Longitudinal Measurements at CLEAR with Cherenkov Diffraction Radiation

Andreas Schlögelhofer for the BI-FCC team

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the European Union's Horizon 2020 research and innovation programme under grant agreement No 951754

Overview

Cherenkov Diffraction Radiation

Numerical Simulations

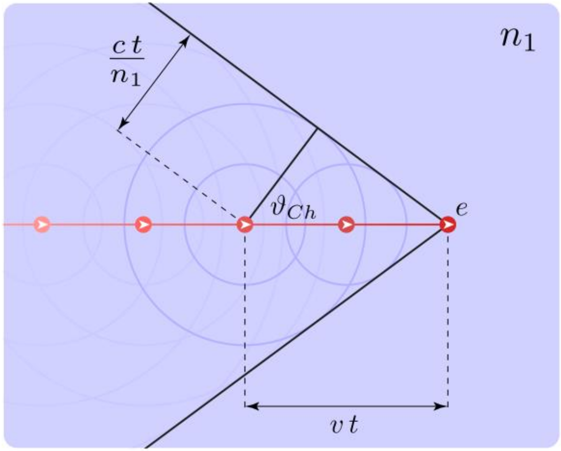
Electro-optical Spectral Decoding with Intensity Modulators

Characterization with Transition Radiation

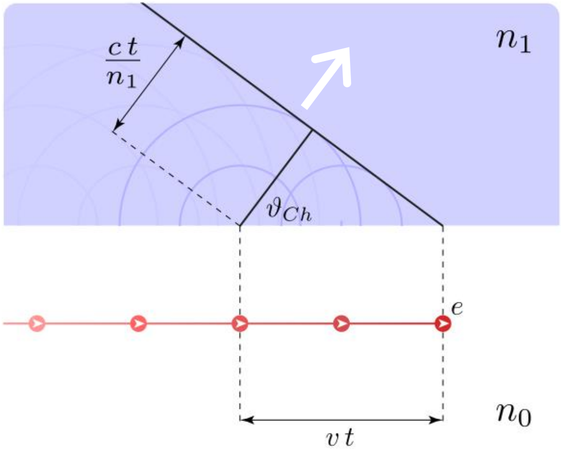
Measurement of Cherenkov Diffraction Radiation

Cherenkov Diffraction Radiation

Cherenkov Radiation



Cherenkov Diffraction Radiation



Frank-Tamm

$$\frac{dW}{dl} = \frac{q^2}{4\pi}\mu_0 \int_0^\infty \omega \cdot \left(1 - \frac{1}{\beta^2 n^2(\omega)}\right) d\omega$$

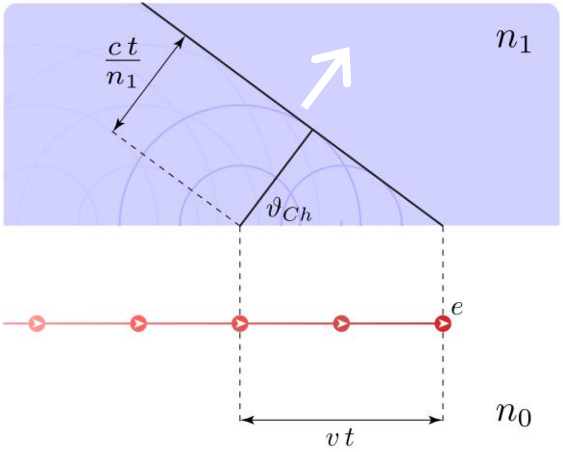
$$cos(\vartheta_{Ch}) = \frac{1}{n\,\beta}$$

[2] I.M. Frank and I.E. Tamm. Coherent visible radiation of fast electrons passing through matter. *Compt. Rend. Acad. Sci. URSS*, 14(3):109– 114, 1937

Cherenkov Diffraction Radiation

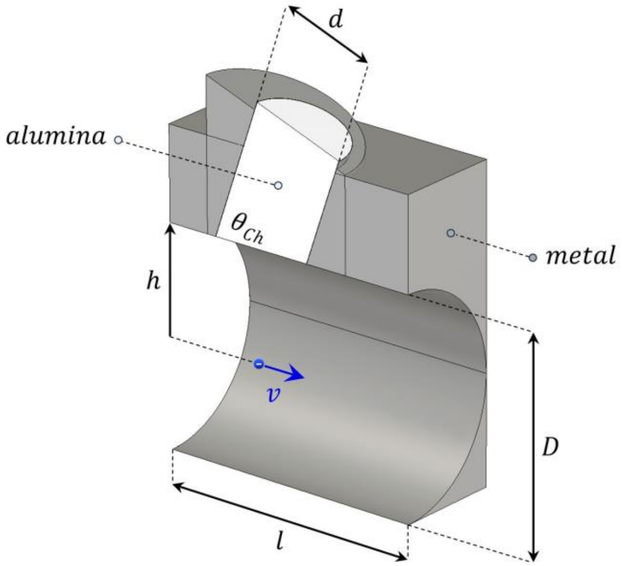
Characteristics:

- Non-obstructive
- Large distance between beam and radiator
- Tuneable angle of emission ϑ_{Ch} = arccos(1/(βn_1))
  → Separation from background radiation
- Surface effect
  → integrated signal
- Suitable for straight sections and vertical planes
  → flexible location
- Incoherent and coherent part of the spectrum



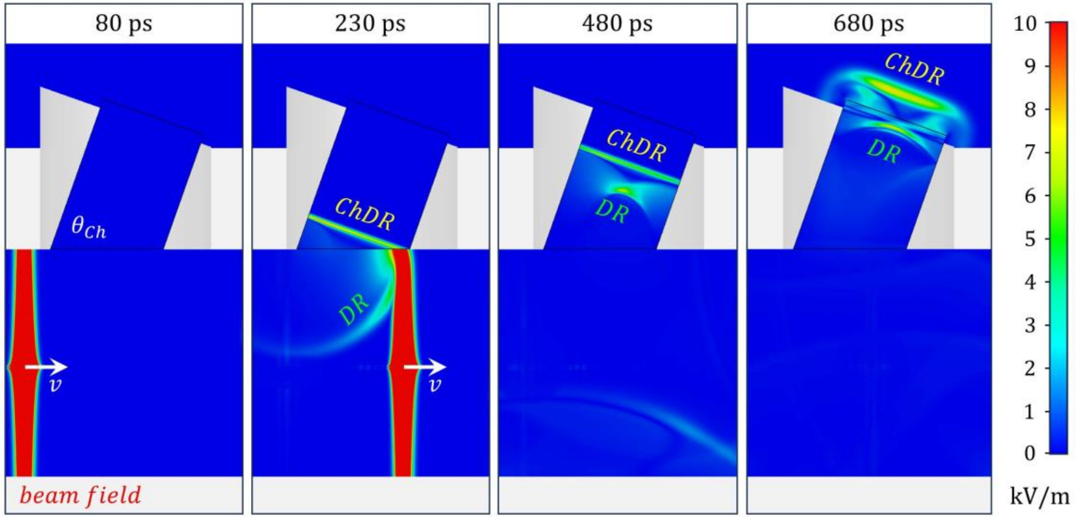
→ broadband signal source suitable for bunch length, however, not used for time signals yet

Numerical Simulations



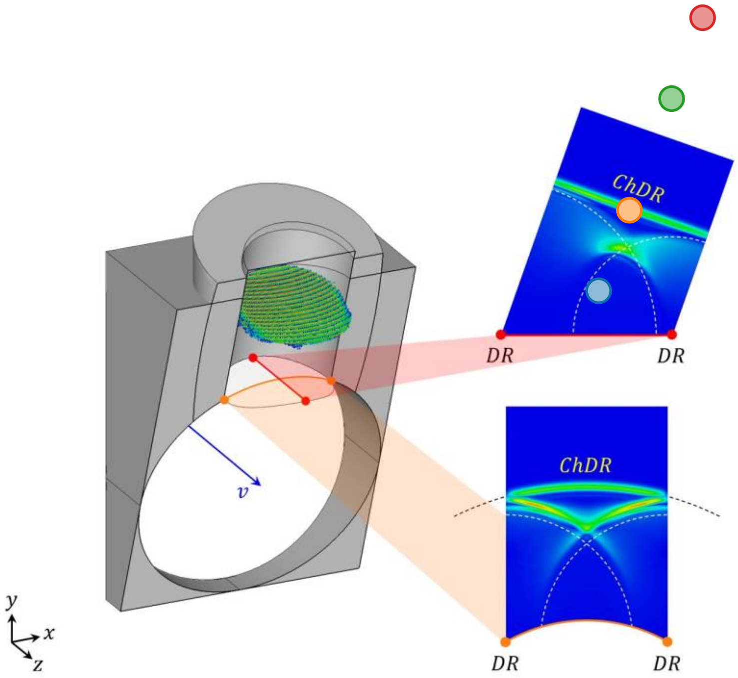
d = 36 mm, D = 80 mm, h = 40 mm, l = 100 mm

E-field, Median plane (yz-plane)

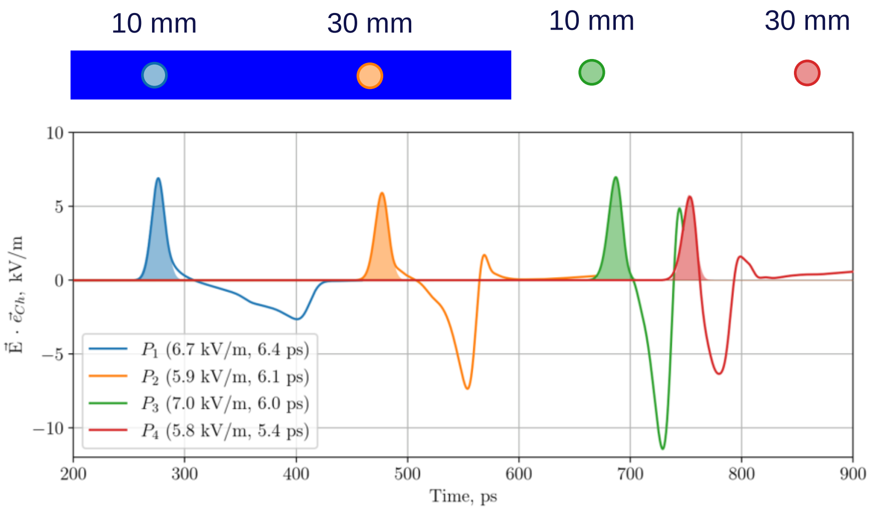


200 MeV, 300 pC, 5 ps (1 σ)

Numerical Simulations

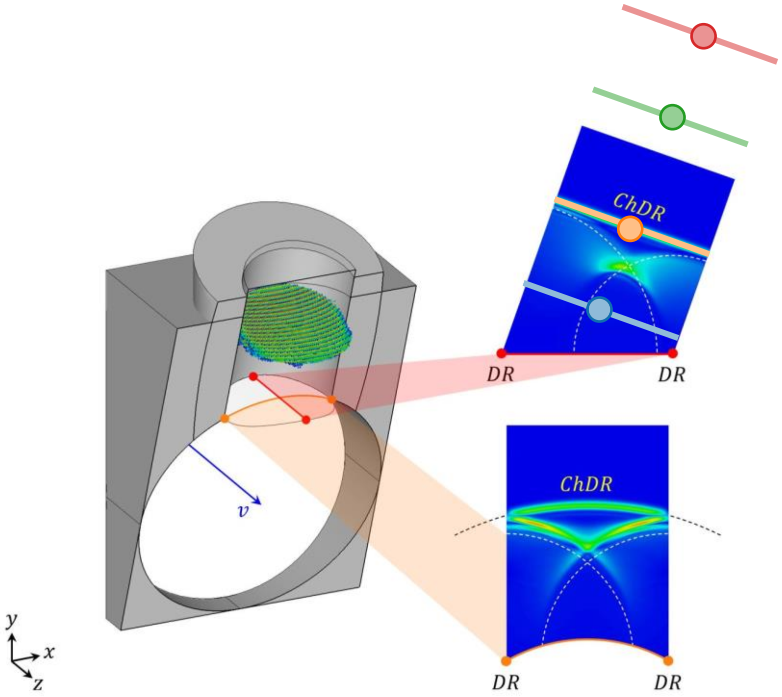


Point probes at central axis

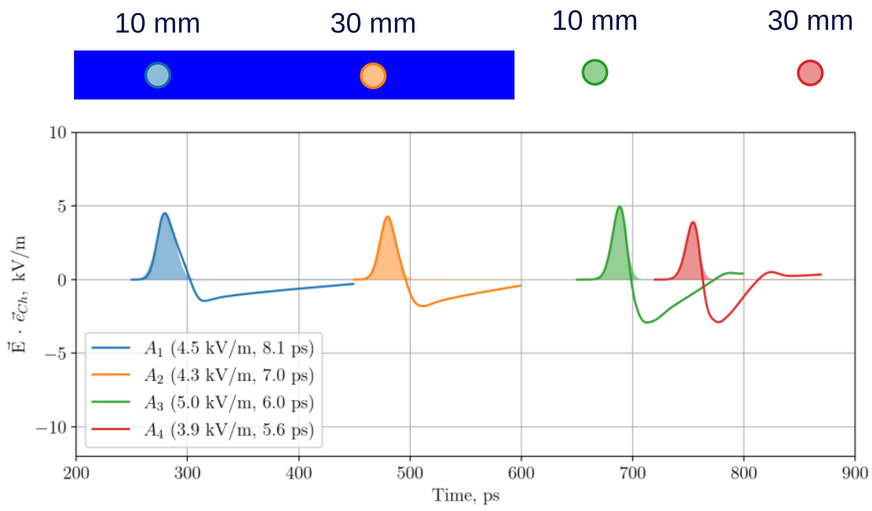


DR contribution from the metal / radiator interface

Numerical Simulations

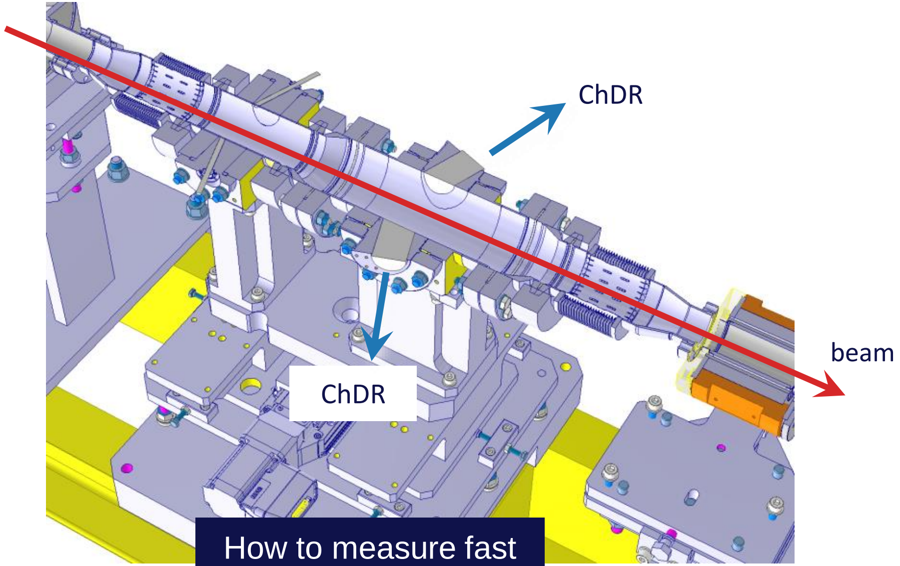


Area integration, Ø 36 mm



DR much less prominent for surface integrated e-fields

Vacuum Installation at CLEAR



How to measure fast broadband signals?

Radiator material	Alumina (Al_2O_3)
Relative permittivity ε_r	9.0
Radiator diameter	36 mm
Flange size	DN 60
Vacuum chamber diameter	80 mm

EOSD with intensity modulators

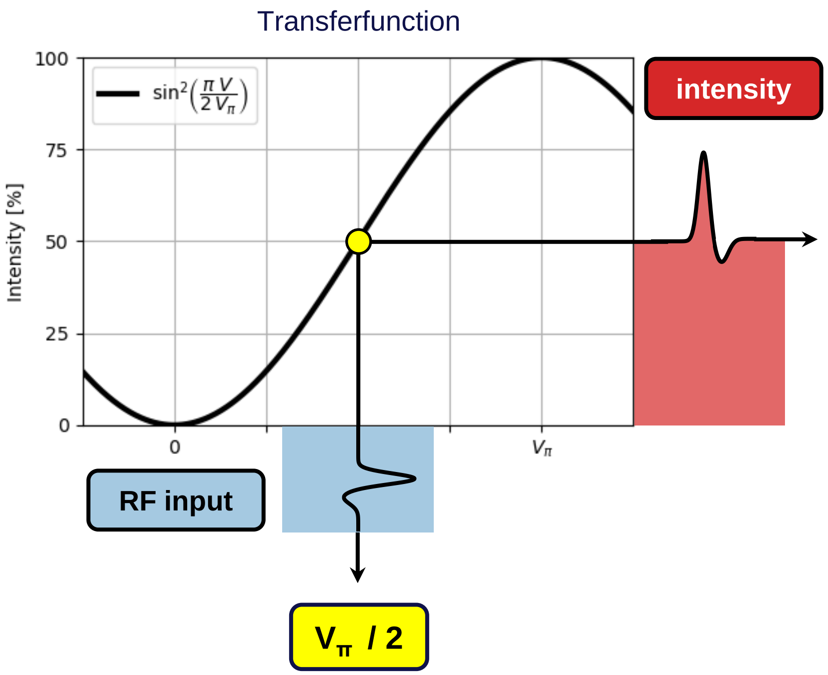
Electro-optical spectral decoding with intensity modulators

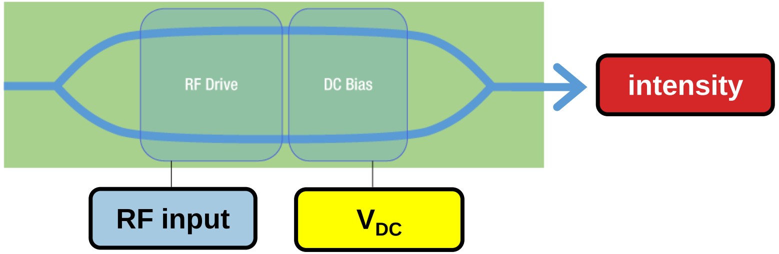
- Modulation of laser light stems from beam generated signal
  → **Cherenkov Diffraction Radiation**
- Birefringent crystal in the modulator
- Laser in fibre
- SMA/SMK connectorized → **horn antenna**

Electro-optical spectral decoding is used to measure the longitudinal beam profile of short bunches → M. Reissig

- Modulation of laser light stems from direct beam field
- Birefringent crystal close to beam
- Laser within vacuum chamber

Electro-optical intensity modulation



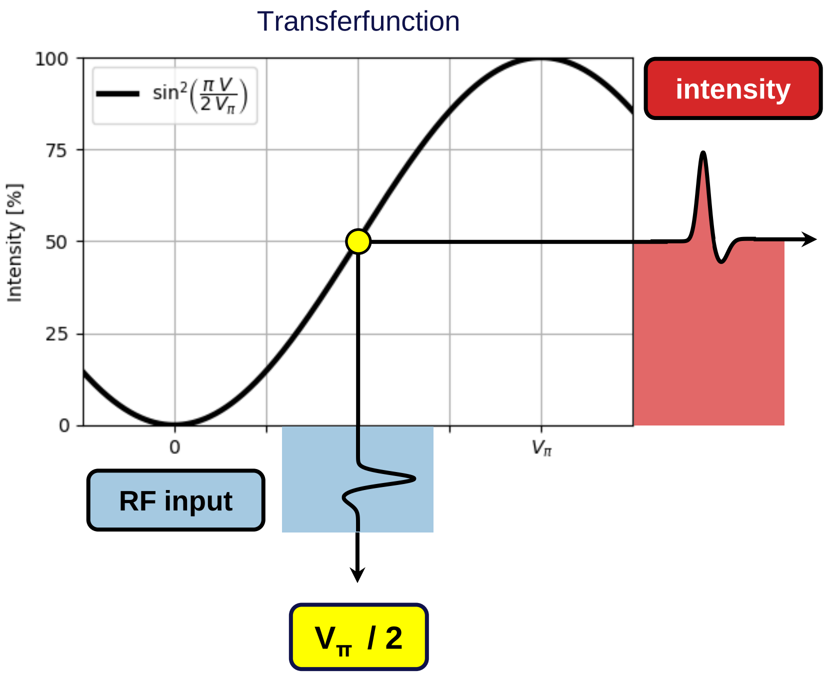


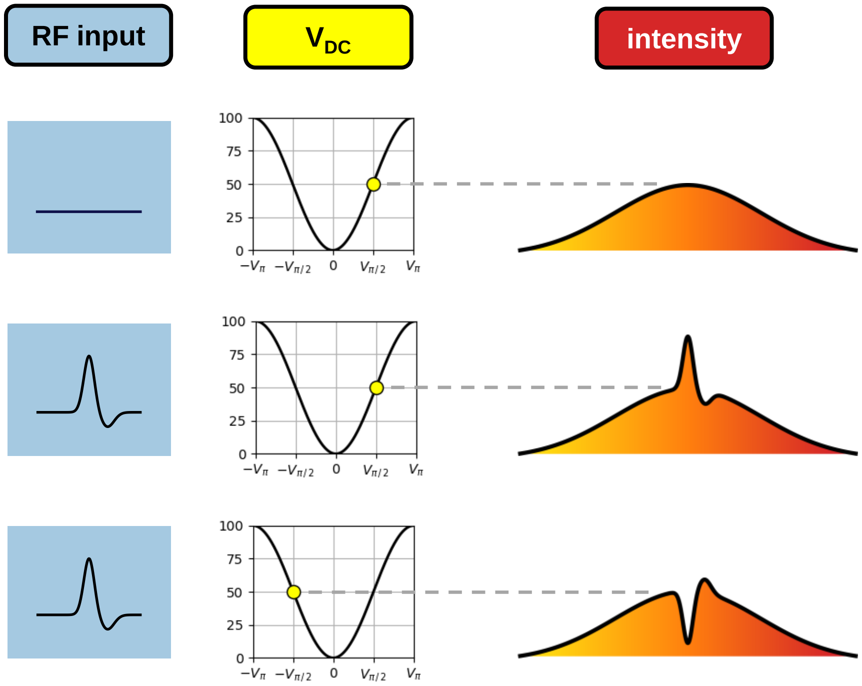
Input Signal

DC bias voltage
to set working point

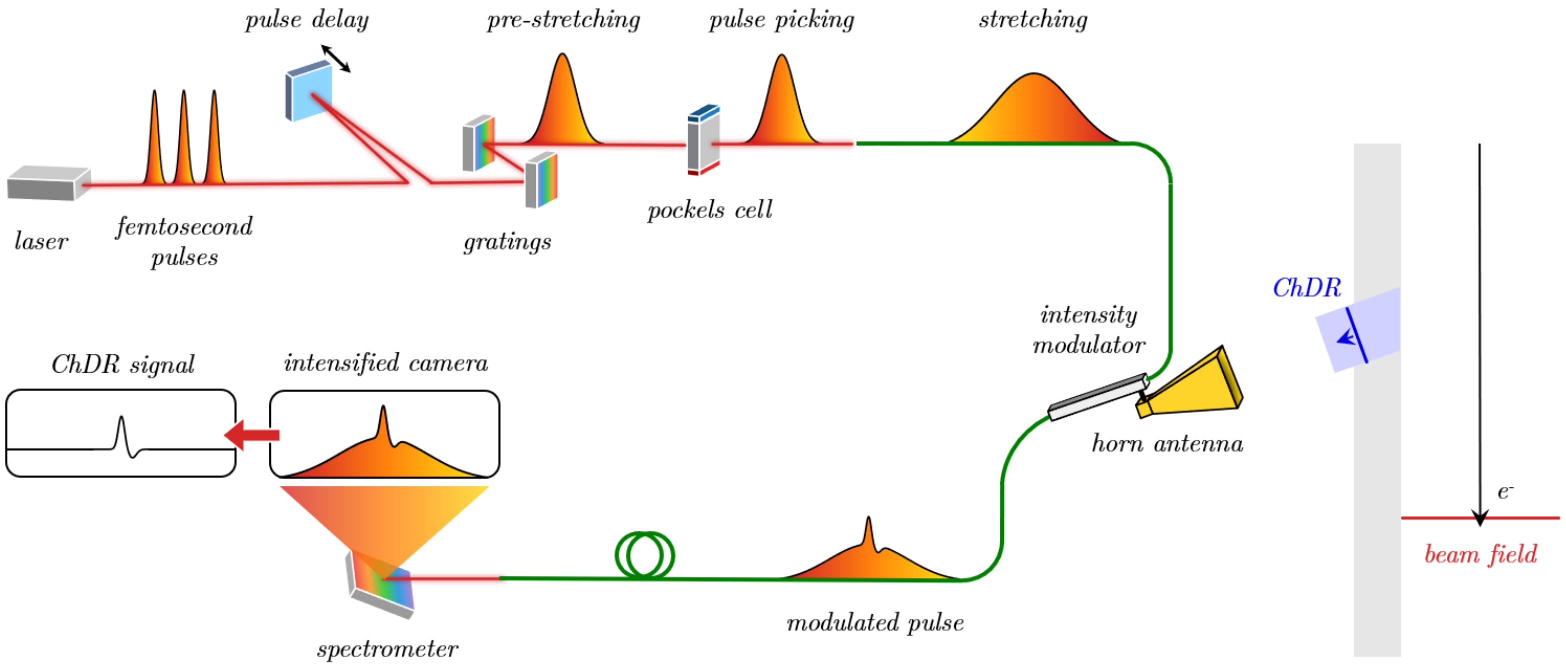
NIR-MX800-LN-20	
Operating wavelength [nm]	780-850
Max. optical input Power [mW]	25
Max. RF input power [dBm]	28
Connector type	2.92 mm (K)
Electro optical bandwidth [GHz]	> 25
V_π DC [V]	3.9

Electro-optical intensity modulation



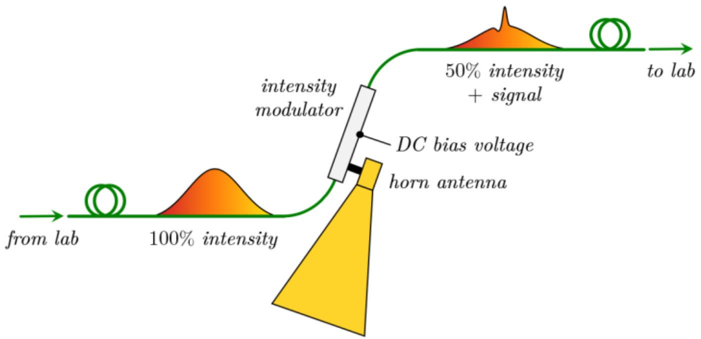


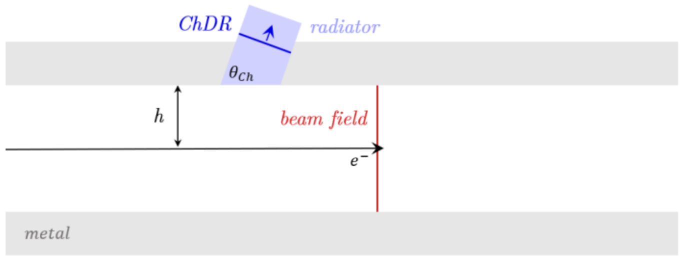
Electro-optical spectral decoding



Signal Sources

Cherenkov Diffraction Radiation

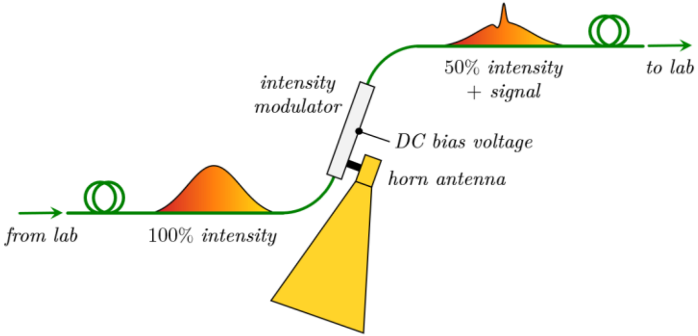


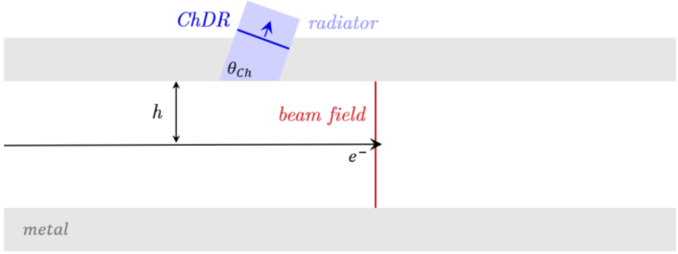


What is the response of the measurement system?

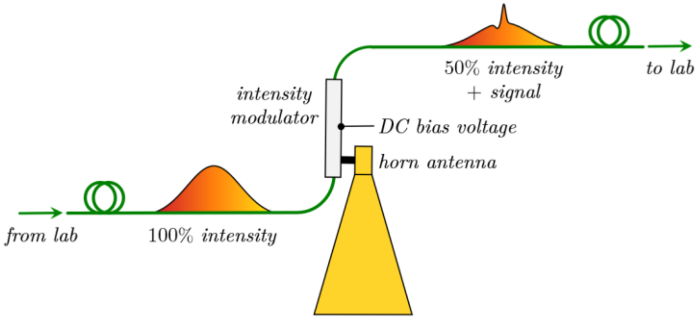
Signal Sources

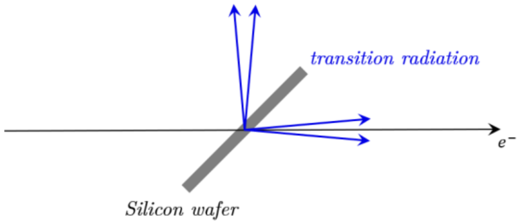
Cherenkov Diffraction Radiation



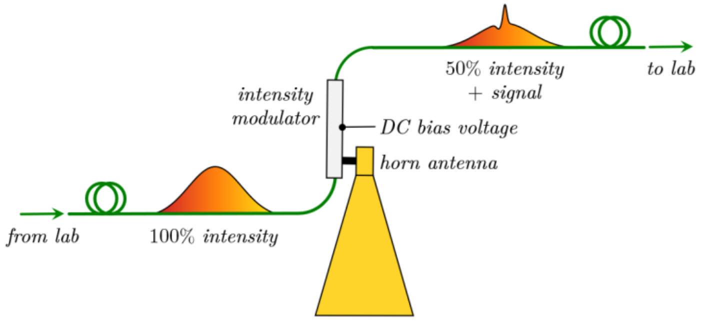


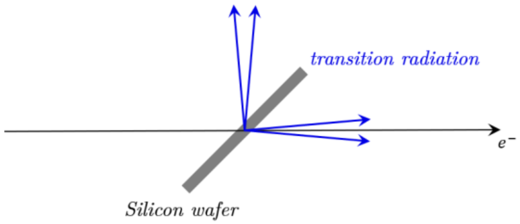
Transition Radiation

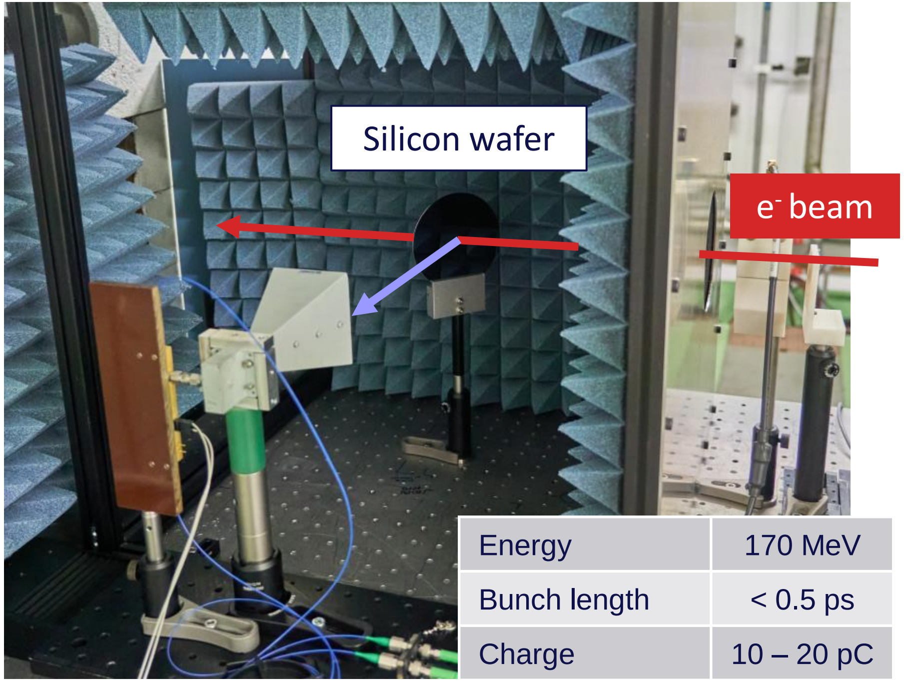




Transition Radiation



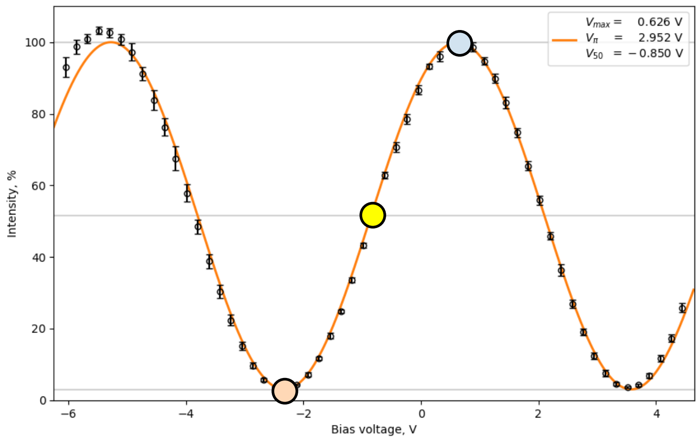




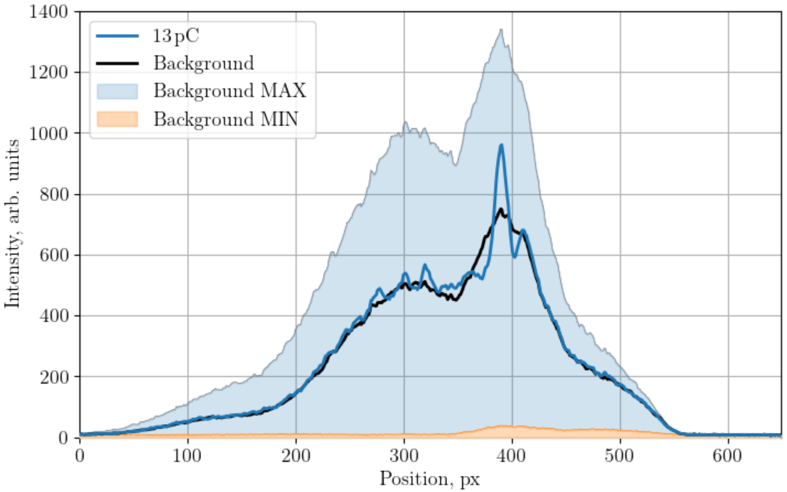
Energy	170 MeV
Bunch length	< 0.5 ps
Charge	10 – 20 pC
Rep. rate	10 Hz

Transition Radiation Signal

MAX



MIN



Coose working point in the center of the linear regime
→ positive and negative modulation linear

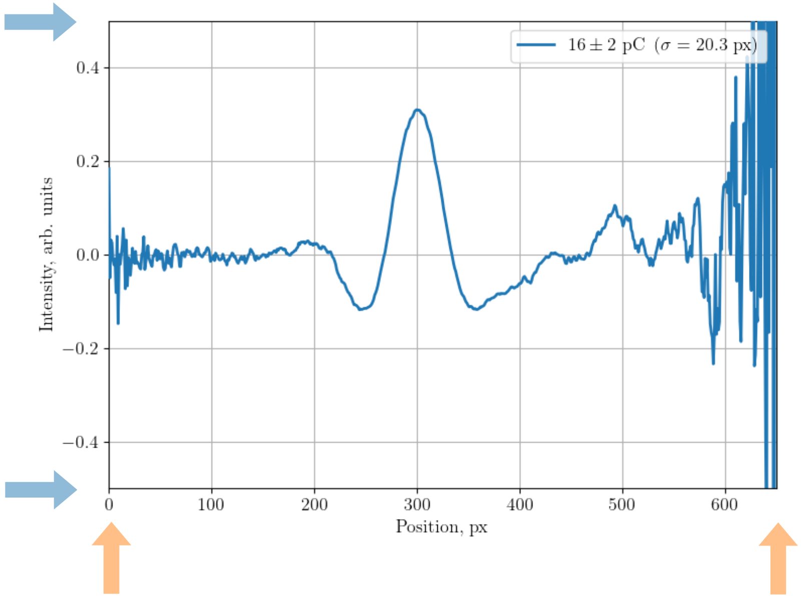
50% working point with modulation from signal on top

Transition Radiation Signal

$$\frac{\text{Signal – Background}}{\text{Background MAX – Background MIN}}$$

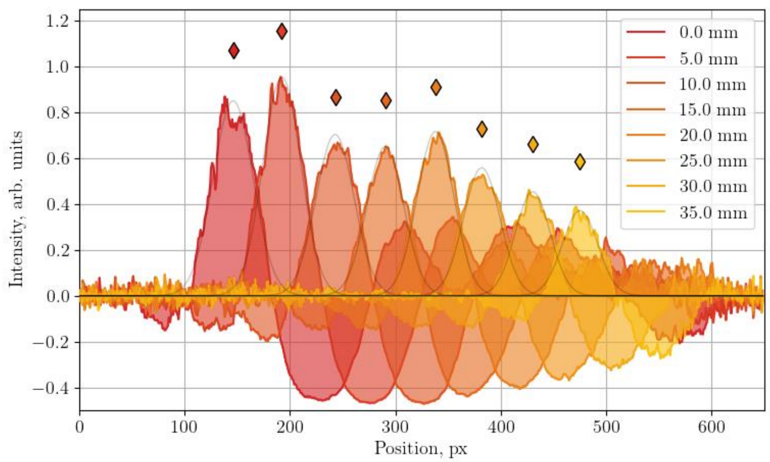
- full modulation range of ±50%
- increase in noise levels as laser pulse fades out
- pulse width given in pixels **σ = 20.3 px**

→ Need for time conversion



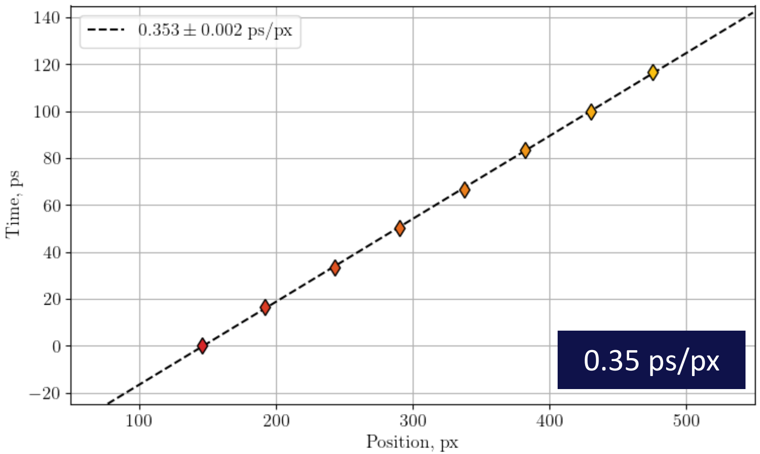
Time Conversion

delays of the laser pulse



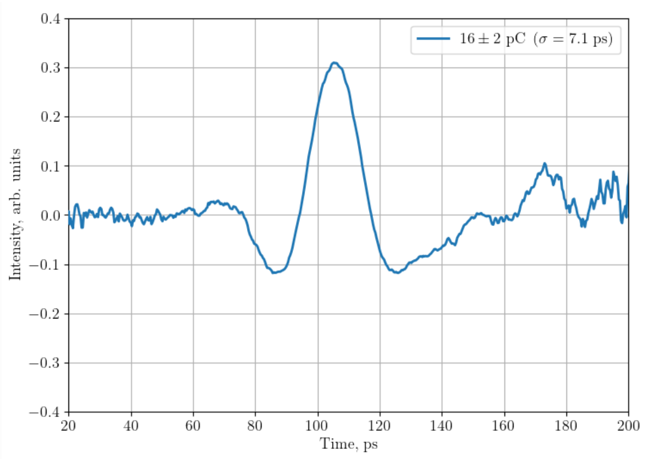
delay the laser pulse with respect to the signal
with the delay stage

time / wavelength **dt / dλ**
wavelength / position **dλ / ds**



check linearity of chirp
calculate px to ps conversion

Timing Jitter and Spectrometer Resolution



σ = 4.8 ps

≈ 40 GHz bandwidth

$$\Delta\nu \approx \frac{0.5}{\tau_{FWHM}}$$

$\sigma_{\text{timing jitter}} \approx 5.0$ ps

Timing jitter depends on the locking between laser pulse and beam, typically σ ≈ 5.0 ps with our current setup

$\sigma_{\text{spectrometer}} \approx 1.6$ ps involves **dt / dλ** and **dλ / ds**

dλ / ds: slit width as small as possible

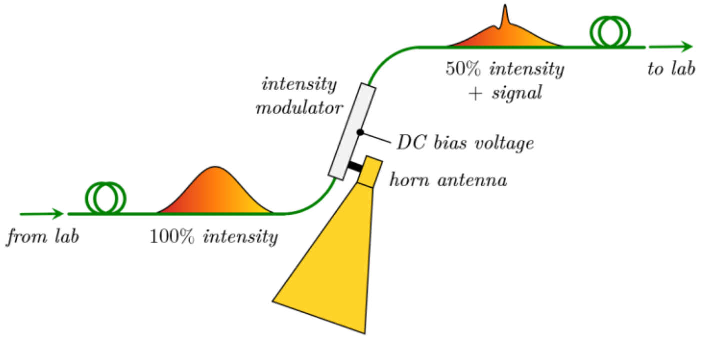
decreases light intensity → intensified camera

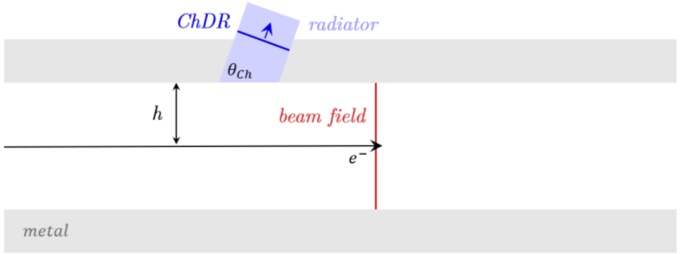
dt / dλ: compressing of laser pulse

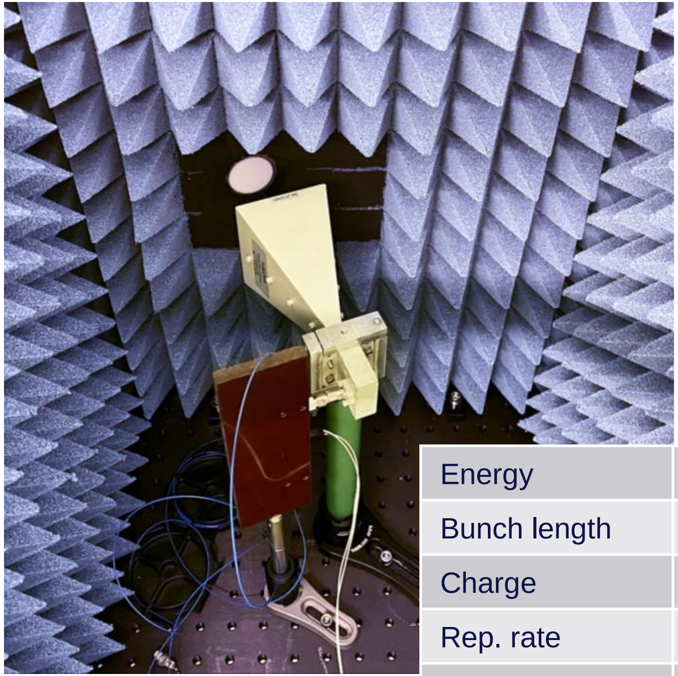
→ **increase time resolution**

→ **higher power density of laser pulse**

ChDR at CLEAR



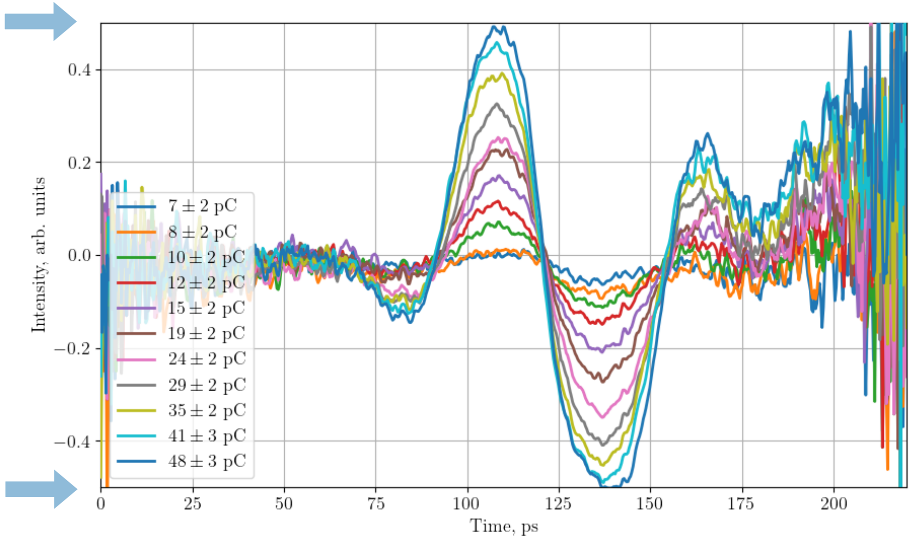




Energy	170 MeV
Bunch length	< 0.5 ps
Charge	10 – 20 pC
Rep. rate	10 Hz
Impact param. h	40 mm

Charge Dependency

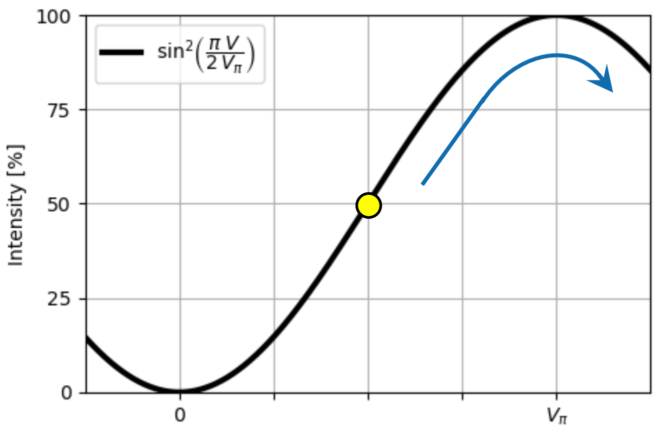
- full modulation range of ±50%
- modulation visible for bunch charges in the order of ~ 10 pC

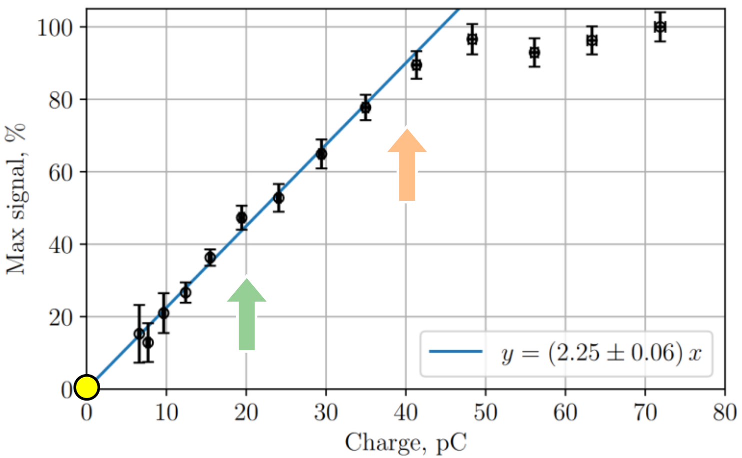


Charge Dependency

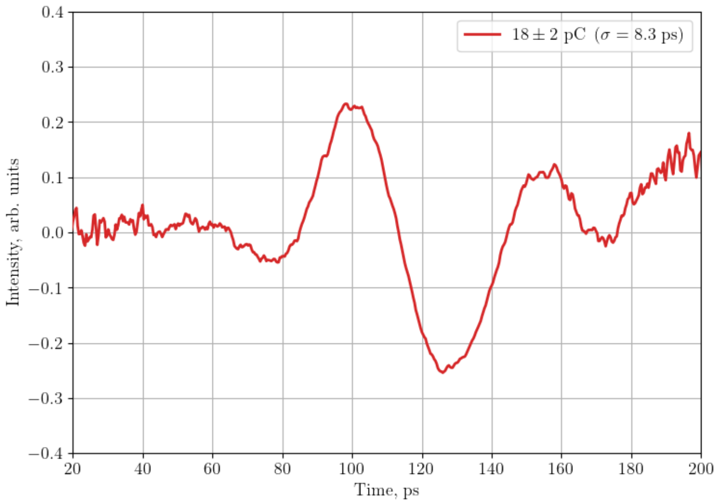
- Avoid distortion and overration from too high signals

- Charges of around 40 pC per bunch max
- 20 pC corresponds to around ¼ of the total modulation range





ChDR Time Signals



$\sigma_{\text{timing jitter}} \approx 5.0$ ps

$\sigma_{\text{spectrometer}} \approx 1.6$ ps

→ $\sigma \approx 6.4$ ps

- shortest ChDR time signal measured
- DR signal visible as expected
- limited by intensity modulator and horn antenna (40 GHz BW)
- timing jitter to be reduced
- broadening of the signal

  → short test bunches of 500 fs (1 σ) and 170 MeV broadening of beam field at 40 mm distance

  → geometric broadening from curved radiator surface

Considerations

Future outlook:

- **controllable stretching** of laser pulse would allow to **tune desired resolution**
- Faster electro-optical modulators are possibly fast enough to digitize ChDR down to the shortest bunch lengths foreseen in the collider ring (**6 ps – 42 ps**) → change to 1550 nm
- **Higher repetition rate:**
  fast linear array detector KALYPSO for high repetition rates → KIT
- **Higher resolution:**
  use Cherenkov diffraction radiation as a signal source in an EOSD scheme with eo-crystals

Acquisition system with high potential:

- **bandwidth of ≈ 40 GHz** preserved over **~100 m** by using fibres instead of cables
- versatile connector, excepts **SMA/SMK**
- high **radiation tolerance**

Conclusion

Coherent Cherenkov Diffraction Radiation:

- **Shortest time signal** from Coherent Cherenkov Diffraction Radiation measured**, σ ≈ 6.4 ps**
- **High signal levels →** bunch charges down to **10 pC** measurable at an impact parameter of **40 mm**
- **Possible alternative signal source for bunch length measurements** compared to more established techniques like electro-optical crystals or synchrotron radiation

Incoherent Cherenkov Diffraction Radiation:

- Using the visible part of the spectrum of ChDR in fused silica radiators
- So far challenging to obtain experimental results with the beam energies (> GeV) and small transverse beam sizes needed (~10 µm) to have sufficient photon flux
- Work in progress

FCC

Thank you for your attention.