# A high resolution bunch arrival time monitor system for FLASH / XFEL

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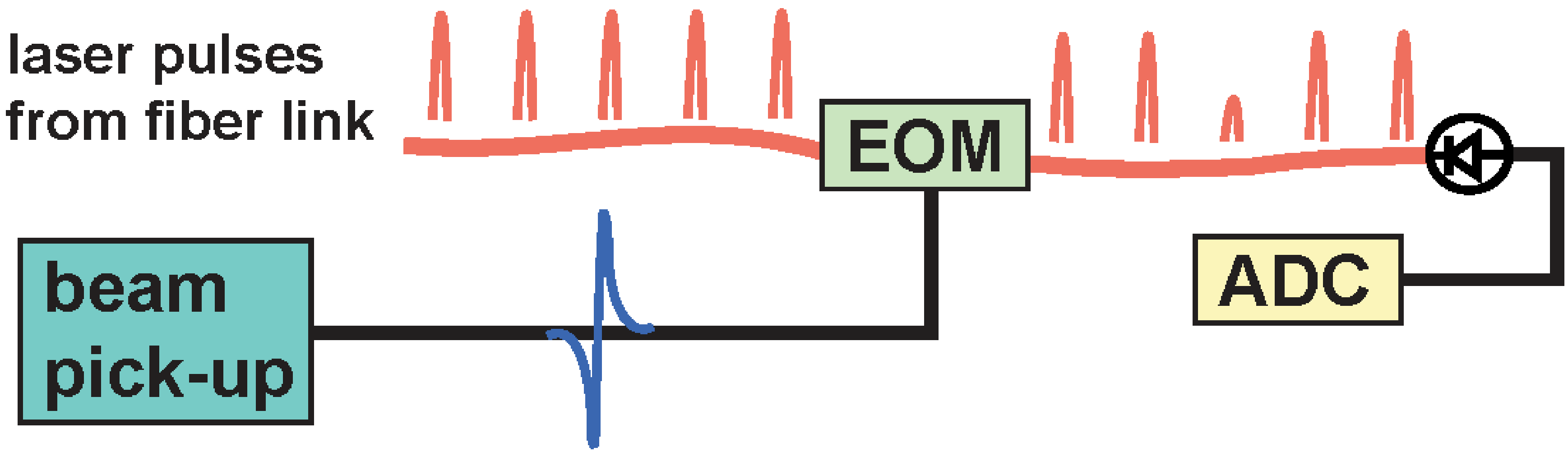
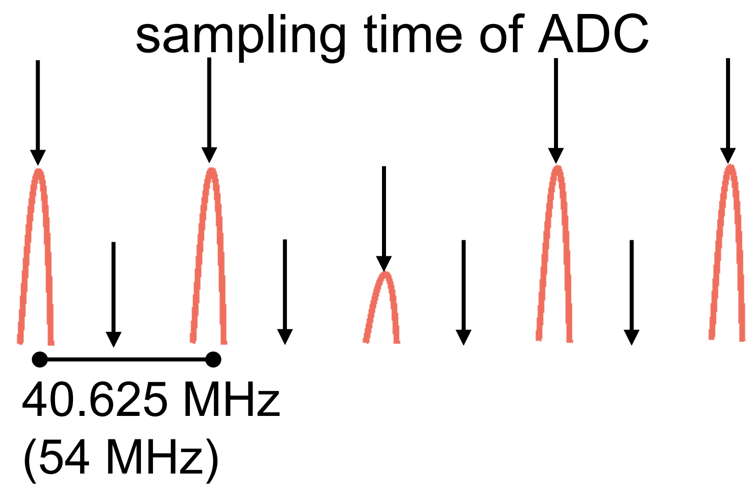
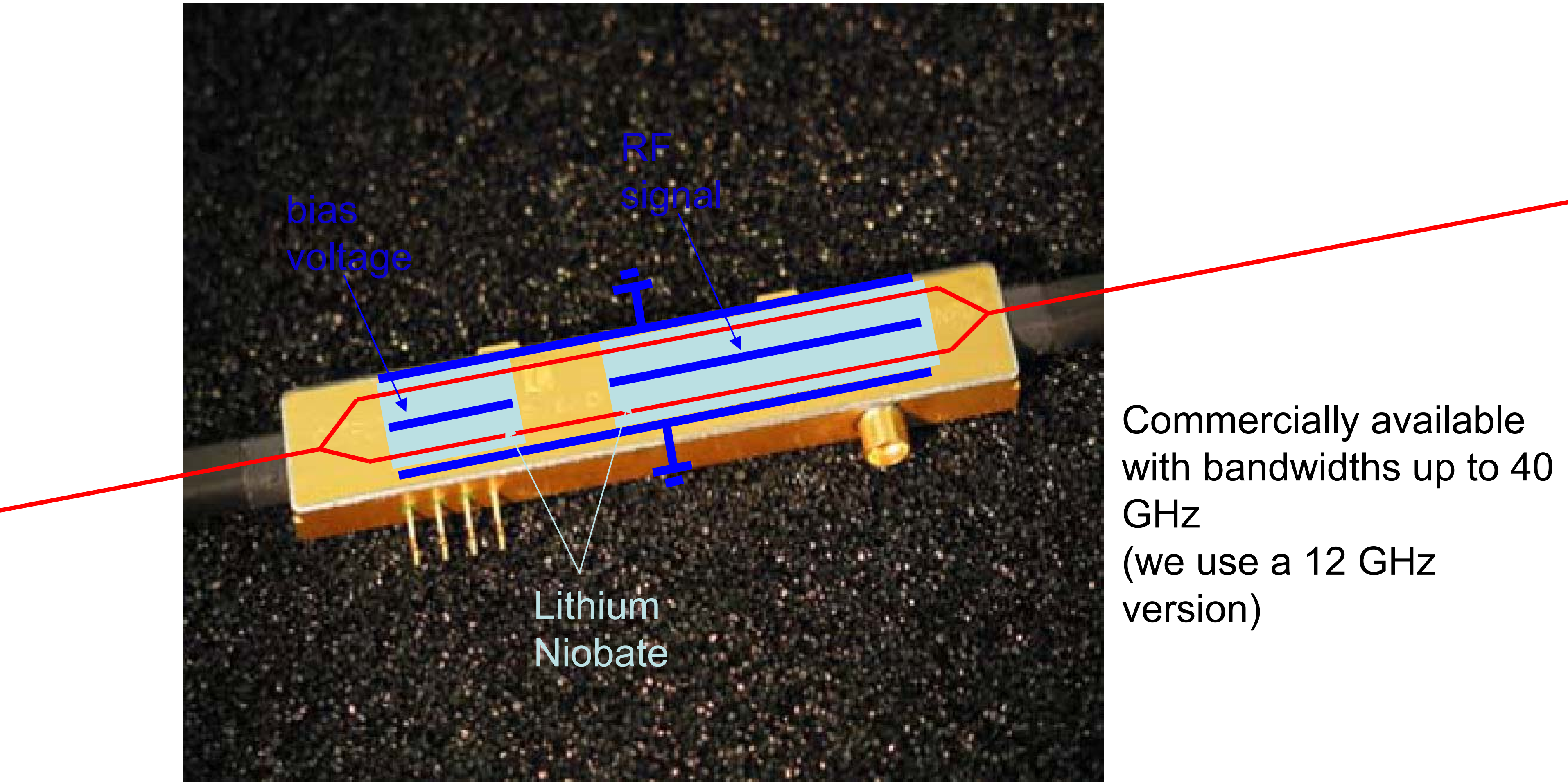
# Principle of the arrival time detection




The timing information of the electron bunch is transferred into an amplitude modulation. This modulation is measured with a photo detector and sampled by a fast ADC.

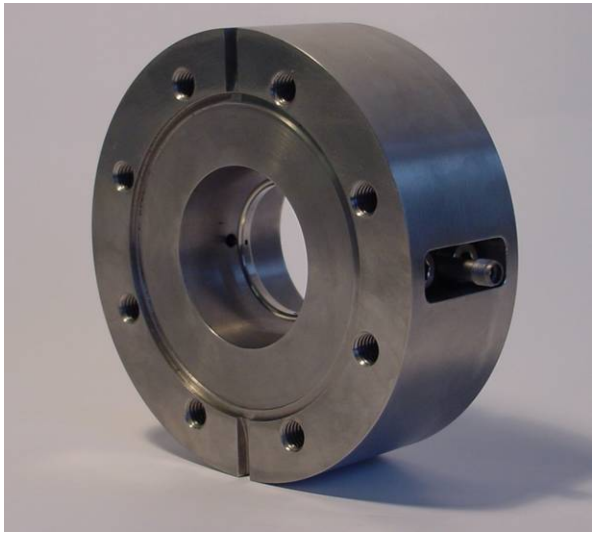


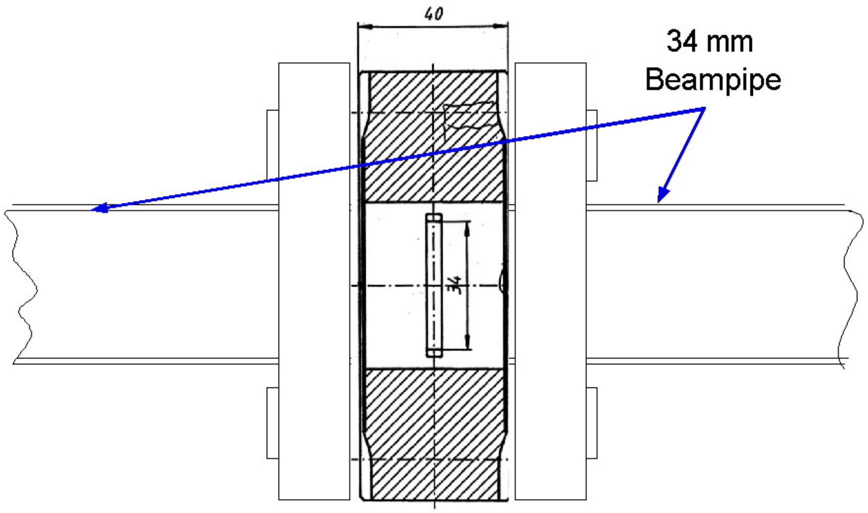
# Electro-Optical-Modulator (EOM)



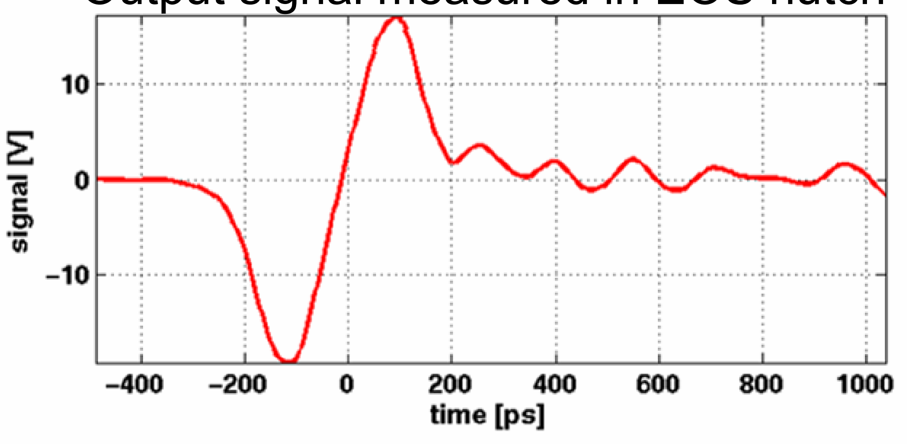

Commercially available with bandwidths up to 40 GHz
(we use a 12 GHz version)

# Beam pick-up



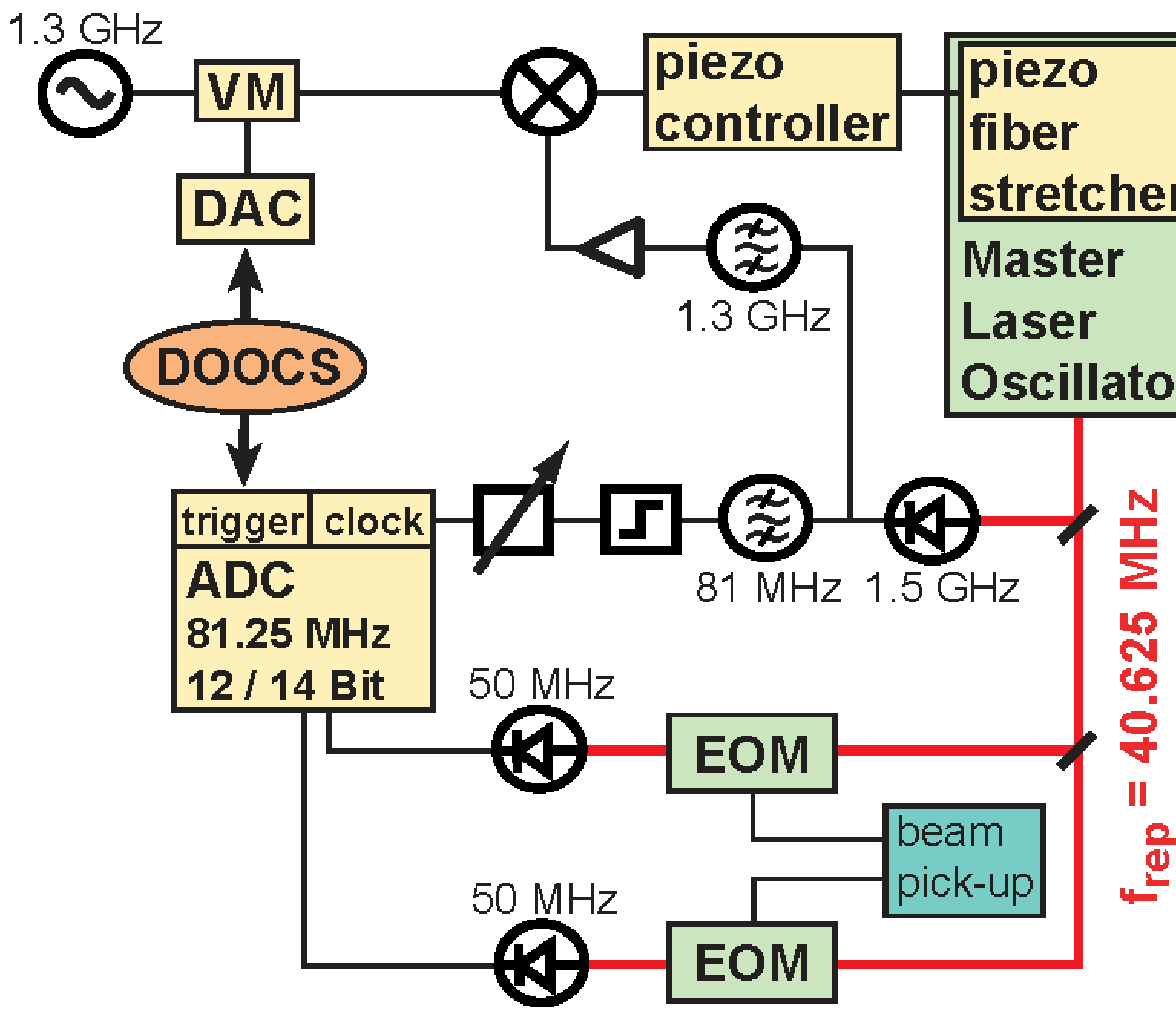



Output signal measured in EOS hutch

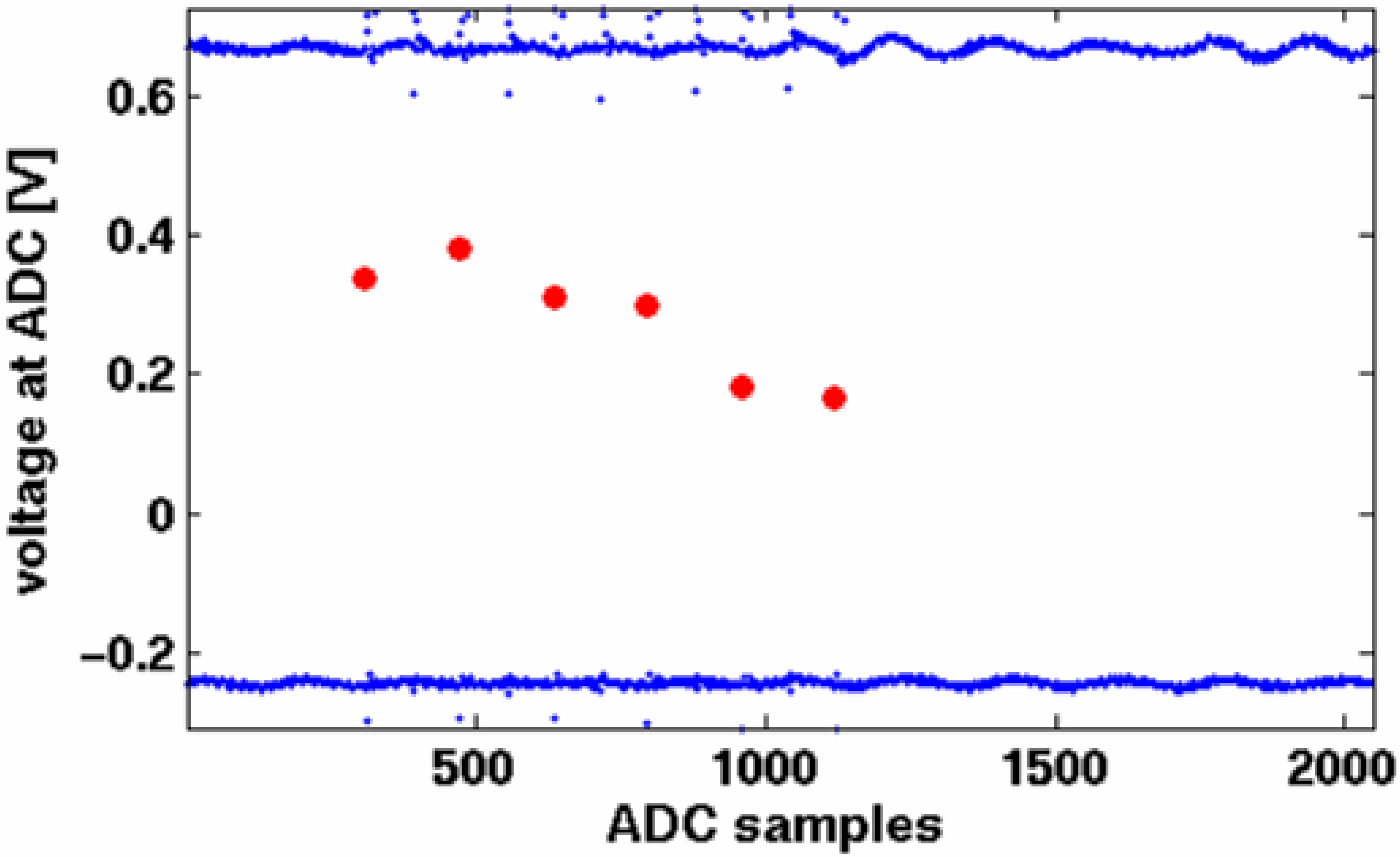



- Isolated impedance-matched ring electrode installed in a „thick Flange“
- Broadband signal with more than 5 GHz bandwidth
- Sampled at zero-crossing with laser pulse

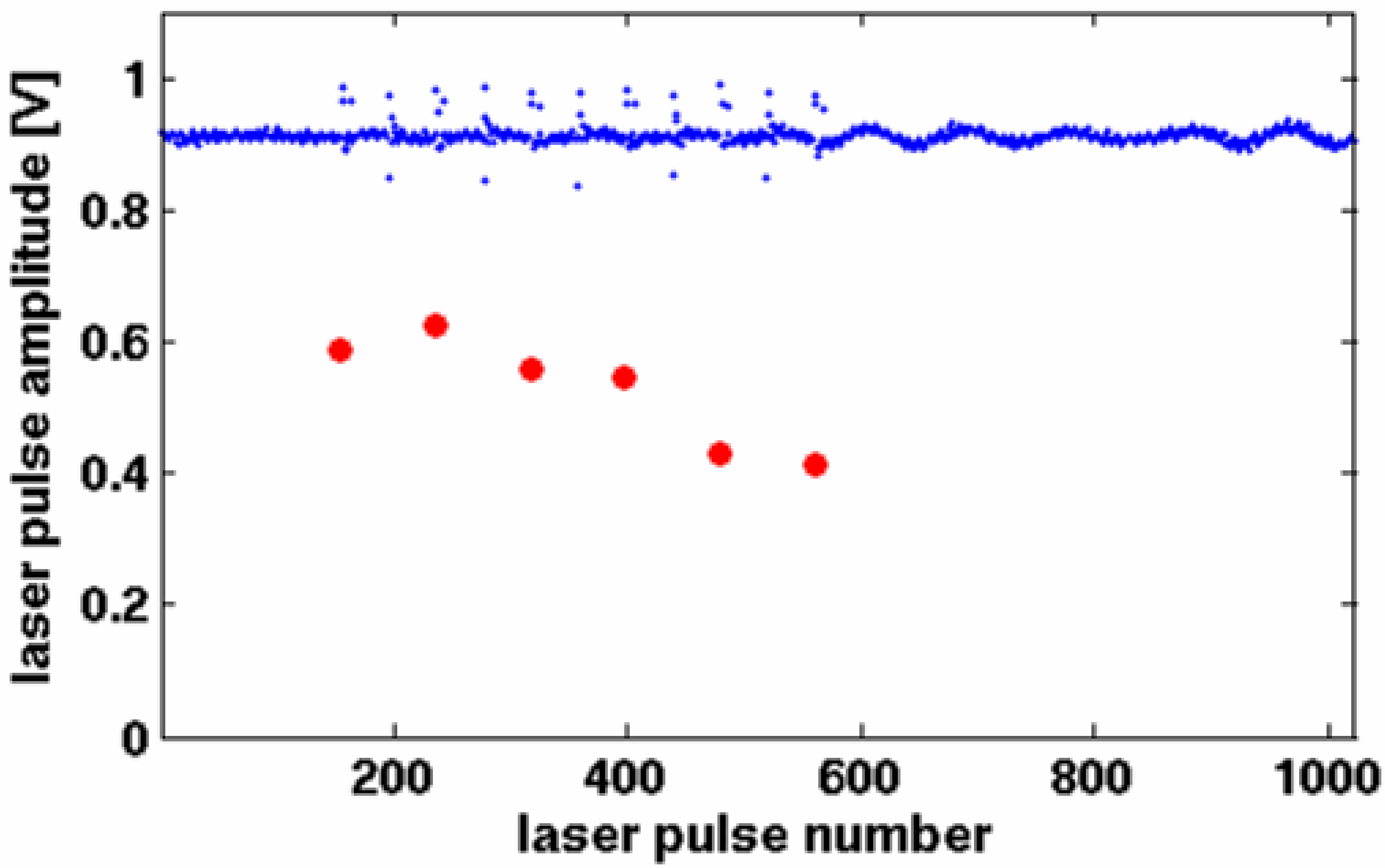
# Test bench for the arrival-time monitor system



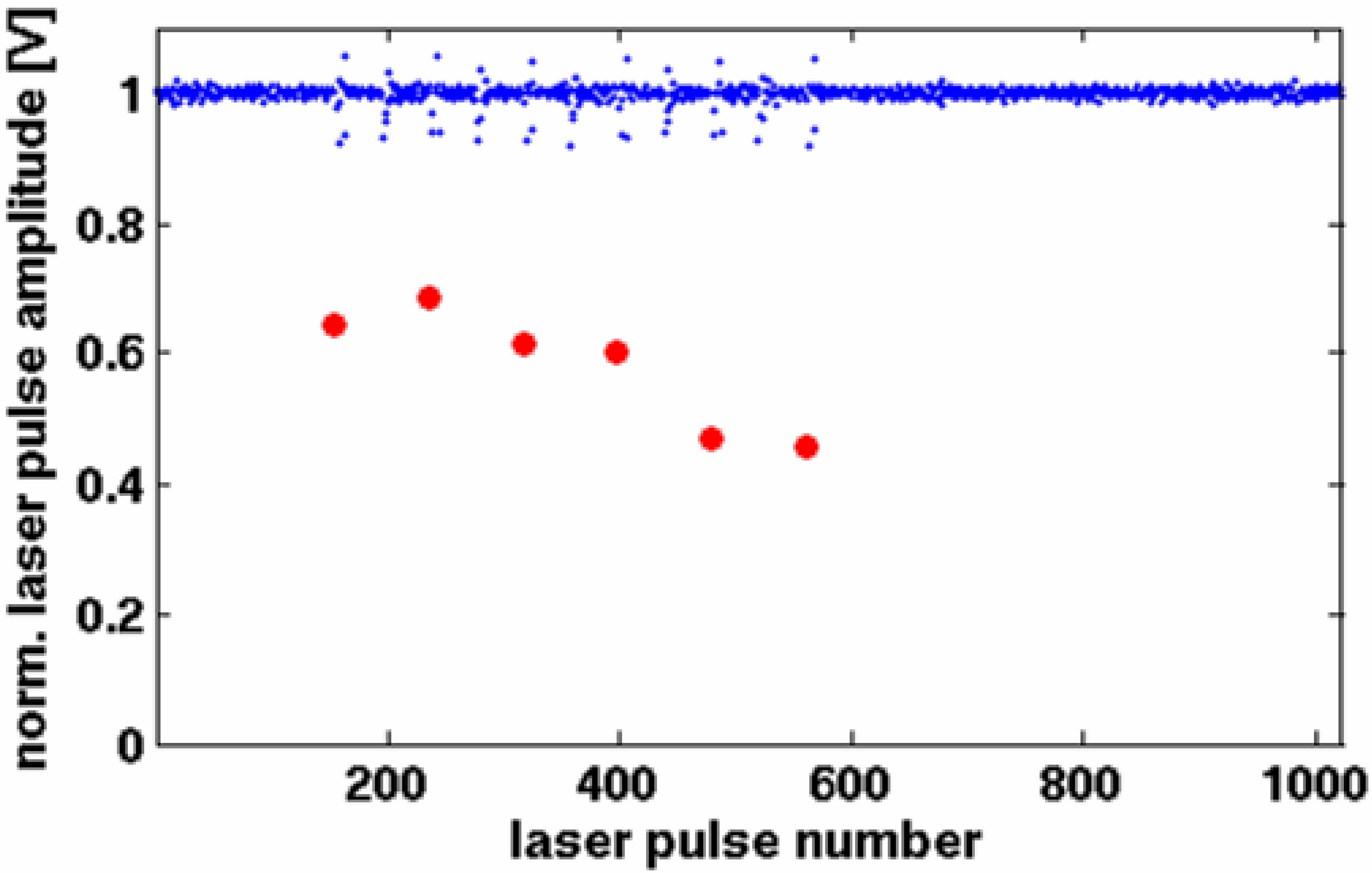
# Raw data of the EOM detector signal



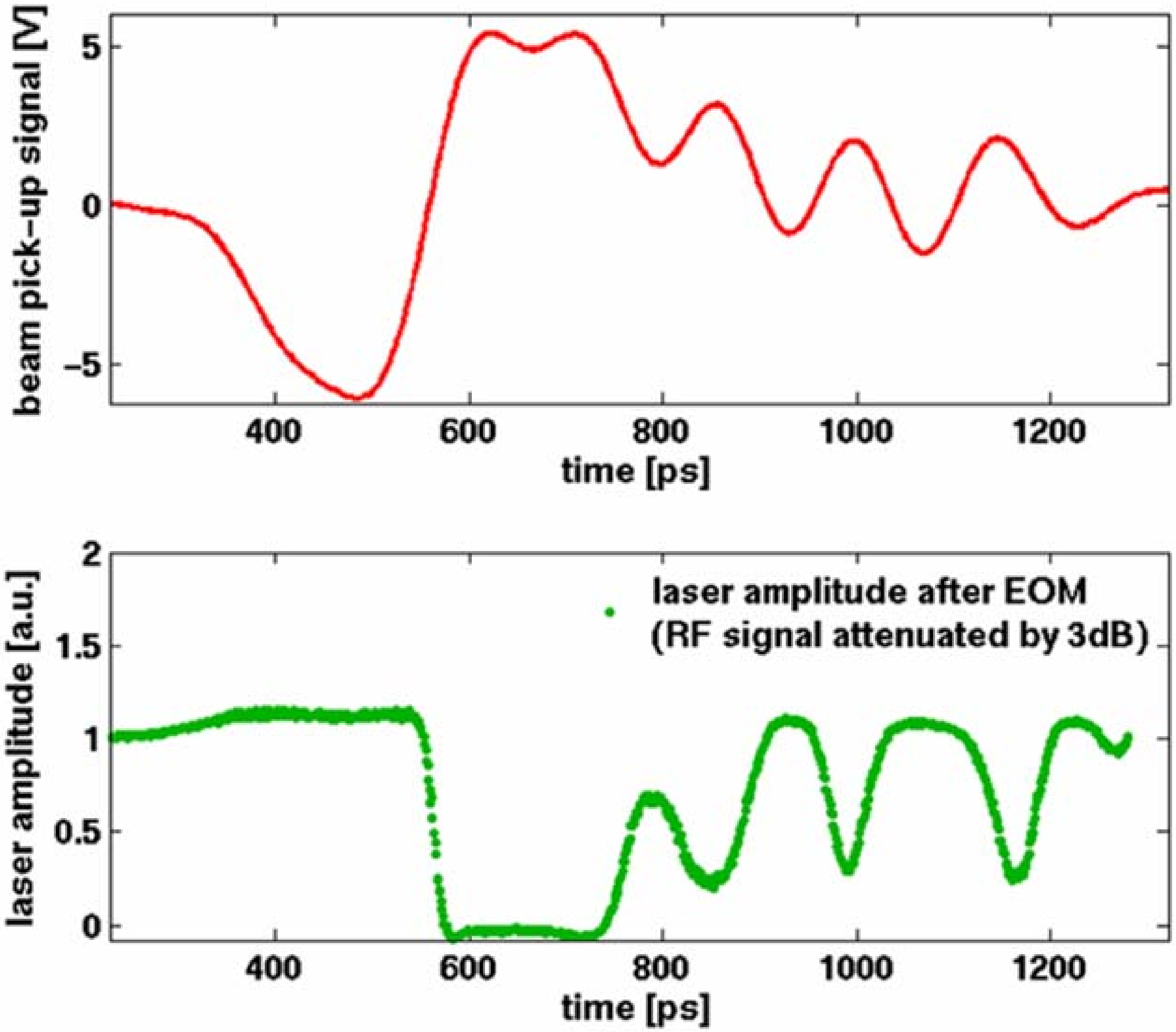
# Amplitude of the laser pulses



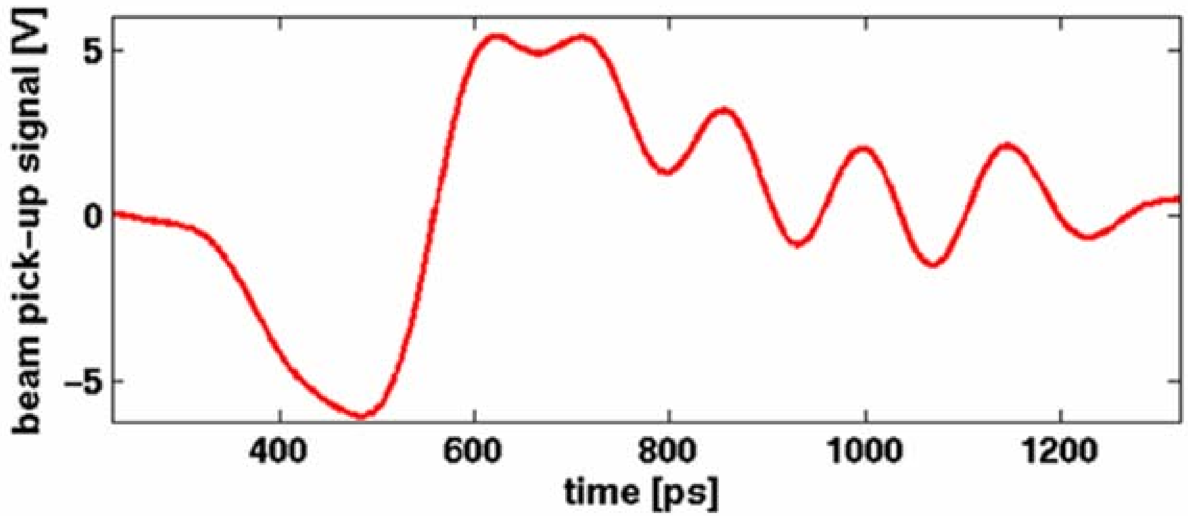
# Amplitude of the laser pulses (normalized)

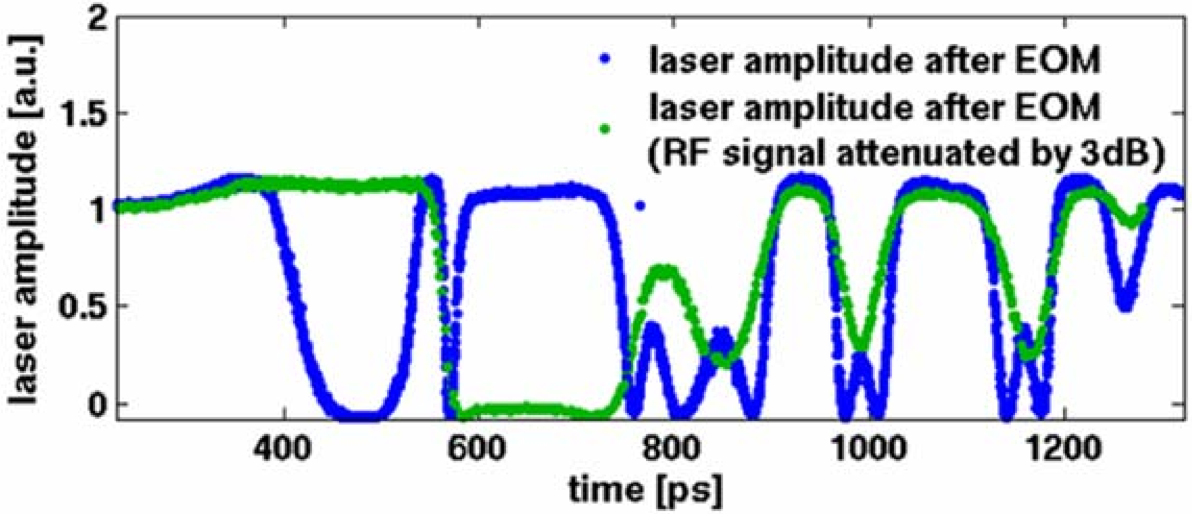


# Scan of laser pulse over beam pick-up signal



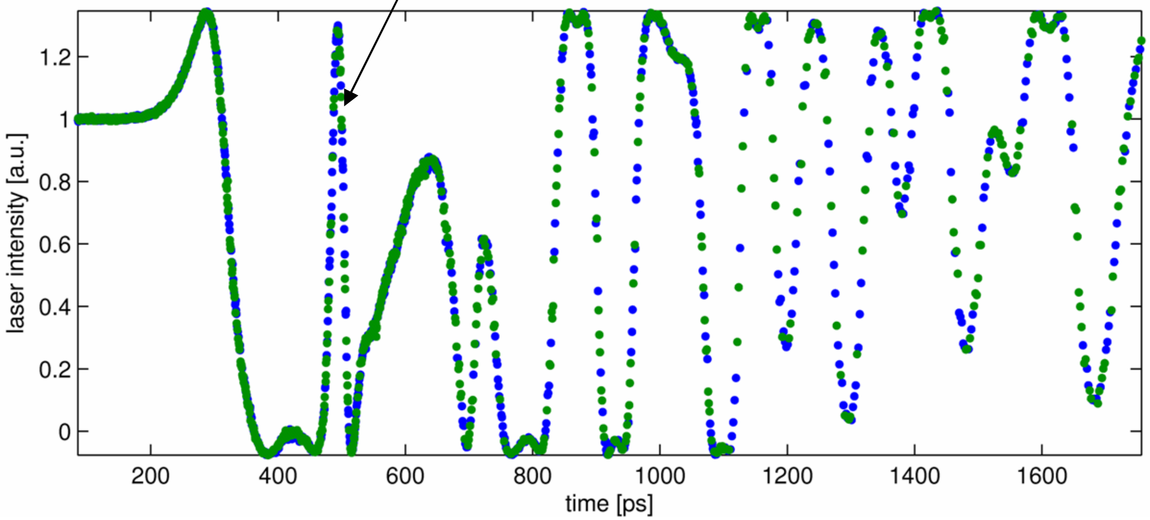
# Scan of laser pulse over beam pick-up signal



# Measurement principle and resolution of the EOM detectors

Zero-crossing of beam pick-up signal




- Laser pulses sample beam pick-up signal at zero-crossing
- Bunch arrival time changes are transferred into laser amplitude changes which are measured

**The resolution of the system is limited by two things:**

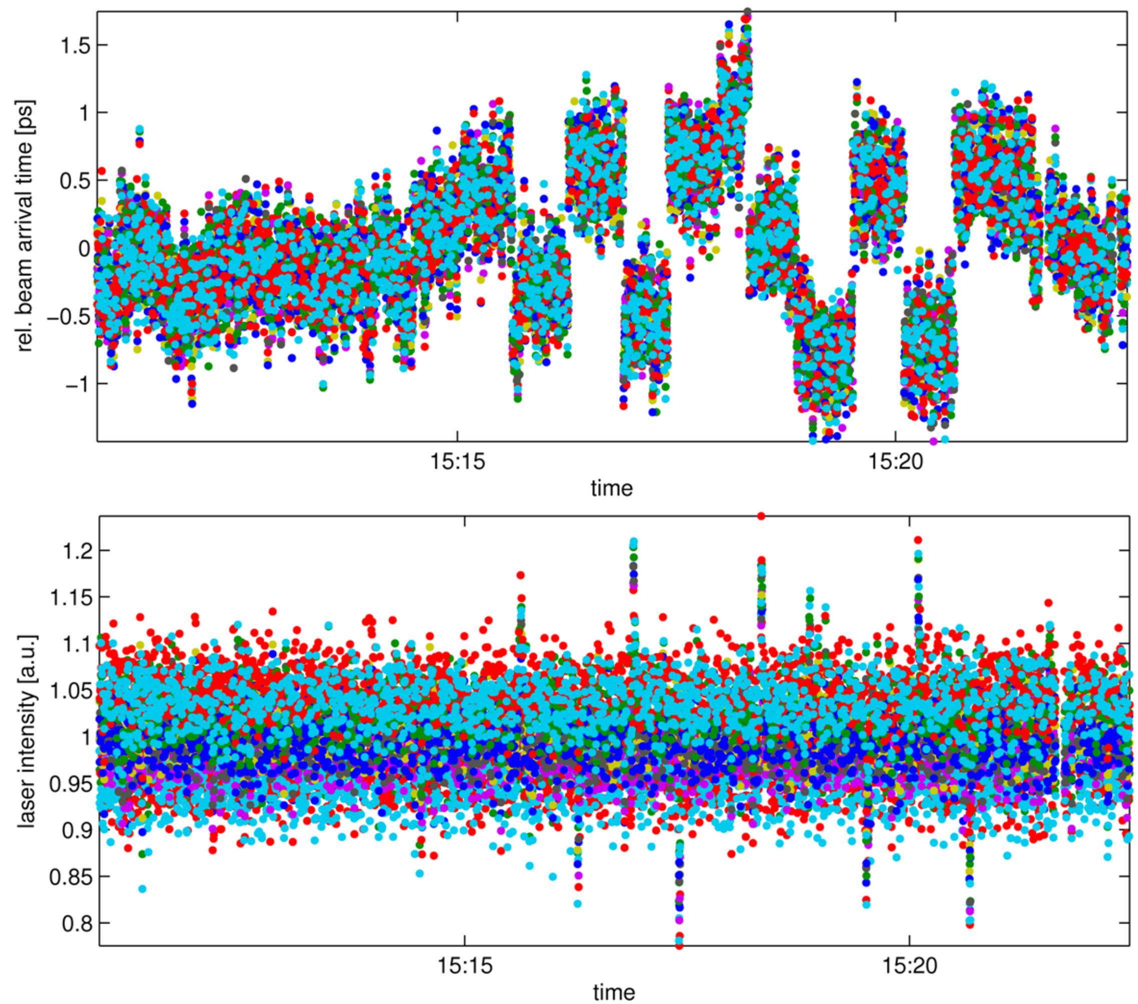
- **Steepness of the slope of the beam pick-up signal**
- **Precision of laser amplitude detection**

Typical values for current setup:

- ~ 60 - 100 fs / (% laser amplitude modulation)
- rms ~ 0.2 – 0.3 % (recently 0.08%) (unmodulated laser pulses)

Resolution of EOM detectors:
~ 20 - 50 fs

# Slow feedback for sample position

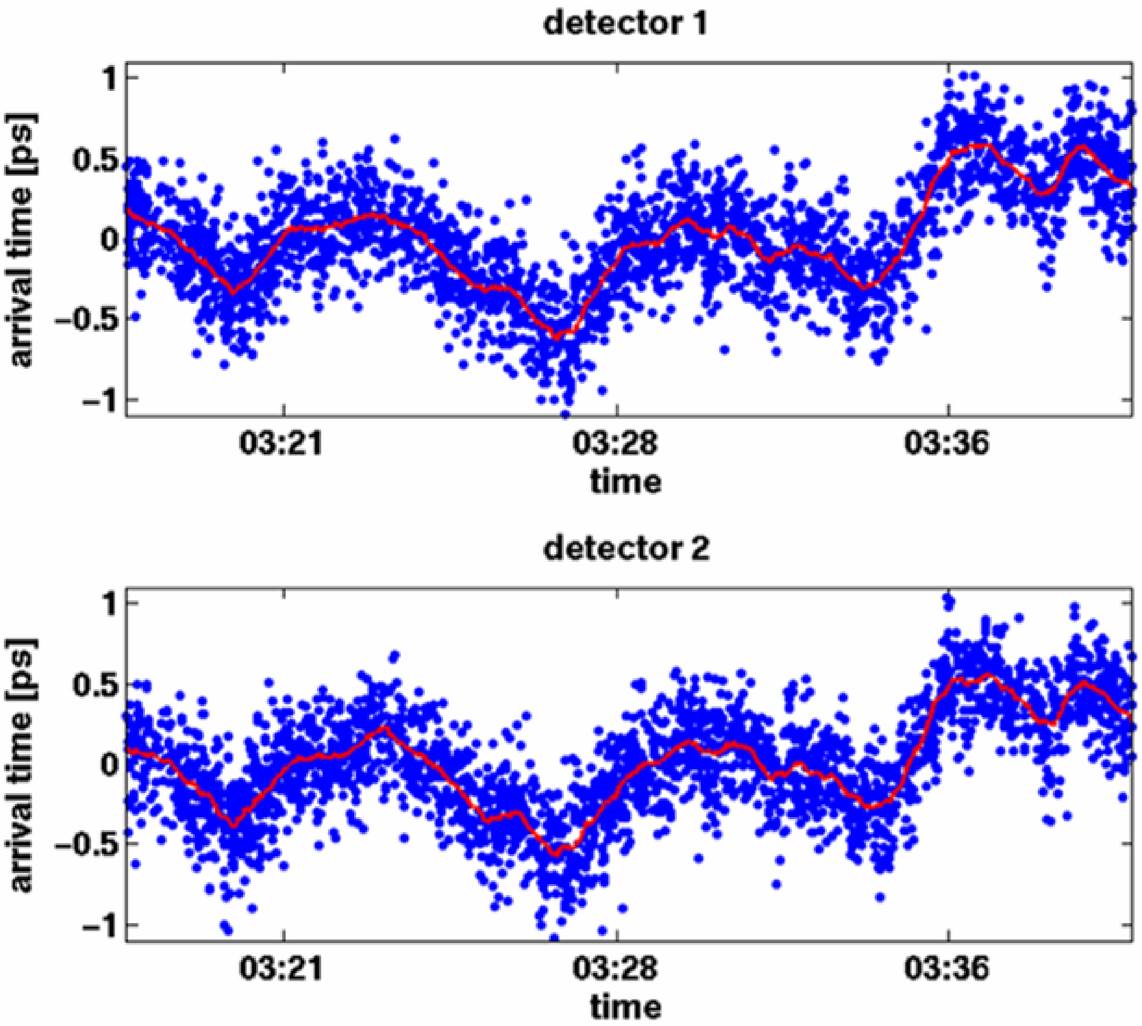



A slow feedback ensures that the laser pulse always samples the zero-crossing of the beam pick-up signal even if the bunch arrival time changes.

Currently the phase of the laser is used as the actuator, but in the final design this will be done by an optical delayline.

Large timing changes will be measured and compensated by a coarse measurement (attenuated beam pick-up signal)

# Comparison measurement between two arrival-time detectors




The signal of the beam pick-up was split and connected to the two EOM detectors.

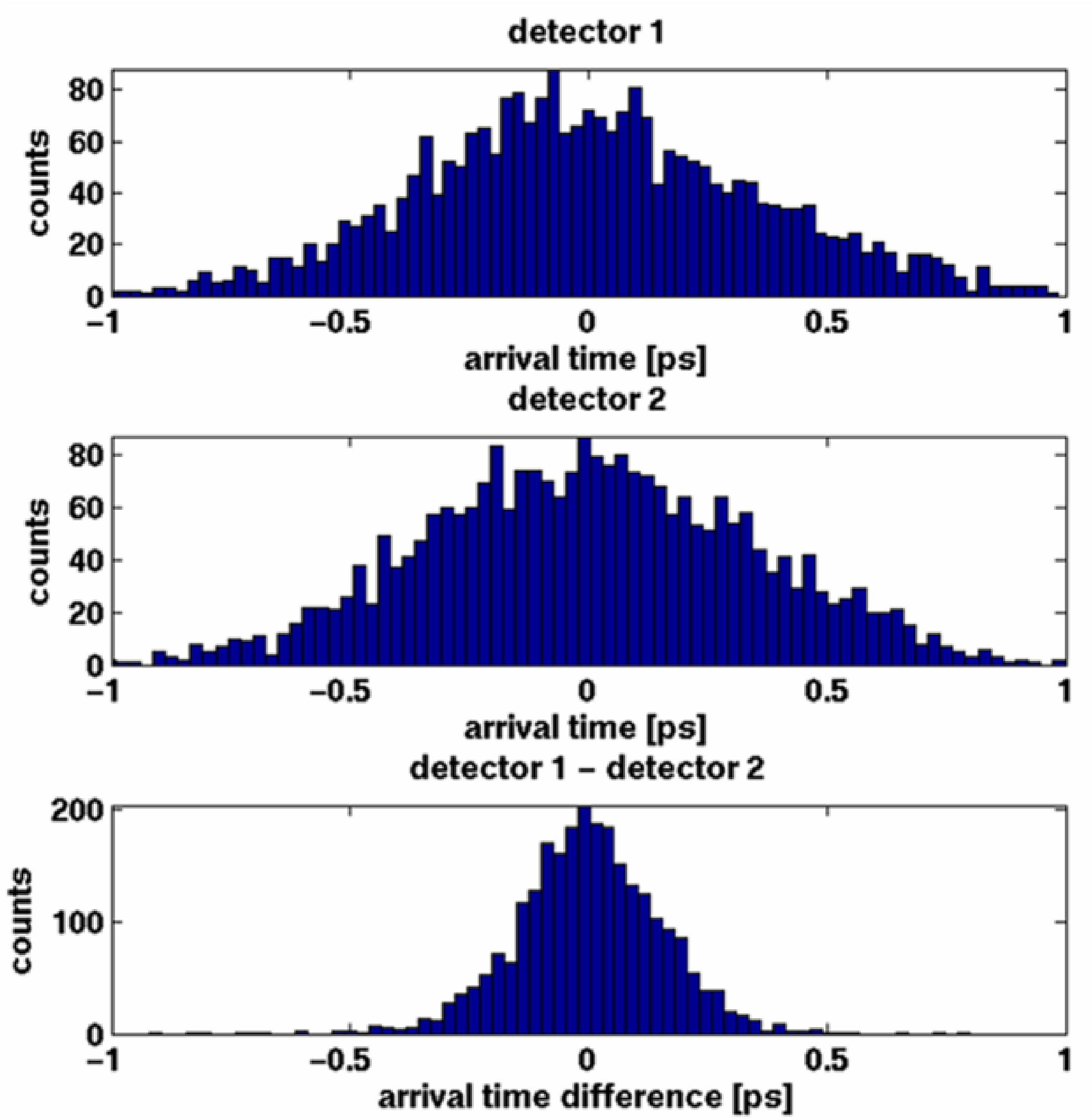
The rms-resolution of the detectors was estimated from the laser amplitude noise and the slope from the calibration:

Detector 1: **99 fs**

Detector 2: **114 fs**

→ estimated jitter between the two detectors: **151 fs**

# Comparison measurement between two arrival-time detectors



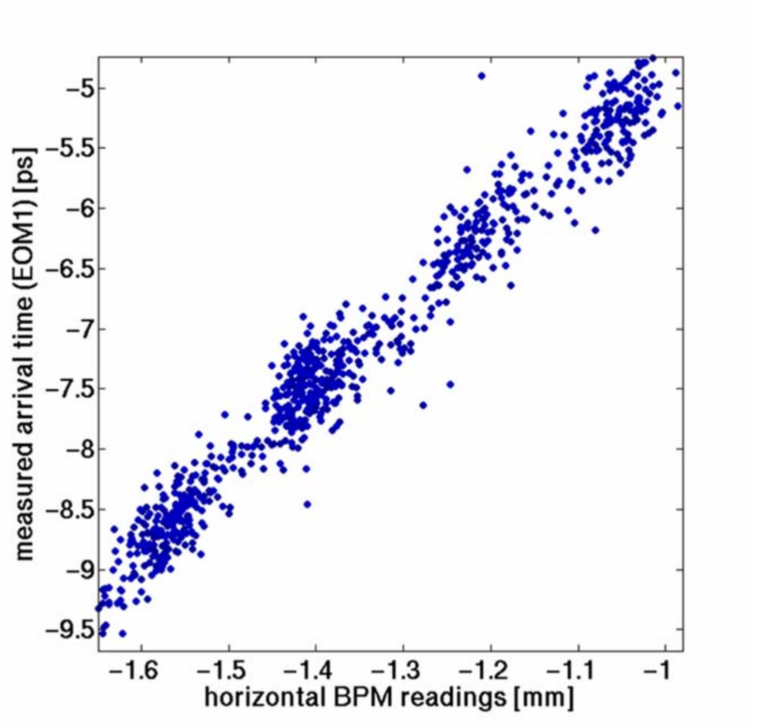

| | rms jitter |
|---|---|
| Detector 1 | **357 fs** |
| Detector 2 | **342 fs** |
| Det. 1 – Det. 2 | **139 fs** |

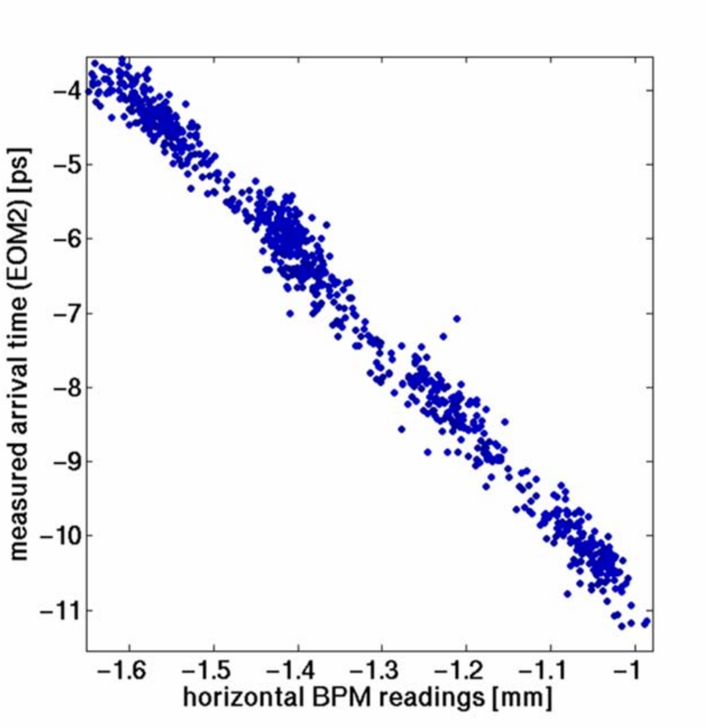
# Position dependence of the beam pick-up signal

Using the two different output ports of the beam pick-up as input for the EOM detectors gives rms resolutions of about 30 fs for both detectors.

But: the measured rms jitter of the difference signal is around 1.5 ps.

➢ Orbit dependence of beam pick-up signal!



# Position dependence of the beam pickup signal

The beam arrival time depends linearly on the beam position in x and y:

$$t_{\text{arrival}} = t_{\text{meas},1} + a_{x,1}x + a_{y,1}y$$
$$t_{\text{arrival}} = t_{\text{meas},2} + a_{x,2}x + a_{y,2}y$$

The constants $a_i$ were determined by changing the orbit at the pick-up with corrector coils:

$$a_{x,1} = (-6.94 \pm 0.05)\frac{\text{fs}}{\mu\text{m}} \qquad a_{x,2} = (10.7 \pm 0.02)\frac{\text{fs}}{\mu\text{m}}$$
$$a_{y,1} = (-0.16 \pm 0.07)\frac{\text{fs}}{\mu\text{m}} \qquad a_{y,2} = (0.29 \pm 0.02)\frac{\text{fs}}{\mu\text{m}}$$

When using the BPM system (~ 20 µm resolution) to correct for the orbit dependence the remaining rms jitter of the difference signal is still 300 fs (dominated by the BPM system).

# Combined beam arrival-time and beam position monitor



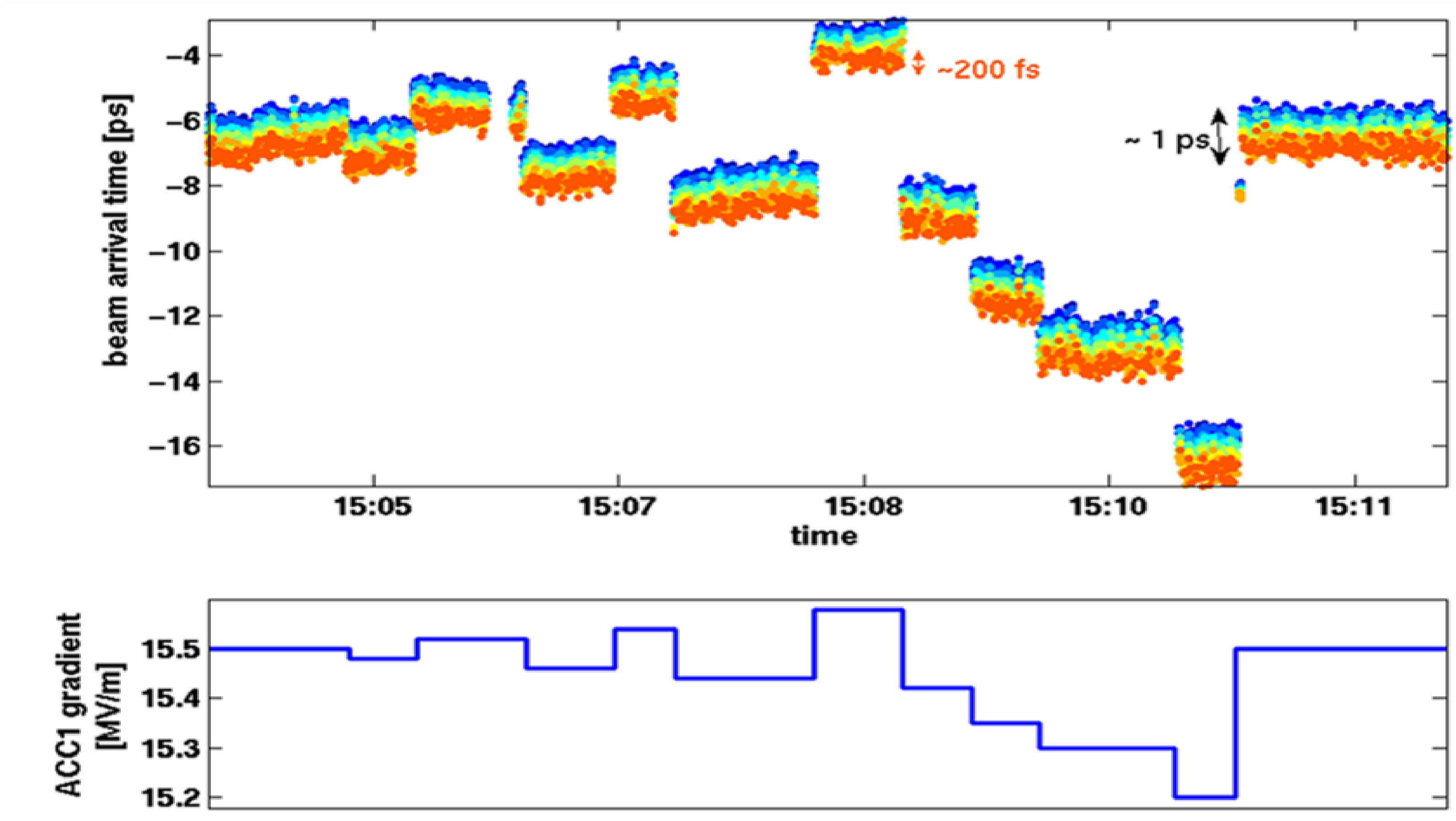
However, we can use the EOM detectors to measure the horizontal beam position:

$$x = \frac{t_2 - t_1 + (a_{2,y} - a_{1,y})y}{a_{1,x} - a_{2,x}}$$

A rms resolution of 33 fs for the EOM detectors and 20 μm for the vertical beam position yields a resolution for the horizontal beam position of 3 μm (rms).

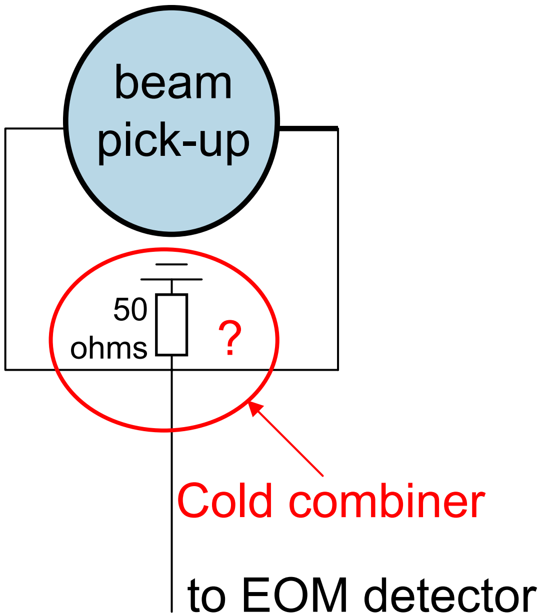
This precise beam position we can use to reduce the error in the arrival time from ~ 300 fs to below 30 fs (rms).

# Bunch arrival-time measurement

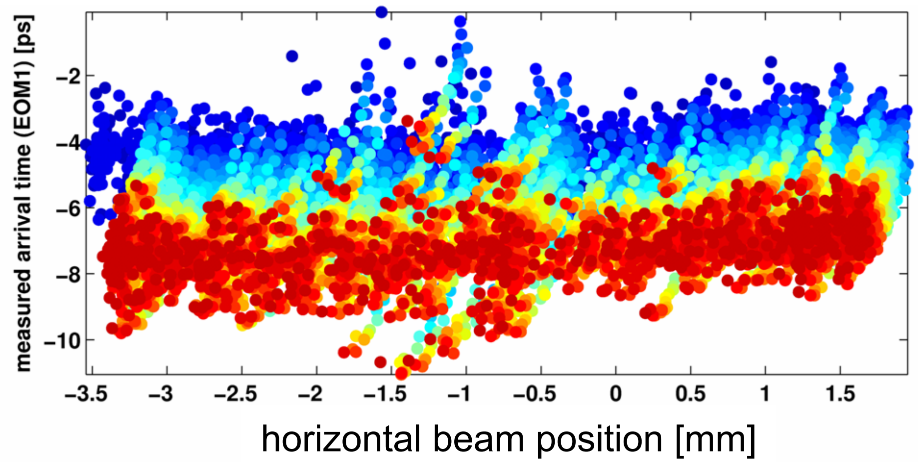


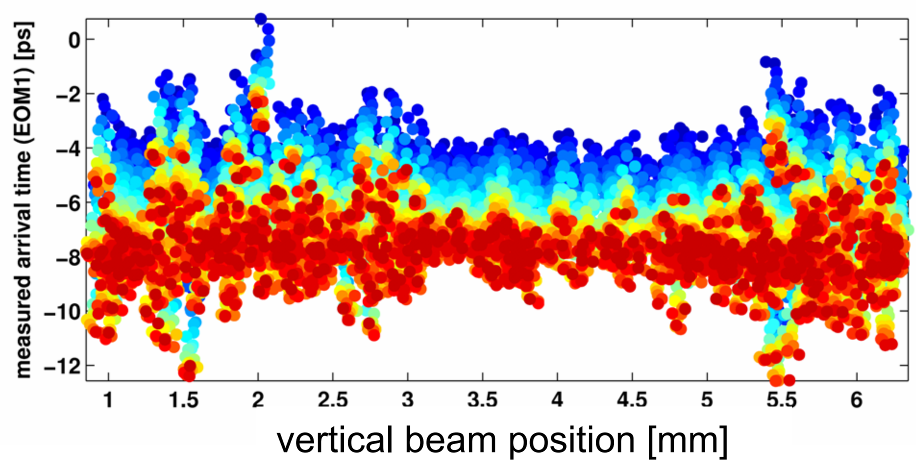

Time change seen by arrival time monitor: ~ 5 ps / (% ACC1 gradient change)
Time change seen by TCAV: ~ 5.8 ps / (% ACC1 gradient change)
Intra-bunch train jitter between two adjacent bunches: ~ 40 – 60 fs

# Reduction of orbit dependence with "cold-combiner"




To minimize the orbit dependence the two output signals of the beam pick-up were combined with a so-called "cold combiner".



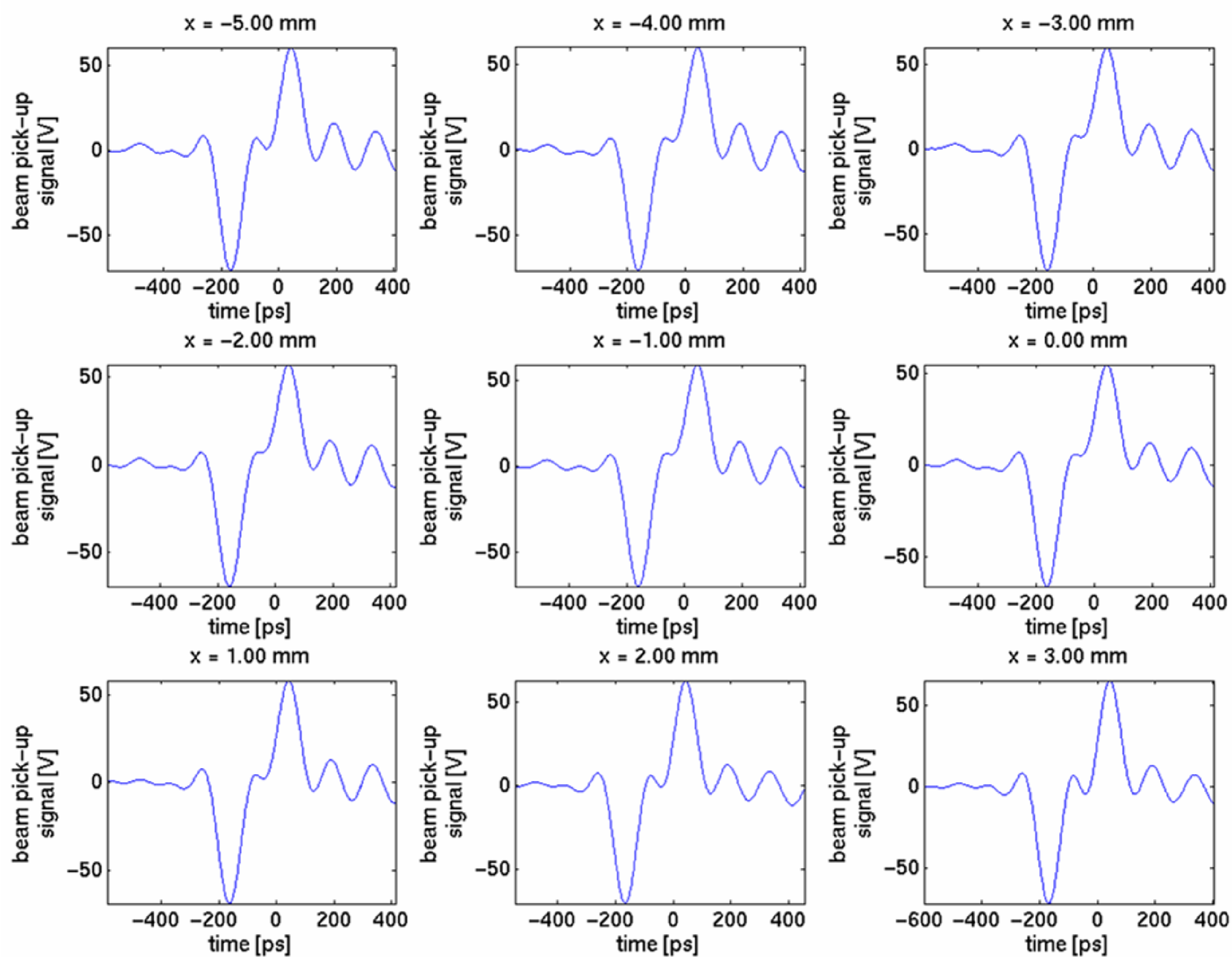

measured orbit dependence:

ax = (-0.190 +- 0.022) ps / mm
ax = (-0.191 +- 0.026) ps / mm

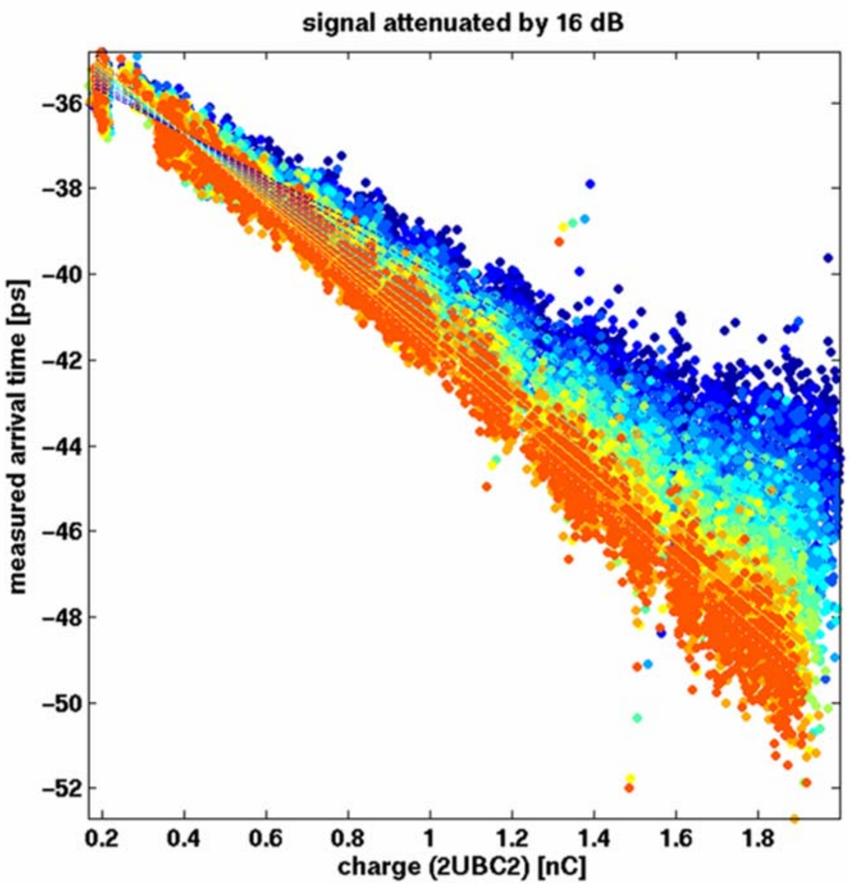
ay = (0.060 +- 0.032) ps / mm
ay = (0.064 +- 0.046) ps / mm

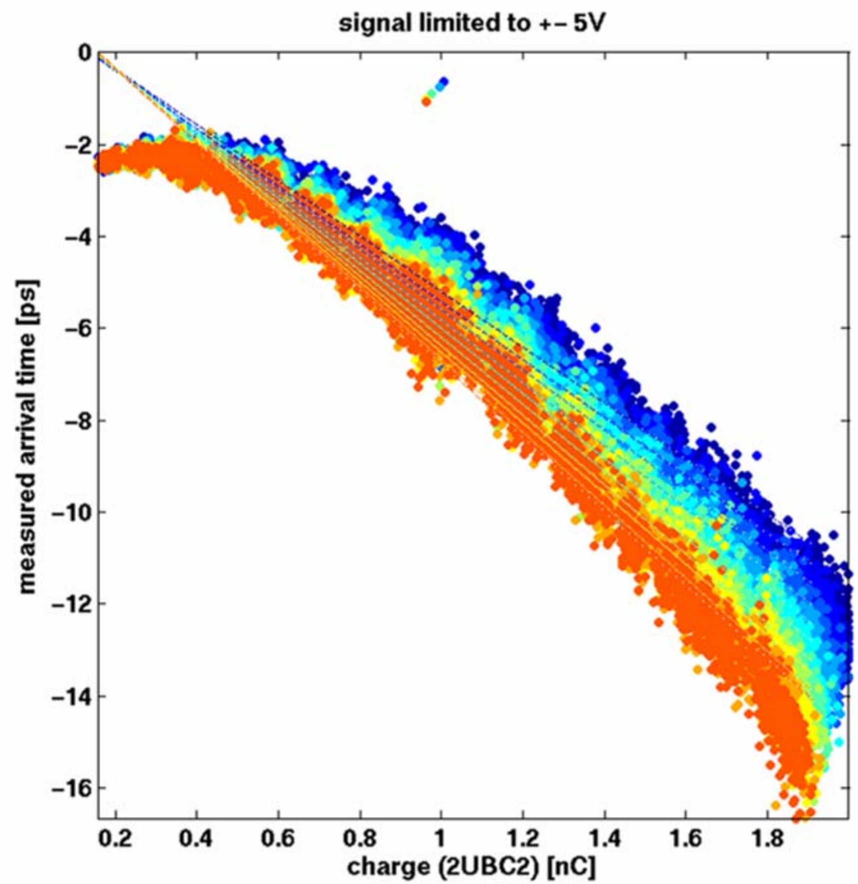
Reduction of the horizontal orbit dependence by a factor of 30-50!

# Measurement of pick-up signal in the tunnel



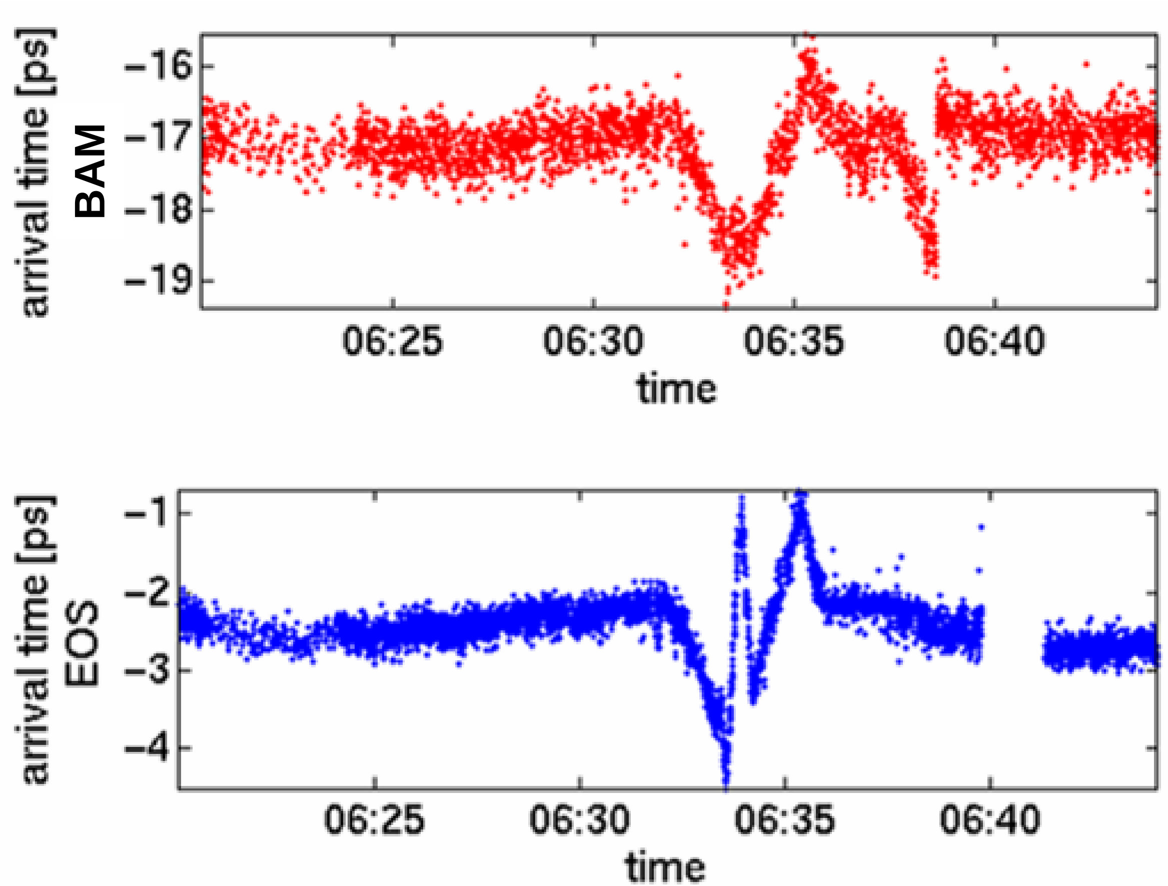
# Charge dependence of BAM measurement with and without limiter




Limiter transfers amplitude modulations of the beam pick-up signal to phase changes! The data has to be analyzed in detail, the nonlinearity might be easy to correct…

# Comparison measurement with EOS experiment

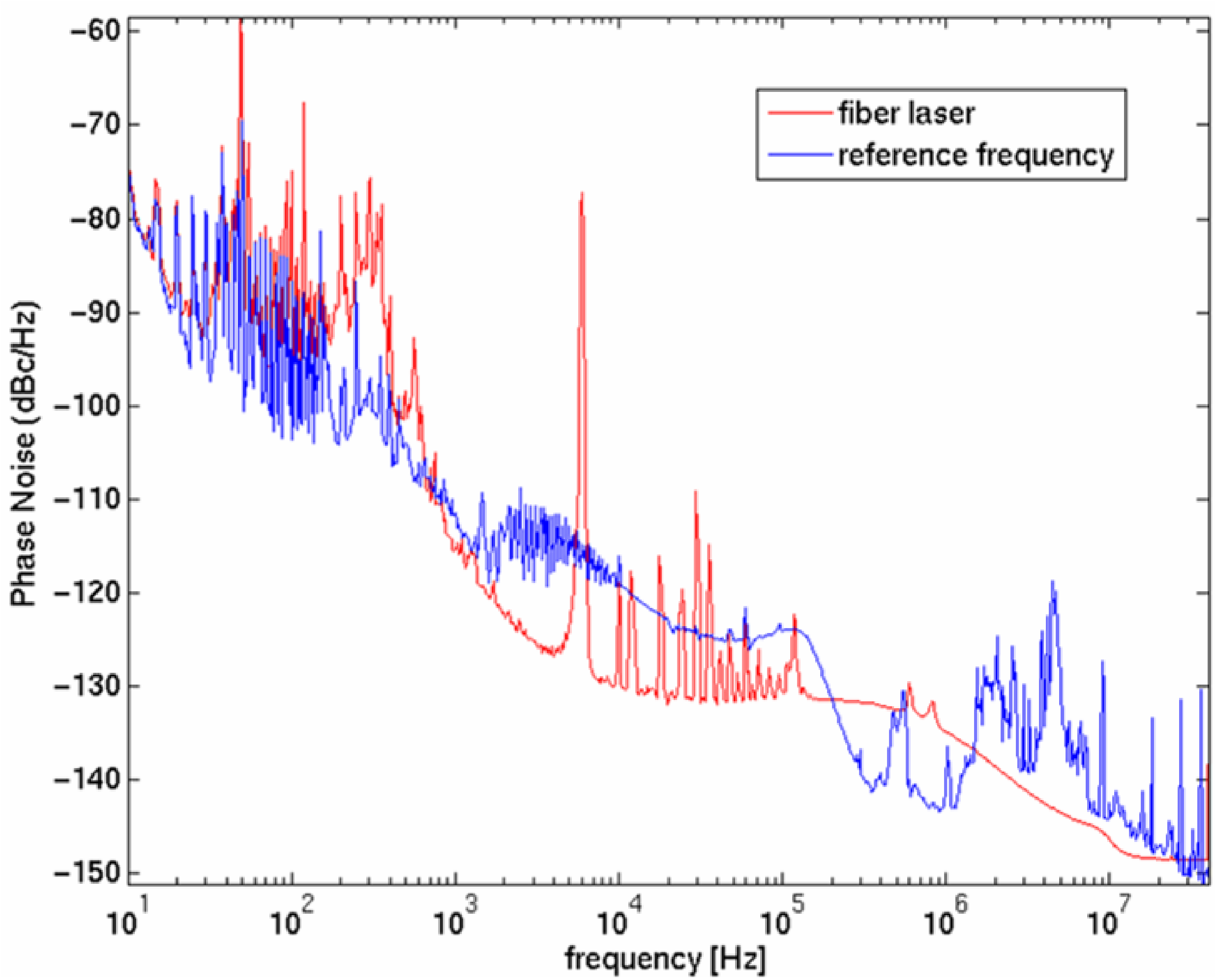



Arrival time jitter between EOS and BAM is about 300 fs!

EOS has clearly the higher resolution. A measurement with the TCAV confirms that this is not due to the difference that EOS detects the high density spike of the electron bunch while the BAM is only sensitive to the center.

Source for bad correlation: laser synchronization

# Phase noise measurement of BAM fiber laser



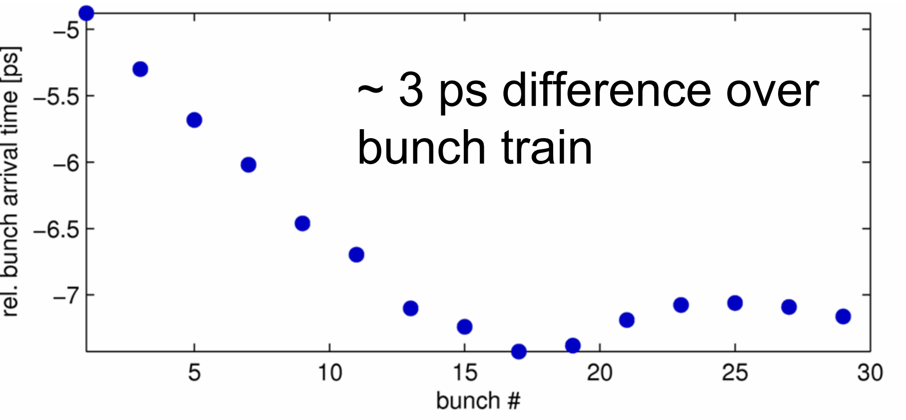

Integrated jitter of reference frequency (10 Hz – 100 kHz): ~ 120 fs

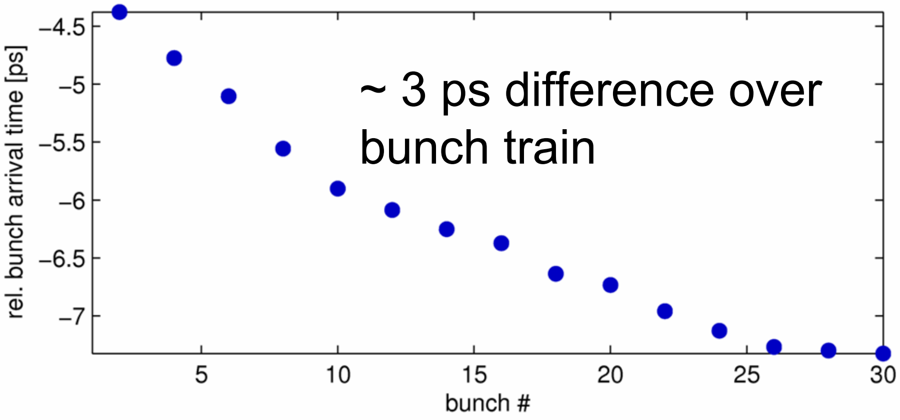
Integrated jitter of Fiber laser (10 Hz – 100 kHz): ~300 – 500 fs (depending on settings)

The synchronization has been improved meanwhile to about 150 fs jitter with respect to the reference.

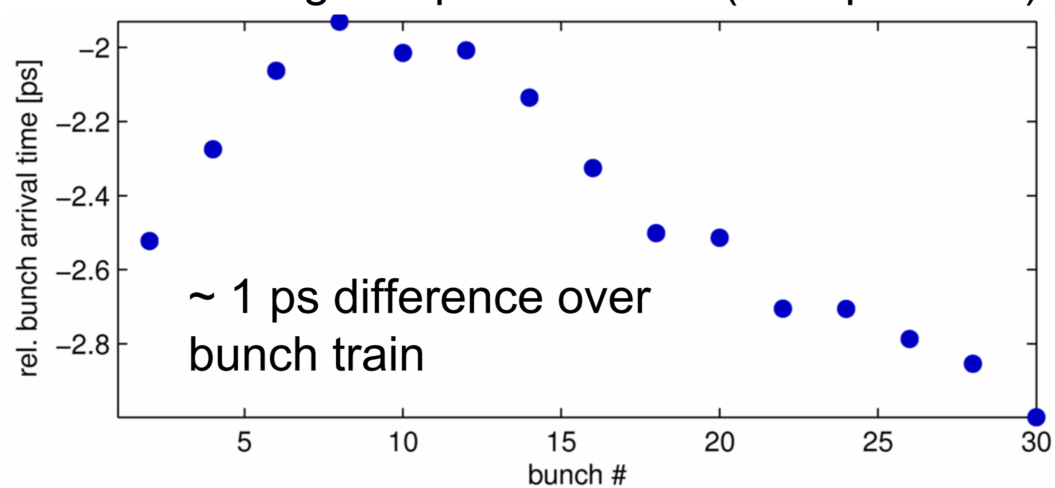
# Measurement of the bunch arrival time over the bunch train

Beam loading compensation off

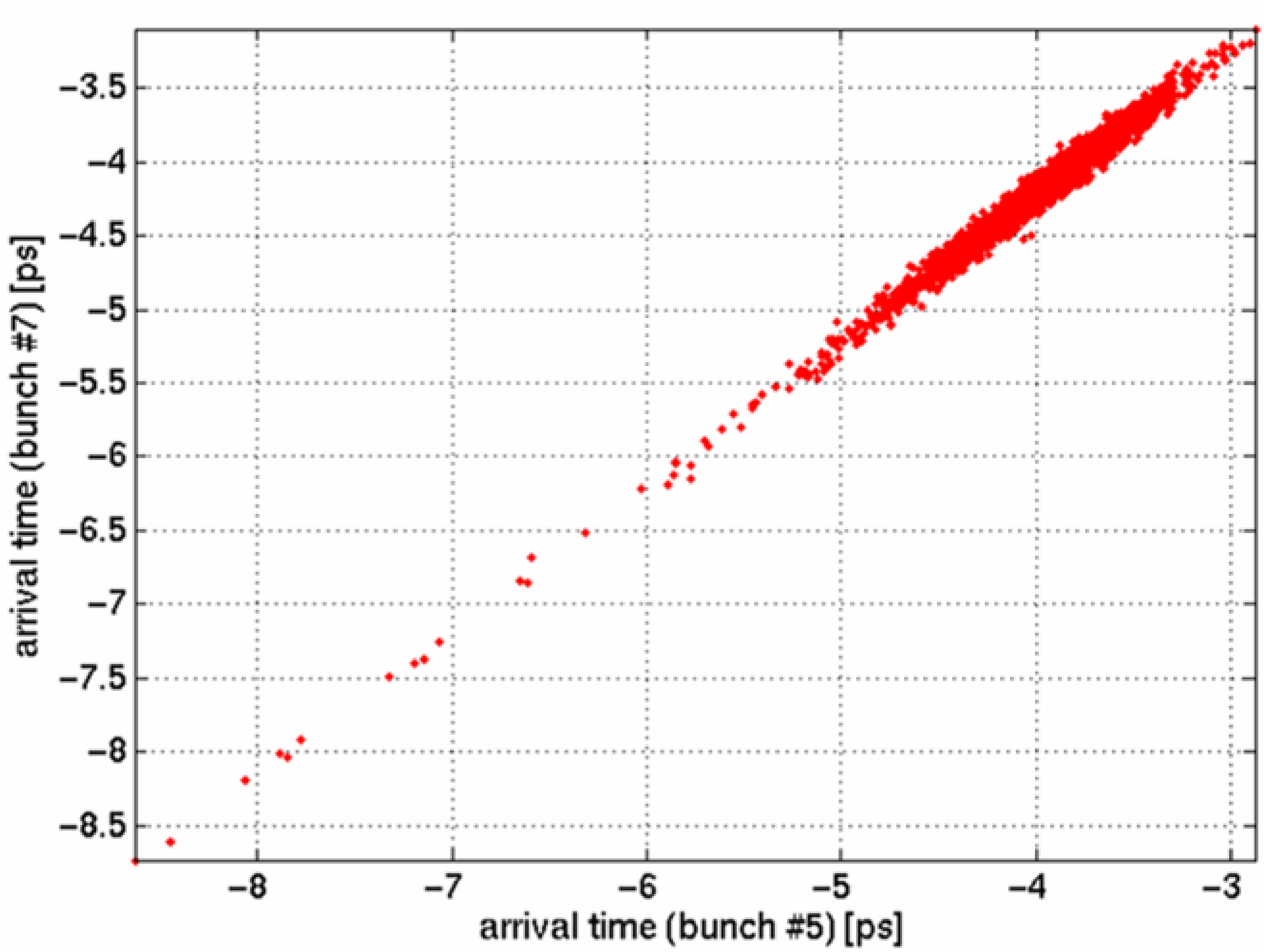



Beam loading compensation on (not optimized)



# Confirmation of high BAM resolution in spite of synchronization problem

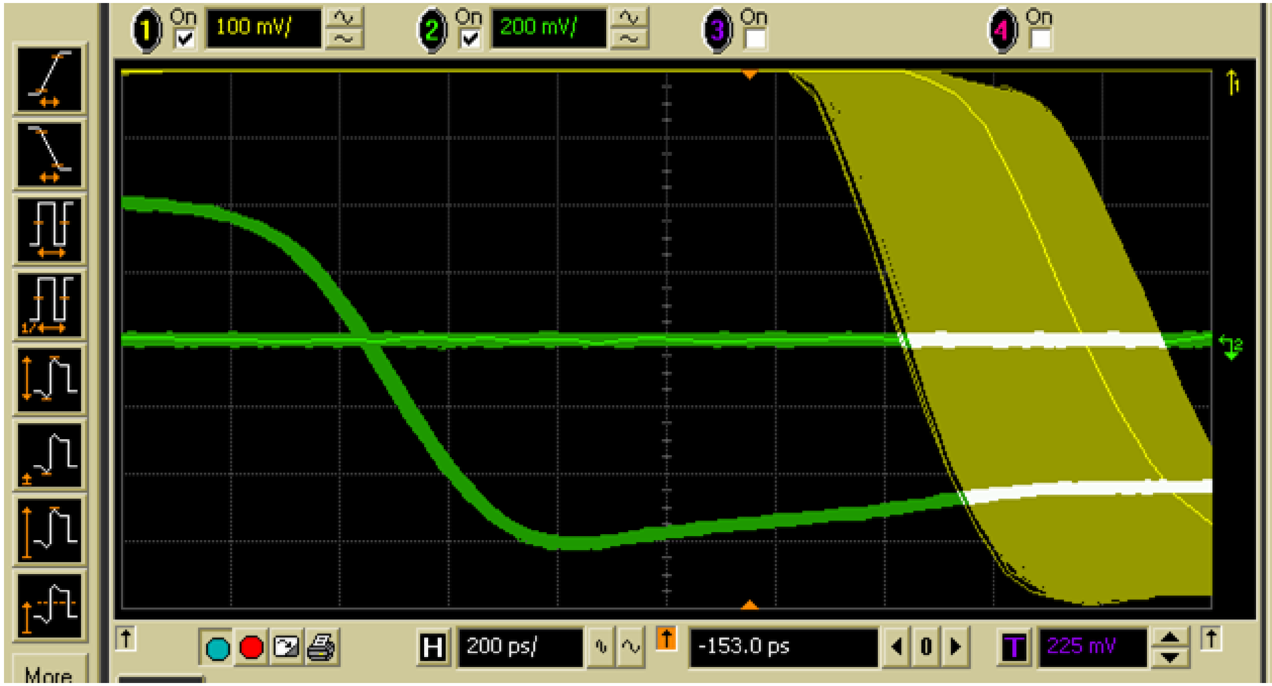



Jitter between two adjacent bunches: **~ 50 fs**

# Laser amplitude measurement: clock jitter of ADC board

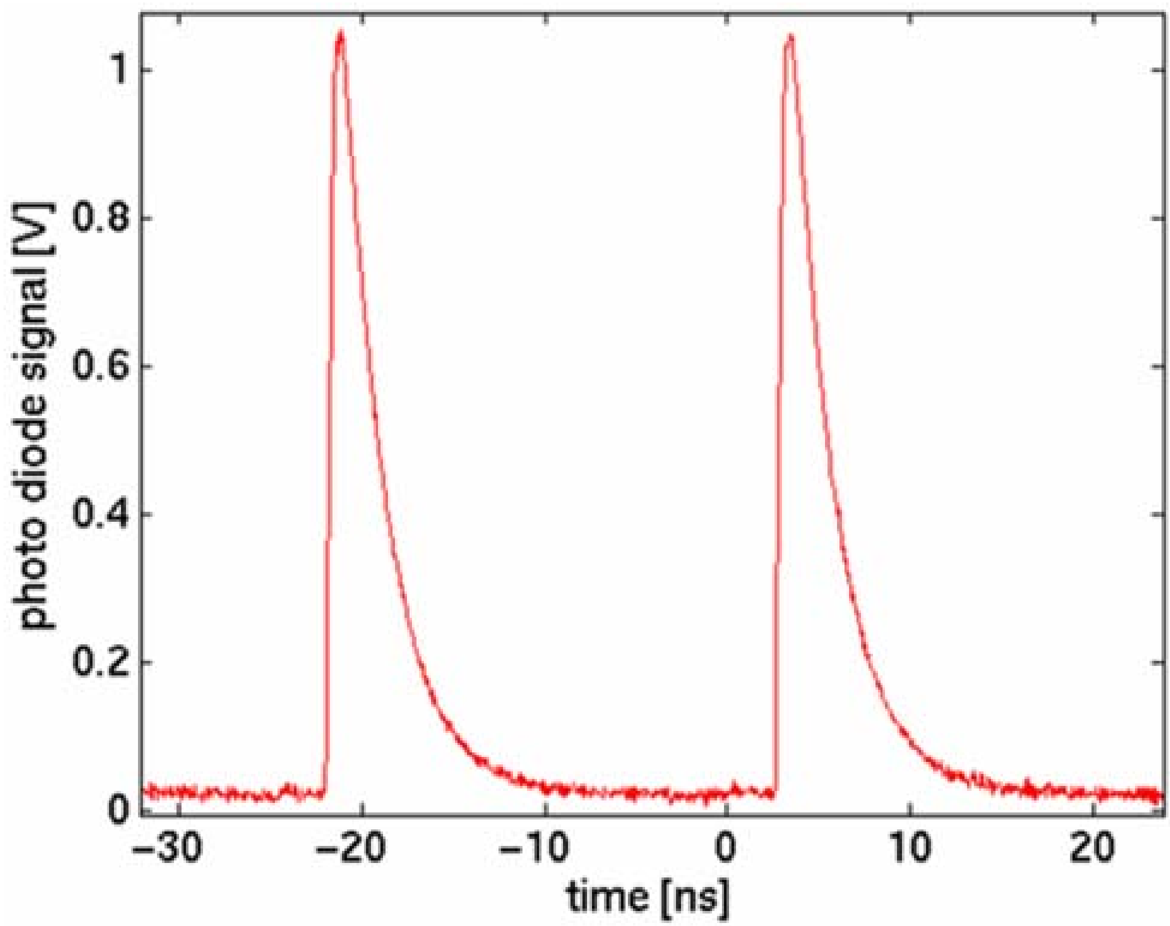
With the SIS ADC board which is currently used to detect the amplitude of the laser pulses the resolution is limited to about 0.2 % (best results was ~ 0.12 %).

Reason: Clock jitter of ADC board (~ 500 – 600 ps peak-peak)



# Laser Amplitude Measurement: Clock Jitter of ADC Board

Why does this clock jitter disturb our measurement?

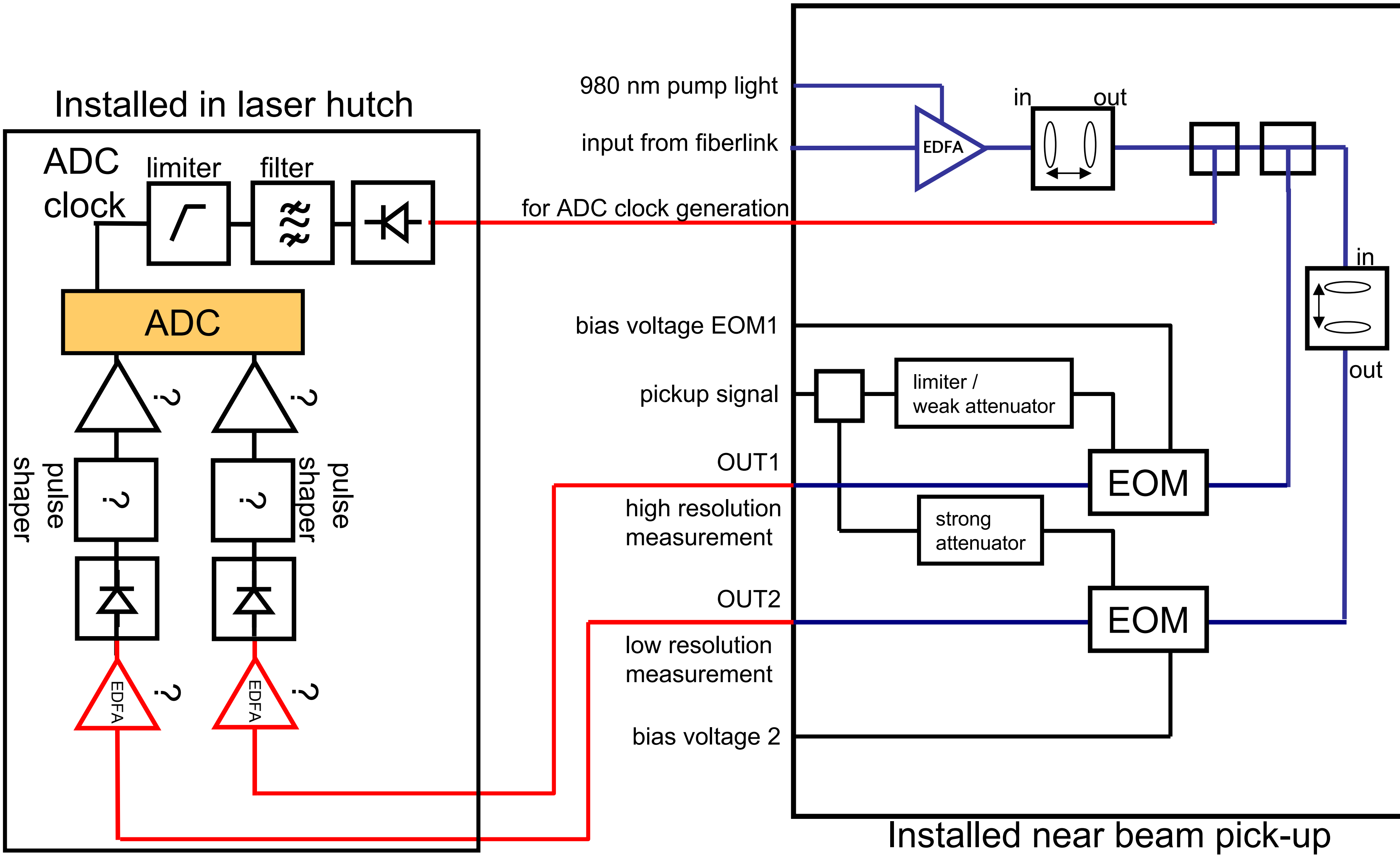



ADC samples different positions of the photo diode signal

- We need a small ADC clock jitter
- We have to stretch the pulse

With a better ADC (Linear Technology Eval board) the resolution of the readout recently could be improved to ~ 0.08 % (~62 dB). This could still be limited by noise on the PD supply voltage.

# Frontends for the BAM

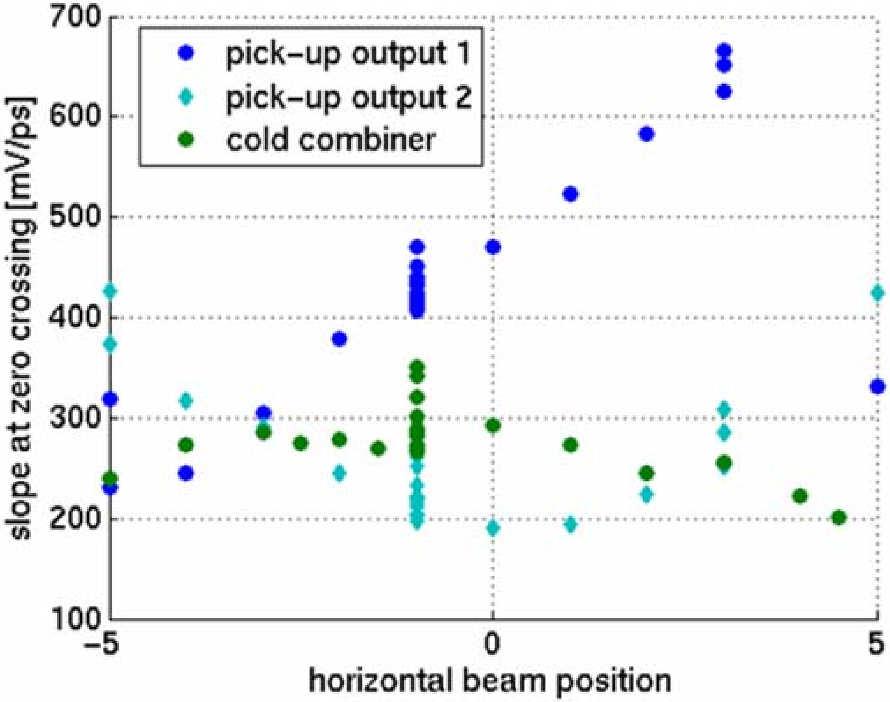


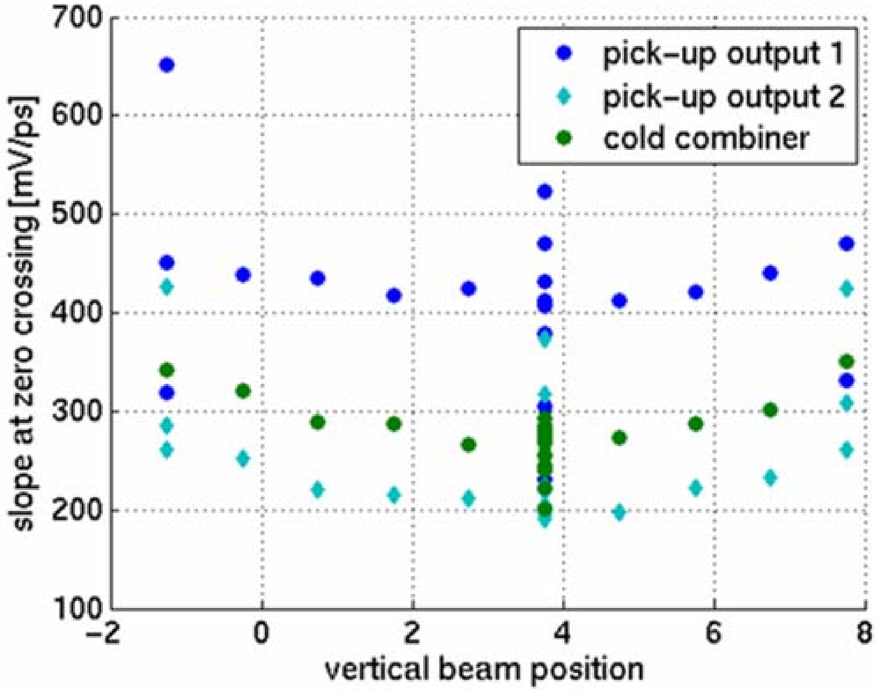
# Outlook

- The beam pick-up which is installed currently will be replaced by a faster one with a different characteristics: same slope at zero-crossing at much lower peak voltage (design by K. Hacker).
- The same measurement technique will be used for the large aperture BPMs in the chicanes (K. Hacker) and for the laser arrival time monitor (LAM) for the injector laser (K.H. Matthiesen).
- Development of the BAM / BPM / LAM front-ends for the installation in the tunnel is ongoing
- Development of fast ADC board (108 MHz, 16 bit) has been started (F. Ludwig, H.J. Wentzlaff)
- Study on readout system for the laser amplitude is ongoing to improve the resolution of the system further.

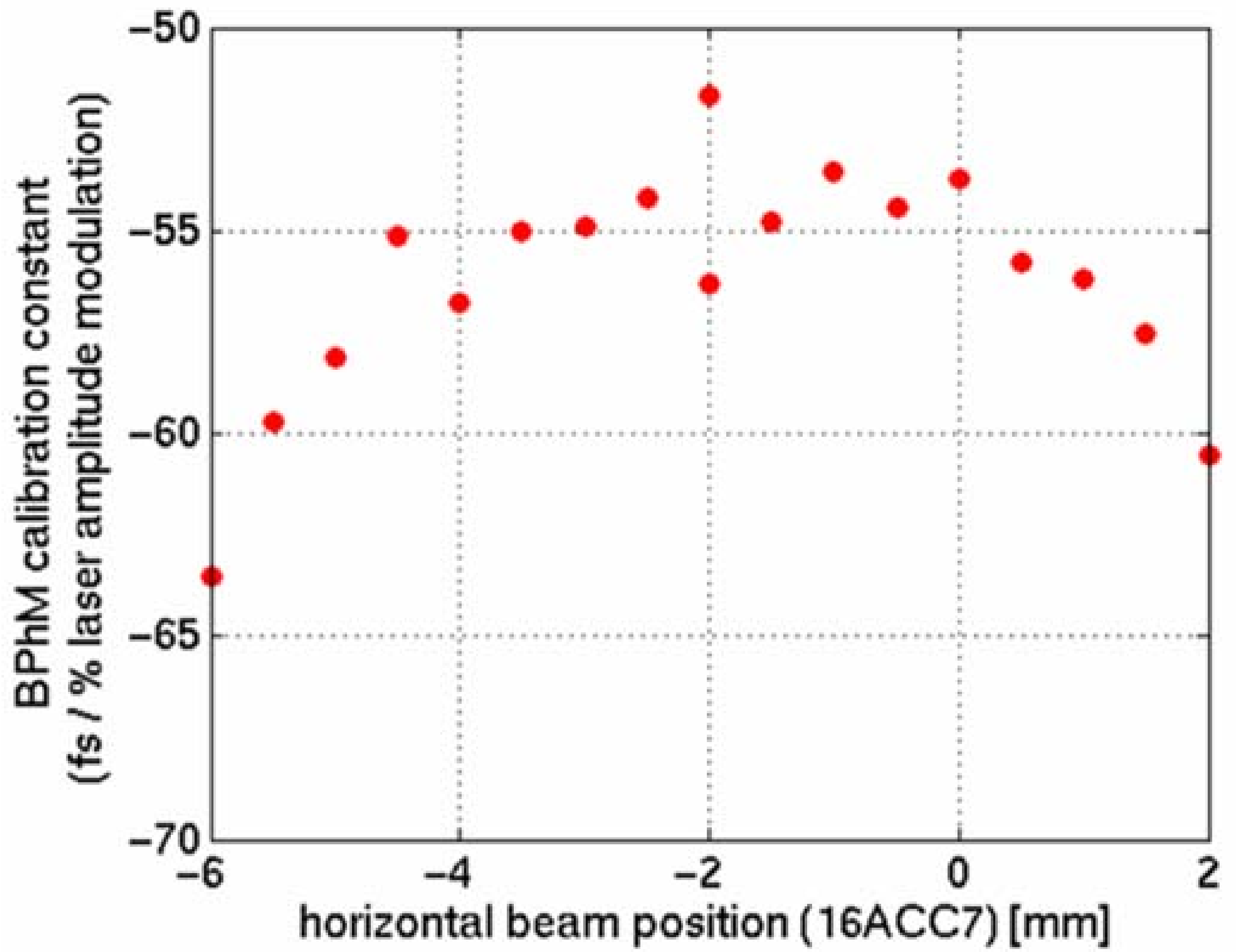
Thank you!

# Dependence of slope of beam pick-up signal on beam position

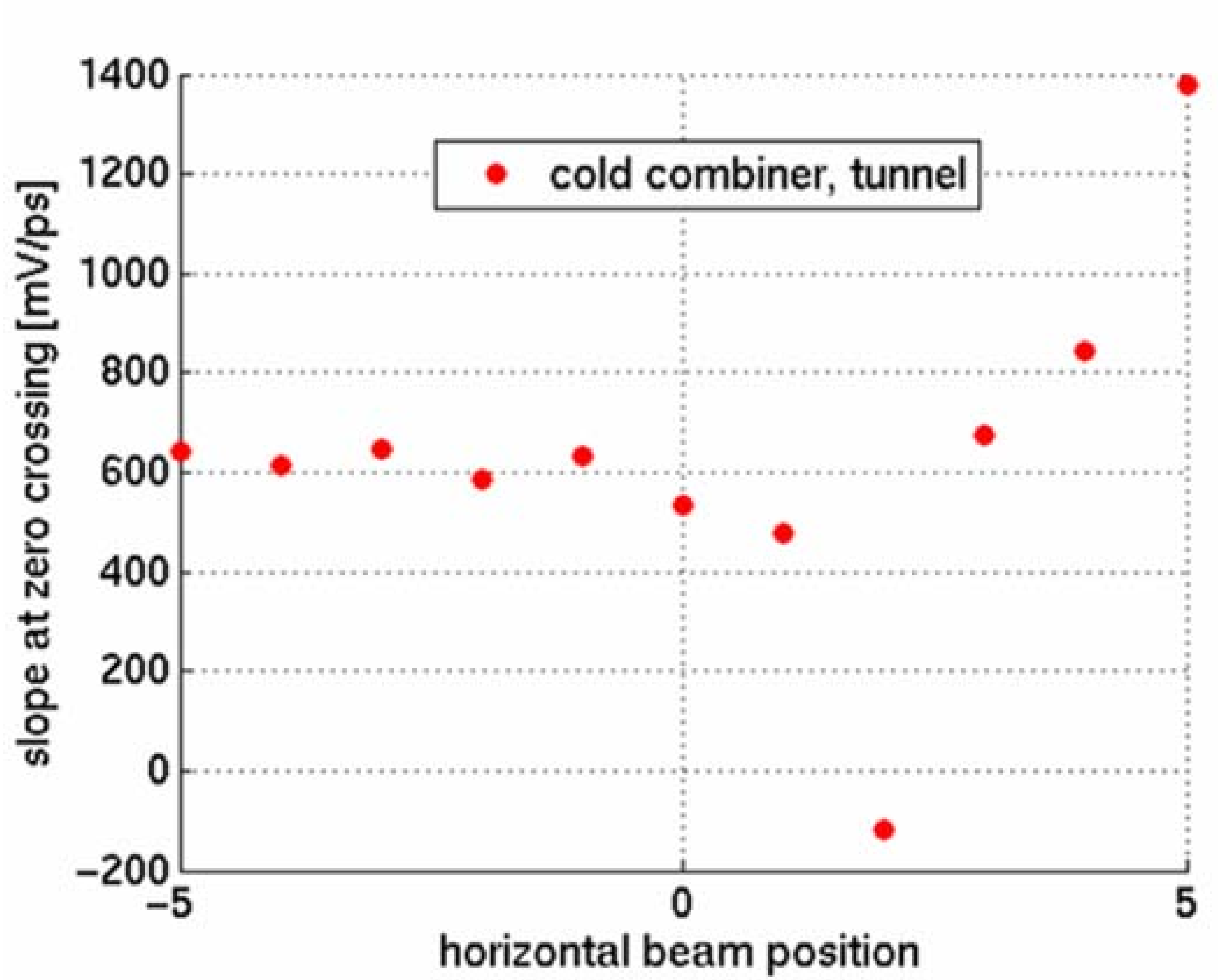


# Dependence of slope of beam pick-up signal on beam position



# Measurement of pick-up signal in the tunnel




But: EOMs die when the voltage is too high…
→ Limiter or weaker signal needed