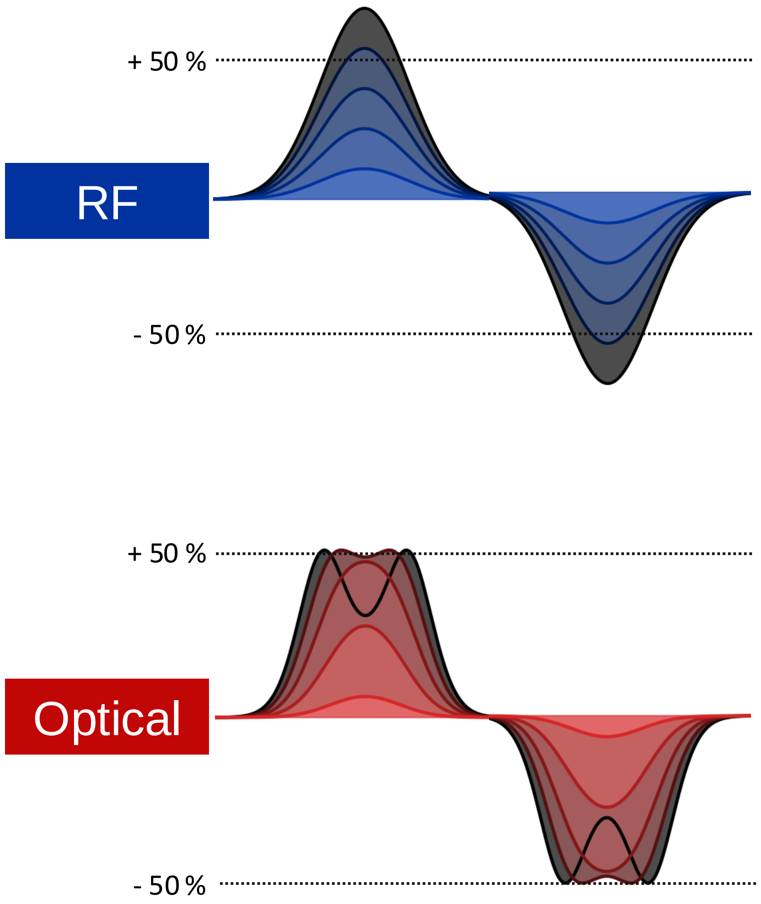
Input Signal Amplitude

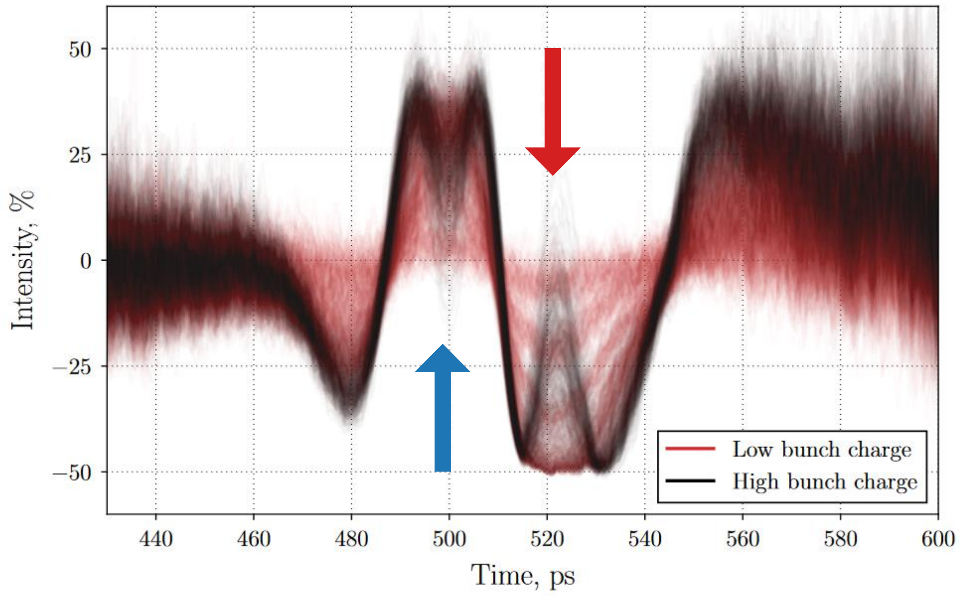


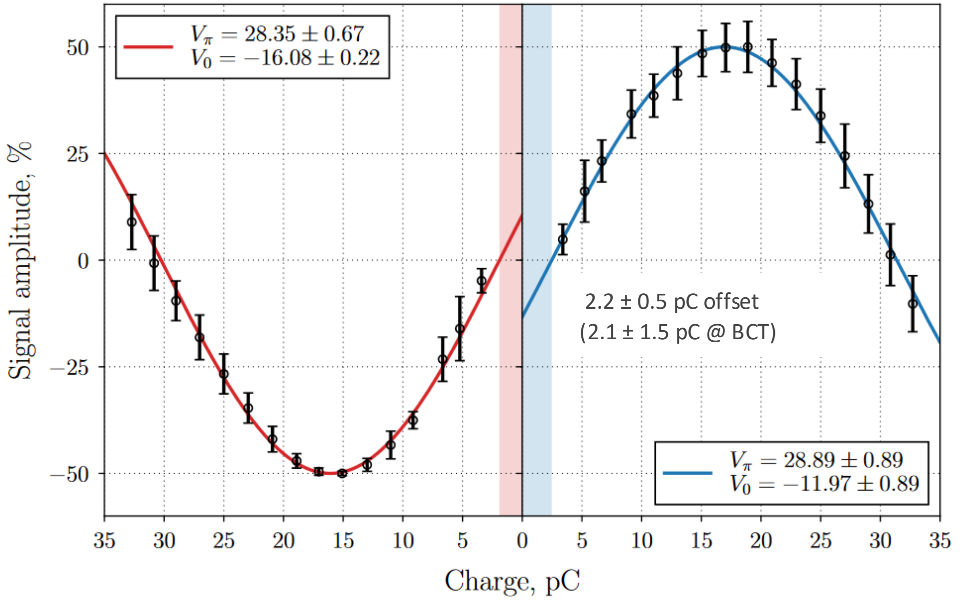
- **Over-rotation:**
  - input signal amplitude too high
  - modulation on next slope of transfer function
  - strong distortion of signals
- **Condition to avoid over-rotation:**

$$V_{RF} < V_\pi (RF) / 2$$

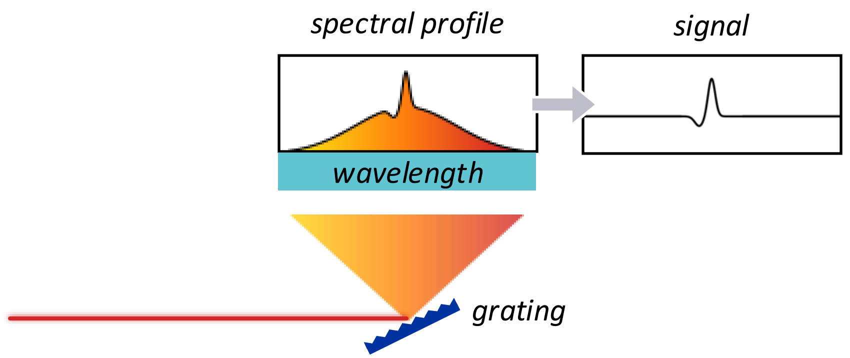
Input Signal Amplitude



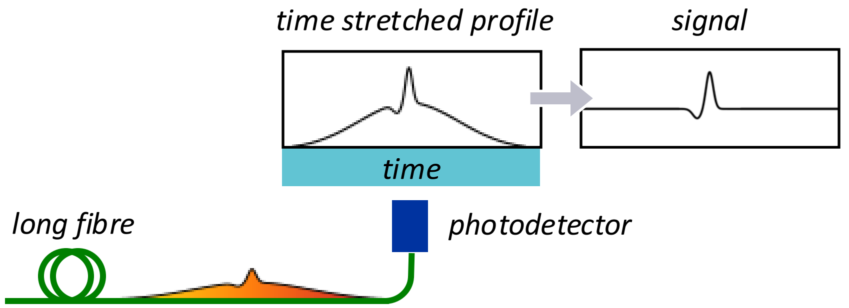




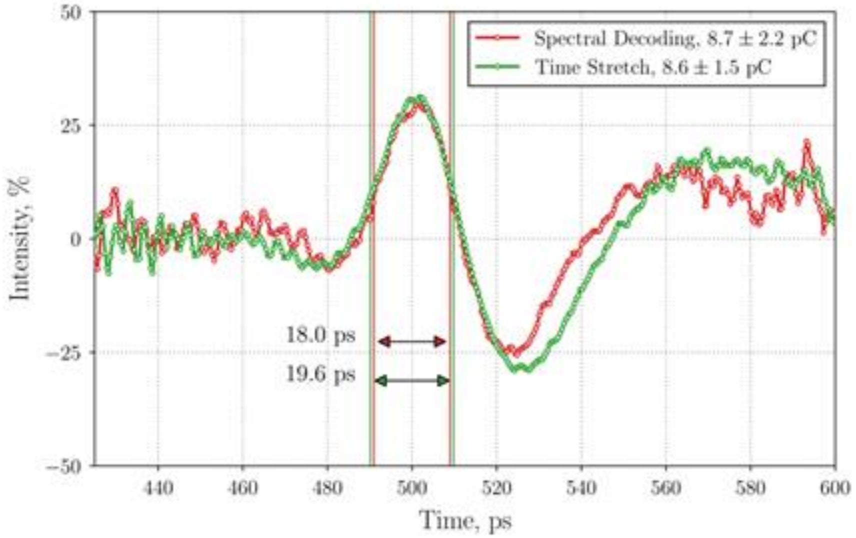
1 Spectral Decoding



2 Photonic Time Stretch



Average over 50



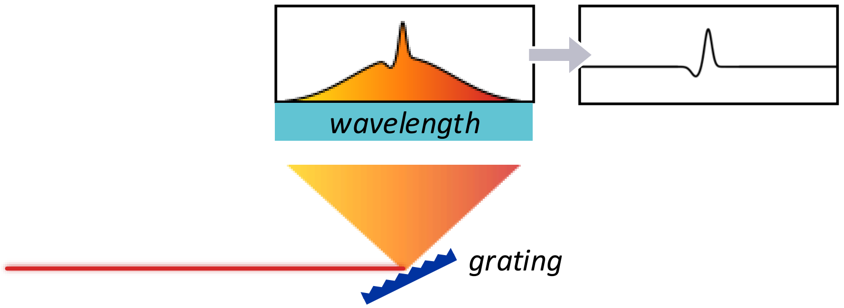
BW > 25 GHz

including various jitter contributions

FWHM: τ < 19.6 ps

→ Bandwidth ≈ 1 / *(2 τ)* **> 25 GHz**

1 Spectral Decoding



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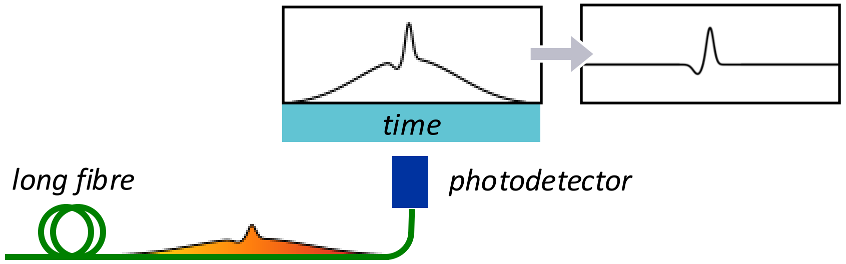
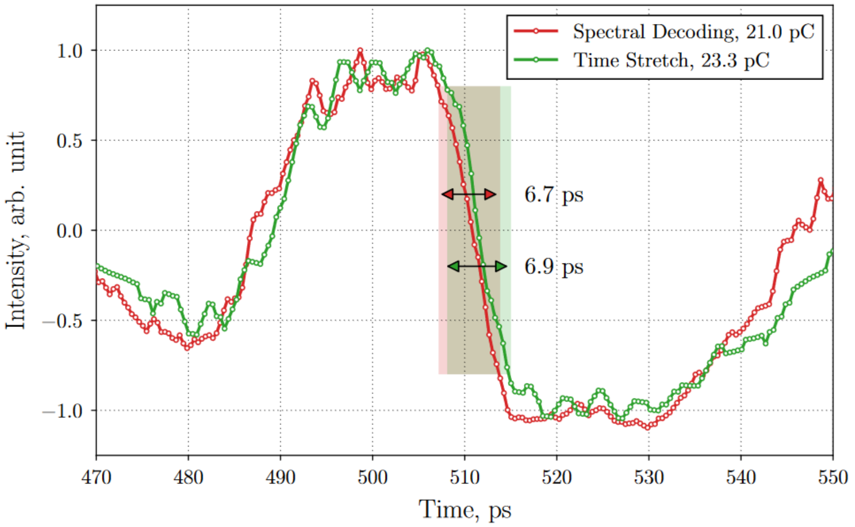


Saturated single shot



BW > 45 GHz

Fall Time t_f < 6.9 ps

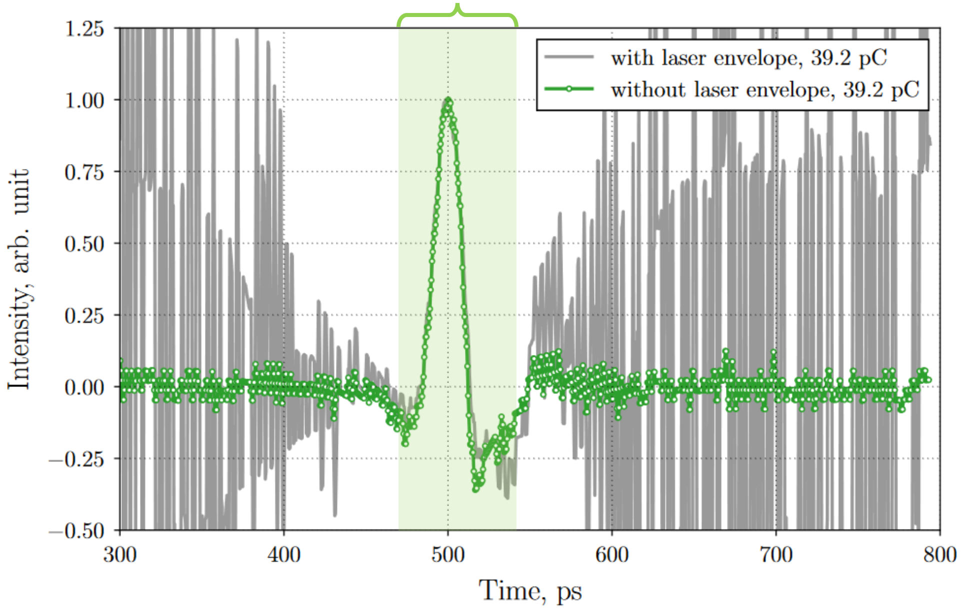
→ Bandwidth ≈ 0.35 / t_f **> 50 GHz**

Slew Rate $SR \geq 2\pi\ V(q)\ f_{max}$

→ f_{max} **≥ 45 GHz**

Photonic Time Stretch

$\tau_c \approx 72$ ps



equivalent: 300 GHz, 2315 GS/s

- **S/N > 10 for single shot measurement**
- **Low laser pulse energy**

Location	Laser pulse energy, pJ
Lab	24.0
Modulator	11.0
Photodiode	0.3

- margin for significant improvement

TUDC2: Collette Pakuza et al.,
"The Study of High-frequency Pick-ups for Electron Beam Position Measurements in the AWAKE Common-beamline"

Future Perspectives

1550 nm setup

- higher optical bandwidth of modulators (>50 GHz)
- less attenuation in fibers allows for higher power density and longer stretching
- much bigger market (lasers, fibres, GaAs modulators, IQ modulators, …)

THAI2: Christelle Hanoun et al,
“Cost-effective Time-stretch Terahertz Electro-optic Recorders, by Using 1550 nm Laser Probes”

Small footprint in large-scale machines

- optical fibres as a more compact alternative to traditional cables

Radiation tolerance?

- entirely analog installation
- moving all electronic devices out of radiation areas
- radiation hardness of modulators and polarization-maintaining fibers to be evaluated

Summary

Photodetector with CW laser

- straightforward system with no limit concerning the acquisition window
- requires high average power and fast electronics

Spectral Decoding with chirped laser pulse

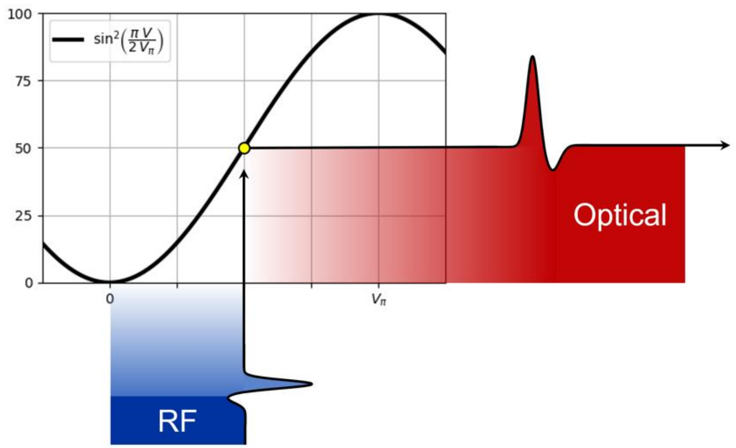
- zero acquisition jitter
- typically a more complicated system to set up and operate

Photonic Time Stretch with chirped laser pulse

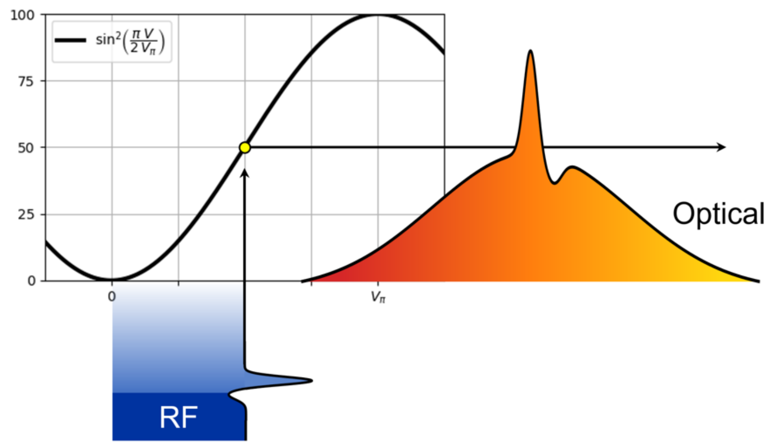
- rather flexible, fibre-based system
- better suited for high repetition rates

- ► current modulator provides up to 45 GHz analog bandwidth
- ► long transmission lines of hundreds of meters
- ► overcome the challenges of transmitting beam-induced signals in the tens of GHz range

Continuous wave laser



Chirped laser pulse



Thank you!

home.cern