A sub-100 fs electron bunch arrival-time monitor system for FLASH

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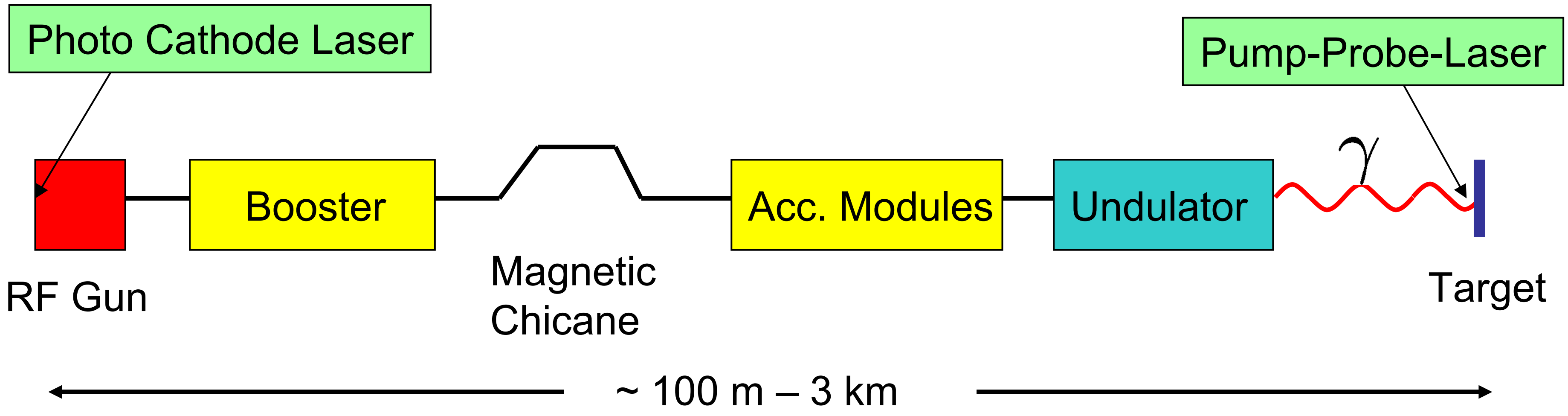
Main Sources of Timing Jitters in FEL Facilities



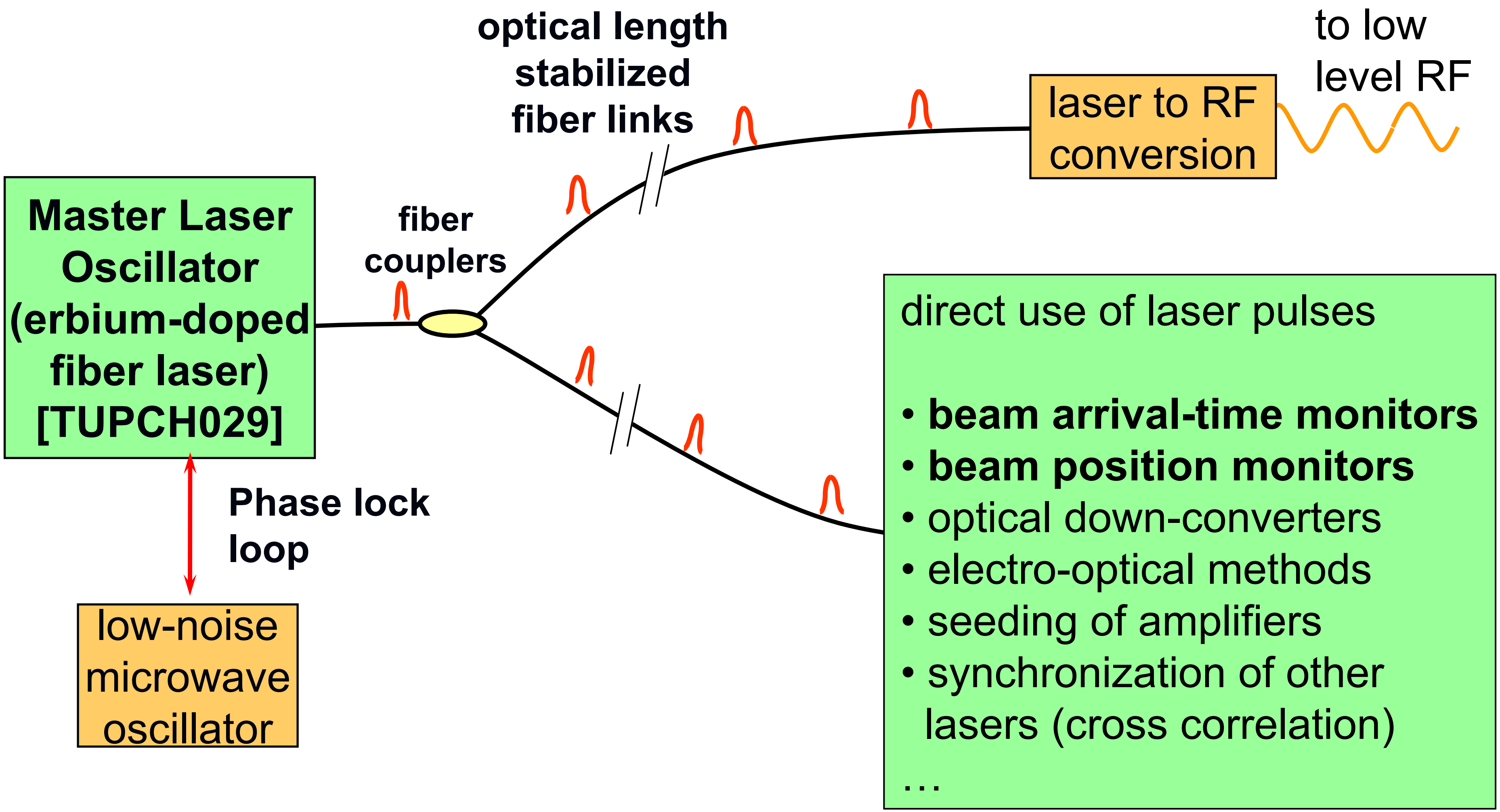
Main sources of γ-ray arrival-time changes

- Arrival-time of photo cathode laser pulses
- Phase of RF gun
- Amplitude and phase of Booster module
- Arrival-time of pump-probe laser

First Goals

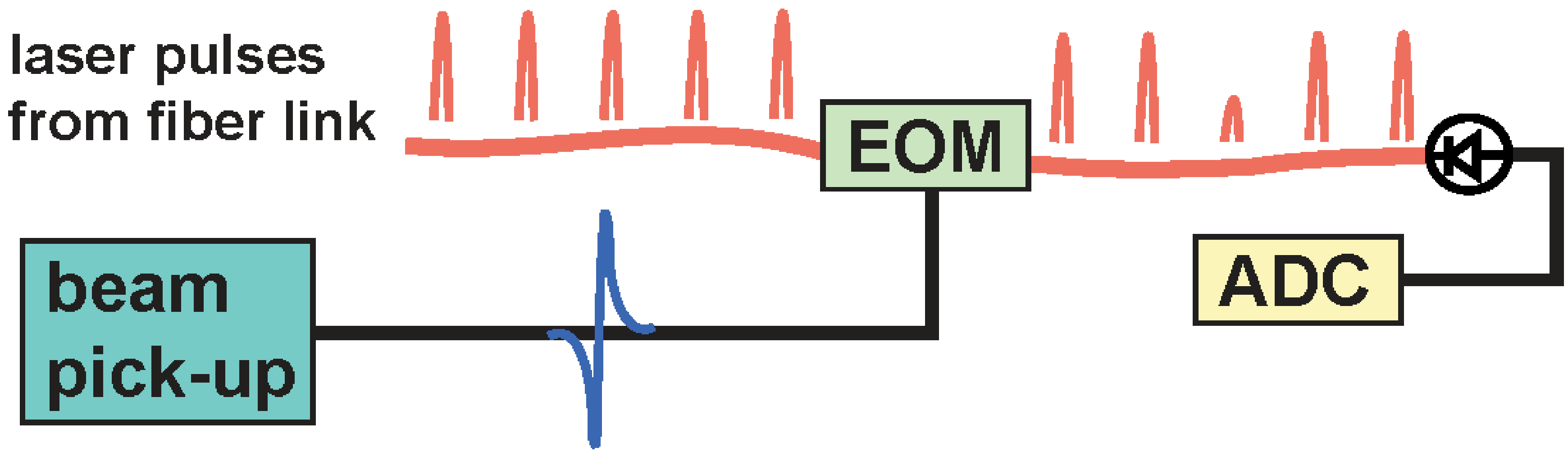
1) Improve timing stability of machine by a new, optical timing system
2) Measure electron bunch arrival-time to post-order data sets
3) Identify and reduce major sources of arrival-time jitter

Optical Timing System

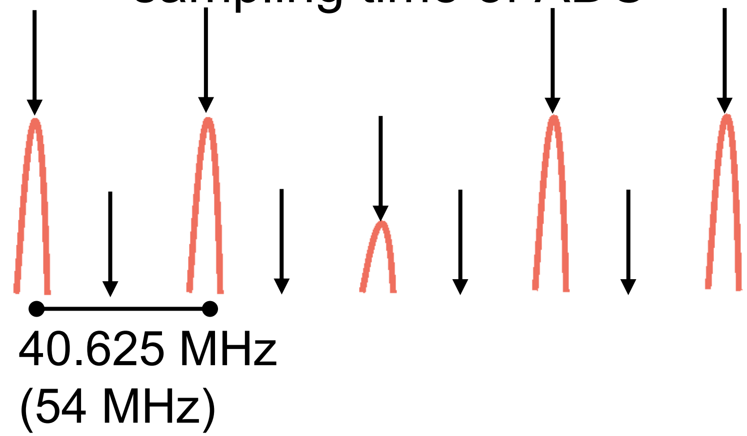


See [TUPCH028], [THOPA03]

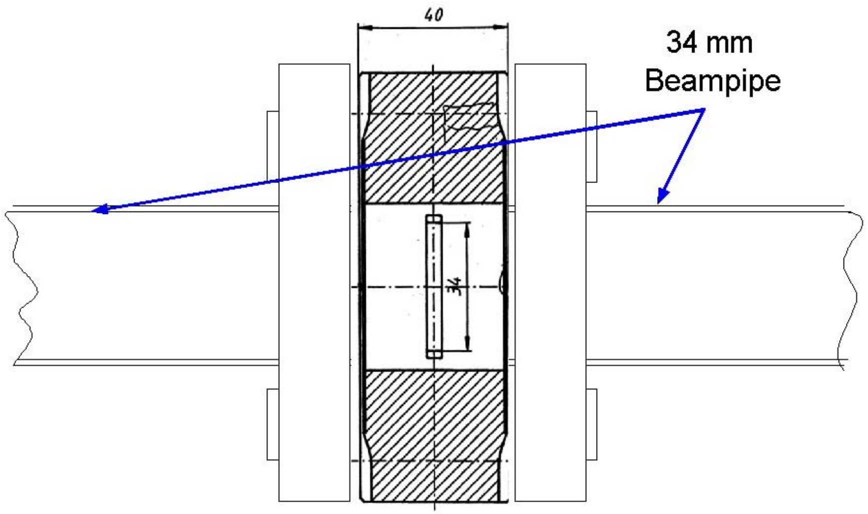
Principle of the Arrival Time Detection

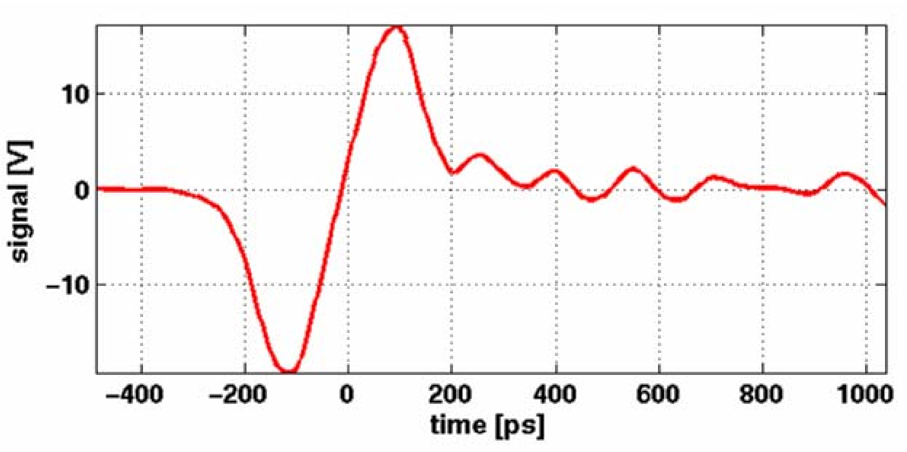


The timing information of the electron bunch is transferred into an amplitude modulation. This modulation is measured with a photo detector and sampled by a fast ADC.



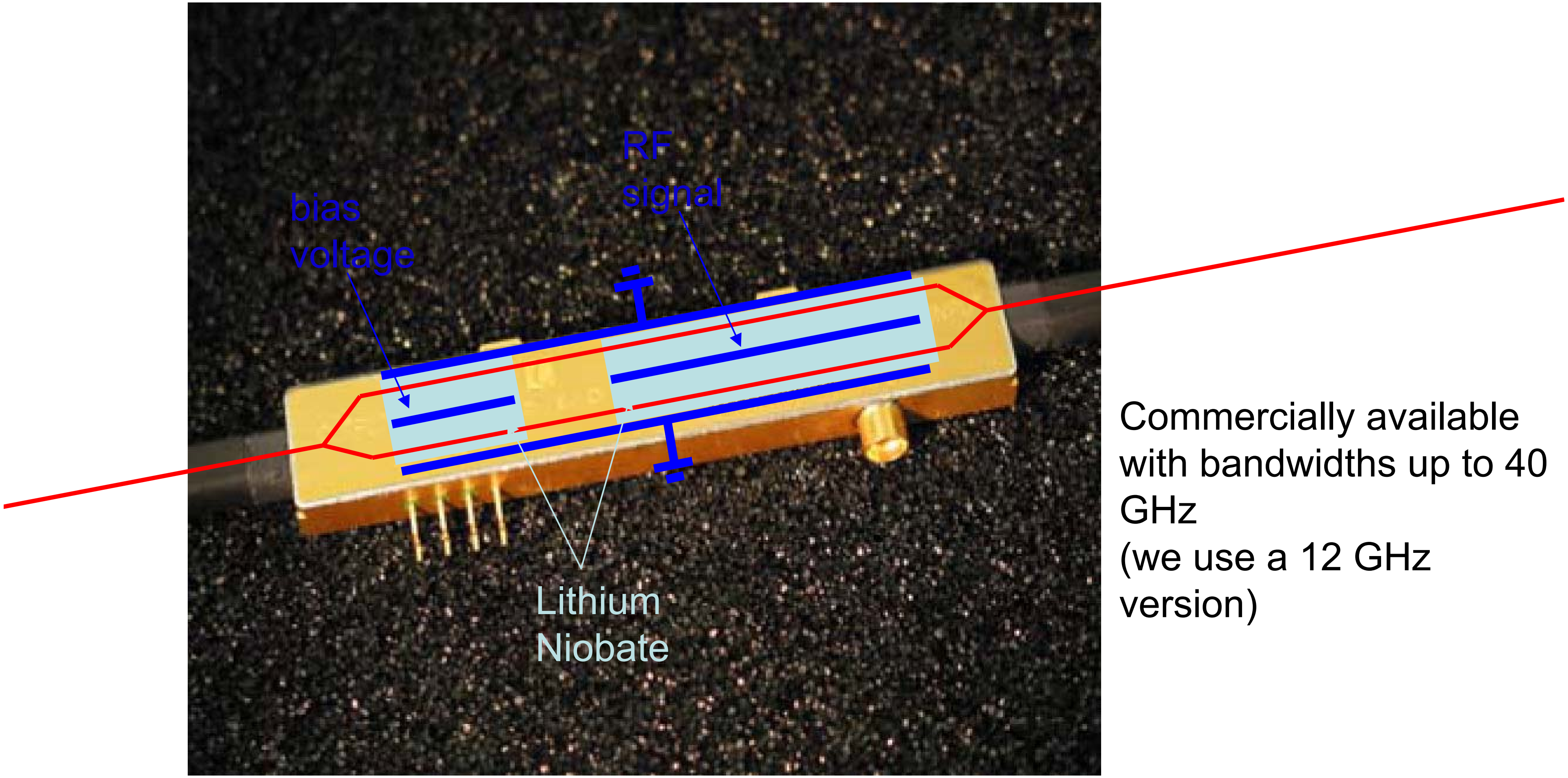
Beam Pick-up





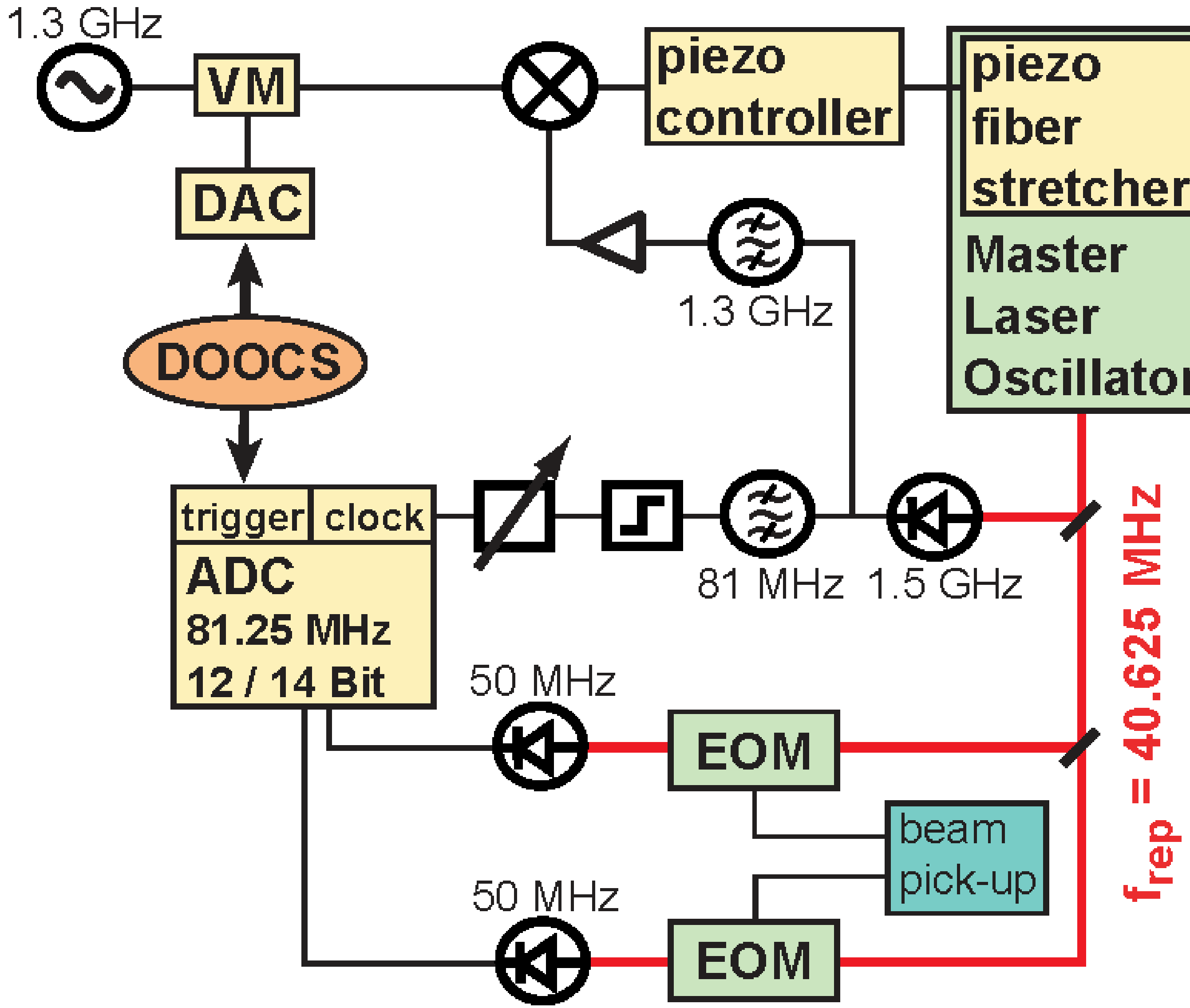
- Isolated impedance-matched ring electrode installed in a „thick Flange“
- Broadband signal with more than 5 GHz bandwidth
- Sampled at zero-crossing with laser pulse

Electro-Optical-Modulator (EOM)

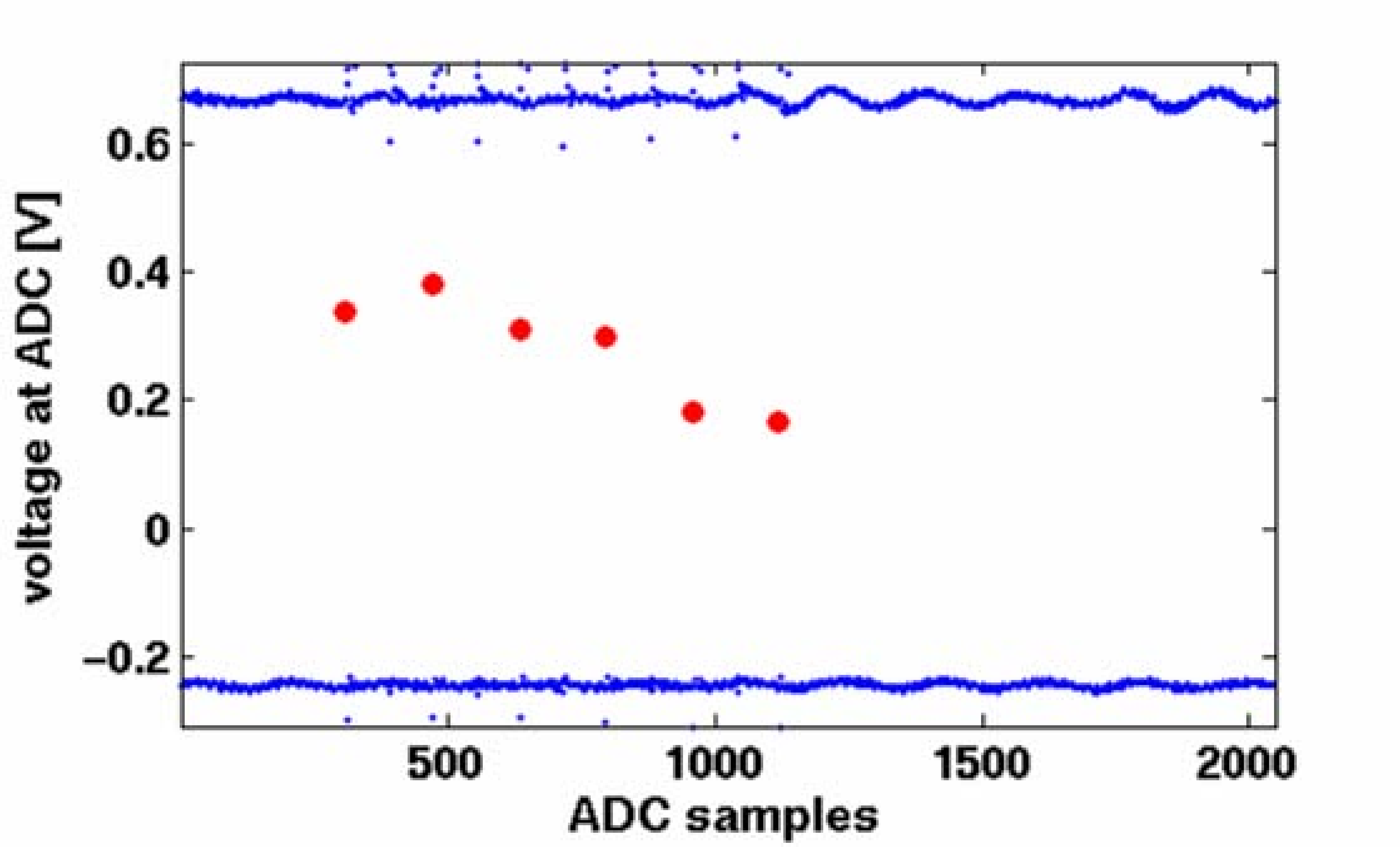


Commercially available with bandwidths up to 40 GHz
(we use a 12 GHz version)

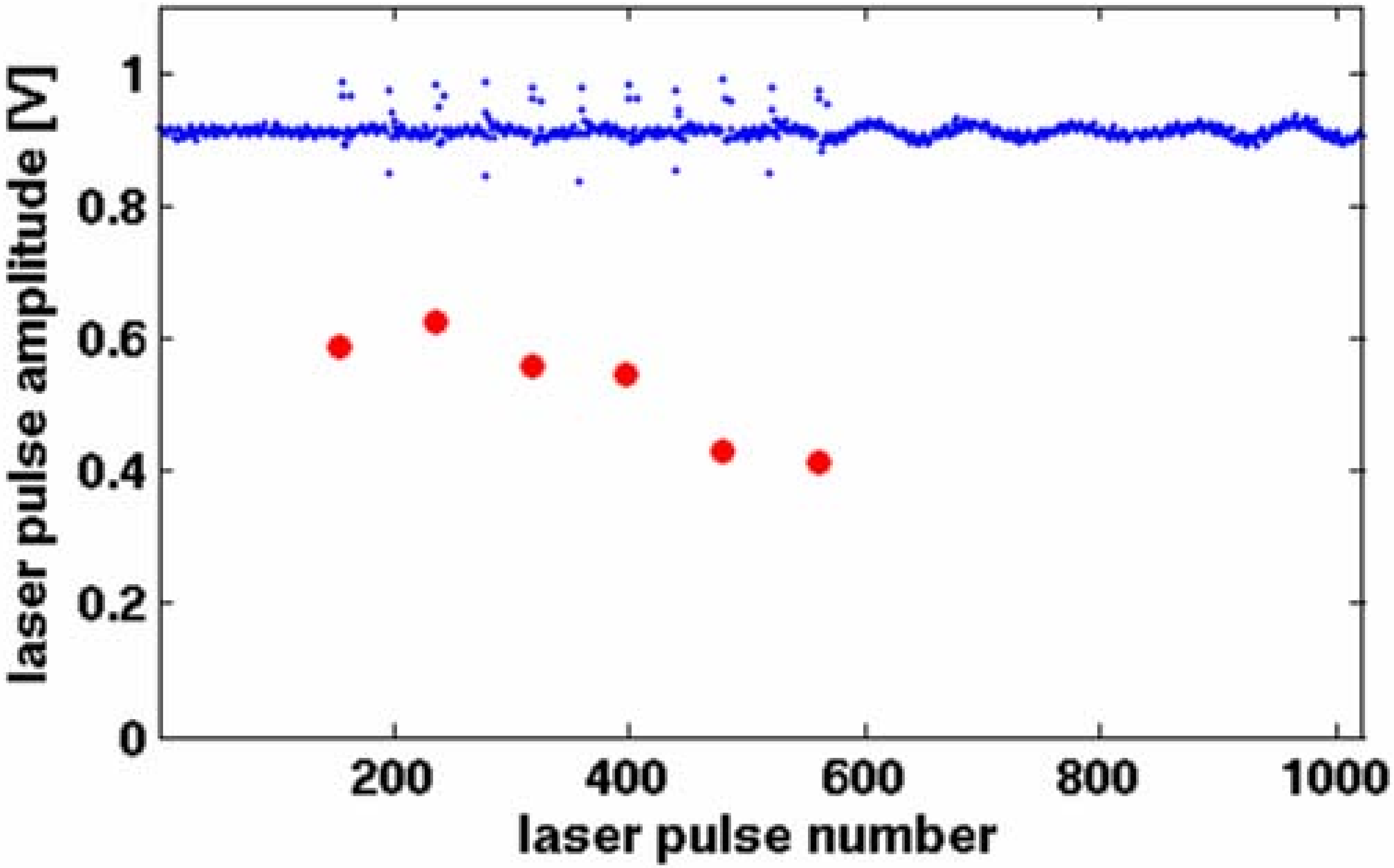
Test Bench for the Arrival-time Monitor System



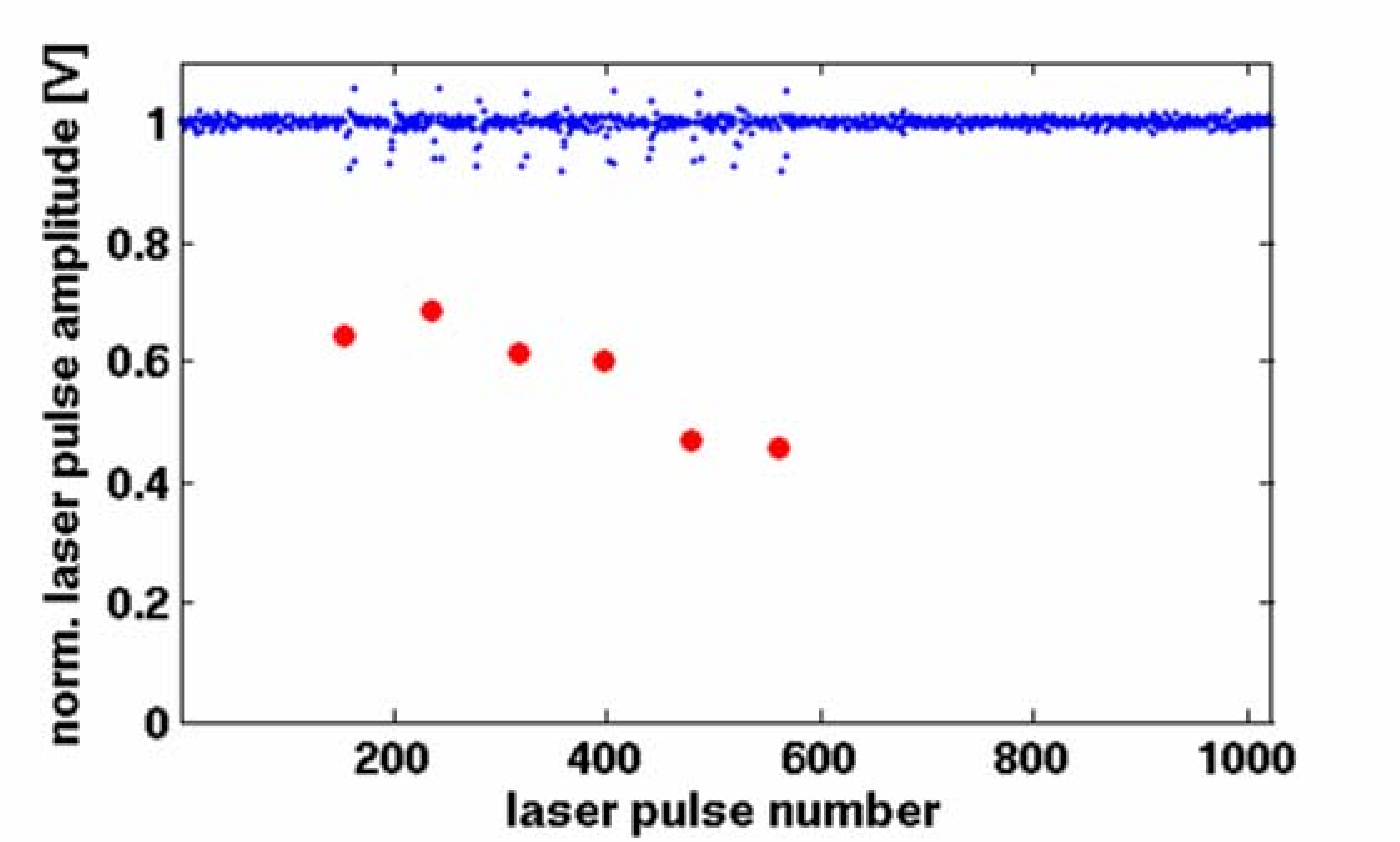
Raw Data of EOM Detector Signal



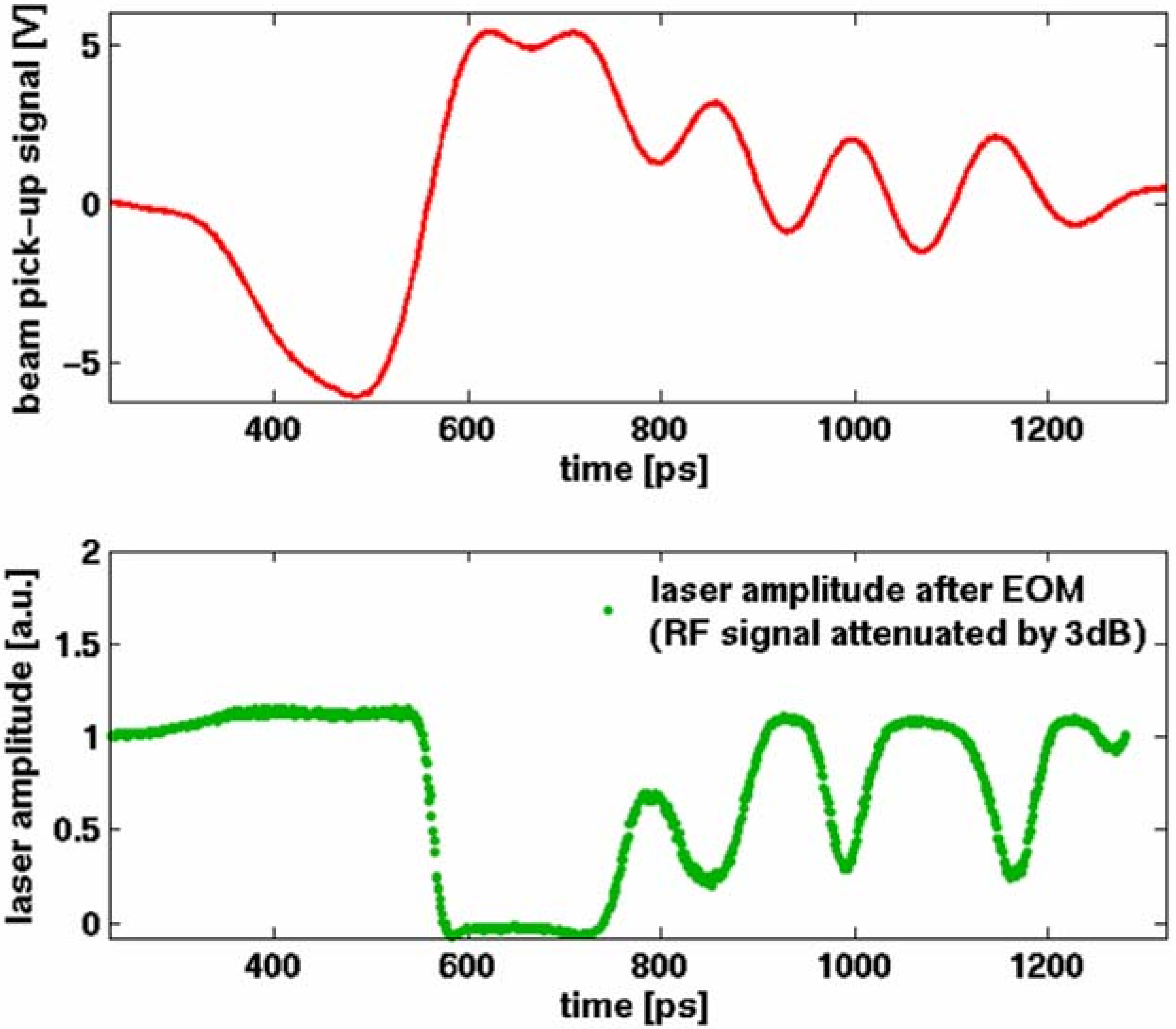
Amplitude of Laser Pulses



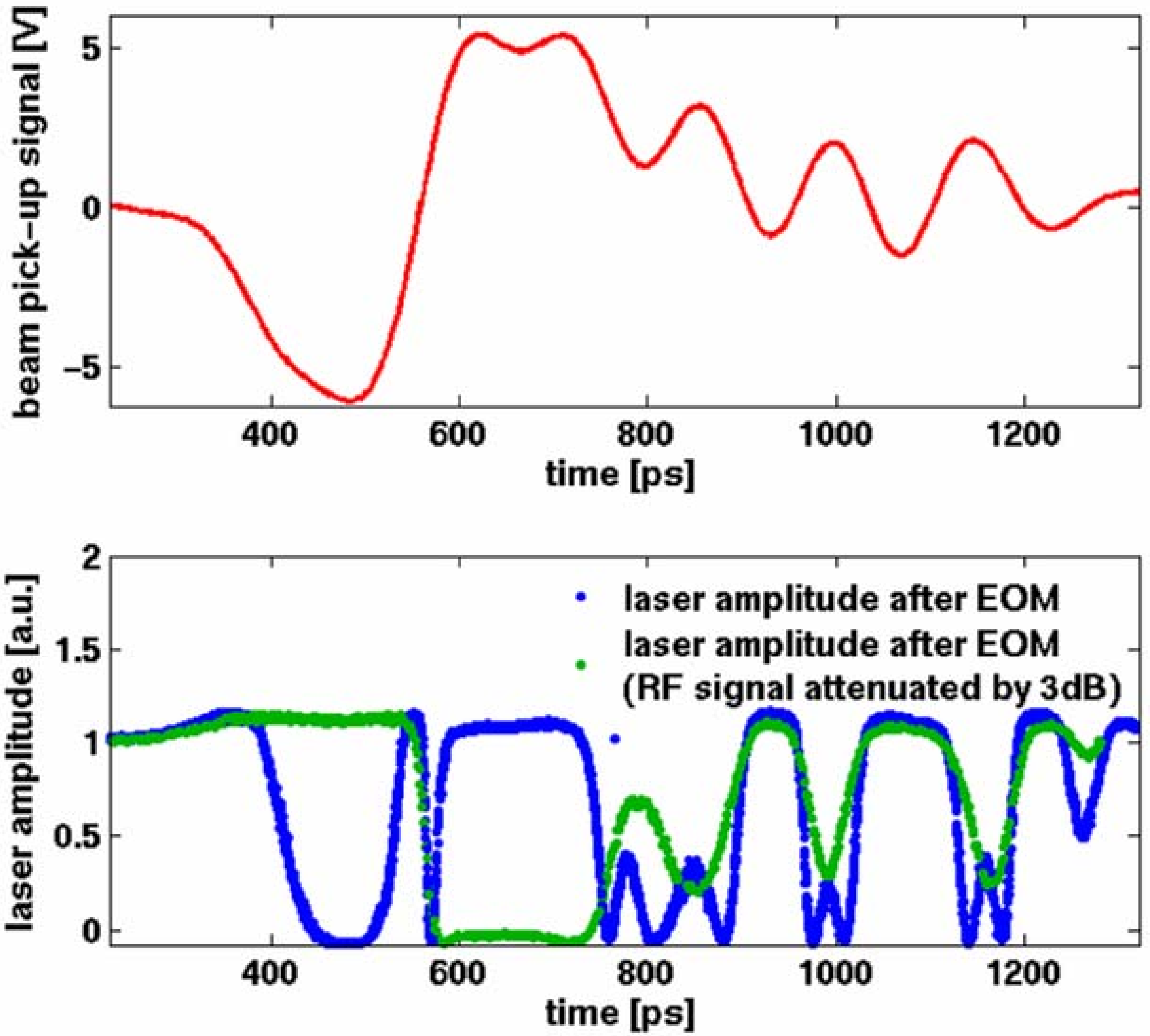
Amplitude of Laser Pulses (normalized)



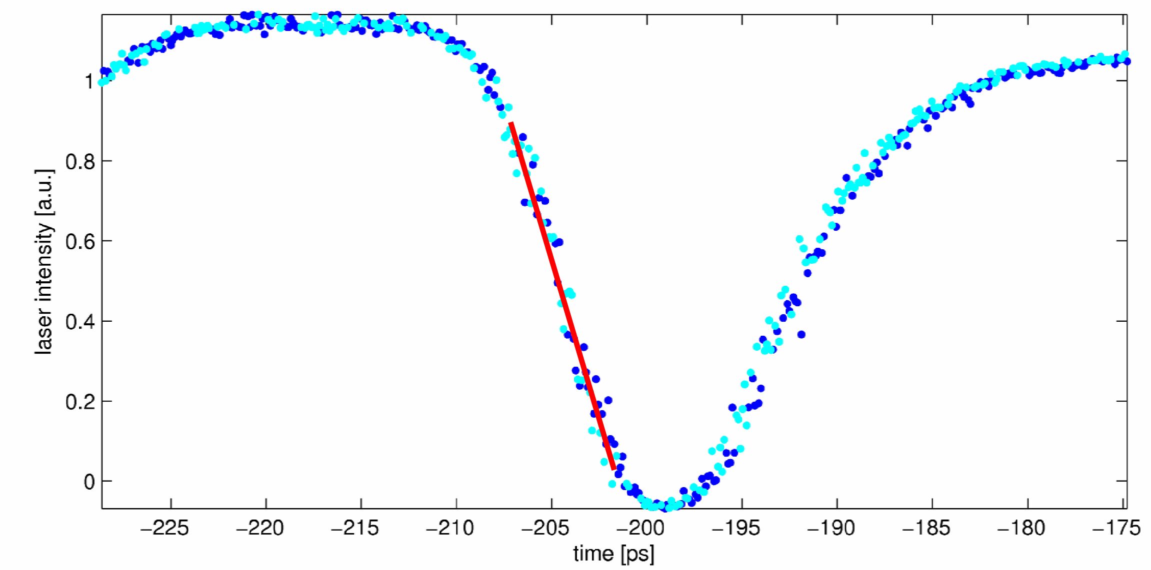
Scan of Laser Pulse over Beam Pick-up Signal



Scan of Laser Pulse over Beam Pick-up Signal



Calibration and Resolution of the EOM Detectors



The resolution can be estimated from the slope of the phase monitor signal and the amplitude noise on the not modulated laser pulses:

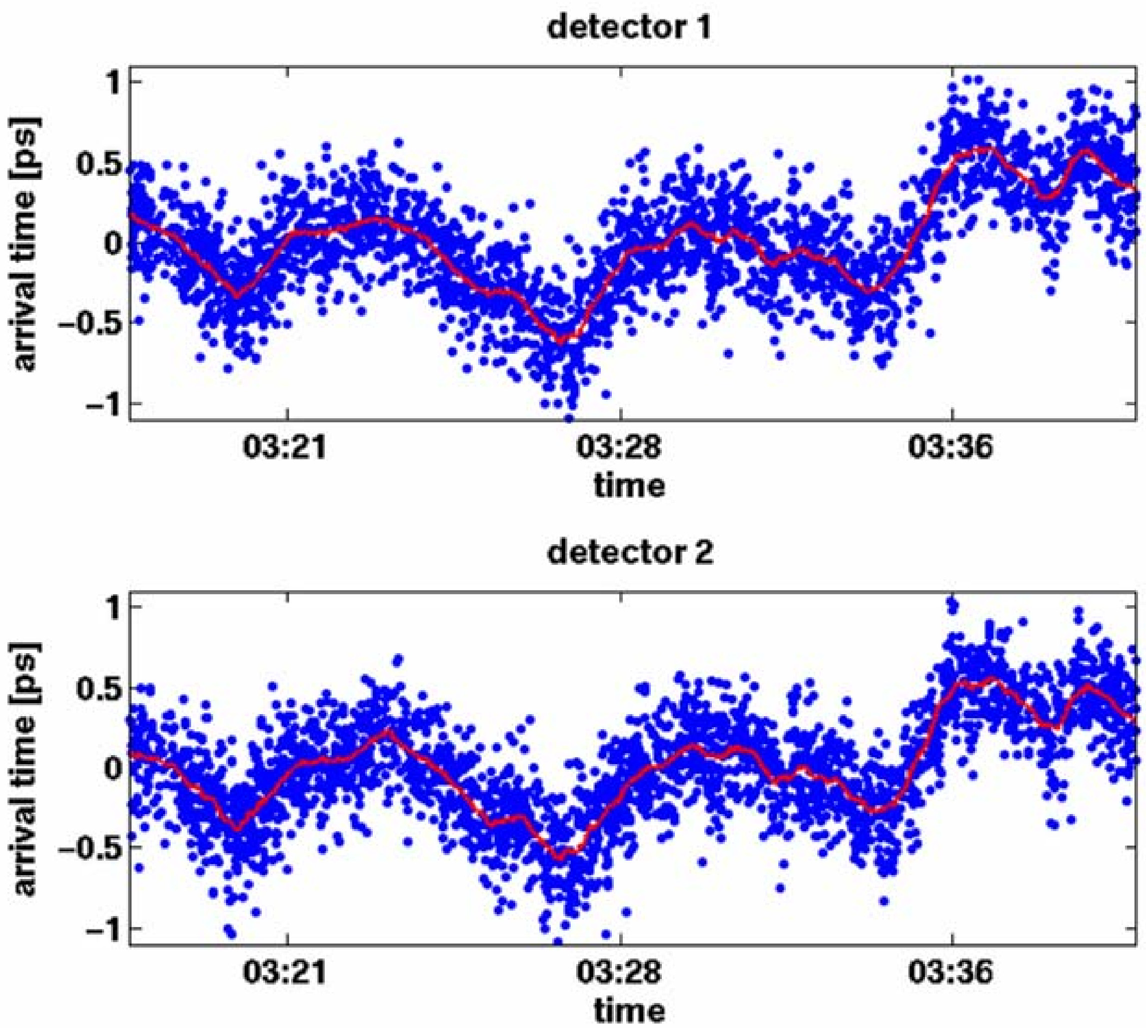
Typical values are:

Slope:
~ 60 - 100 fs / (% modulation)

Laser amplitude detection:
rms ~ 0.2 – 0.3 %

➢ Resolution of EOM detectors:
~ 20 - 50 fs

Comparison Measurement between two Arrival-time Detectors



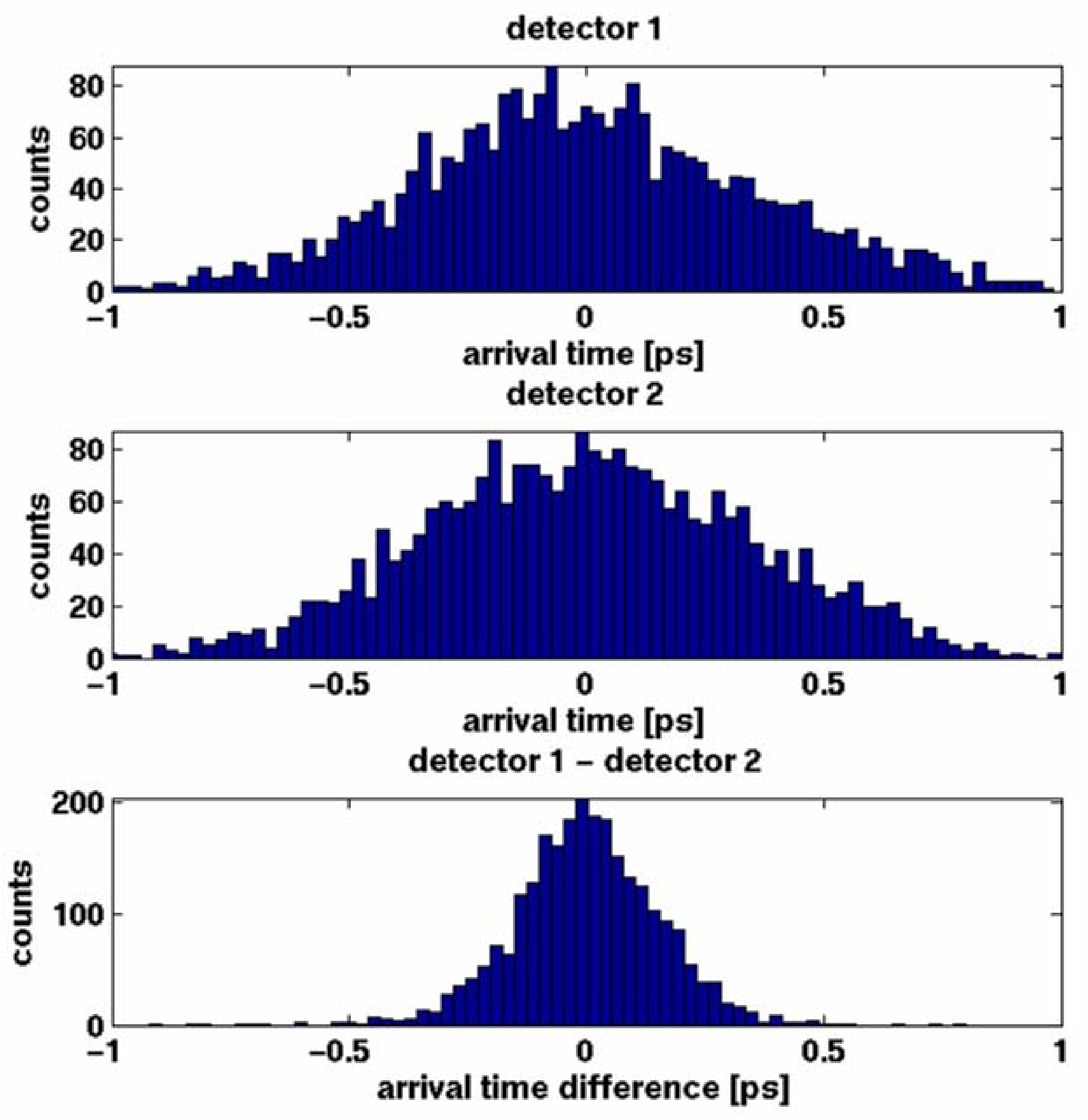
The signal of the beam pick-up was split and connected to the two EOM detectors.

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**

Comparison Measurement between two Arrival-time Detectors



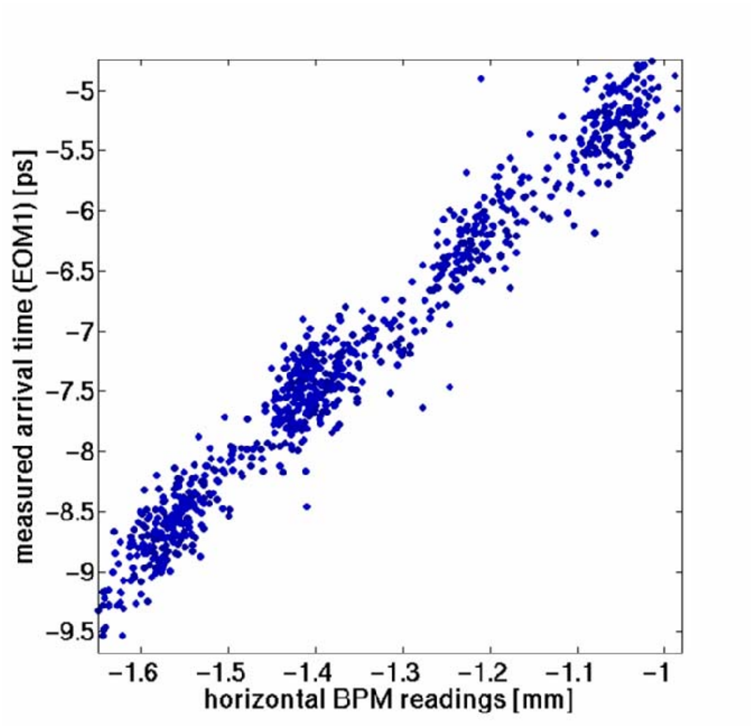
	rms jitter
Detector 1	**357 fs**
Detector 2	**342 fs**
Det. 1 – Det. 2	**139 fs**

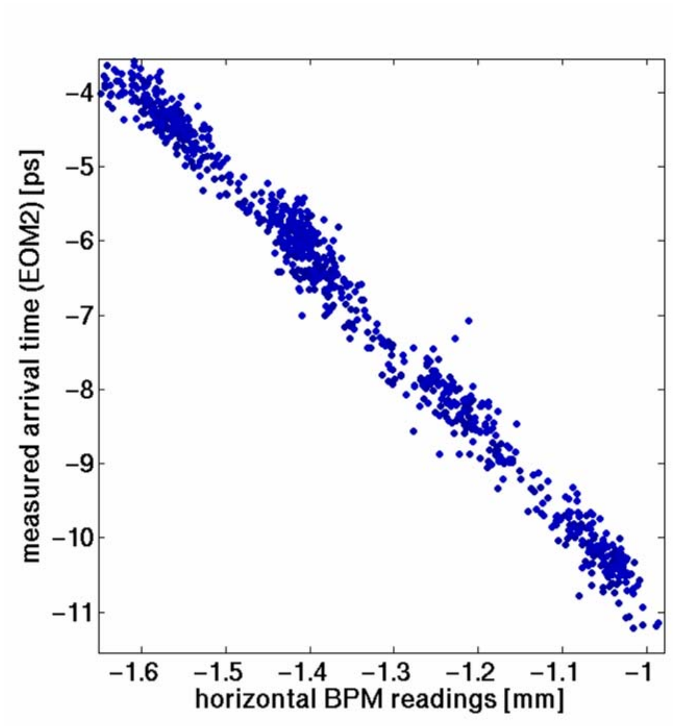
Position Dependence of the Beam Pick-up Signal

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).

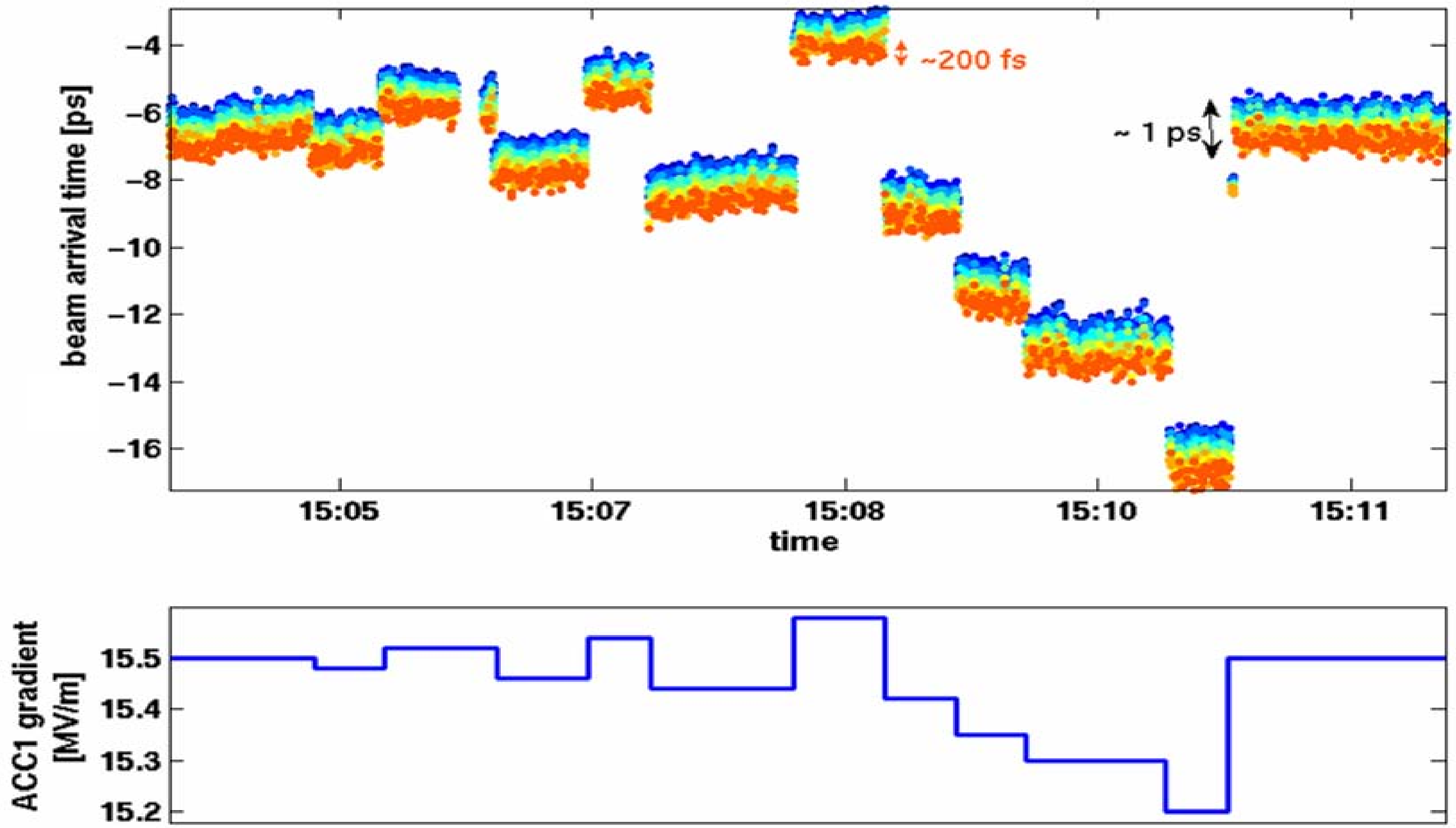
However, we can use the EOM detectors to measure the horizontal beam position:

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

An 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).

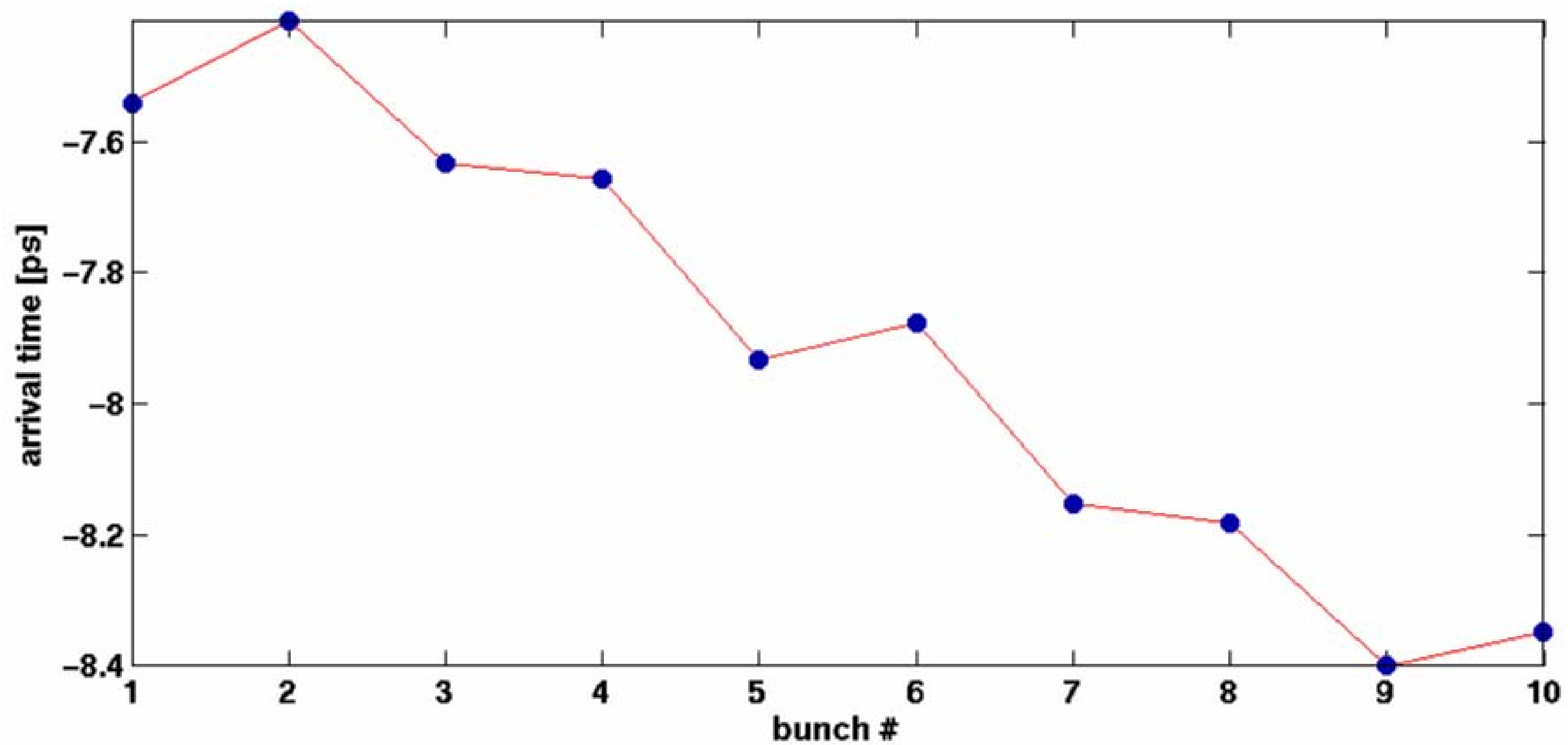
This precise beam position we can use to reduce the error in the arrival time from ~ 300 fs to below 30 fs (rms).

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

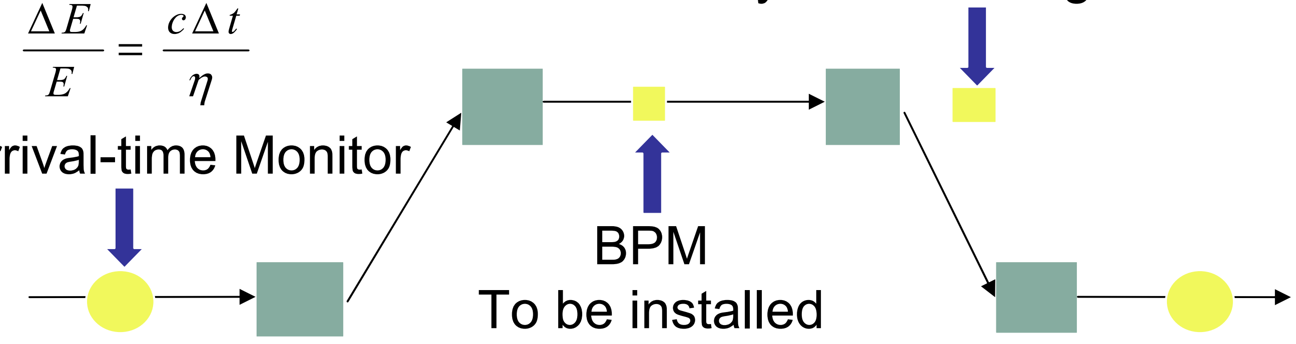
Beam Arrival-time Measurement



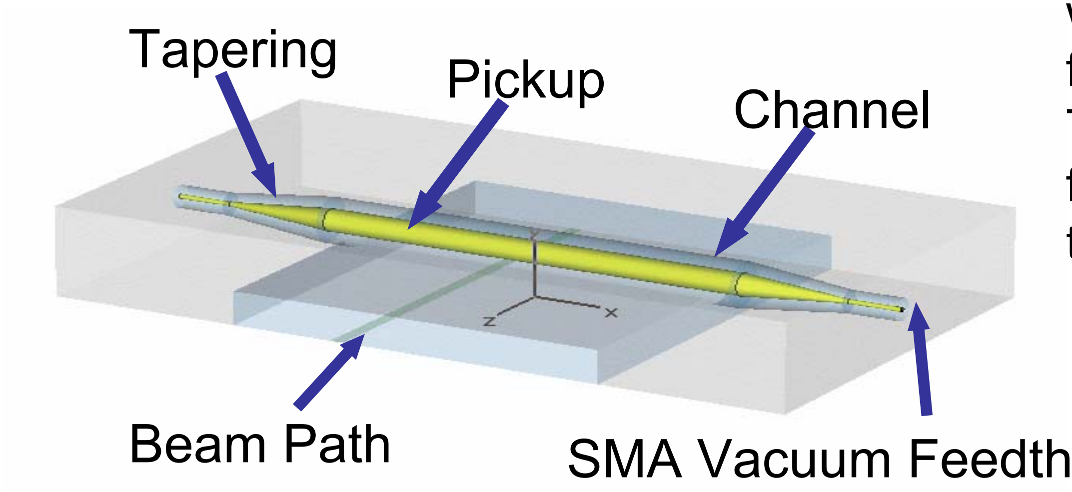
250 kHz oscillation of arrival time visible.
(intermediate frequency of down-converters for cavity RF regulation)

BPM with Large Horizontal Aperture for Magnetic Chicanes

$$\frac{\Delta E}{E} = \frac{c\,\Delta t}{\eta}$$

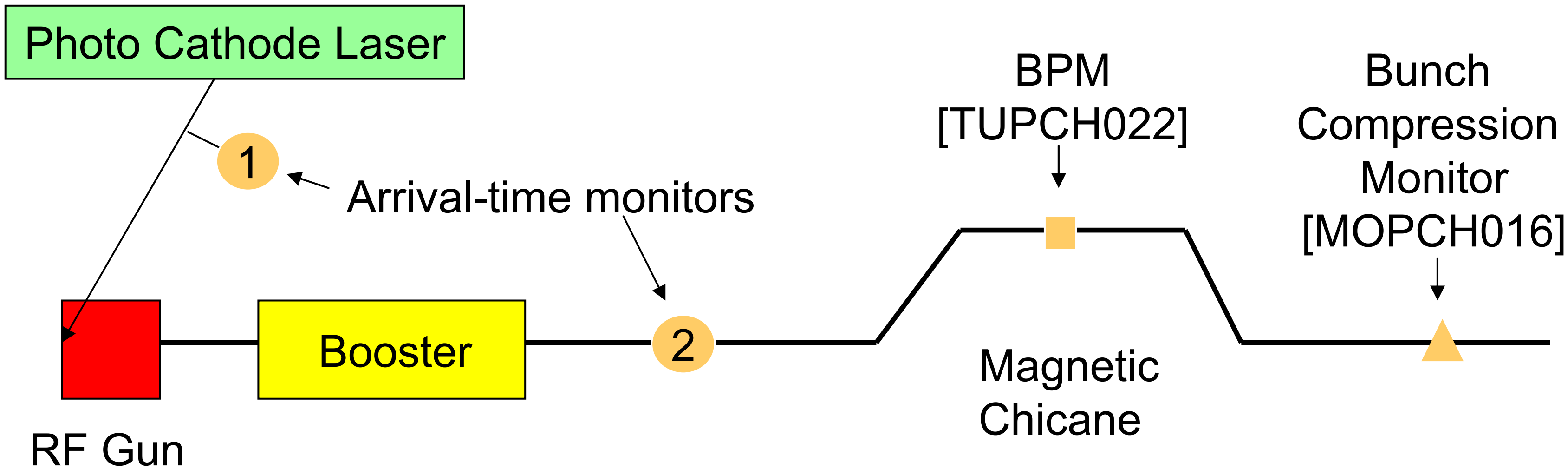


The arrival time of the pickup signals at both ends is measured with the same technique as used for the beam arrival time monitor. The beam position is determined from the difference of both arrival times.



Courtesy of
K. Hacker (DESY)

Identification of Sources for Arrival-time Changes



Detection of main arrival-time jitter sources

- Arrival time of photo cathode laser pulses **(1st arrival time monitor)**
- Phase of RF gun **(difference between 1st and 2nd arrival time monitor)**
- Amplitude of Booster module **(BPM in magnetic chicane)**
- Phase of Booster module **(Bunch Compression Monitor)**
- Arrival time of pump-probe laser **(cross-correlation with timing system)**

Summary

- We have demonstrated a new measurement method which is suitable to analyse fast electrical transients with very high precision. This technique can be used for example for:
  - Beam arrival time monitors
  - Beam position monitors
  - Optical down-converters
  - photo detector signals for arrival time measurements of lasers

- A resolution of ~ 30 fs for the beam arrival time measurement was achieved with the potential to reach sub-10 fs level.

- The orbit dependence of the beam pick-up allowed us to demonstrate the principle of beam position measurements with this technique.