Remote Sensing of Fast Beam Signals Using Electro-optical Modulators

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Outline

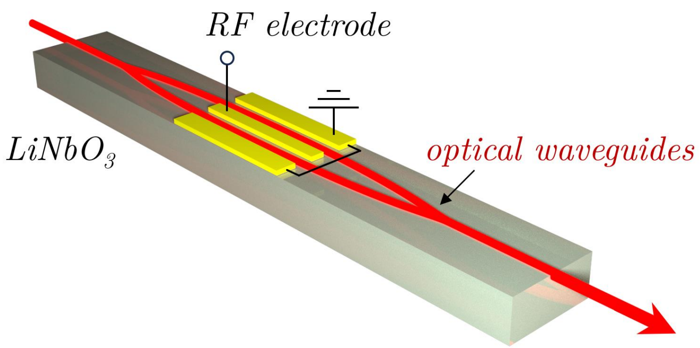
- **Fast beam signals**
- **Radio-over-fibre with electro-optical modulators**
- **Experimental results**
  - Continuous Wave
  - Spectral Decoding
  - Photonic Time Stretch
- **Future perspectives**
- **Summary**

Fast Beam Signals

“Fast” in this talk: 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.

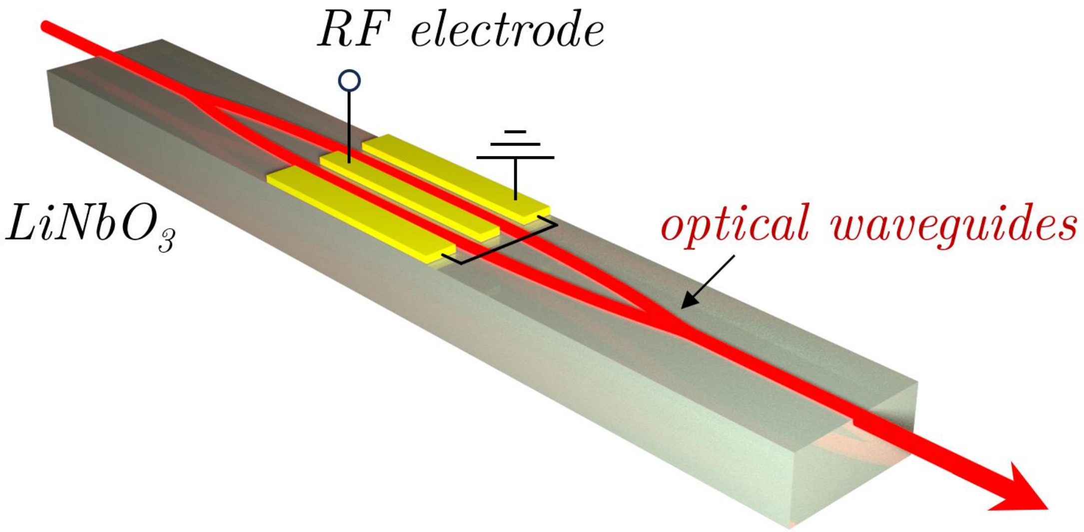
→ Set up and test prototype with various beam-induced signals

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

Radio-over-fibre with electro-optical modulators

- **Modulation due to Pockels effect**
  - linear variation of refractive index in response to an applied electric field
- **Electro-optic material**
  - Lithium niobate ($LiNbO_3$)
  - Gallium arsenide (GaAs)
  - Indium phosphide (InP)
- **Interference-based modulation of light**
  - laser light split into two arms, modulated, and recombined
  - designed for continuous wave laser

Mach-Zehnder electro-optical modulator



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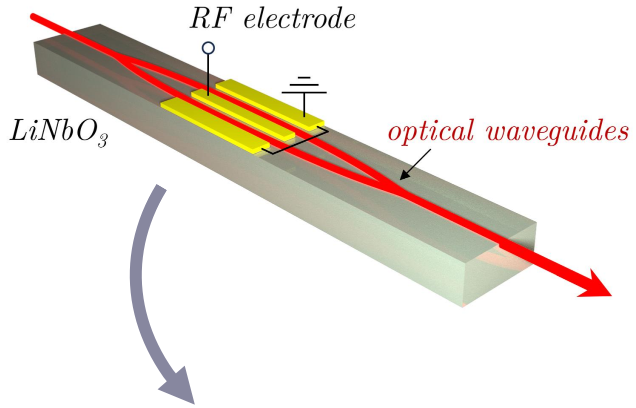
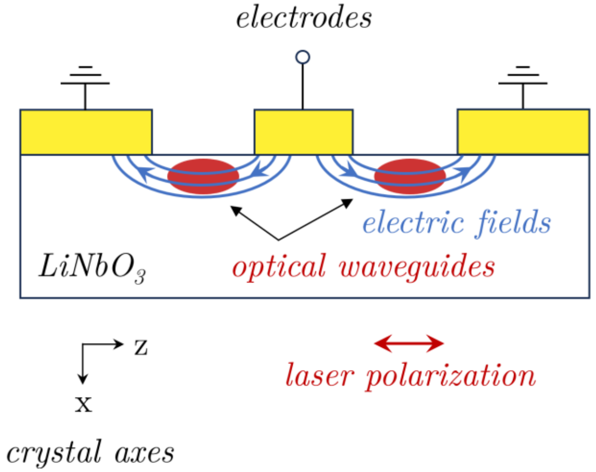
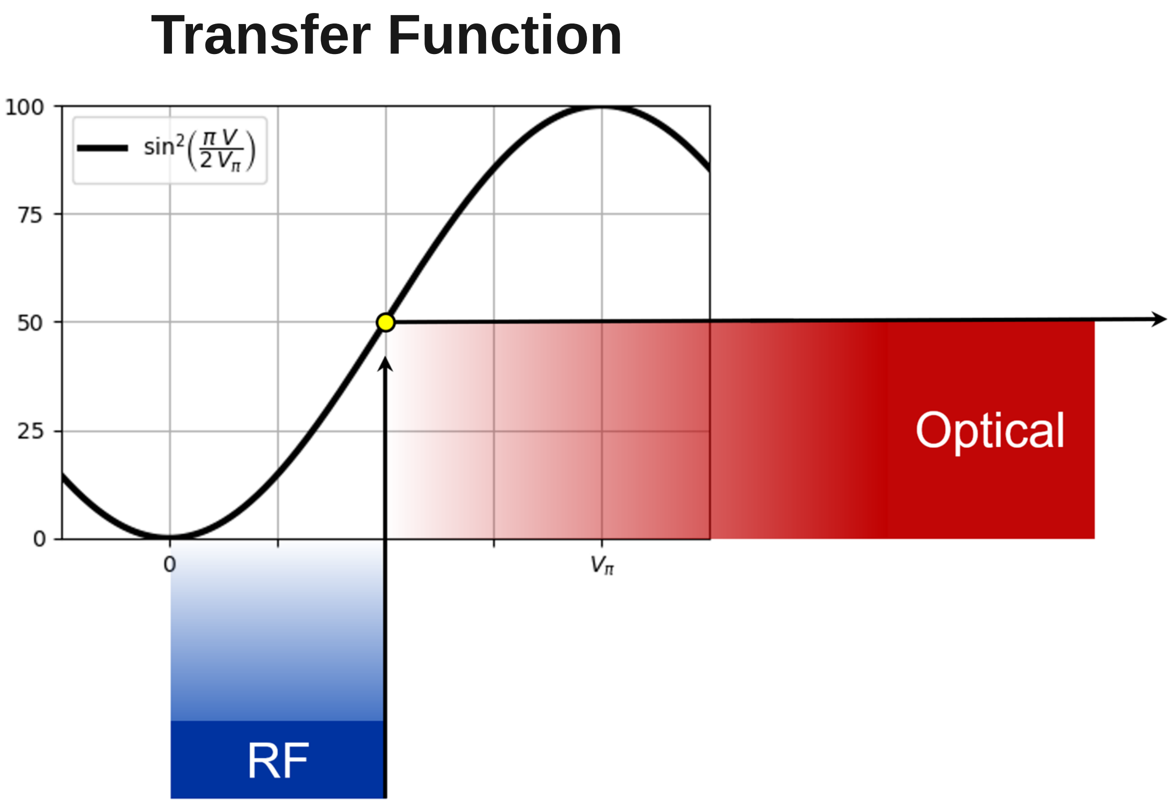
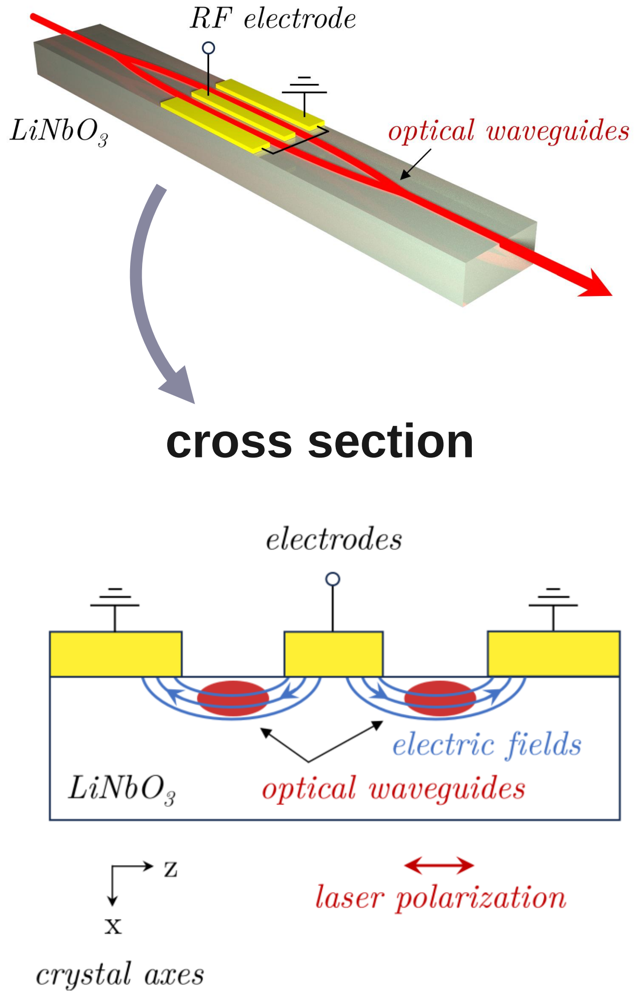


cross section

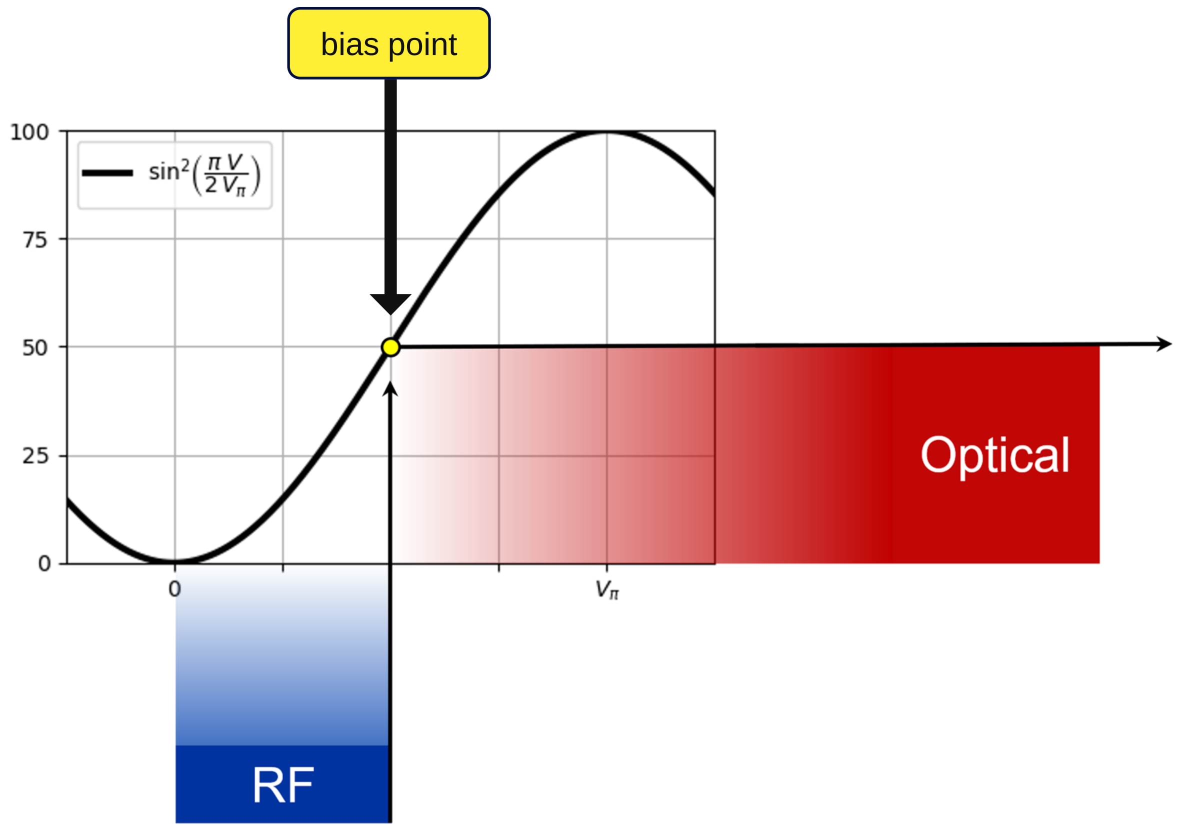


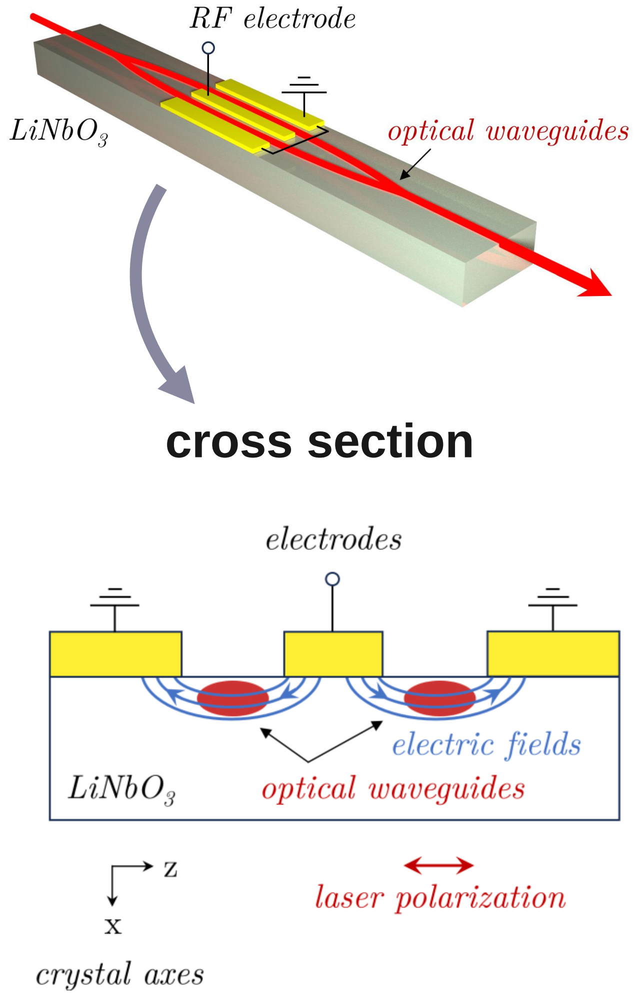
Radio-over-fibre with electro-optical modulators



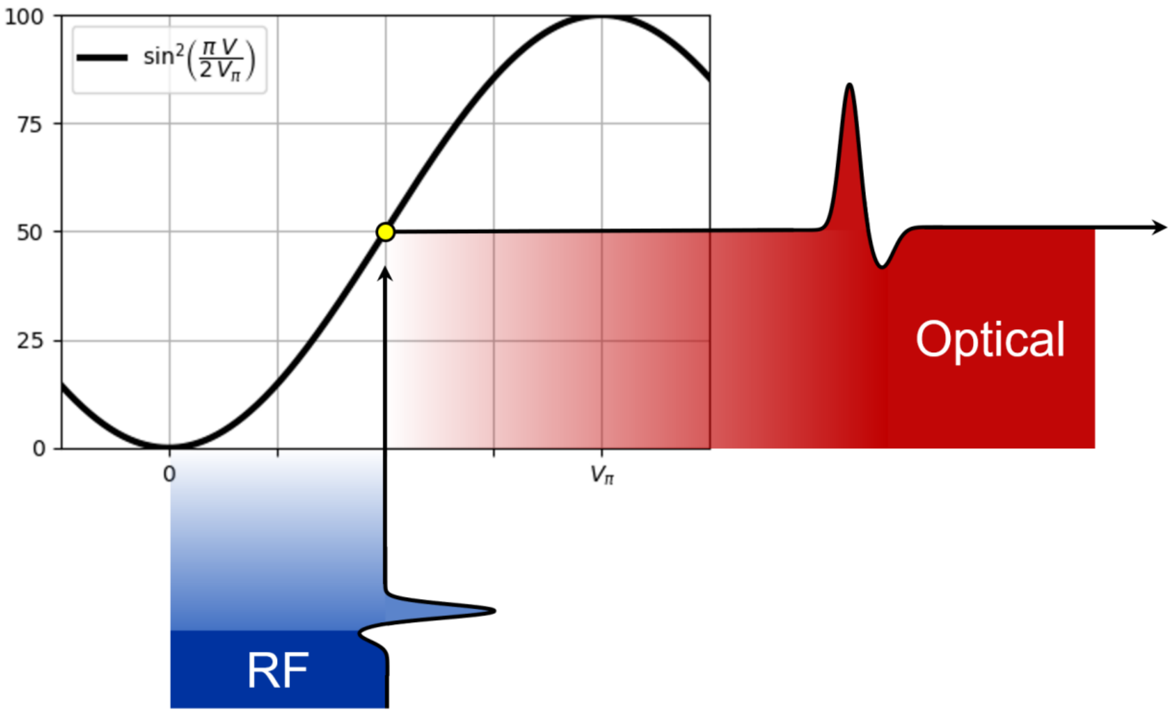


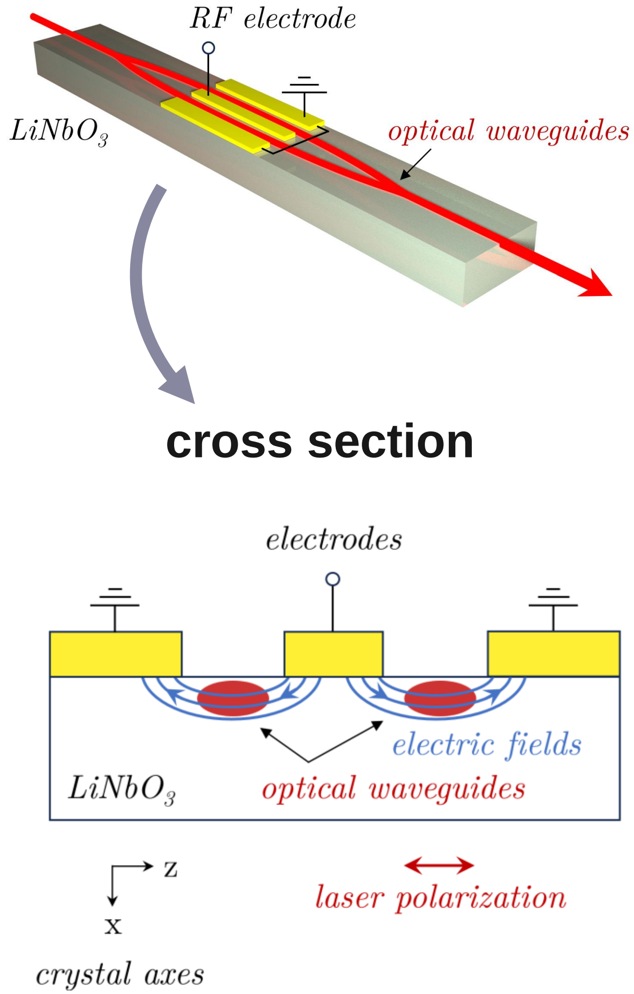
Radio-over-fibre with electro-optical modulators





Radio-over-fibre with electro-optical modulators

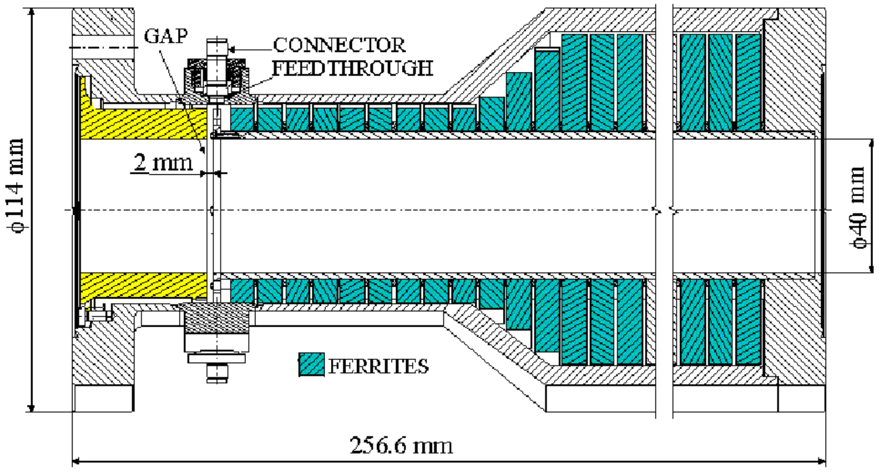




Continuous wave laser measurement

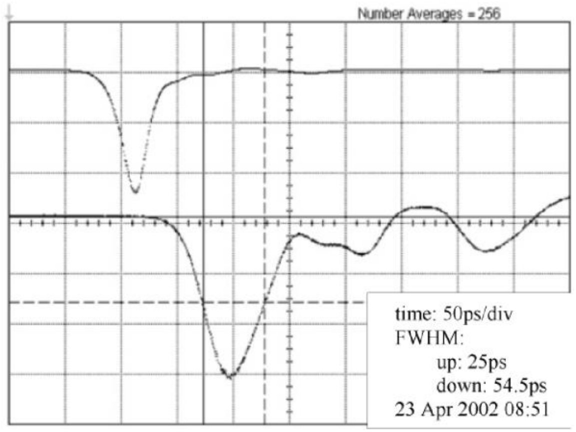
Wall Current Monitor

Patrick Odier, *“A New Wide Band Wall Current Monitor”, 6th European Workshop on Beam Diagnostic and Instrumentation for Particle Accelerators (DIPAC 2003), Mainz, Germany, May 2003*



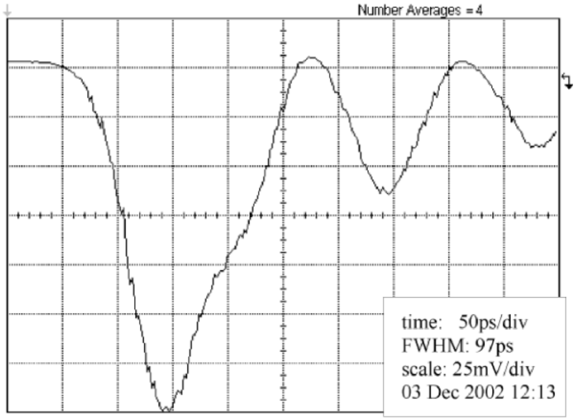
	Design value
Low-frequency cutoff	10 kHz
High-frequency output	10 GHz

lab measurement (2002)



BW > 9.1 GHz

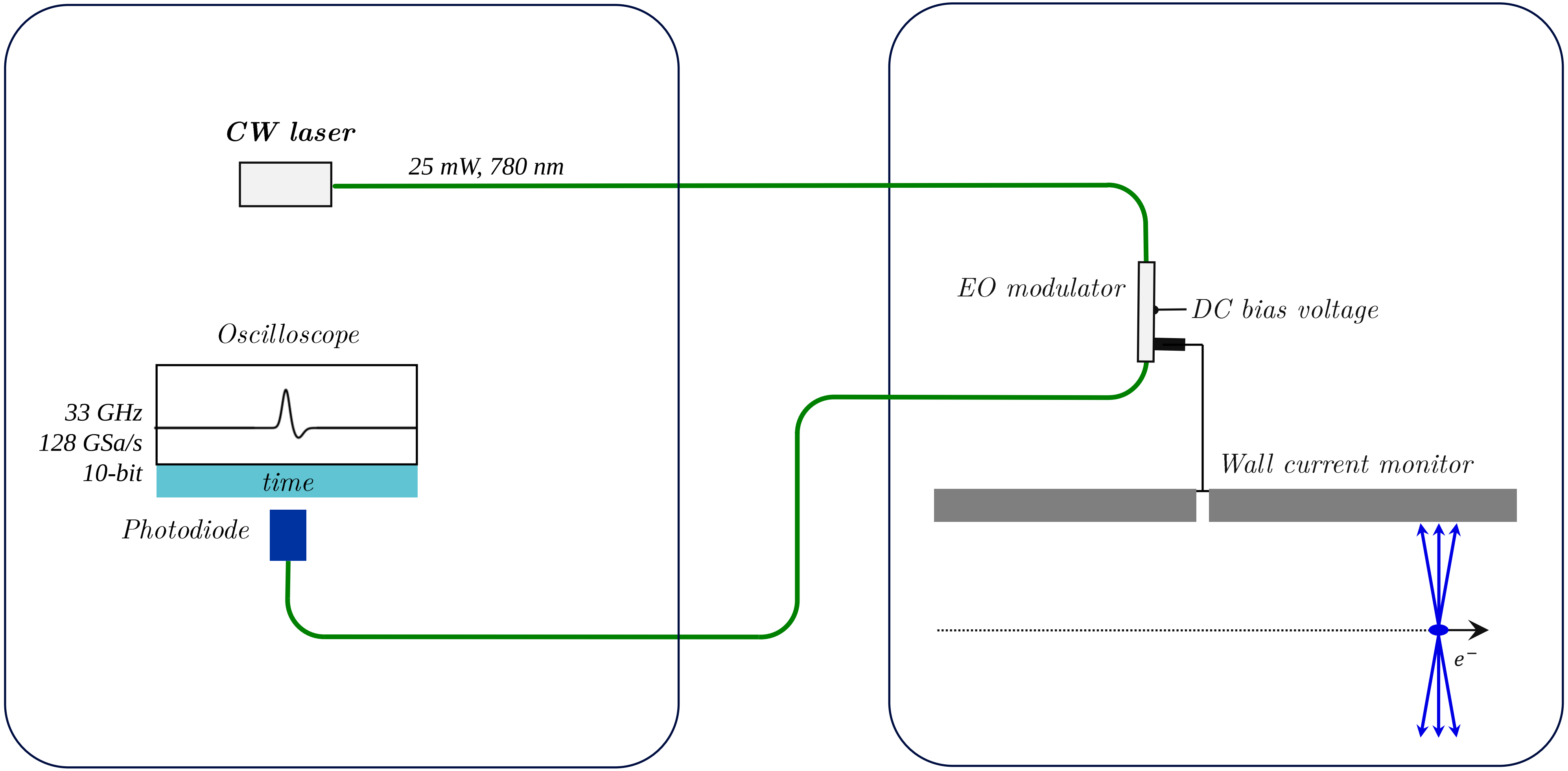
beam measurement (2002)



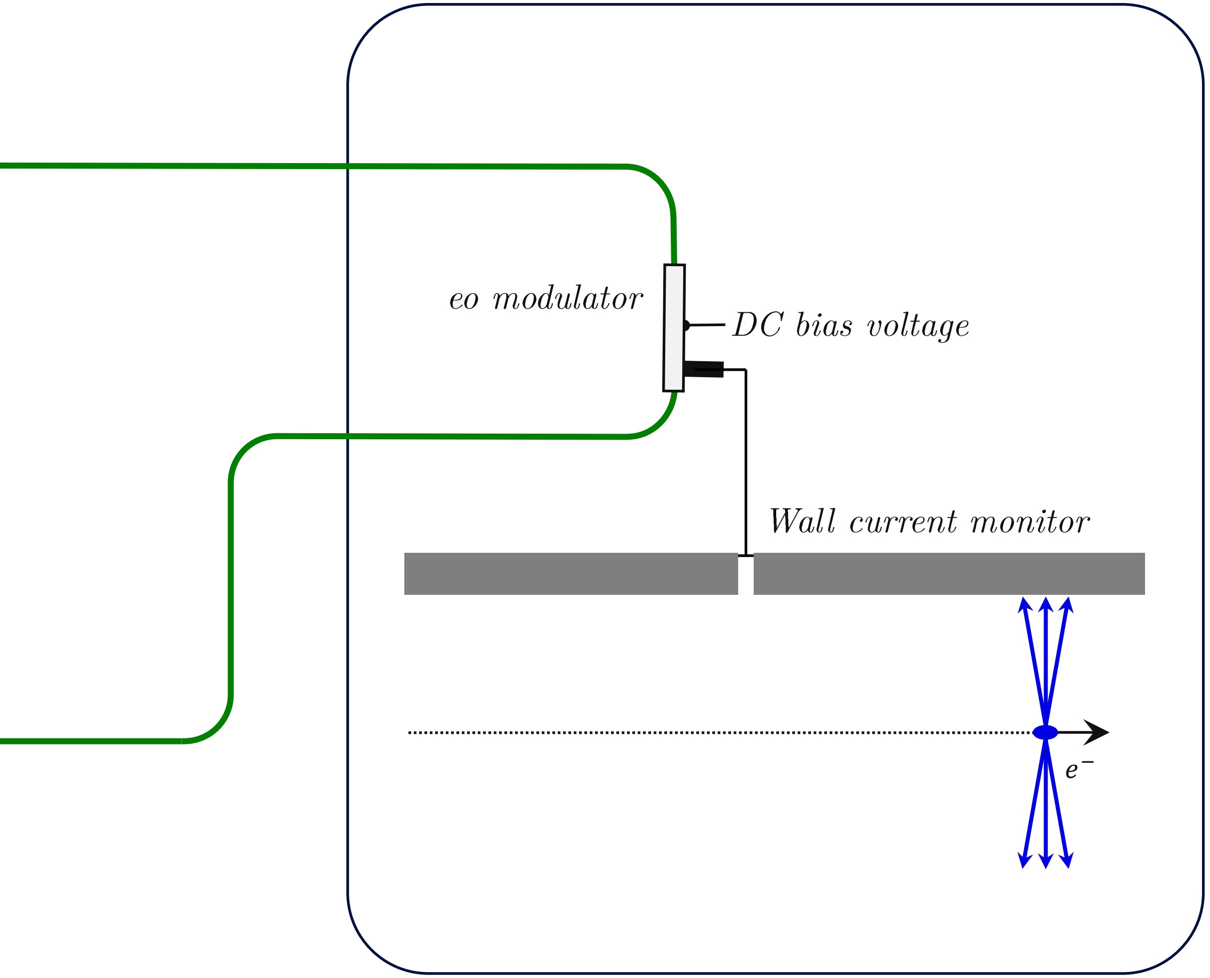
long cables →

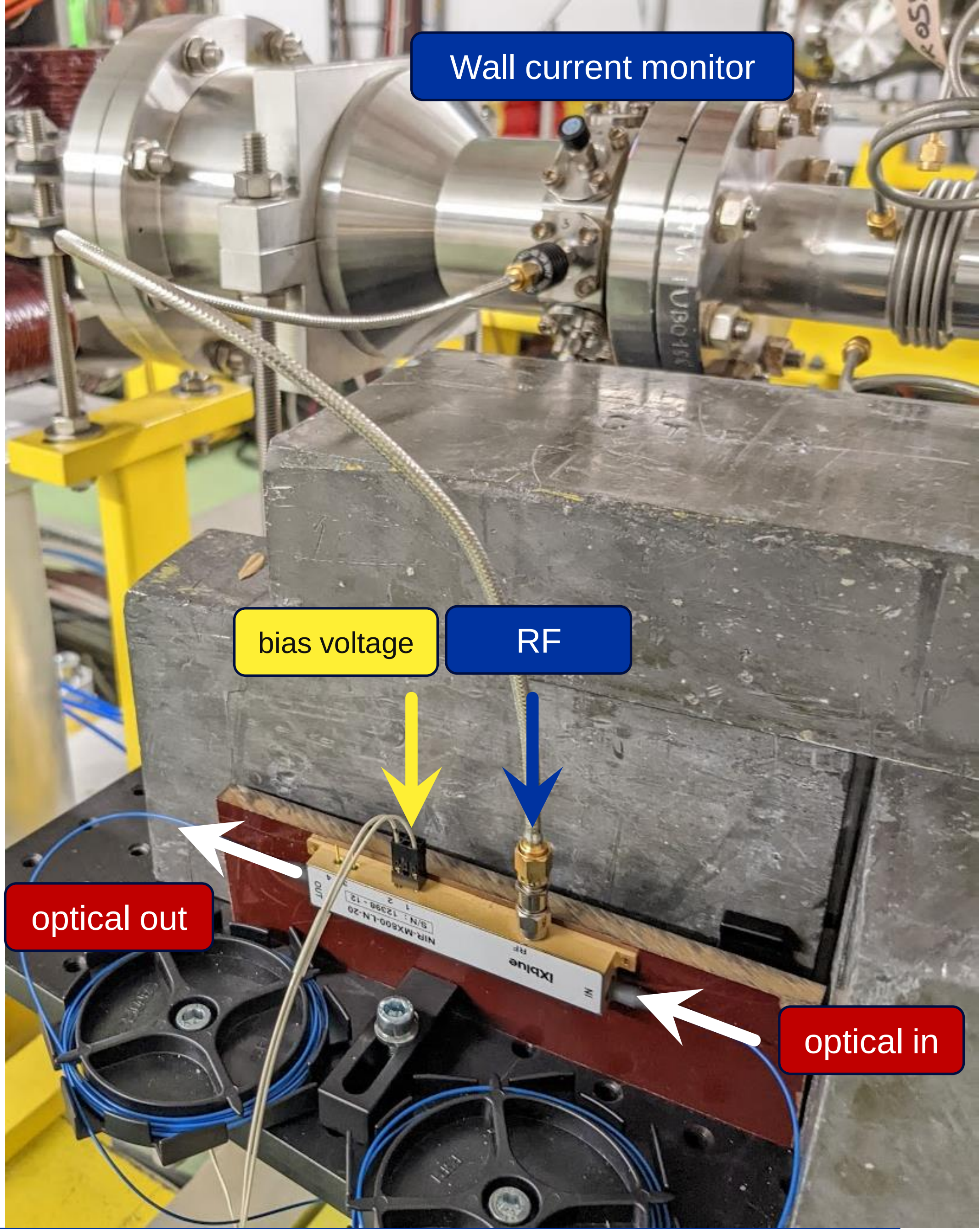
BW > 5.2 GHz

CW laser measurement



CW laser measurement





CW laser measurement

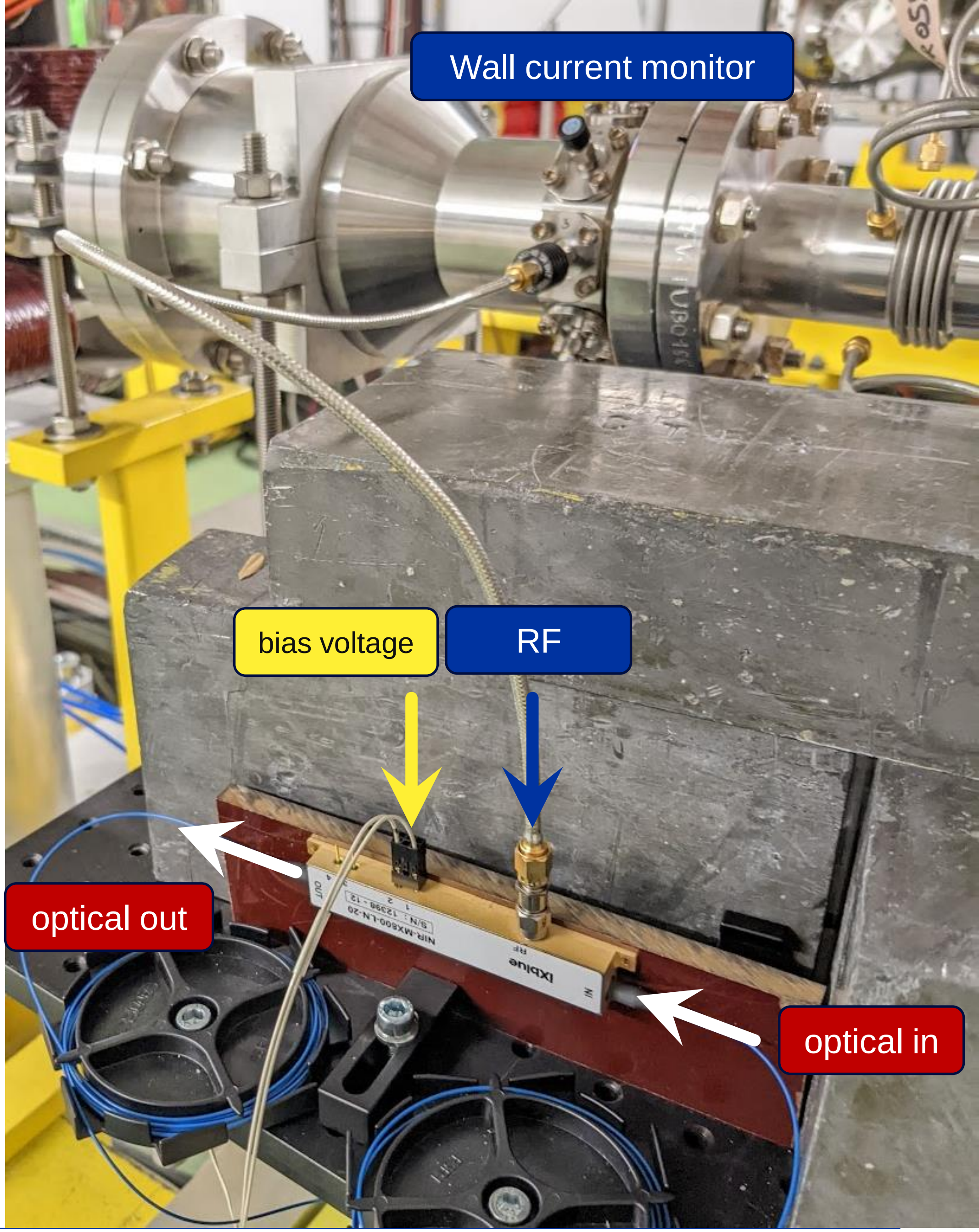
Beam	Electron beam @ CLEAR	
	Energy	200 MeV
	Bunch length	5 ps (1σ)
	Bunch charge	100 pC
	Bunch spacing	667 ps

↓

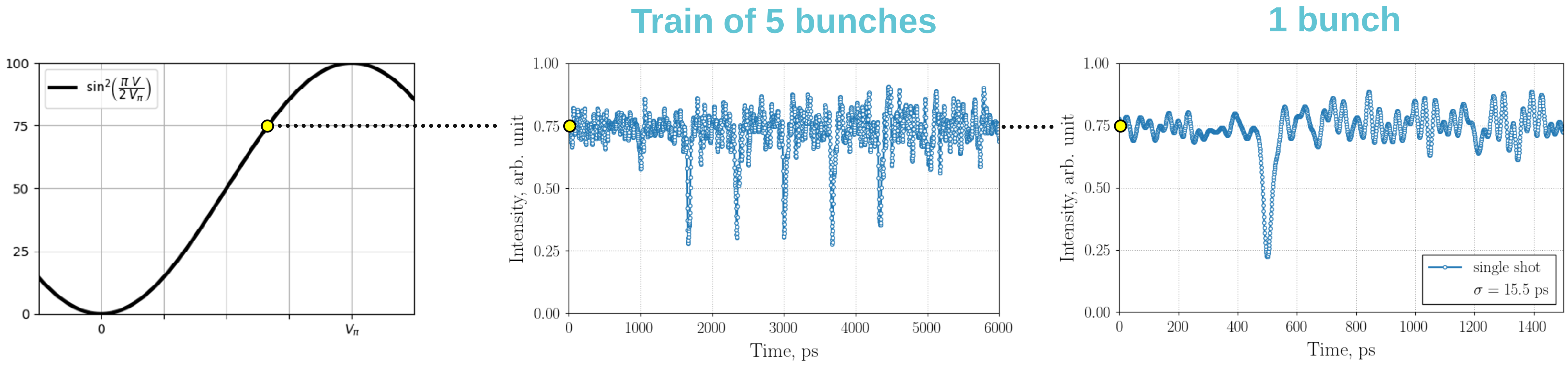
10 GHz Wall Current Monitor

↓

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



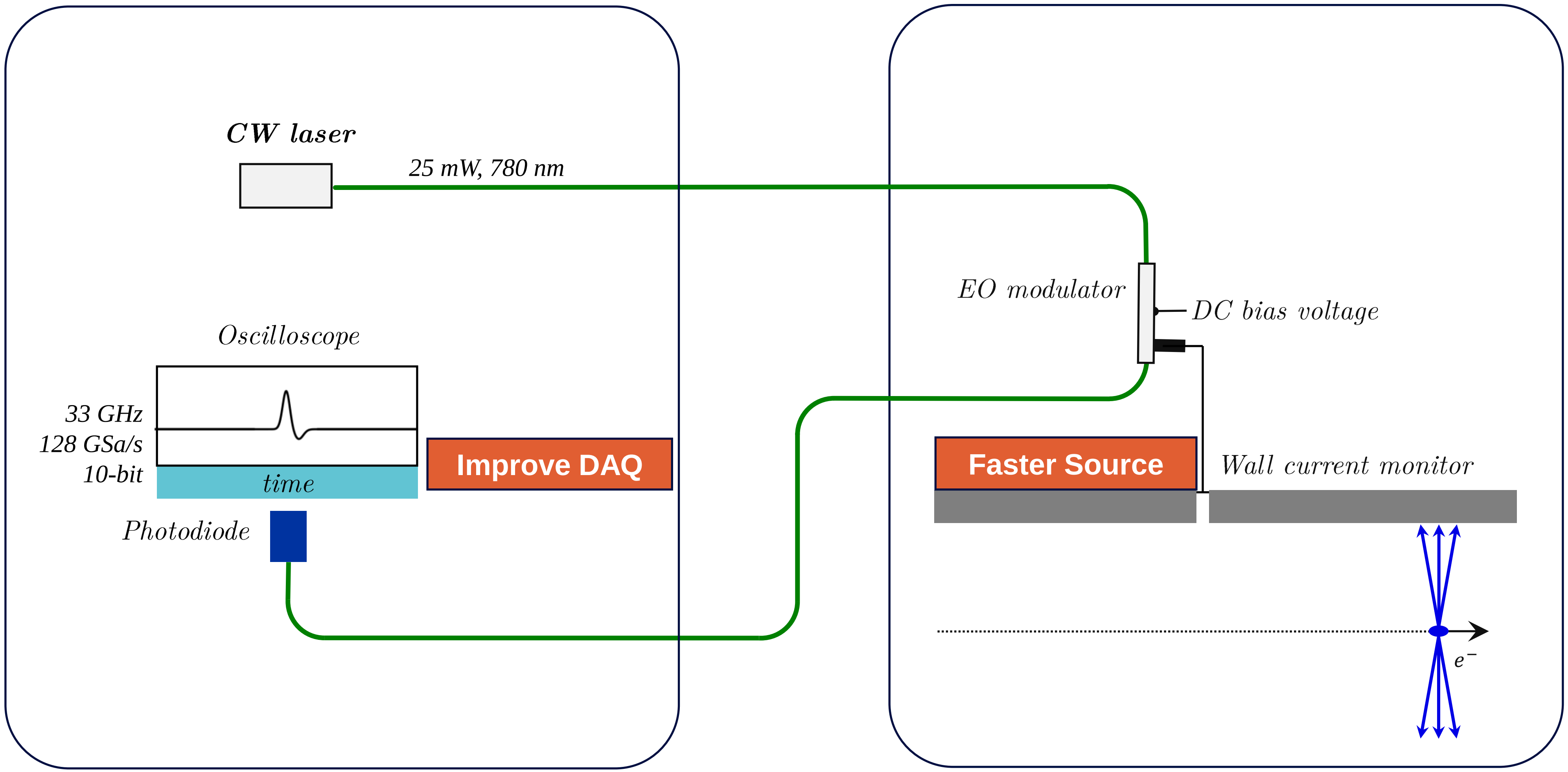
Wall Current Monitor



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

- **13 GHz instead of 5.2 GHz**
- **13 GHz ≪ 25 GHz of modulator BW**

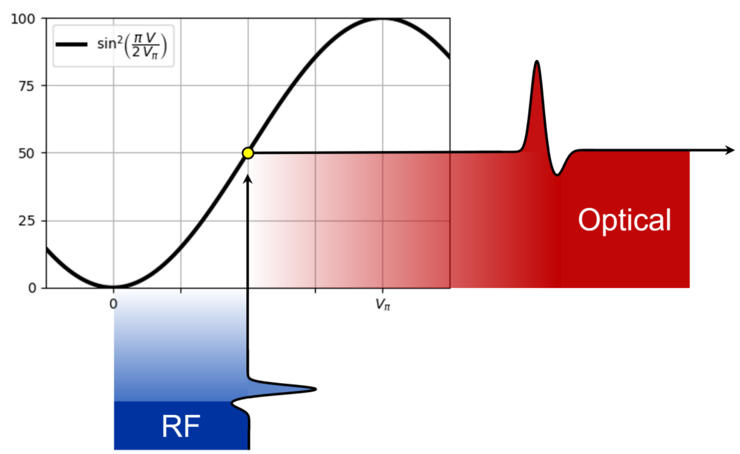
CW laser measurement



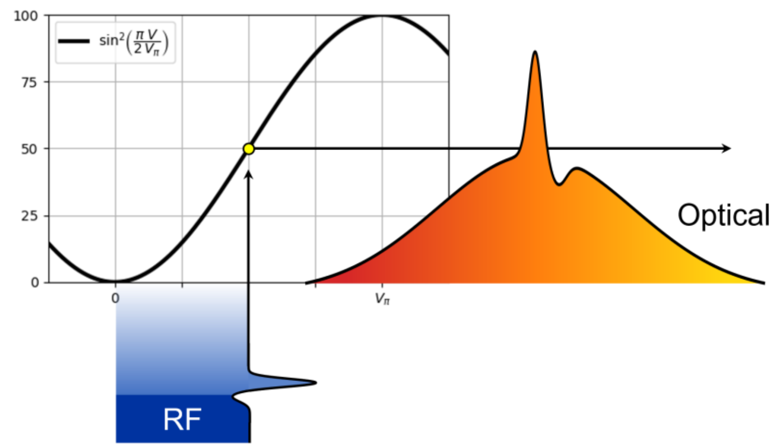
DAQ: Spectral Encoding

- **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

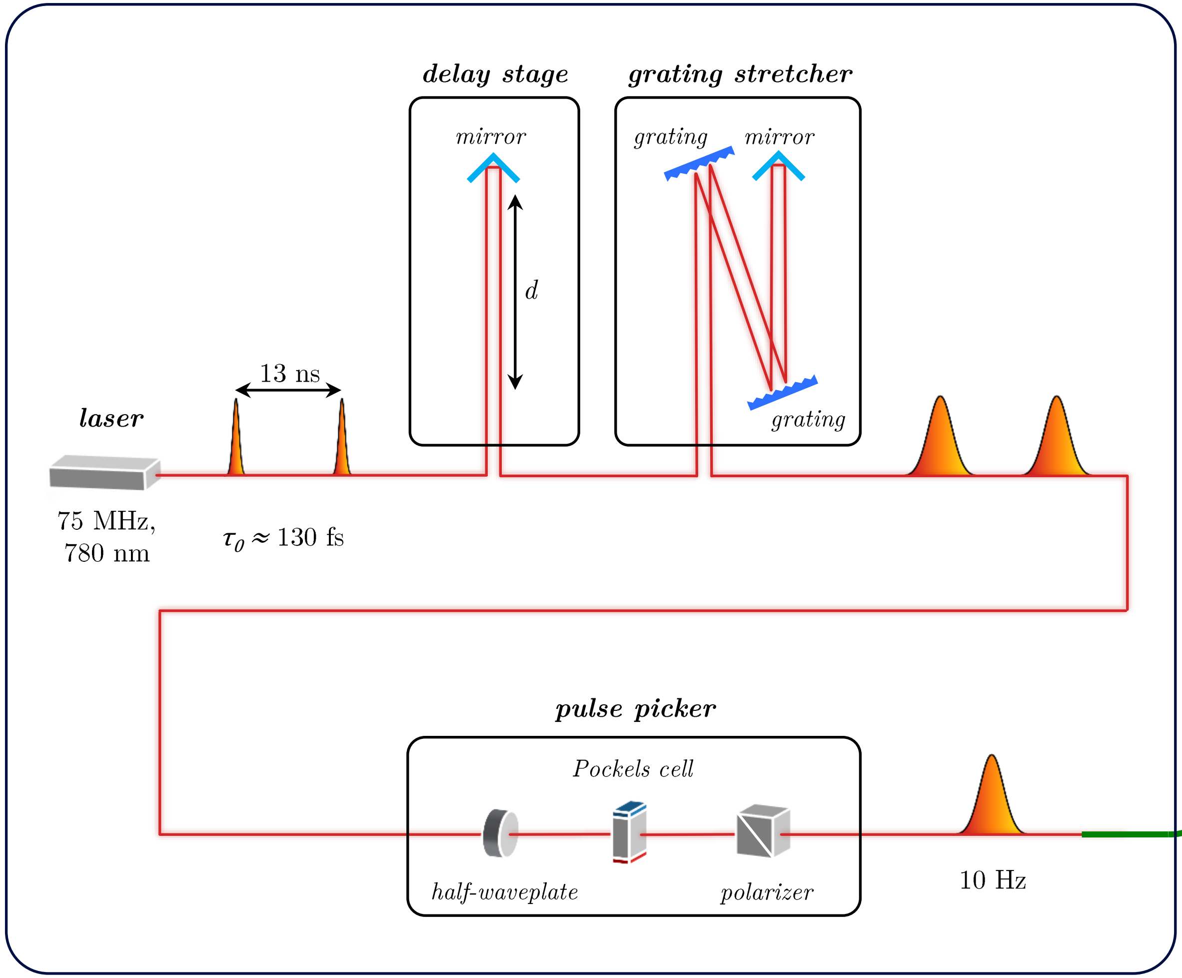
Continuous wave laser



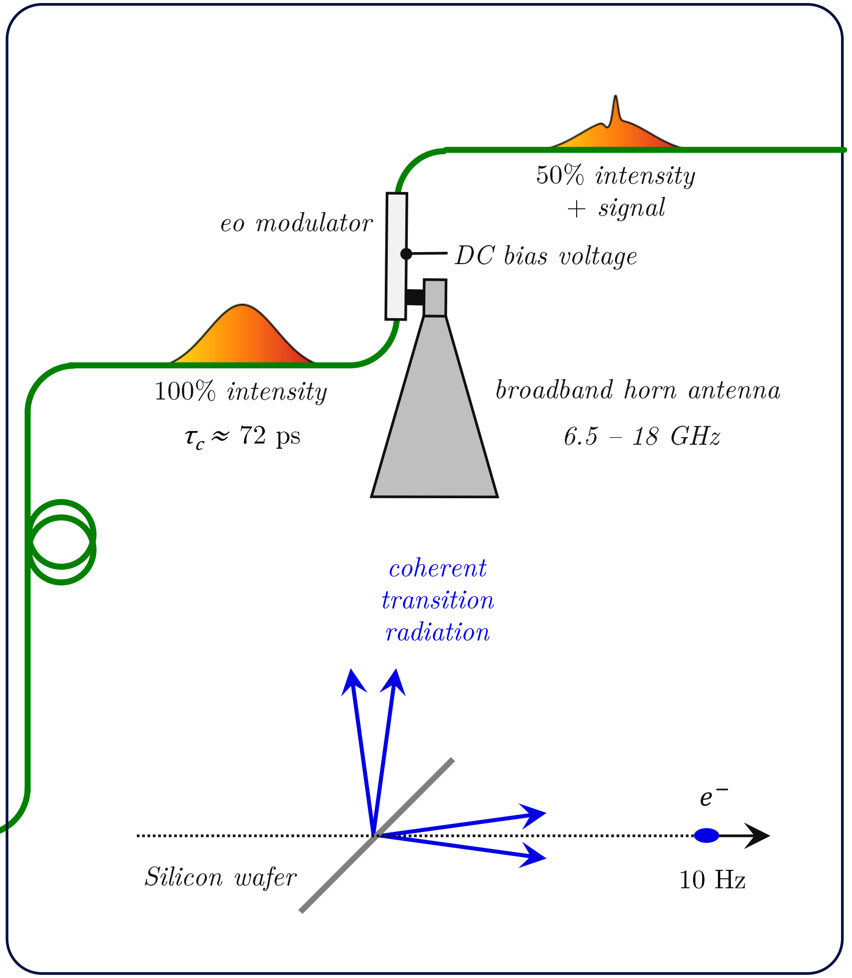
Chirped laser pulse



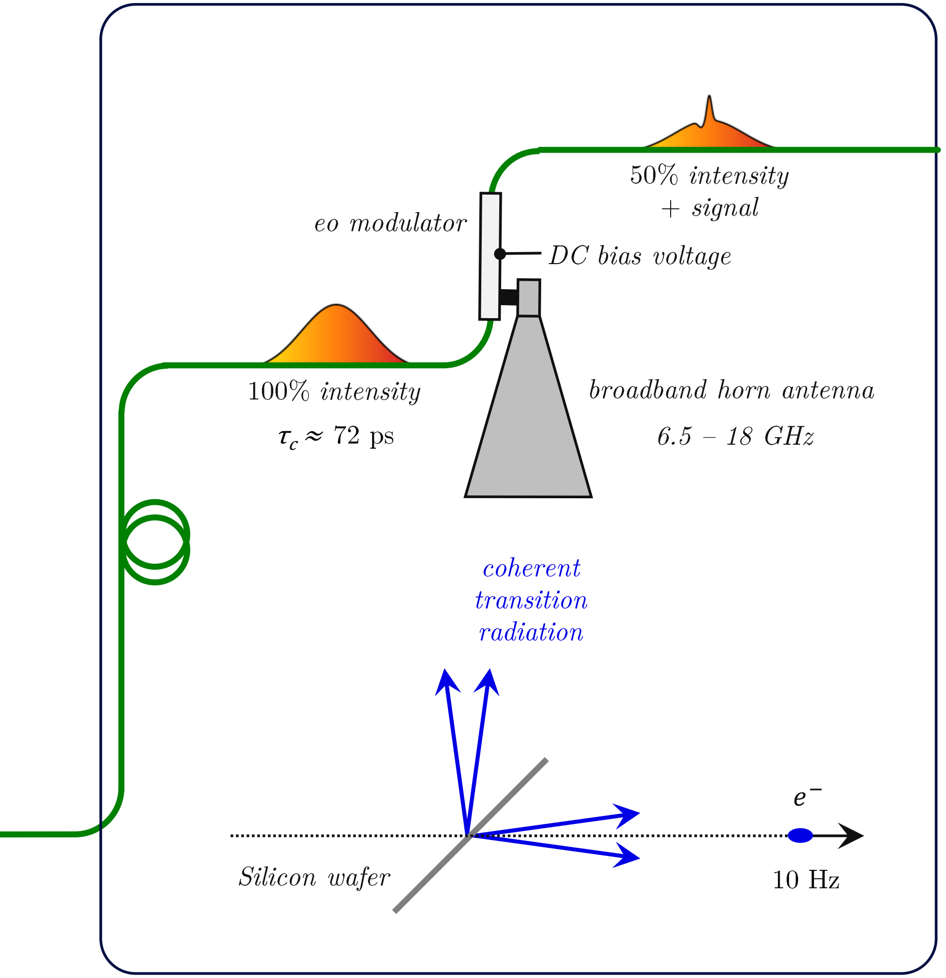
Preparing pulse



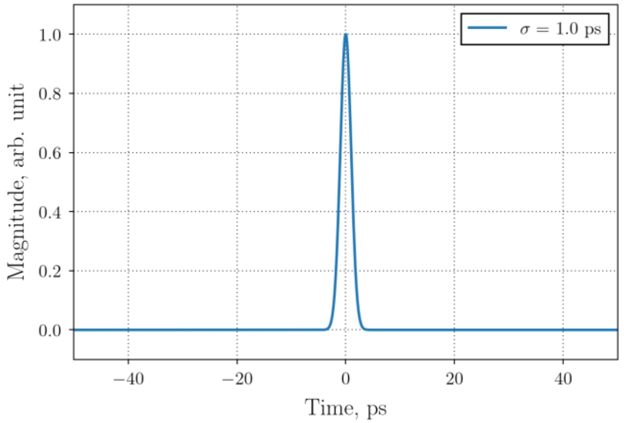
Encoding



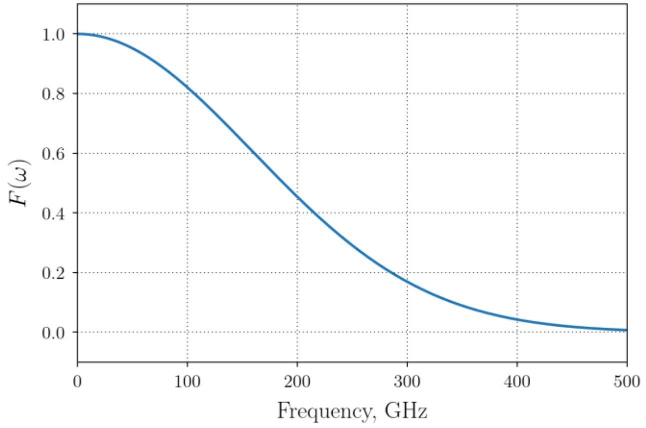
Encoding



1 ps (1σ) Gaussian bunch



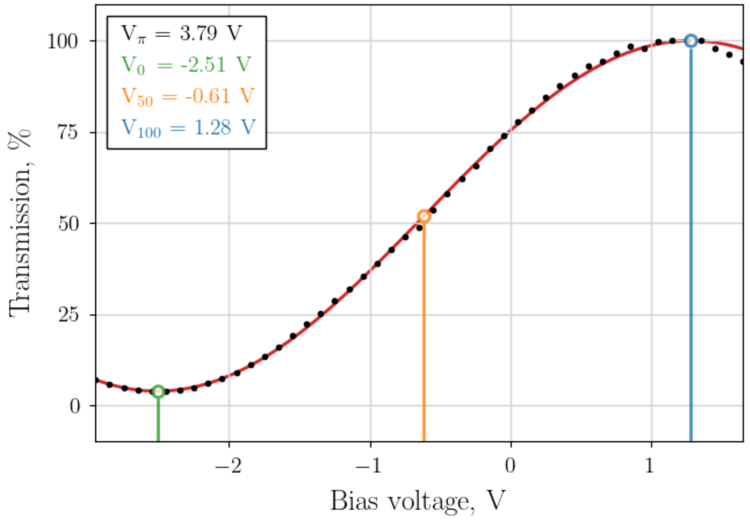
Bunch form factor

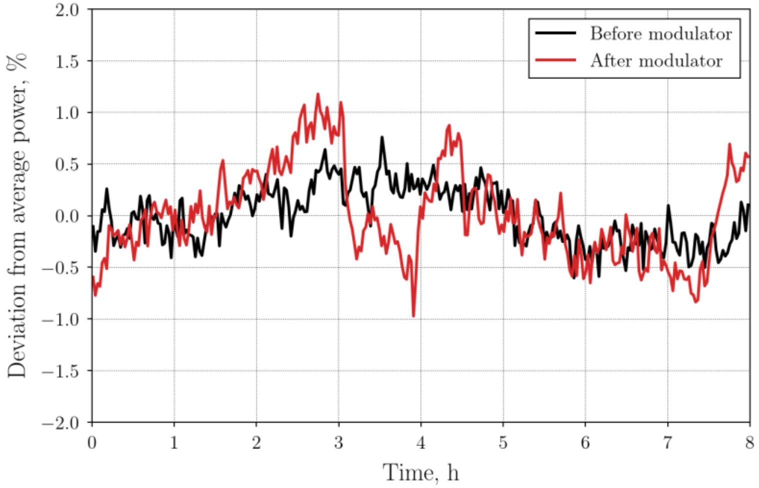


Coherent emission

$$\frac{dW}{d\omega} = \left(\frac{dW}{d\omega}\right)_1 \cdot \left(N + N\left(N-1\right)\left|F(\omega)\right|^2\right)$$

Transfer Function





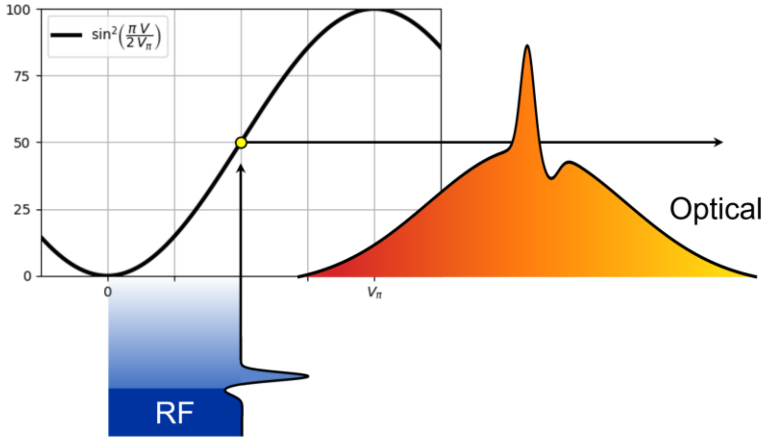
- **Single pulse transfer function**
- **DC extinction ratio**
  - Reduced due to optical bandwidth (7 nm FWHM)
  - > 20.0 dB for CW laser (data sheet)
    down to 15.8 dB for pulsed laser

    → 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

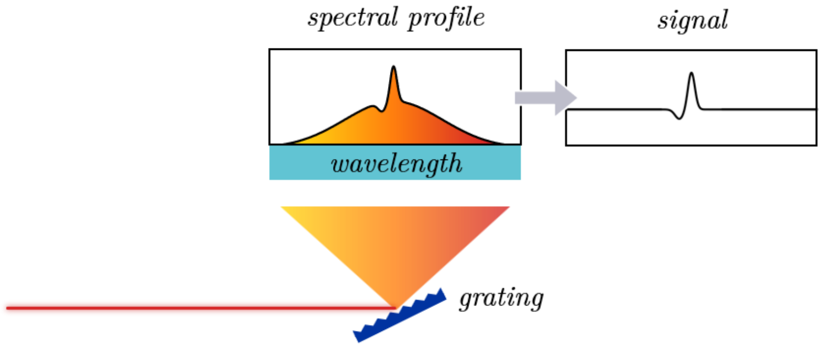
Encoding ✓

Decoding ?

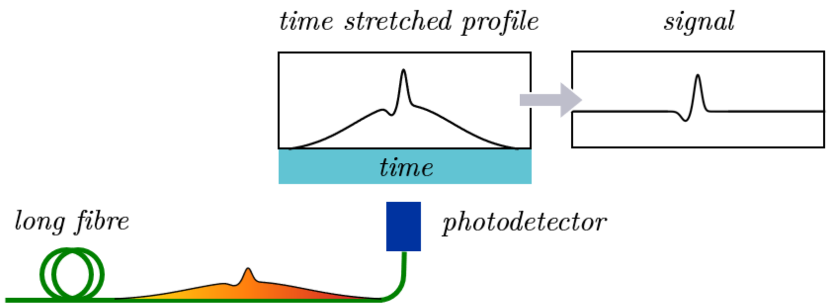
Chirped laser pulse



1 Spectral Decoding



2 Photonic Time Stretch



Decoding ?

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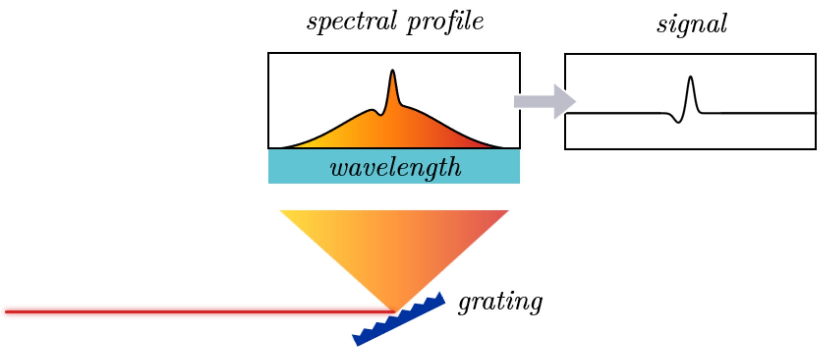

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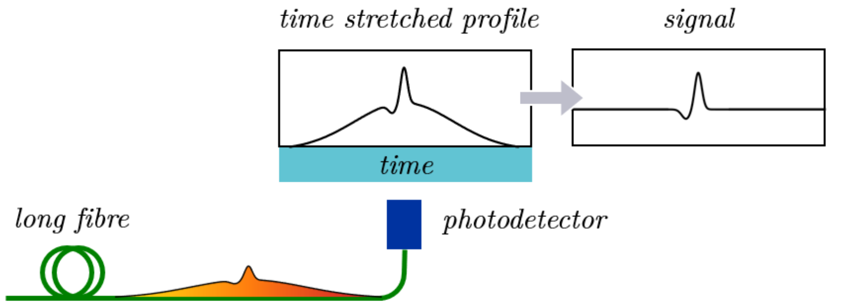


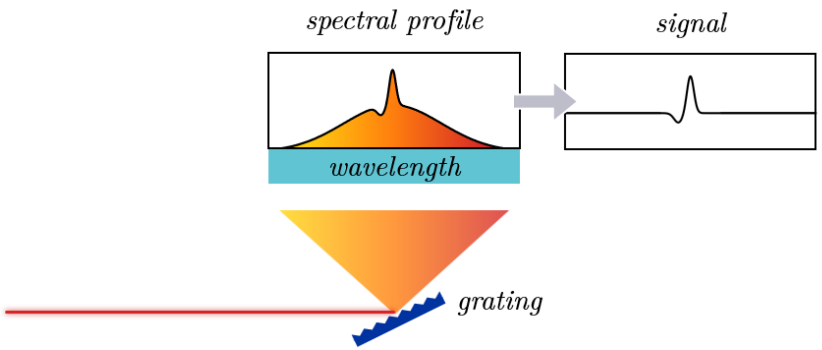
- **Jitter:**
  - no acquisition jitter present
  - only relative jitter between beam-induced signal and laser pulse remains
- **Temporal resolution:**
  - limited by spectrometer resolution
- **Setup:** more complicated
  - free space setup, alignment, intensified camera, …

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

Decoding ✓

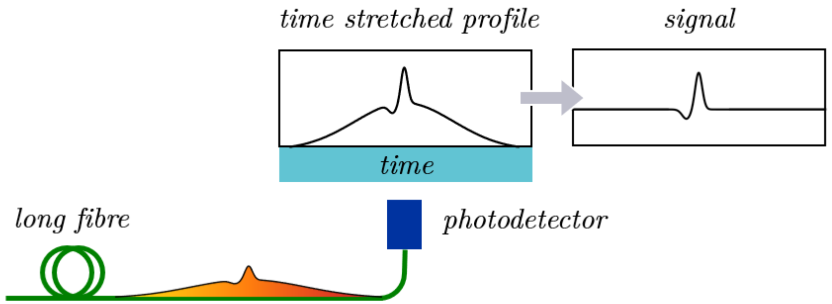
1

Spectral Decoding



2

Photonic Time Stretch

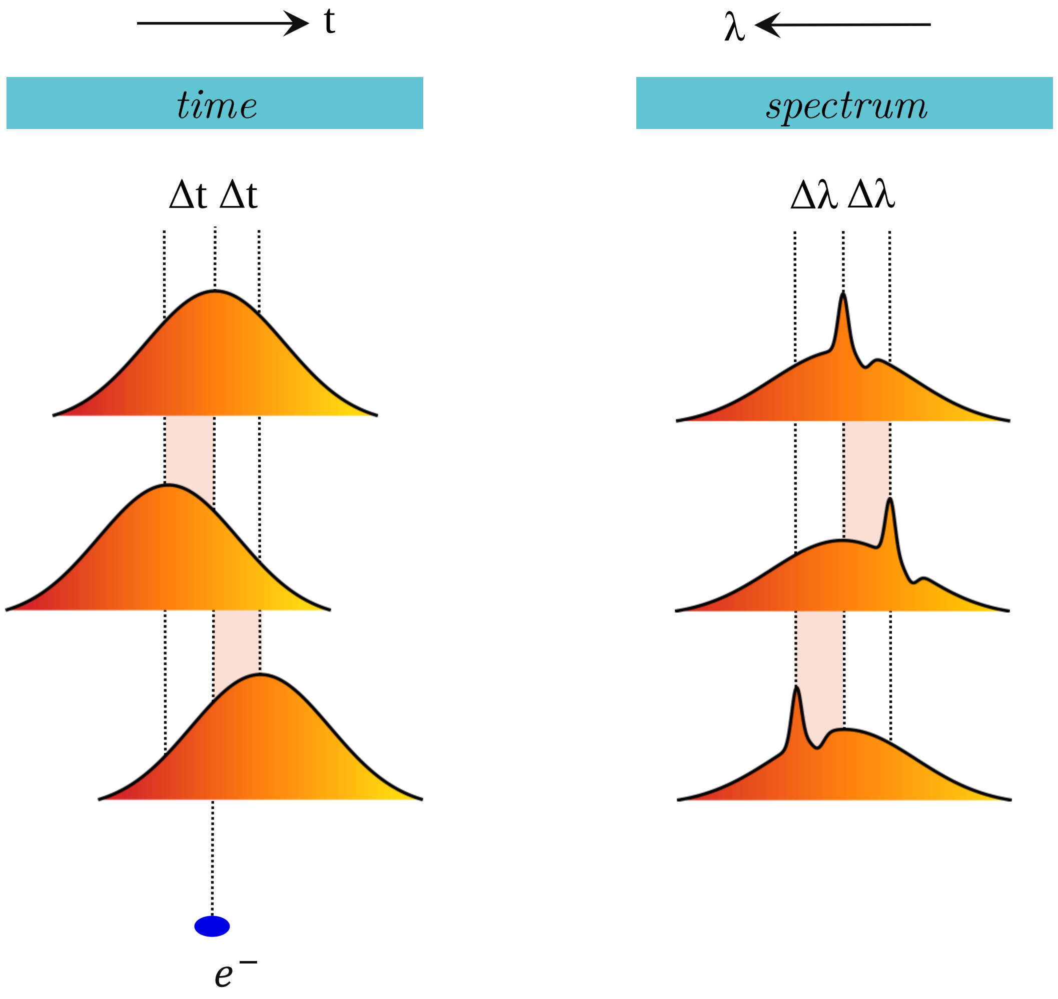


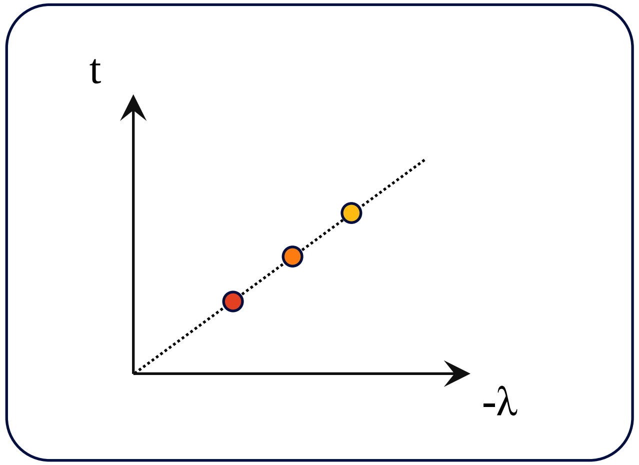
$\Delta\lambda \rightarrow \Delta t$

$\Delta\lambda \rightarrow \Delta t$

Time Conversion?

Time Conversion





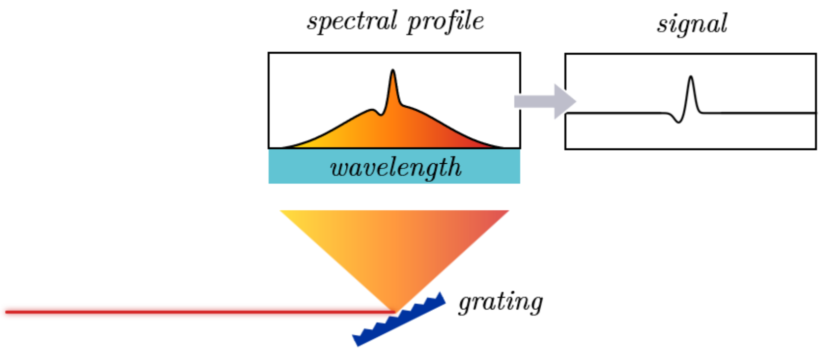
- **Relationship between wavelength and time**

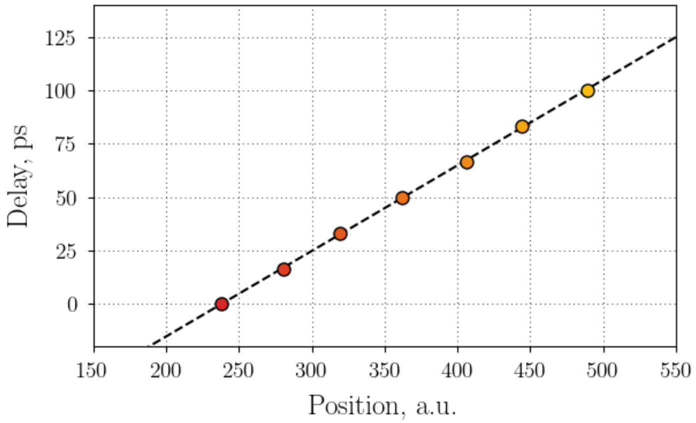
Decoding

Time Conversion

1

Spectral Decoding



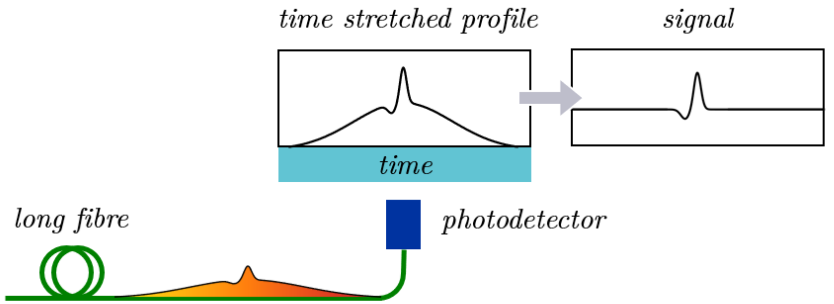


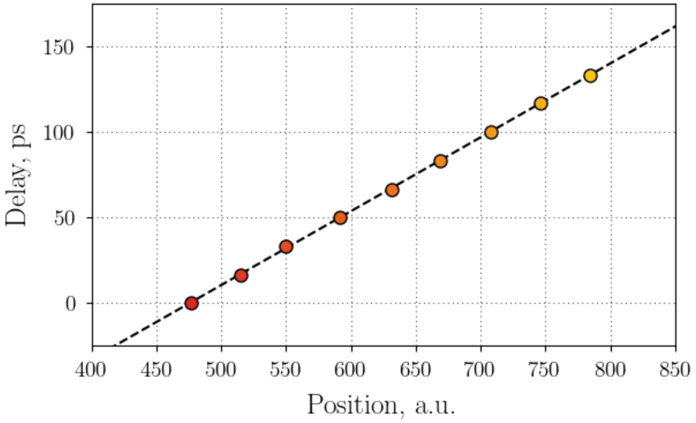
400 ± 3 fs/pos

~ 2500 GS/s

2

Photonic Time Stretch



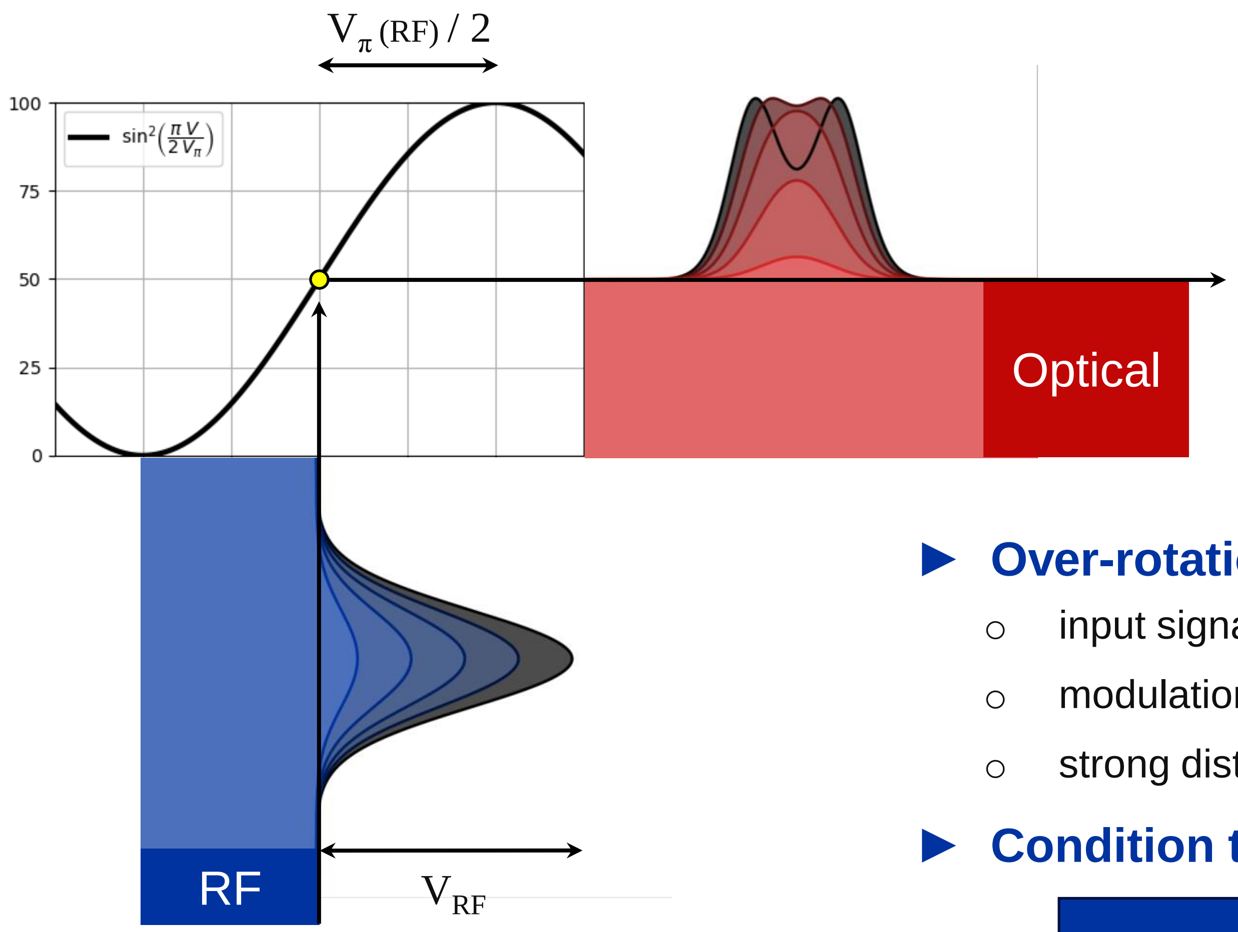


432 ± 2 fs/pos

~ 2315 GS/s

Pulsed laser measurement

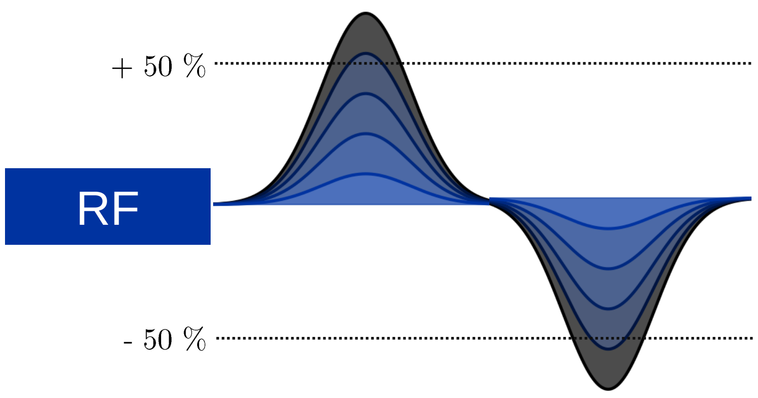
Input Signal Amplitude

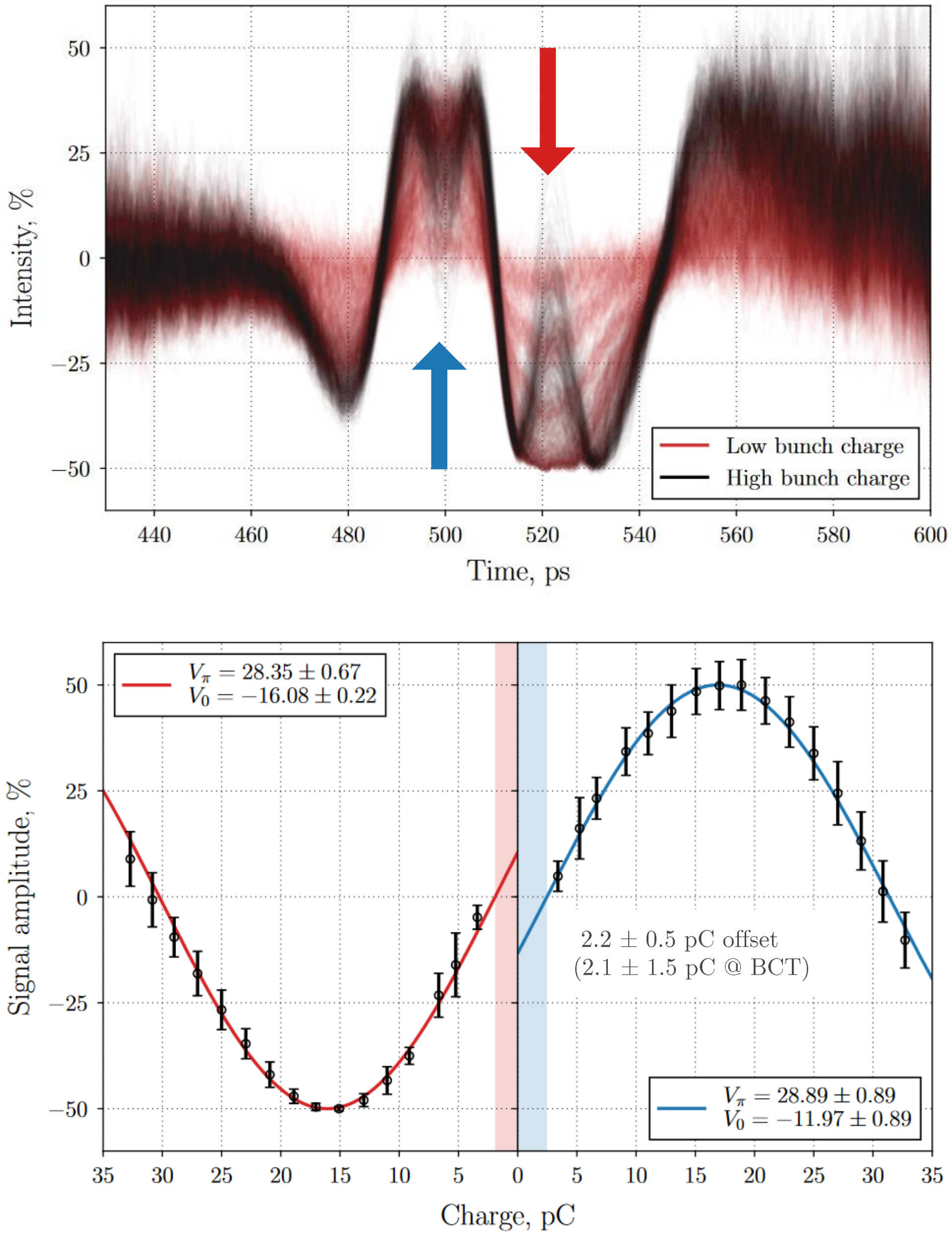


- **Over-rotation:**
  - input signal amplitude too high
  - modulation on next slope of transfer function
  - strong distortion of signals
- **Condition to avoid over-rotation:**

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

Input Signal Amplitude





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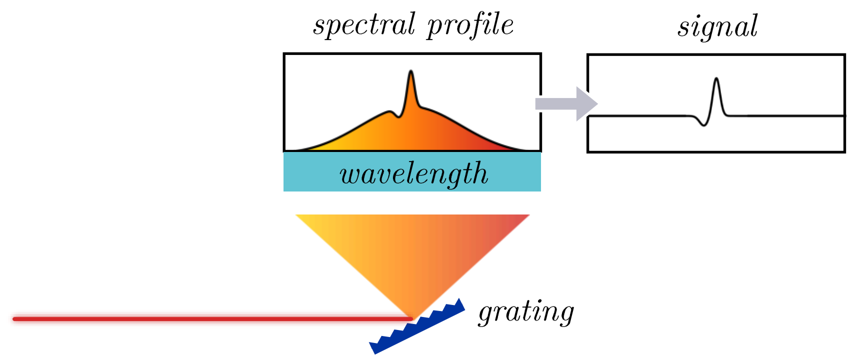
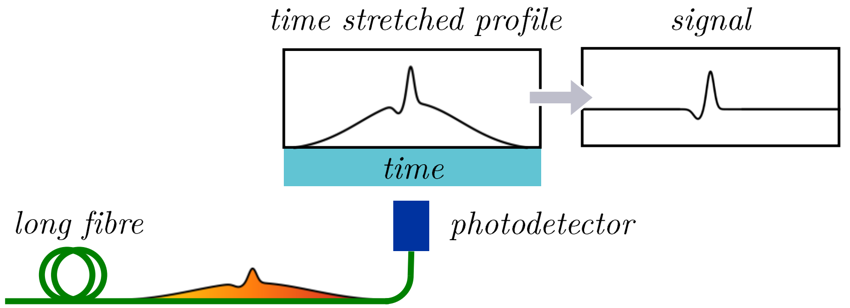
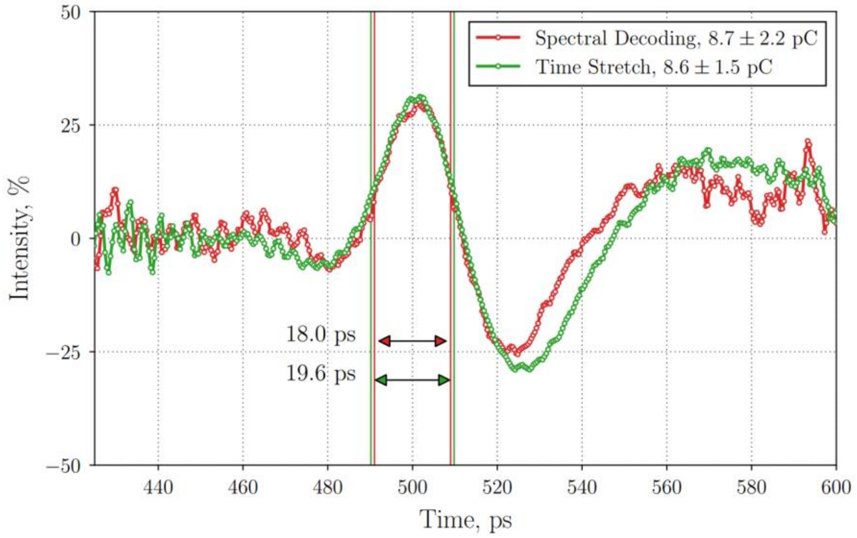


2 Photonic Time Stretch



Average over 50 shots



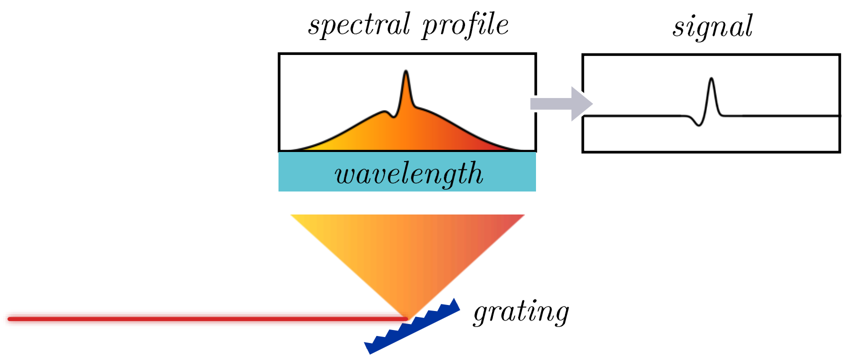
BW > 25 GHz

including various jitter contributions

FWHM: τ < 19.6 ps

→ Bandwidth ≈ 1 / $(2\ \tau)$ **> 25 GHz**

1 Spectral Decoding



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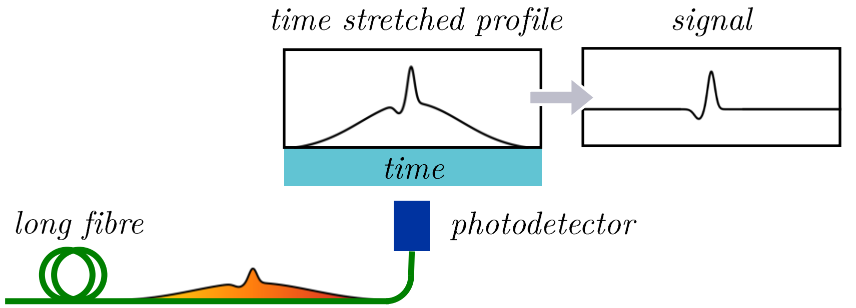
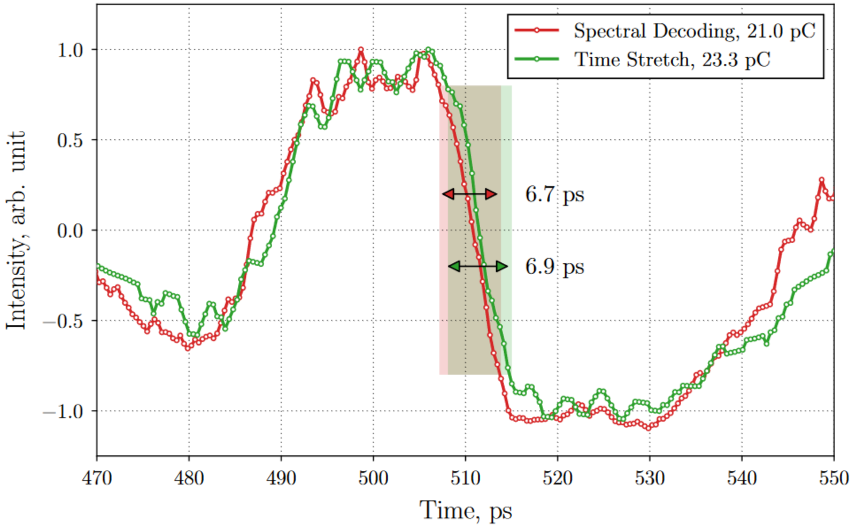


Saturated single shot



BW > 45 GHz

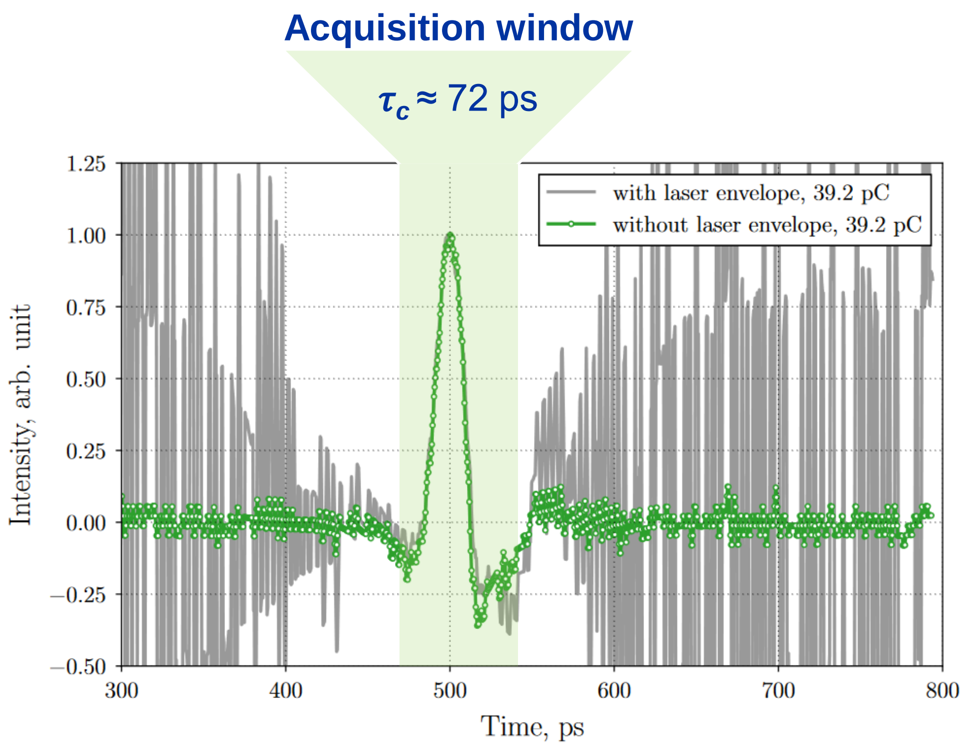
Fall Time $t_f < 6.9$ ps

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

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

→ f_{max} **≥ 45 GHz**

Current limitations



Coherent Cherenkov Diffraction Radiation

TUDC2 (IBIC 2024): Collette Pakuza et al., *"The Study of High-frequency Pick-ups for Electron Beam Position Measurements in the AWAKE Common-beamline"*

TUPO22 (IBIC 2023): Andreas Schlögelhofer et al., *"Characterisation of Cherenkov Diffraction Radiation Using Electro-Optical Methods"*

Photodetector + Oscilloscope

Analog bandwidth	33 GHz	stretching x 9	**300 GHz**
Sampling rate	256 GSa/s		**2315 GSa/s**

Pulse Chirping

$1/(2\sqrt{\tau_0 \tau_c})$ **163 GHz**

Modulator + Antenna

Bandwidth limitation of current setup **45 GHz**

Signal/Noise

Single shot on photonic time stretch **> 10**

Low laser pulse energy provides margin for significant improvement

Lab	24.0 pJ
Modulator	11.0 pJ
Photodiode	0.3 pJ

Future Perspectives

Using 1550 nm instead of 780 nm

- higher optical bandwidth of modulators (>50 GHz)
  - current setup is limited by the modulator (+ antenna)
- less attenuation in fibers for higher power density and longer stretching
  - **first stretching:** increase length of acquisition window
  - **second stretching:** slower readout electronics
- much bigger market (lasers, fibres, GaAs modulators, IQ modulators, …)

THAI2 (IBIC 2024): 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 continuous wave 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

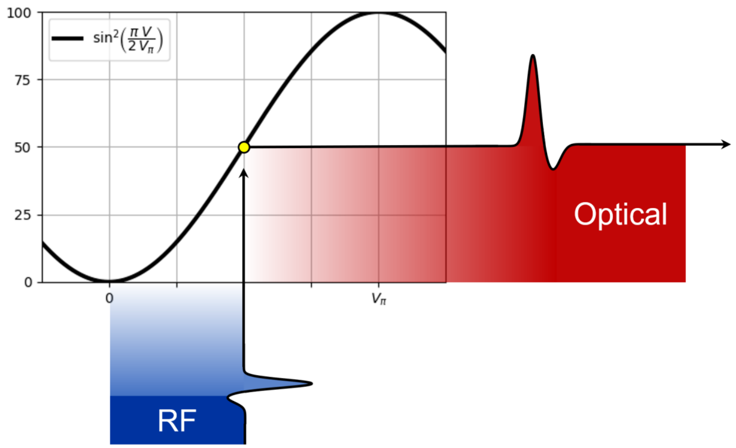
- rather flexible, fibre-based system
- better suited for high repetition rates

▶ current setup 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