



# Fast readout system for beam signal digitalization in the FCC era

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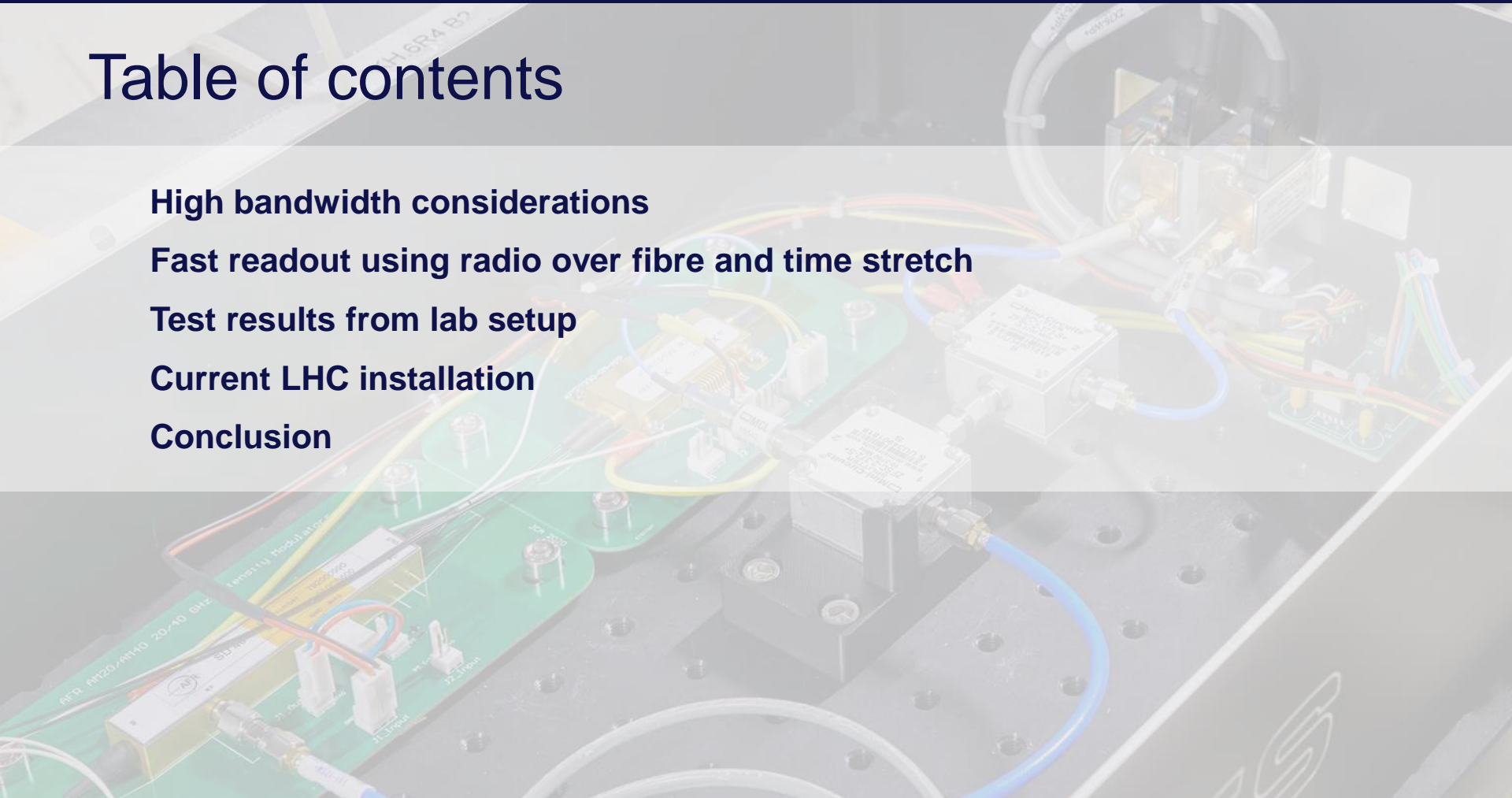
**High bandwidth considerations**

**Fast readout using radio over fibre and time stretch**

**Test results from lab setup**

**Current LHC installation**

**Conclusion**



# How to maintain a high bandwidth?

**Short propagation distance** for high frequency signals leads to the requirement of short transmission lines ( $\sim 2$  dB/m @ 20 GHz)

- ▶ radiation hardness of high frequency components

?

Can we avoid long distance RF transmission?

# What about resolution?

Maintaining **high resolution at high bandwidth**

- ▶ limited by ADC performance
- ▶ comes at a high price (8 GHz, 20 GSa/s, 10-bit, EUR  $\sim$ 100k)

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Can we overcome this limit?

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## Radio-over-fibre

Encoding and transporting RF signal using an optical carrier

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A dark blue circular icon containing a white question mark, indicating a question or a point of uncertainty.

Can we overcome this limit?

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## Time stretch

Lowering ADC requirements by stretching time

# Radio-over-fibre with electro-optical modulators



## Modulation due to Pockels effect

- linear variation of refractive index in response to an applied electric field

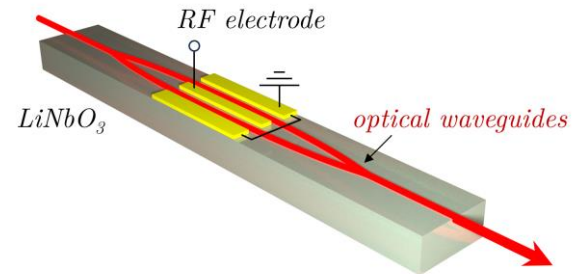
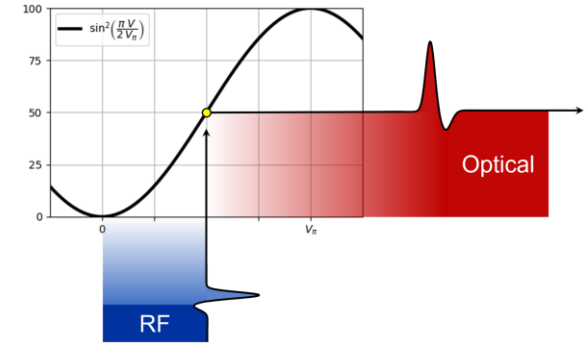
## Electro-optic material

- Lithium niobate ( $\text{LiNbO}_3$ )
- Gallium arsenide (GaAs)
- ...

## Interference-based modulation of light

- laser light split into two arms, modulated, and recombined
- designed for continuous wave lasers

- ▶ large variety of off-the-shelf products for telecommunication



# Spectral encoding



## Use a chirped laser pulse instead of a continuous wave laser

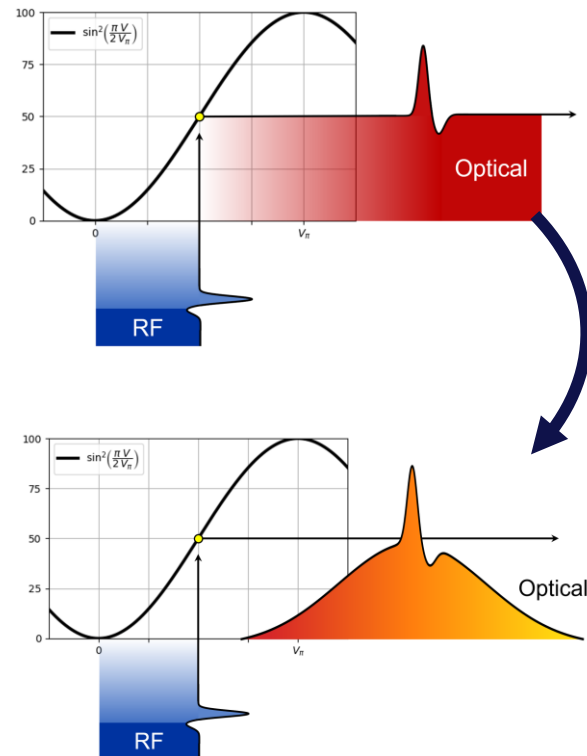
- increase power density of the laser

## Narrow optical spectrum

- keep reasonable performance of Mach-Zehnder interferometer

## Encode the signals on the laser spectrum

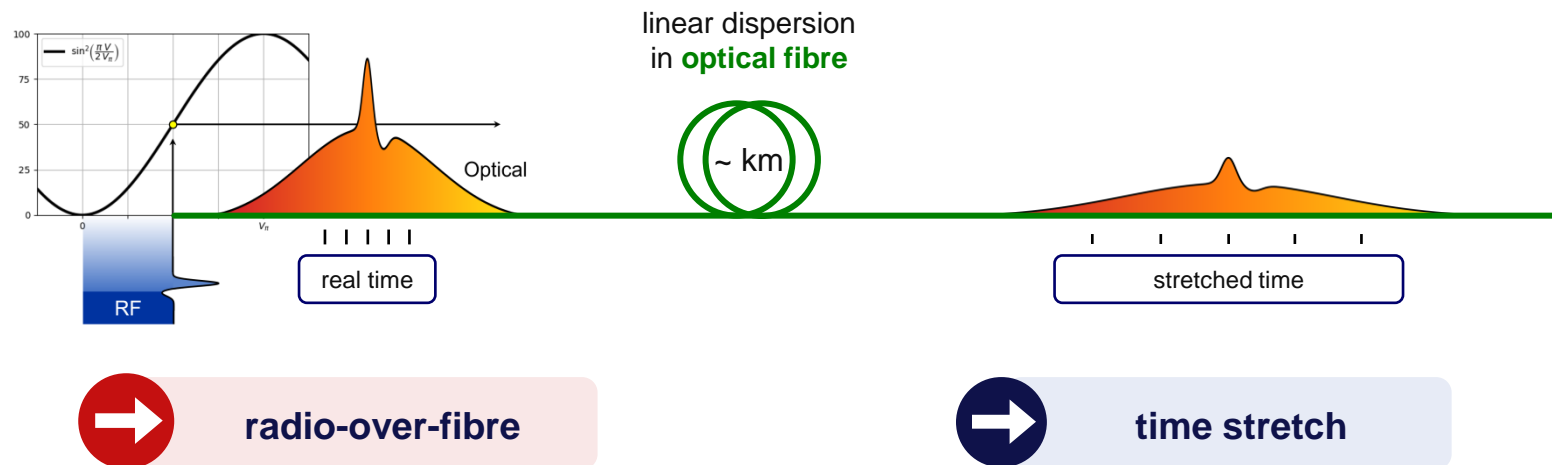
- possibility to use laser spectrum also for decoding



# Time stretch through spectral encoding

## Stretch the spectrum in time using dispersion in optical fibres

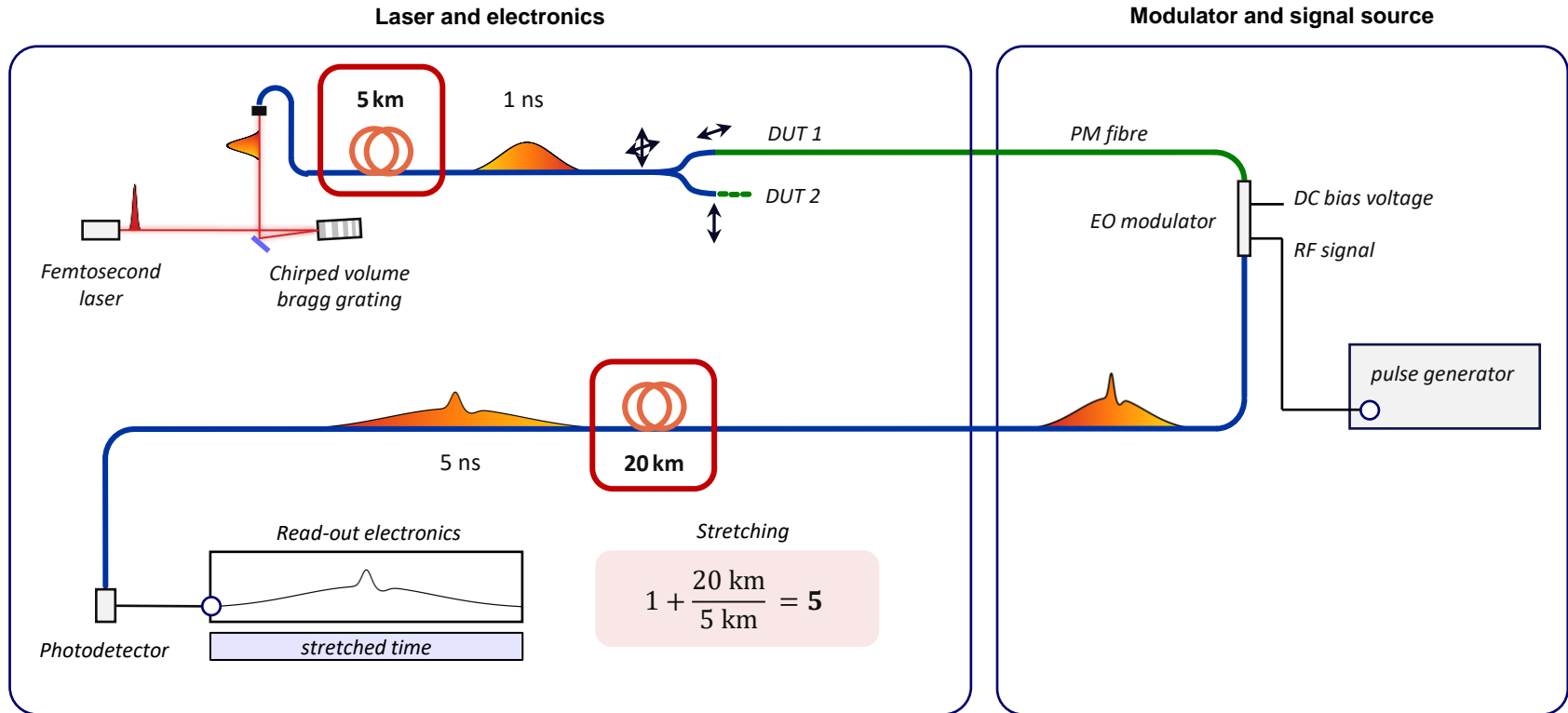
- moving away from real-time sampling
- opens up the possibility for lower bandwidth, continuous acquisition (RFSoc)



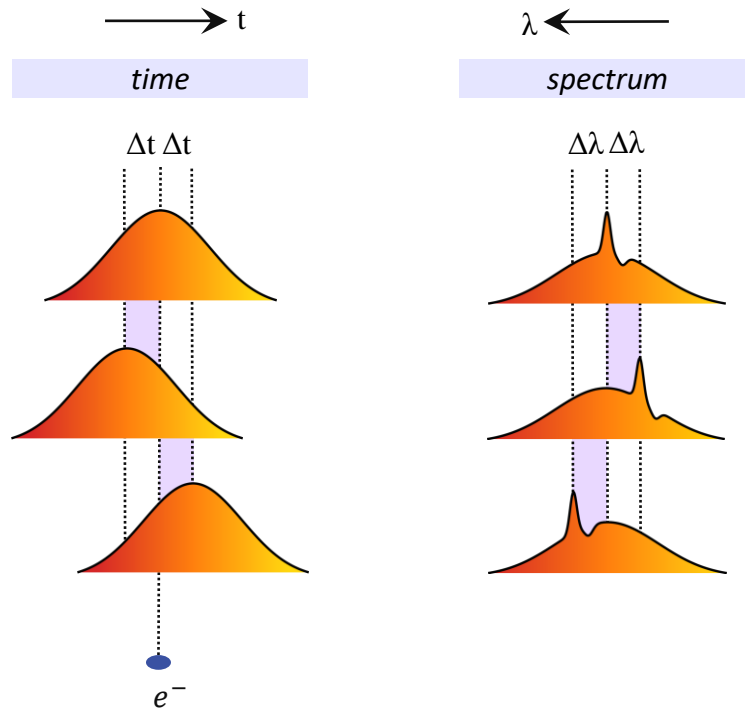


# Test setup

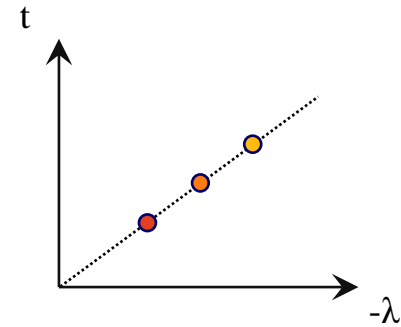
# Test setup



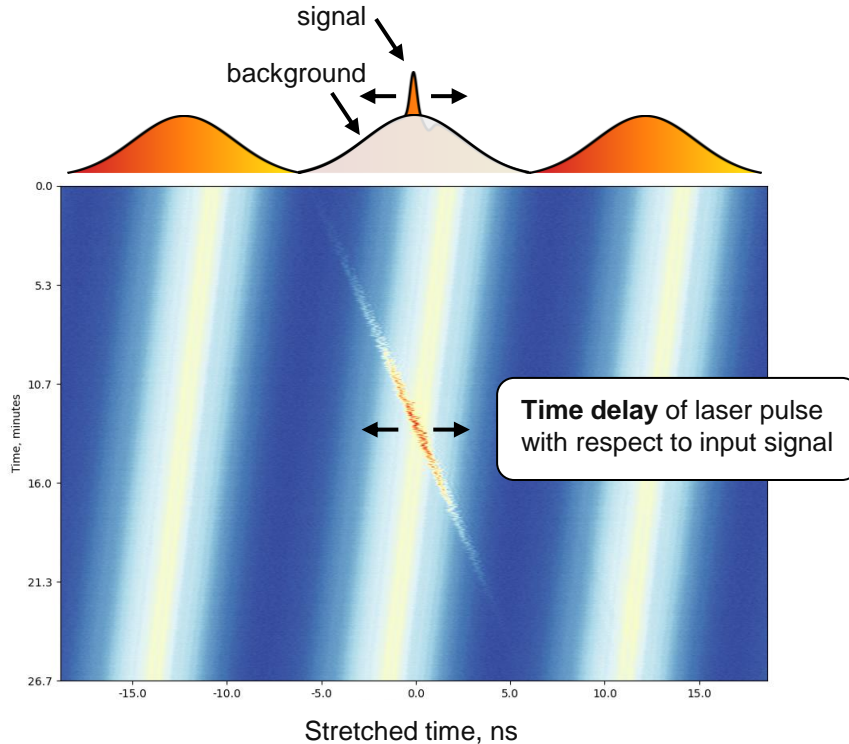
# Time conversion



Establish relationship between wavelength and time



# Time conversion



$$1 + \frac{2^{nd} \text{ Stretching}}{1^{st} \text{ Stretching}}$$

→ stretching factor **4.68** with test setup



Laser pulse spacing: 12.5 ns

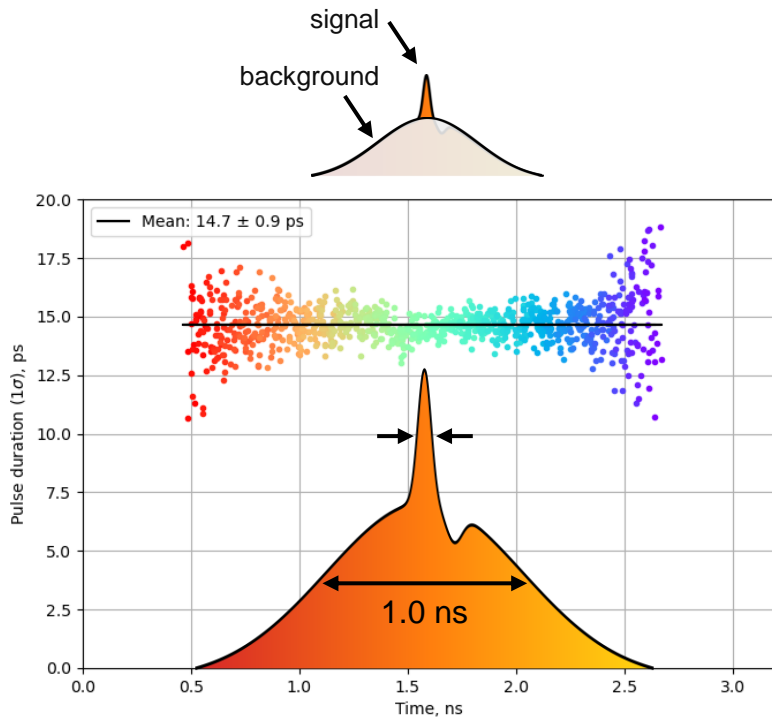
**LHC:**  
 Bunch length ( $4\sigma$ ): 920 to 1200 ps  
 Bunch spacing: 25 ns

**FCC-ee:**  
 Bunch length ( $4\sigma$ ): 25 to 200 ps  
 Bunch spacing: 25 ns

Factor 6 to 36 shorter bunch lengths in FCC-ee provide margin for much longer stretching

→ stretching factor **in the order of 100** feasible

# Stretching and bandwidth



$$1 + \frac{2^{nd} \text{ Stretching}}{1^{st} \text{ Stretching}}$$

14.7 ps (1σ) ≈ 14.4 GHz

14.4 GHz / 4.68 ≈ 3.1 GHz

→ limited by the bandwidth of a 3 GHz oscilloscope



Current commercial Mach-Zehnder modulators have an analog bandwidth of **up to 50 GHz**

### FCC-ee:

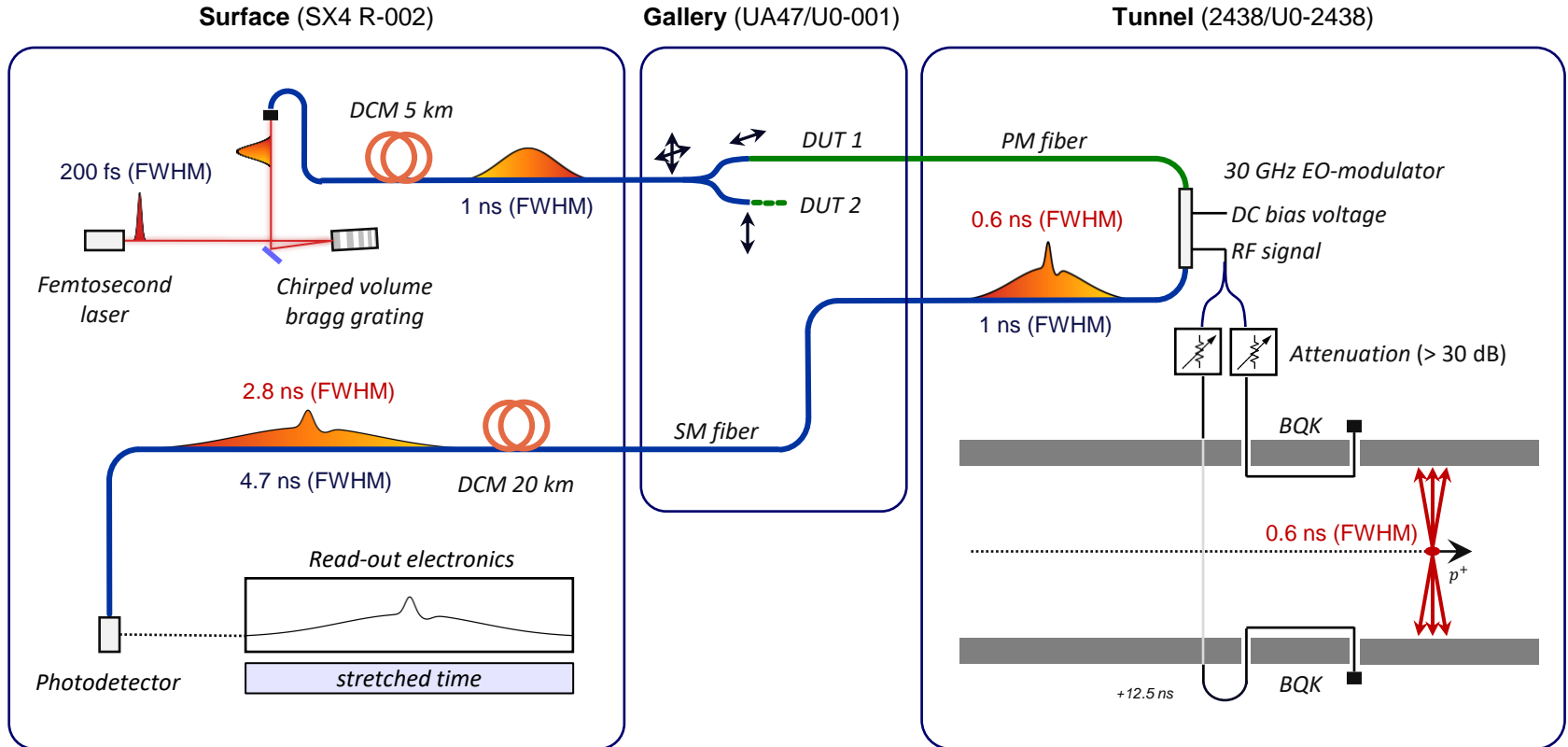
Stretching factor in the order of 100 realistic with a 25 ns bunch spacing.

→ 500 MHz ADC would be sufficient for a 50 GHz equivalent signal digitalization

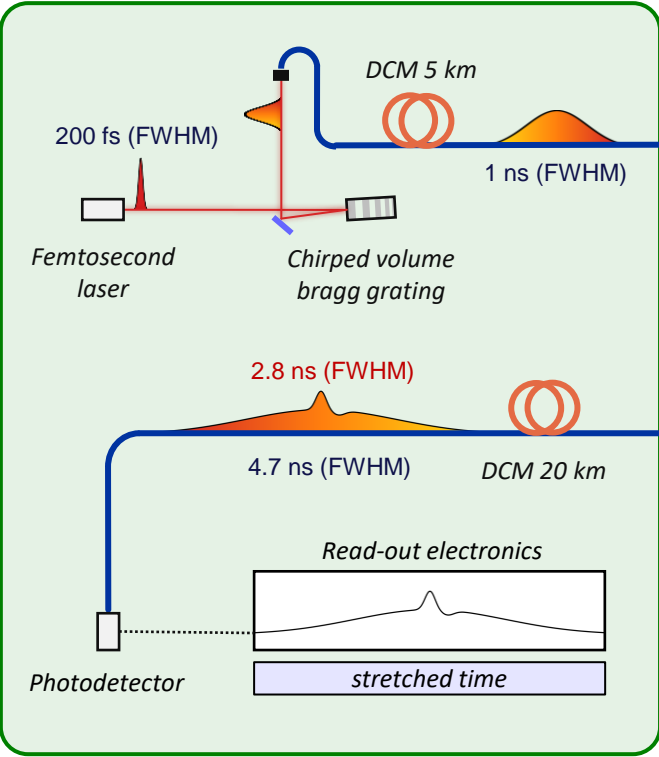


# LHC installation

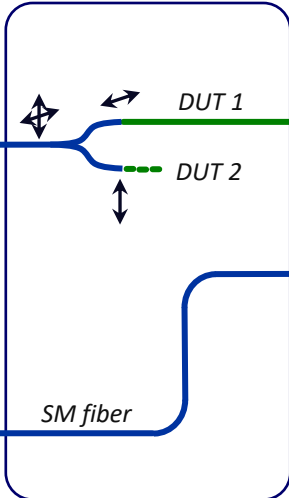
# LHC installation



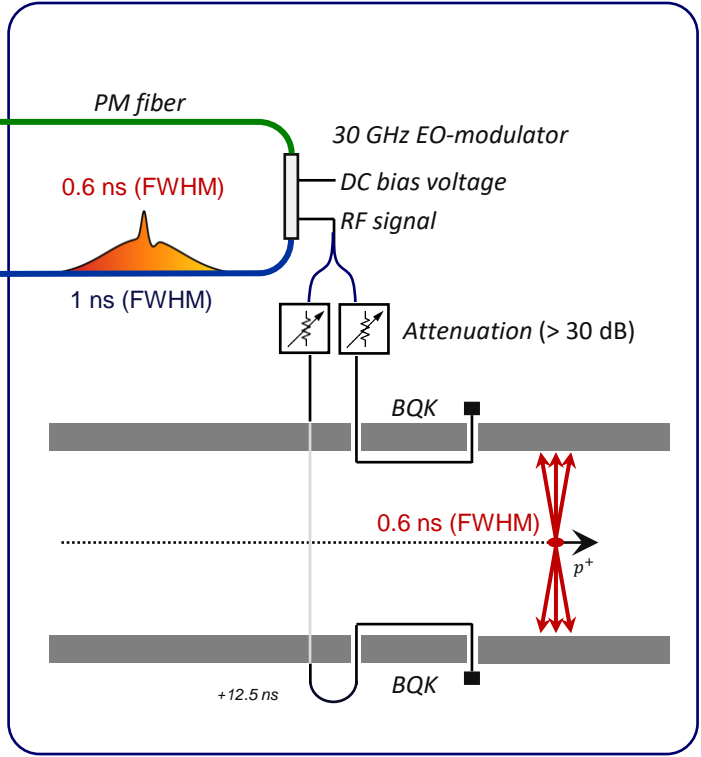
Main part of the setup on the surface is **accessible 24/7**

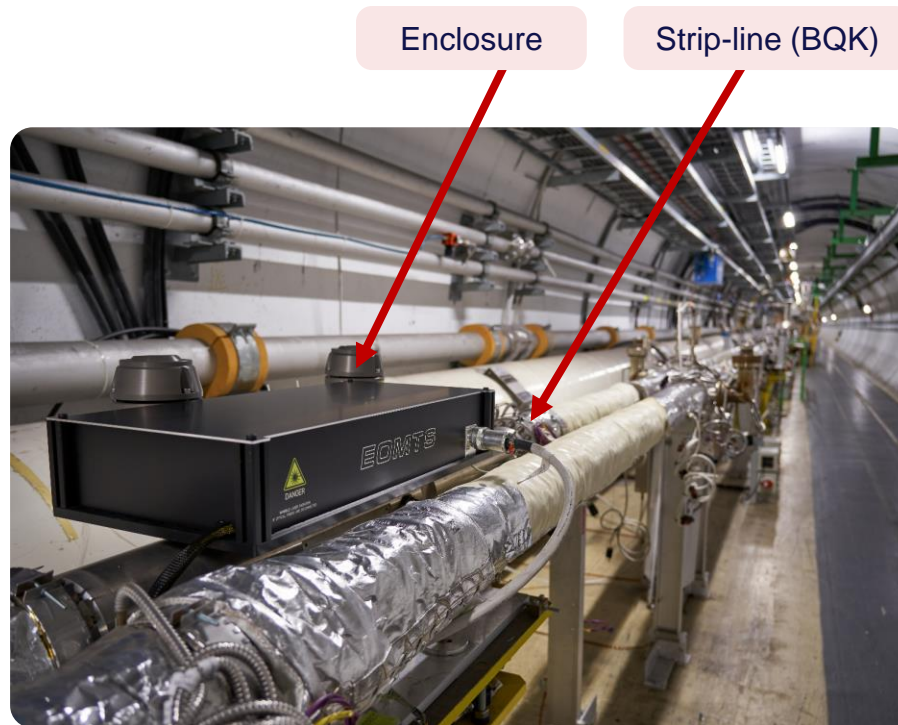
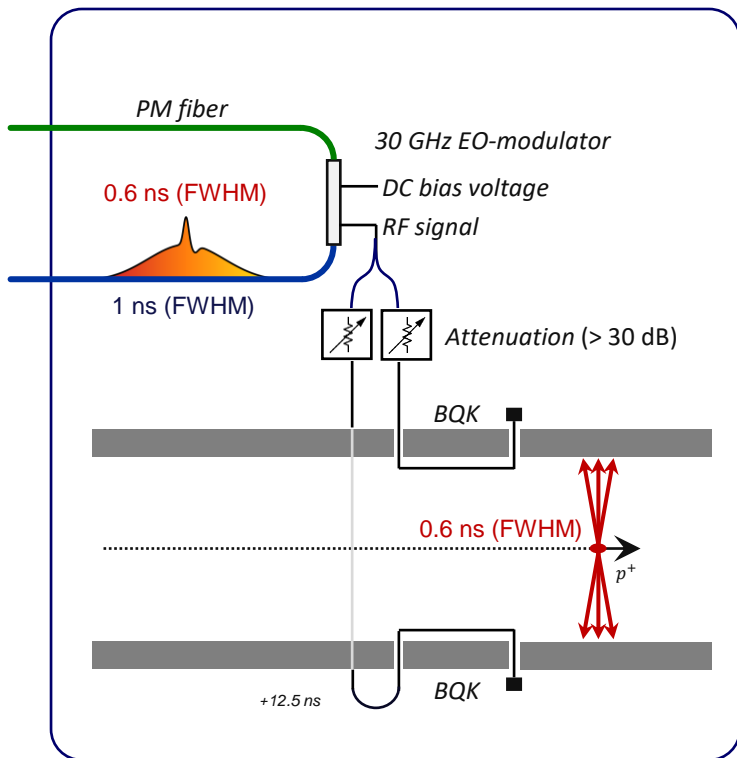


**Gallery (UA47/U0-001)**

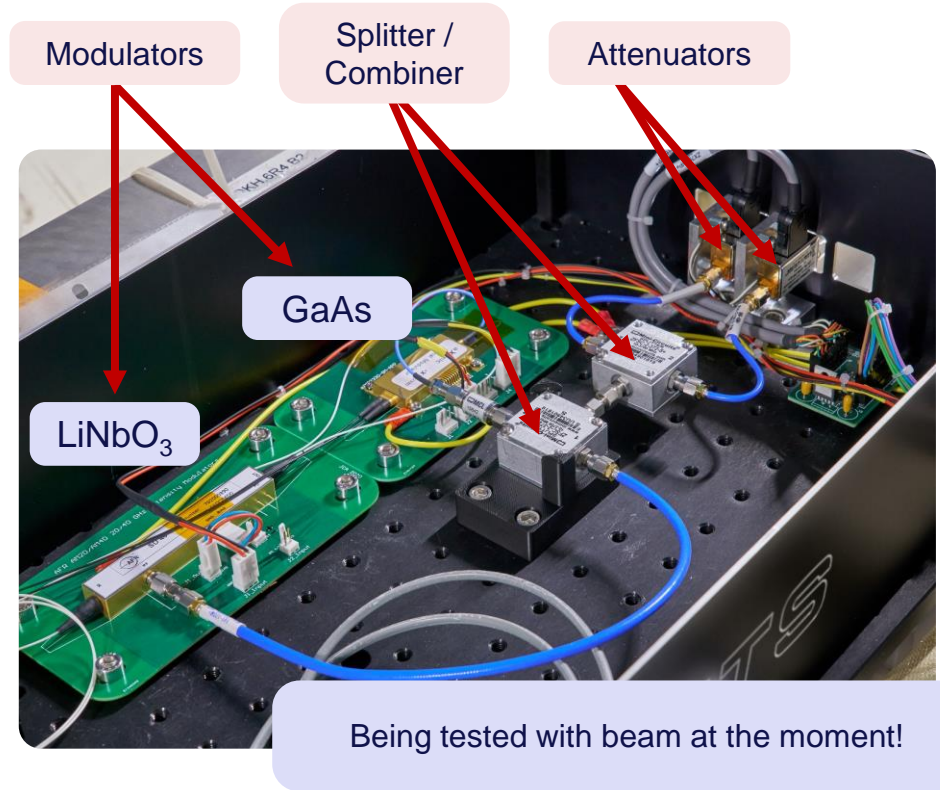
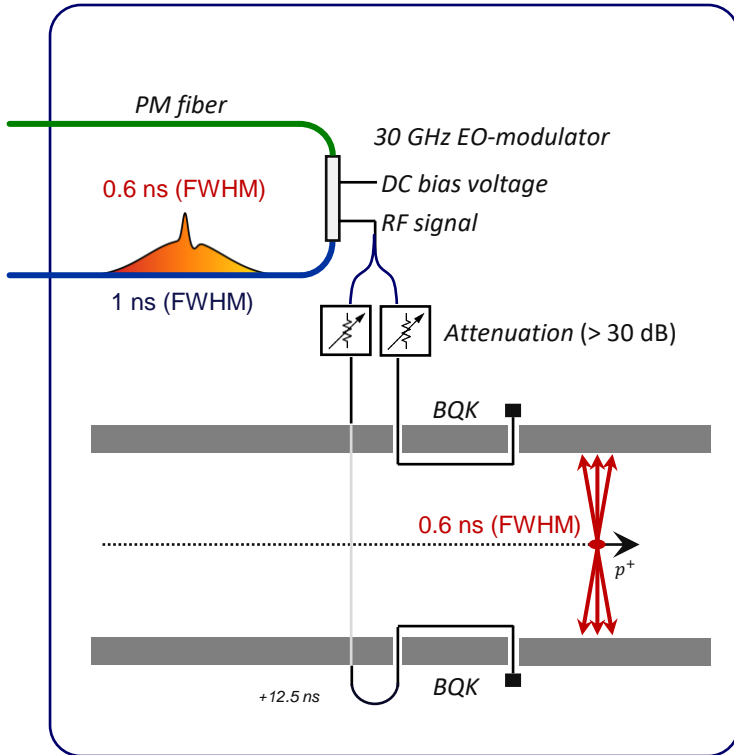


**Tunnel (2438/U0-2438)**



**Tunnel (2438/U0-2438)**


### Tunnel (2438/U0-2438)



# Setup considerations

▶ **Laser pulses need to be synchronized to particle beams**

- e.g. for protons in the LHC: 40.078 885 MHz to 40.078 970 MHz (0.45 Hz/s during ramp)
- Not a problem in FCC-ee main ring

▶ **Radiation hardness of various parts still to be assessed**

- GaAs vs. LiNbO<sub>3</sub> modulators
- Polarization maintaining fibers

▶ **Vertical resolution being tested with beam**

- various detection schemes possible, in case the current setup underperforms in resolution:
  - 1) optical background subtraction using a balanced photodetector
  - 2) IQ modulator to encode difference and sum optically

# Conclusion

- ▶ **High-bandwidth, high-resolution acquisition is challenging**
  - demonstrated high linearity of time stretching
  - demonstrated an analog bandwidth of 14.4 GHz, which can be easily adapted with different stretching stages
  - current modulator technology limits bandwidth up to 50 GHz
  - time stretching can make efficient use of the 'void' created through bunch spacing
  
- ▶ **Versatile setup**
  - most critical components accessible 24/7
  - modifications for various detection schemes possible (balanced detection, IQ modulation, ...)
  
- ▶ **Big scale projects**
  - long transmission lines part of the design
  - fibres have a much smaller footprint than high-frequency cables
  
- ▶ **First proton beam tests ongoing right now**



Thank you  
for your attention.