Optical Synchronization Techniques for VUV and X-Ray Free Electron Lasers

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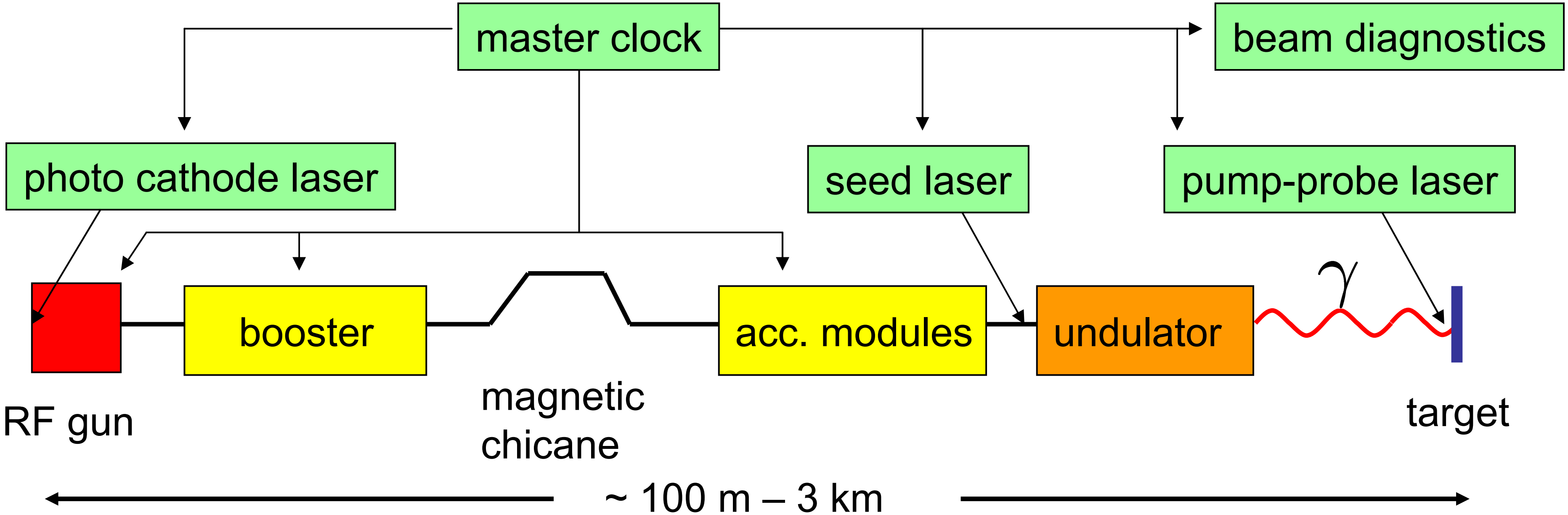
Outline

- Motivation
- The synchronization system at FLASH
  - laser system
  - distribution unit
  - fiber links, Er-doped fiber amplifiers
  - endstations:
    - bunch arrival time monitor
    - locking of external lasers
    - laser to RF conversion

Synchronization needs in an FEL facility



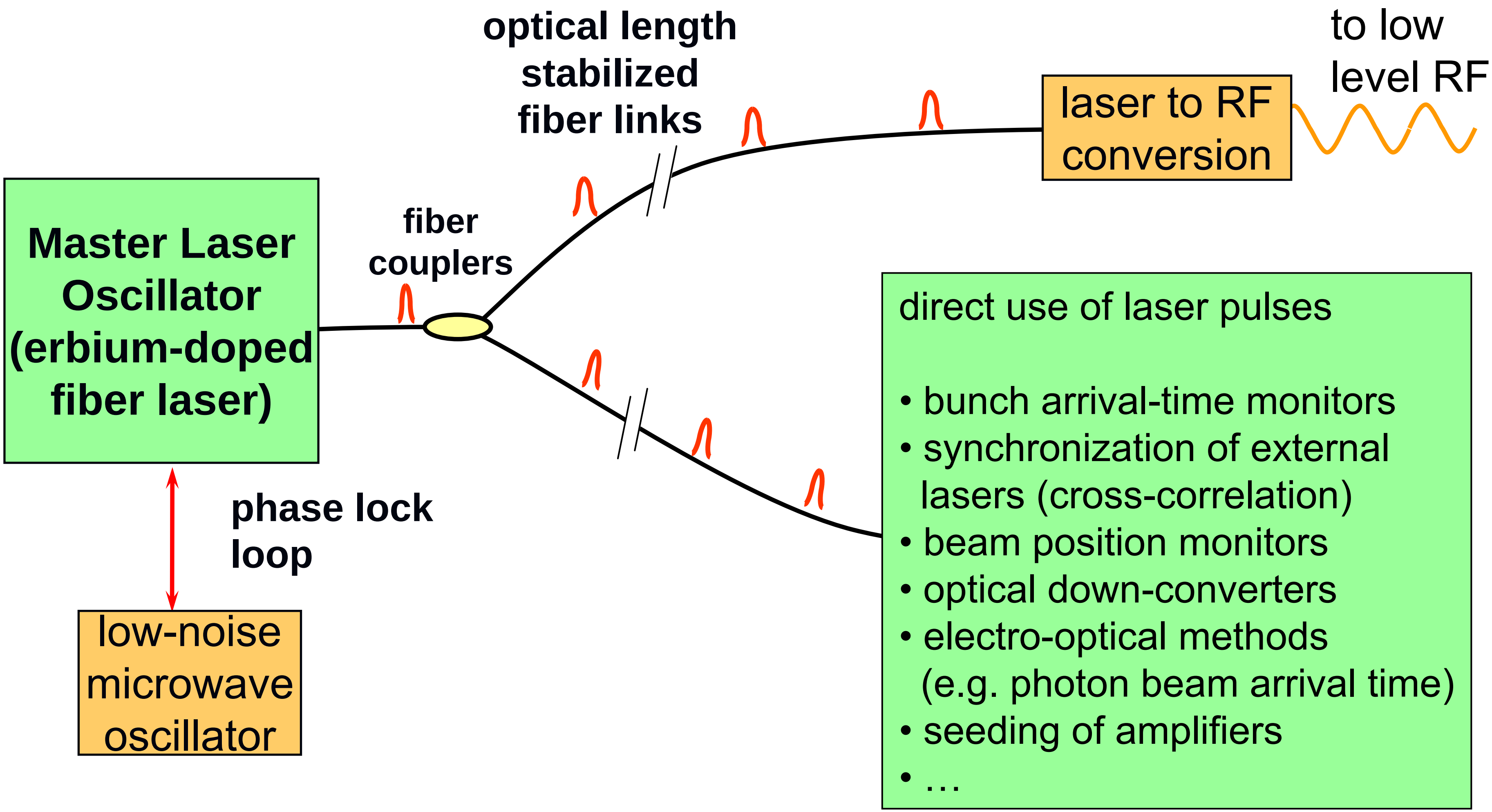
Goal:

- measure and stabilize timing jitter + drift between FEL and pump-probe laser on the 10 fs scale

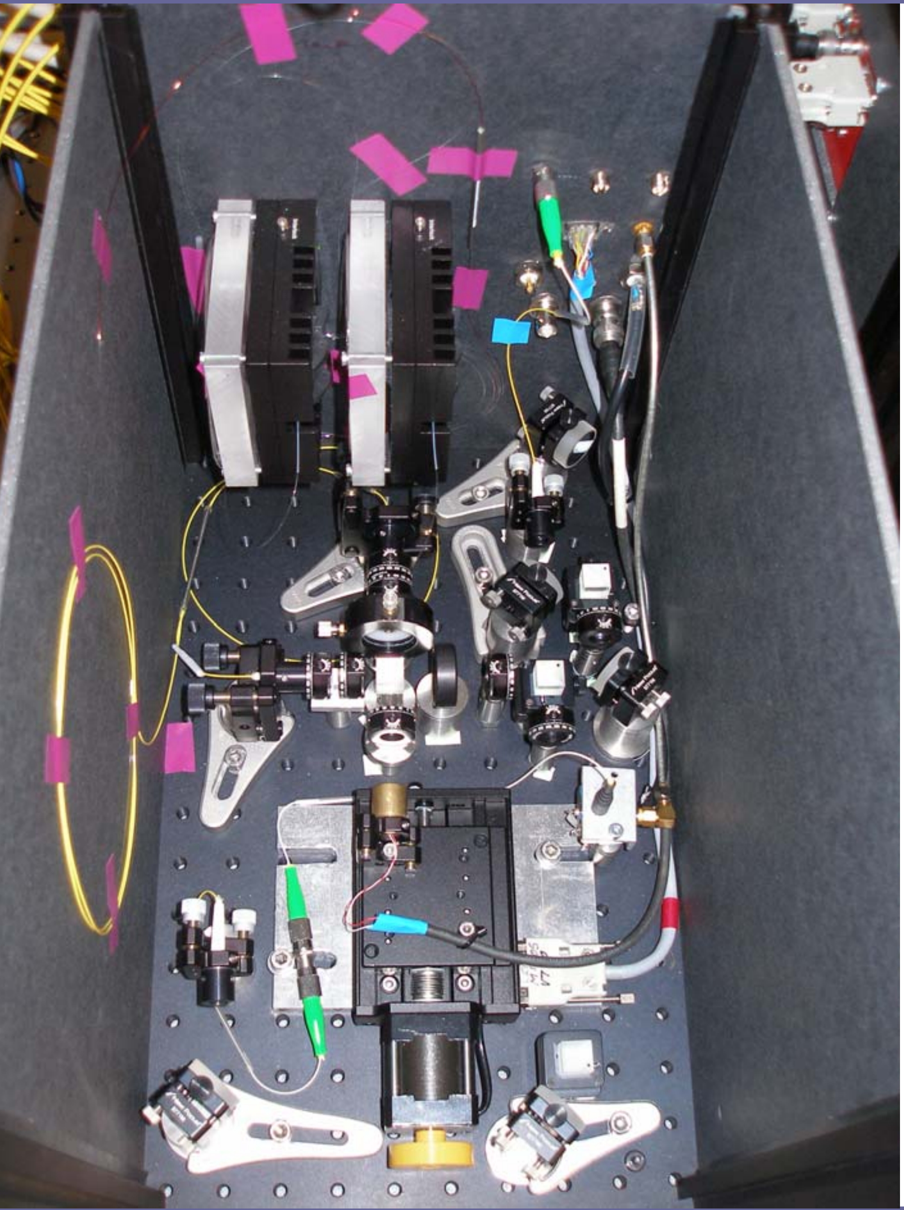
Main sources for arrival-time changes of the FEL radiation

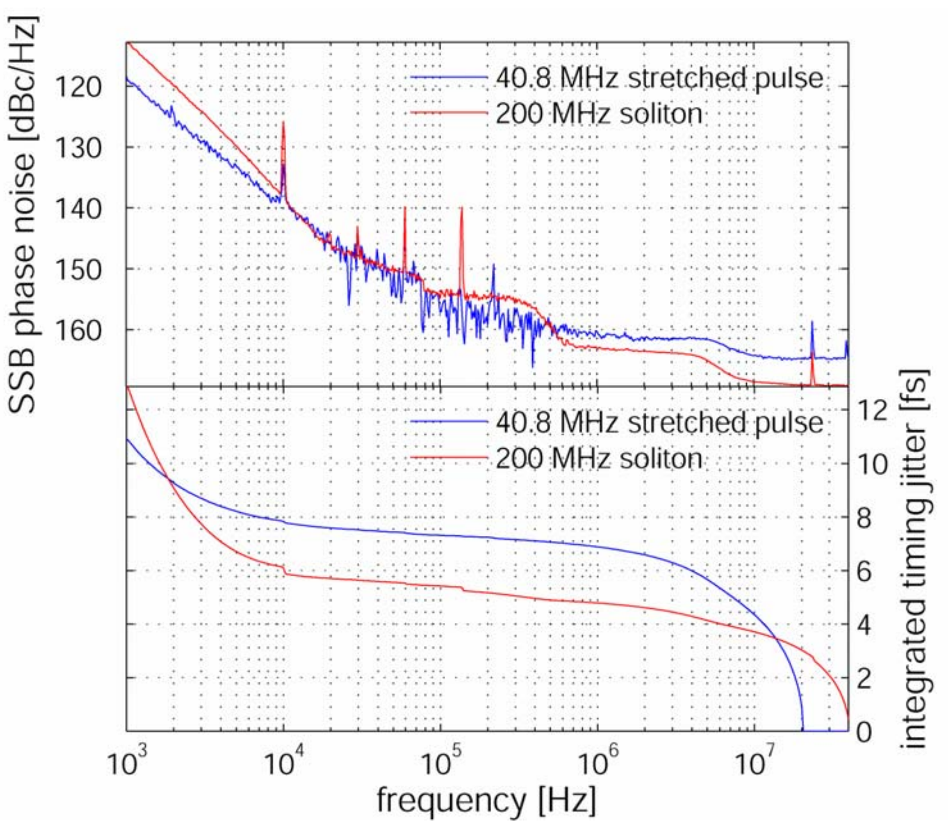
- arrival-time of the photo cathode laser pulses
- phase of the RF gun
- amplitude and phase of booster module
- arrival-time of potential seed lasers

Layout of the optical synchronization system



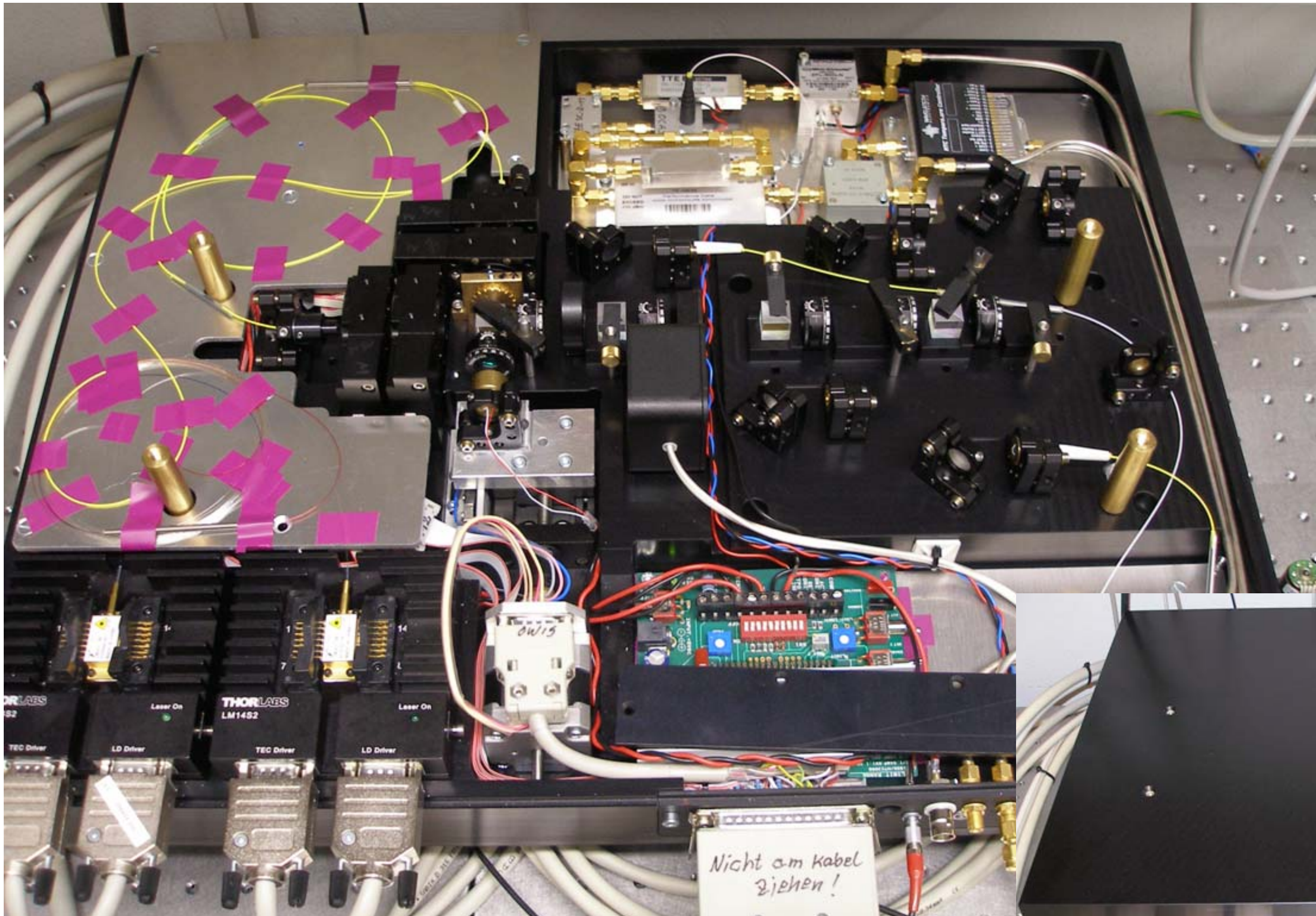
The fiber laser system





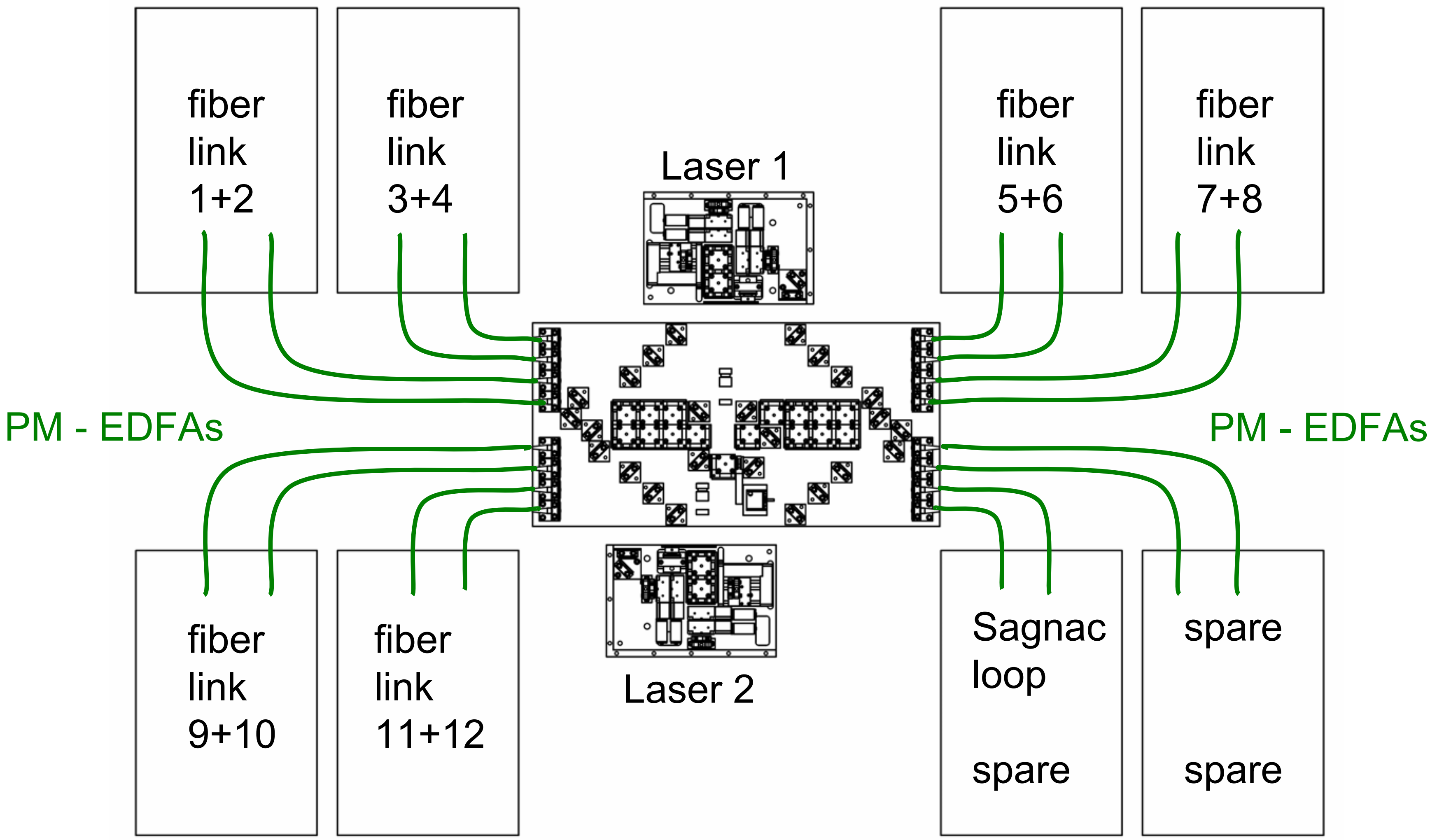
A redundant 216 MHz soliton laser will be used as a reference oscillator. The higher repetition rate compared to the previous 54 MHz stretched pulse laser system has several advantages for the subsystems.

First prototype of a 216 MHz laser

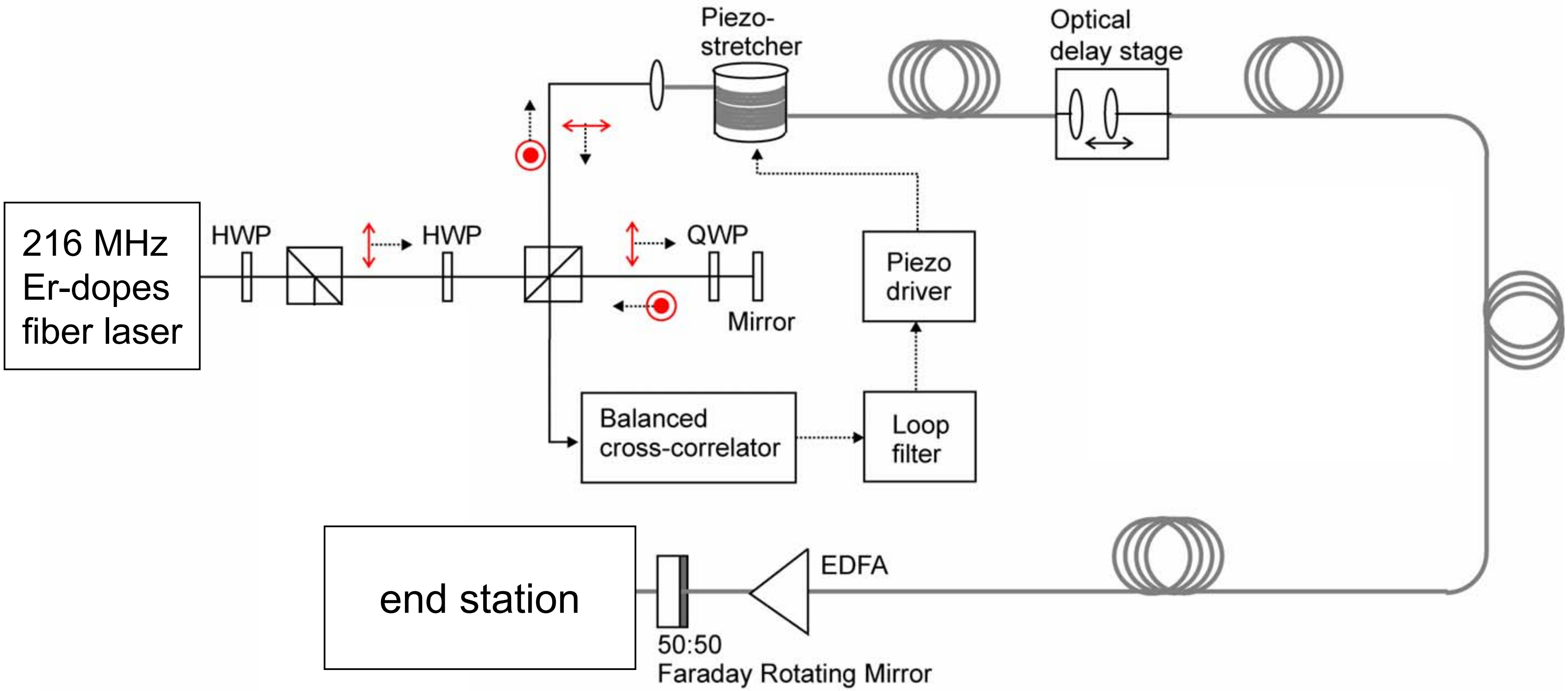


Prototype of a 216 MHz laser and a small distribution unit. The second iteration is on its way.

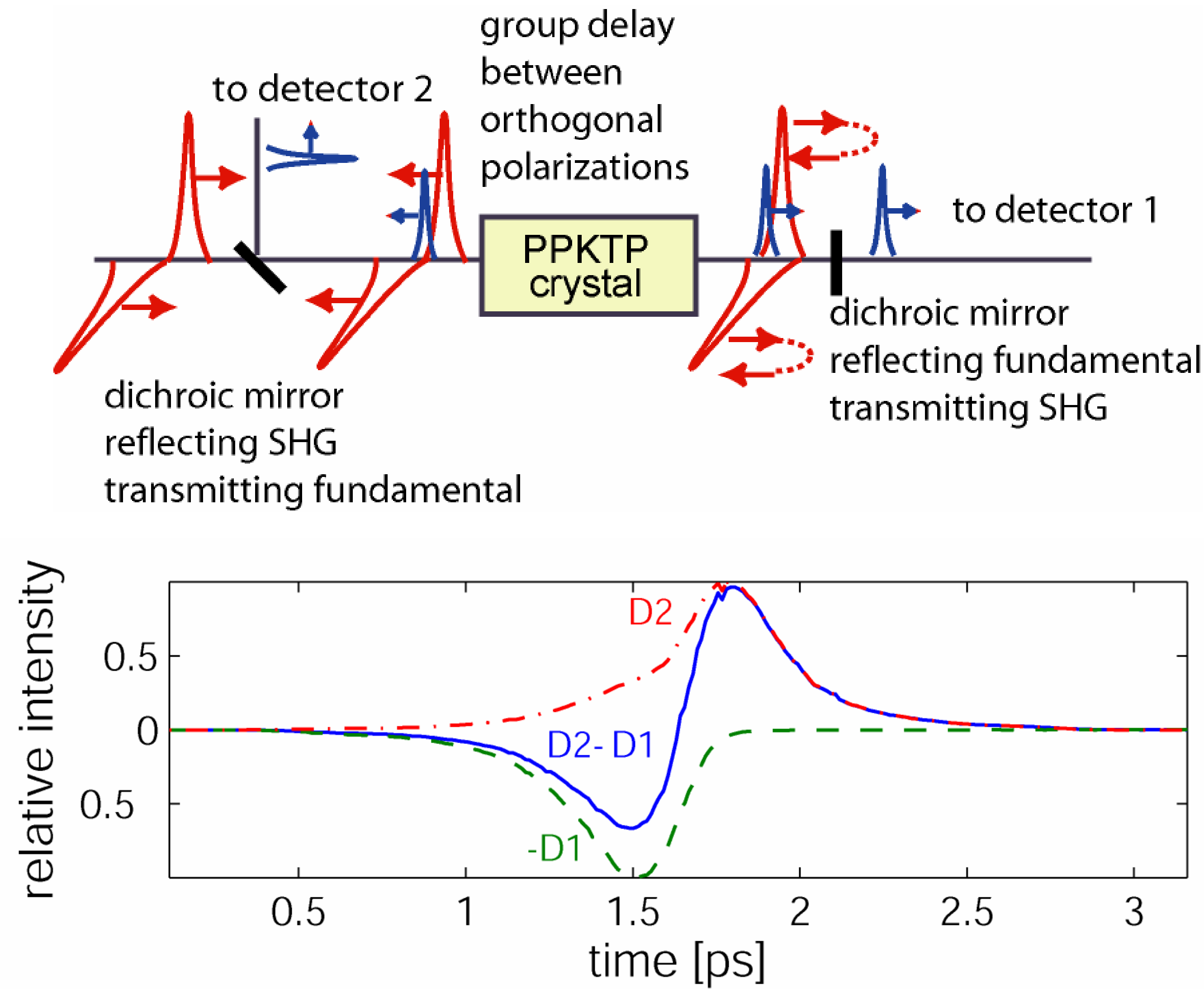
Distribution unit
Schematic layout



Fiber link stabilization: Schematic setup

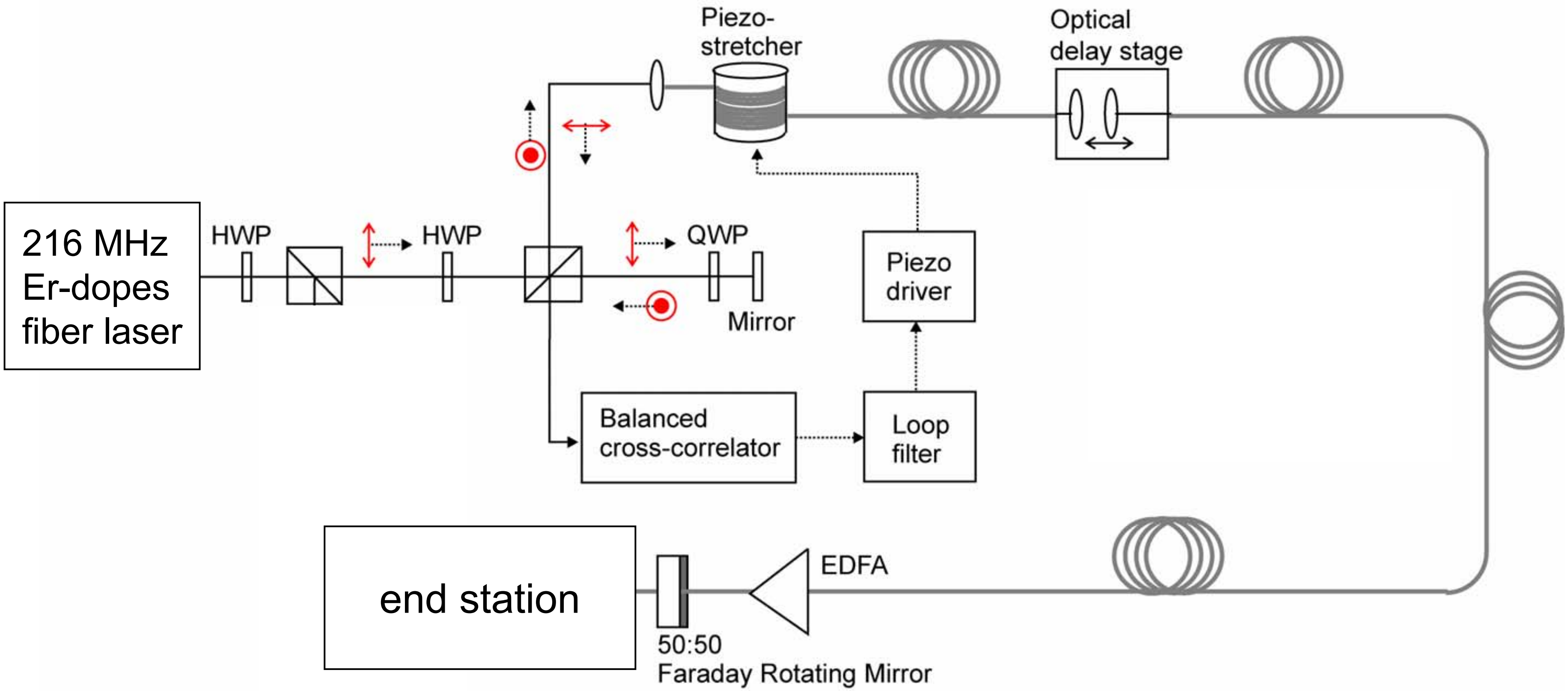


Fiber link stabilization: Balanced optical cross-correlator

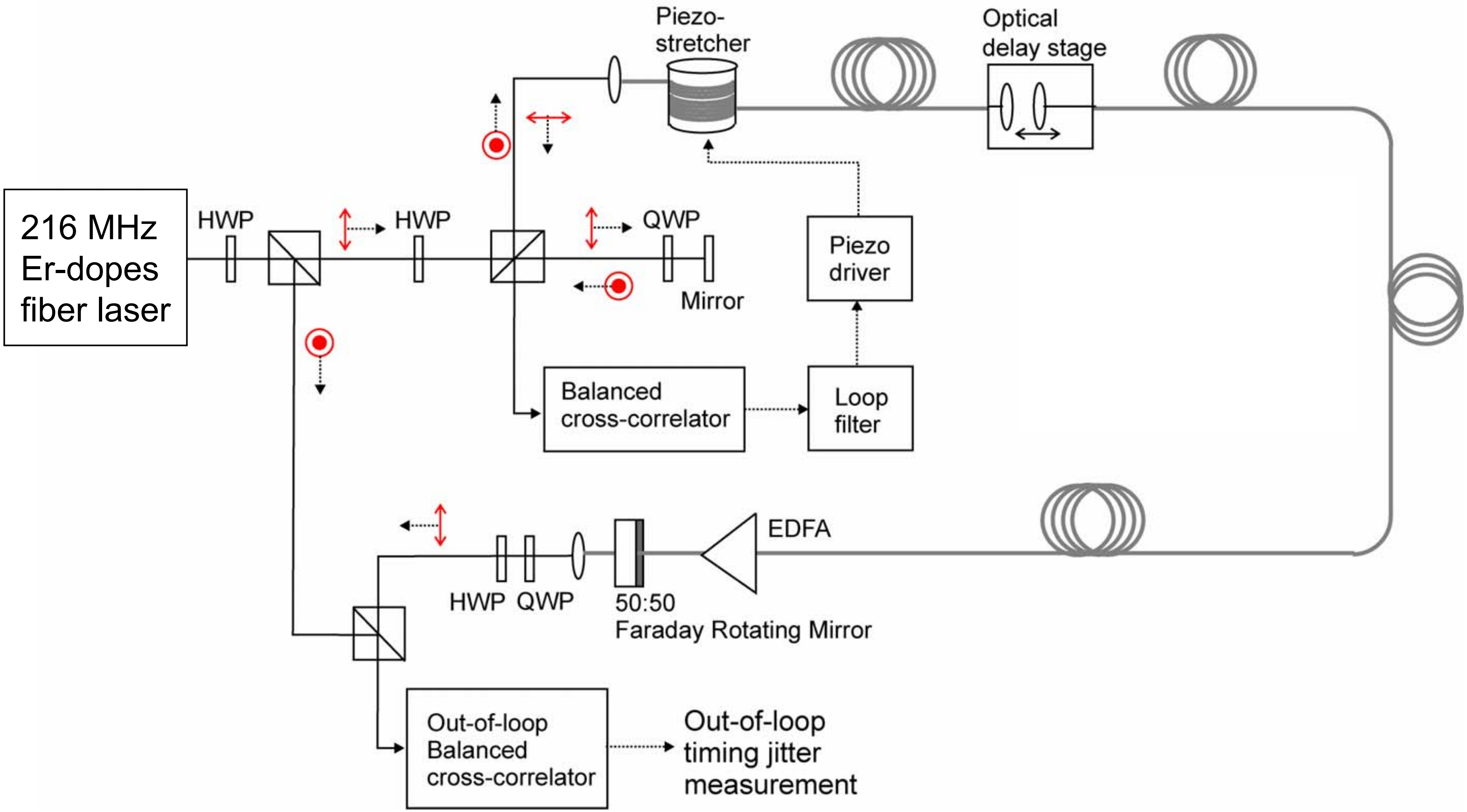


Development in collaboration with MIT

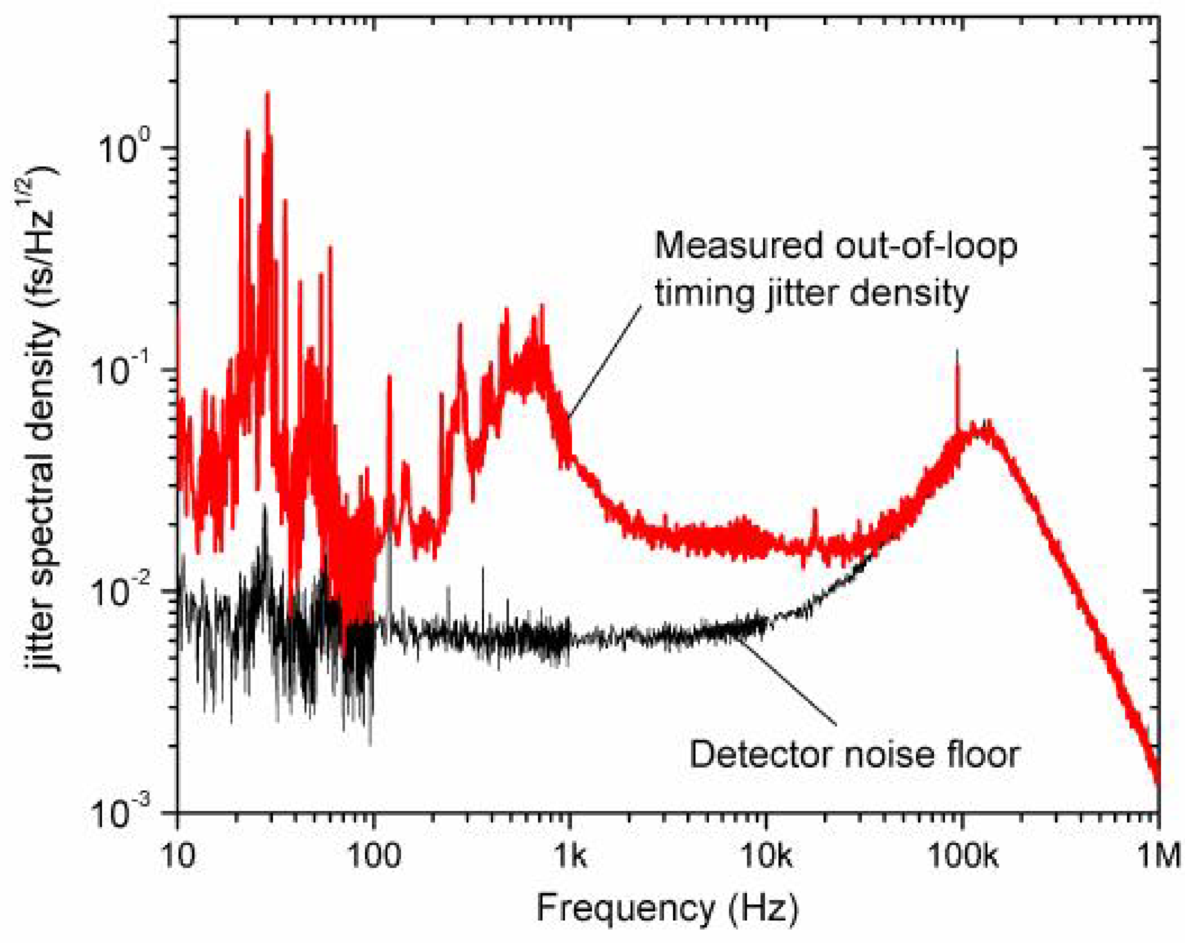
Fiber link stabilization: Schematic setup



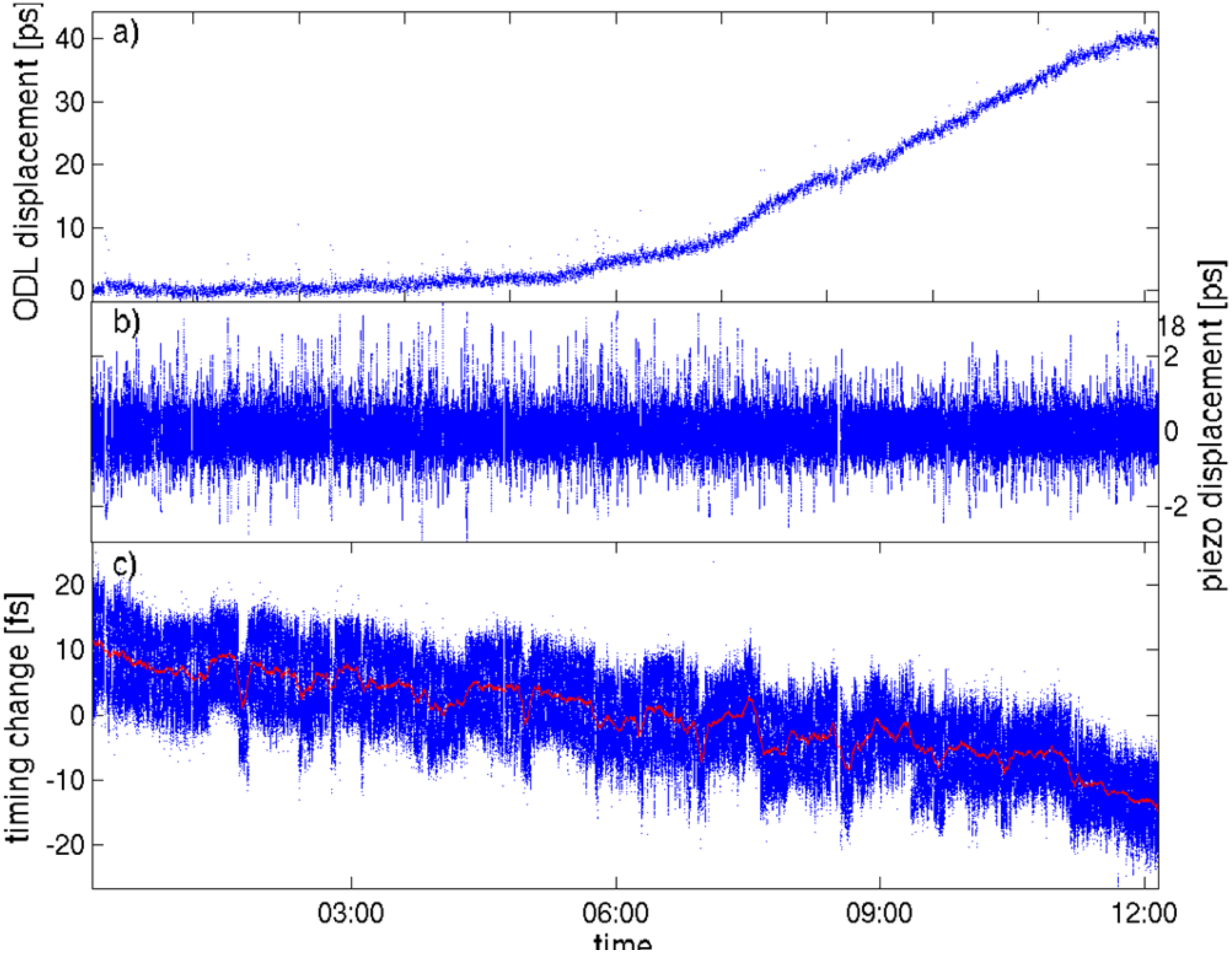
Fiber link stabilization:
Schematic setup to determine fiber link stability



Frequency distribution of fiber link timing changes

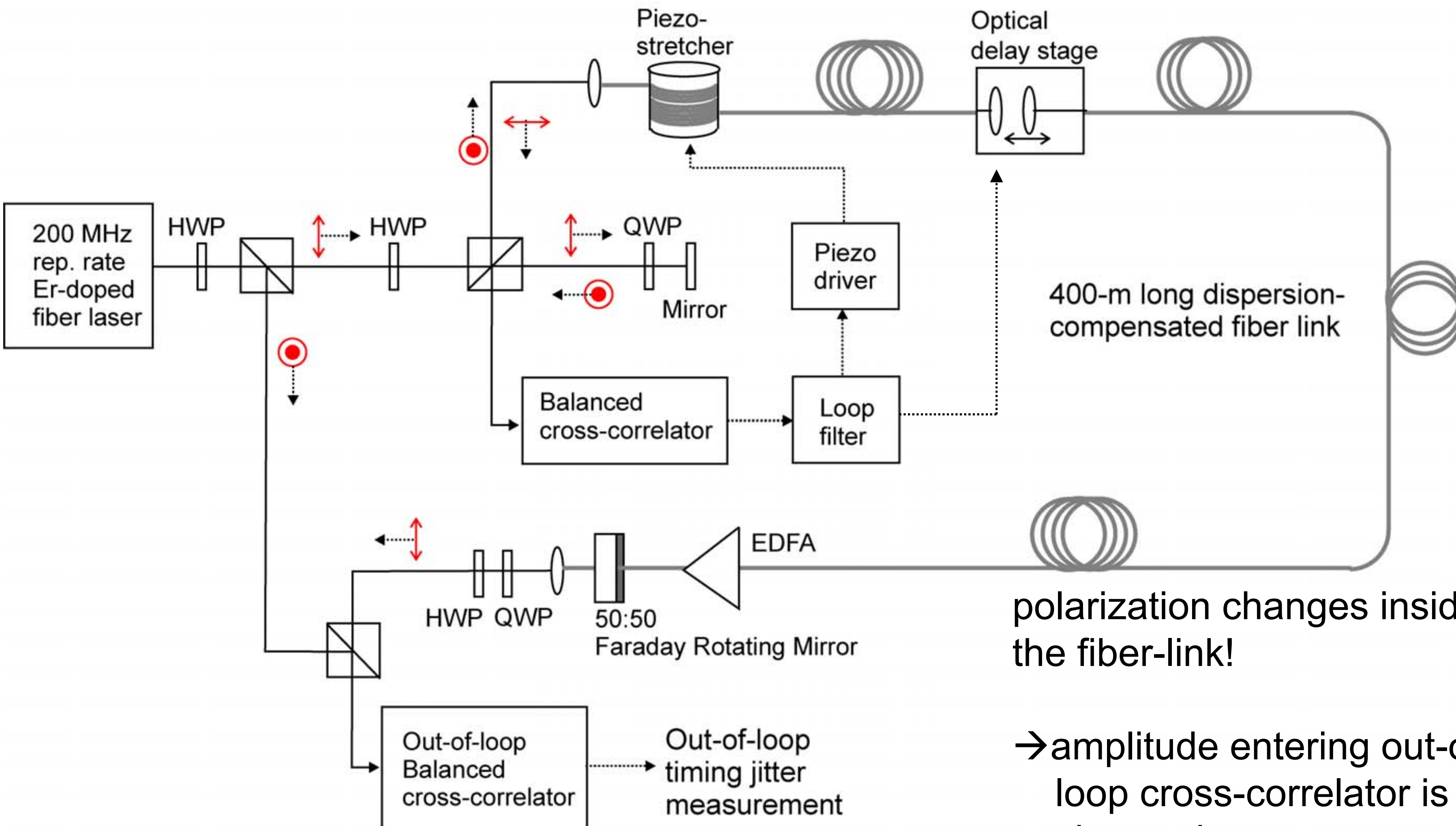


Fiber link stabilization
Long term stability



rms timing jitter over 2 minutes: (4.4 ± 1.1) fs
timing drift over 12 hours: 25 fs
measurement bandwidth: 200 kHz

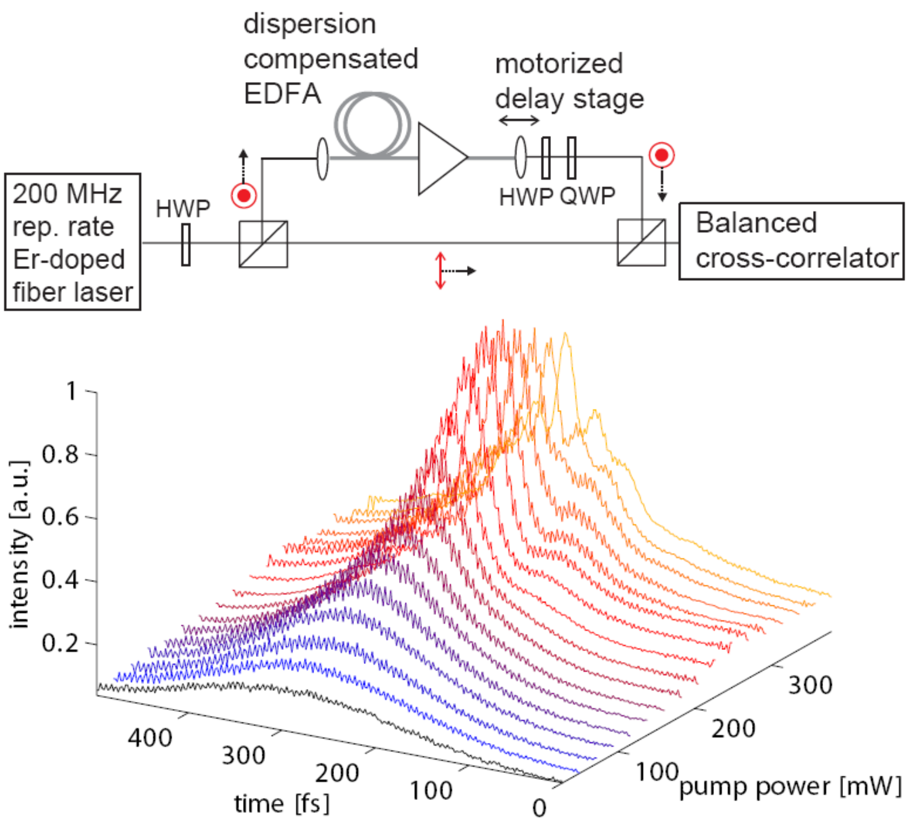
Fiber link stabilization
Timing drift a measurement artifact?

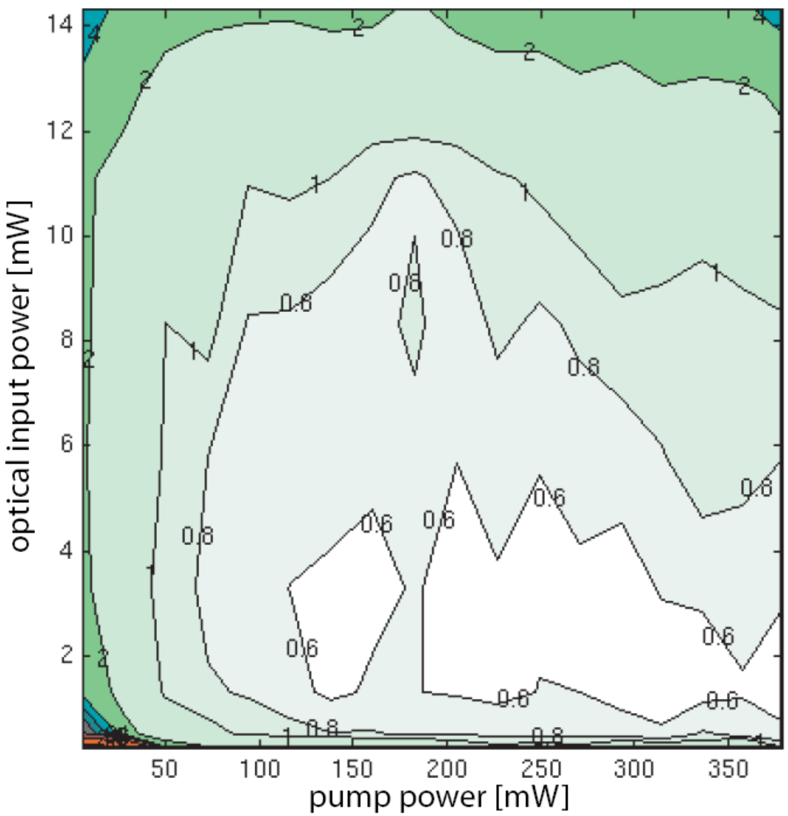


polarization changes inside the fiber-link!

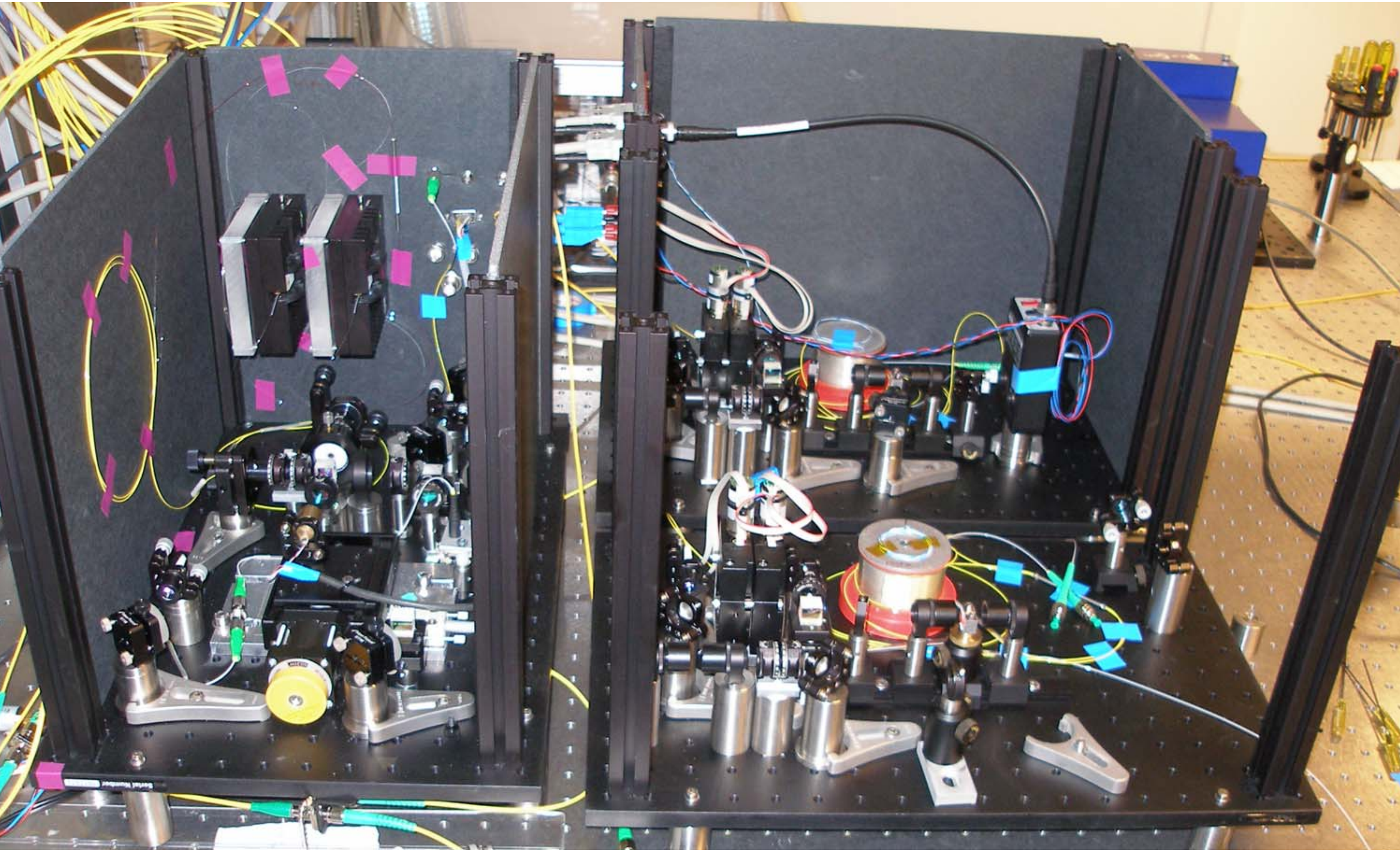
→amplitude entering out-of-loop cross-correlator is changed

Characterization of Er-doped fiber amplifiers

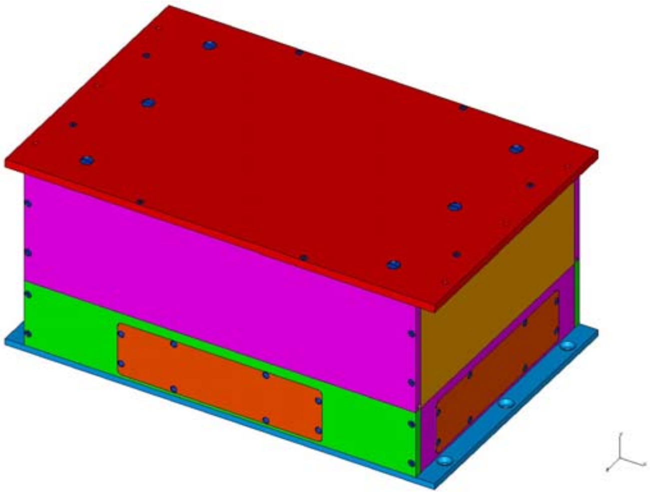




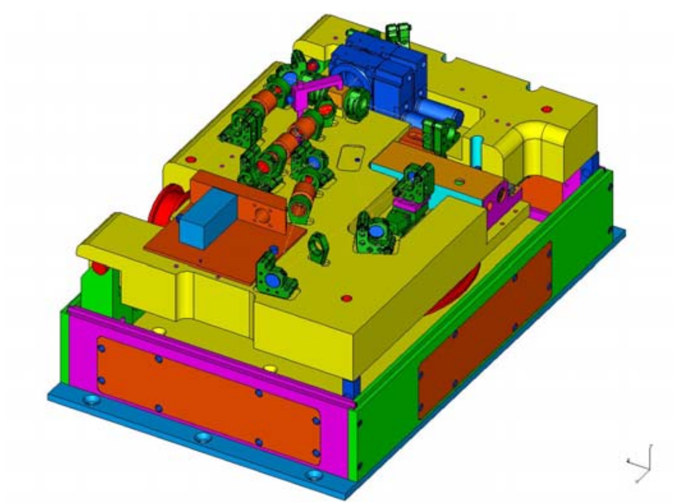
Prototypes of master laser and fiber link stabilization

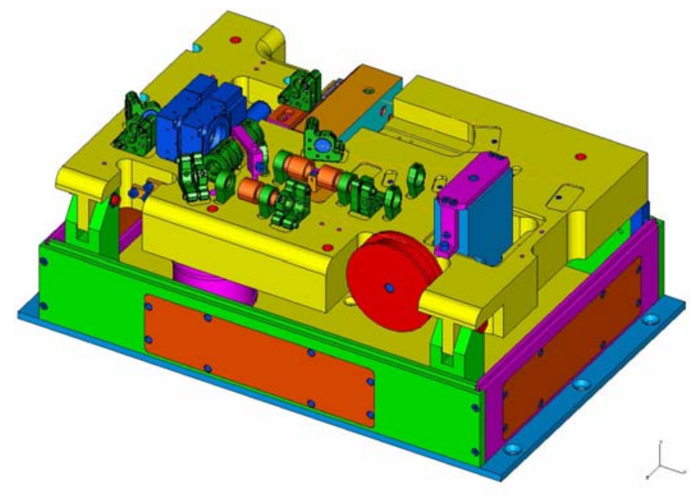


Mechanical design

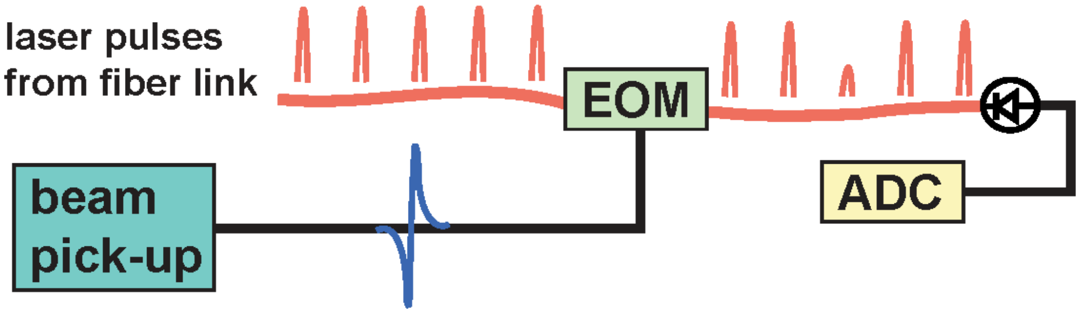


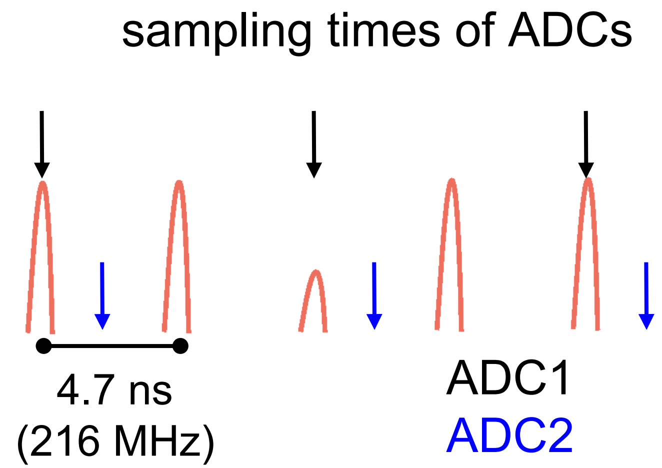
Construction of fiber link mechanics together with K. Jaehnke (ZM1).
Installation: summer 2008.



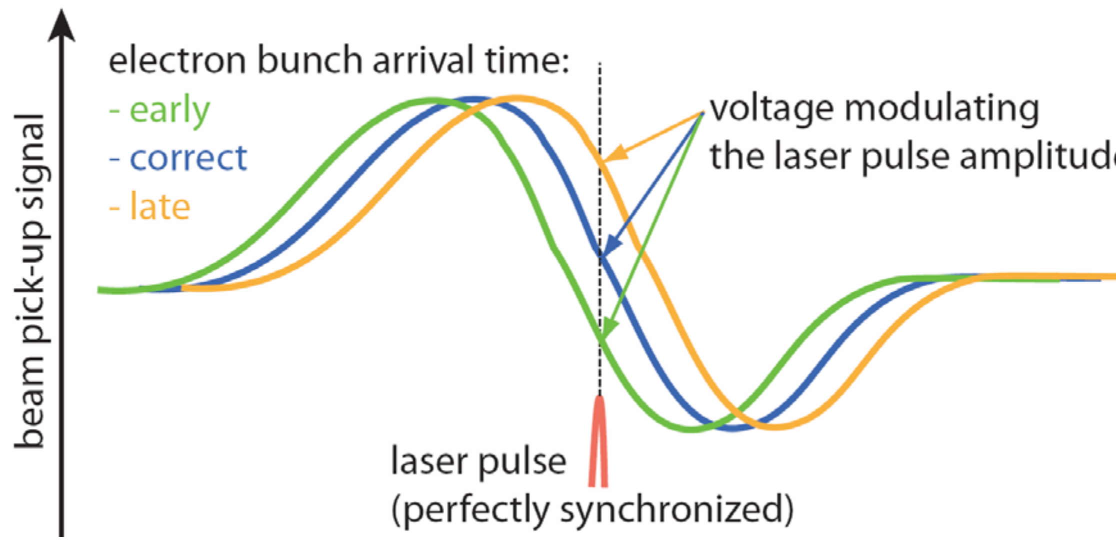


Bunch arrival time monitor (BAM)
Detection prinziple

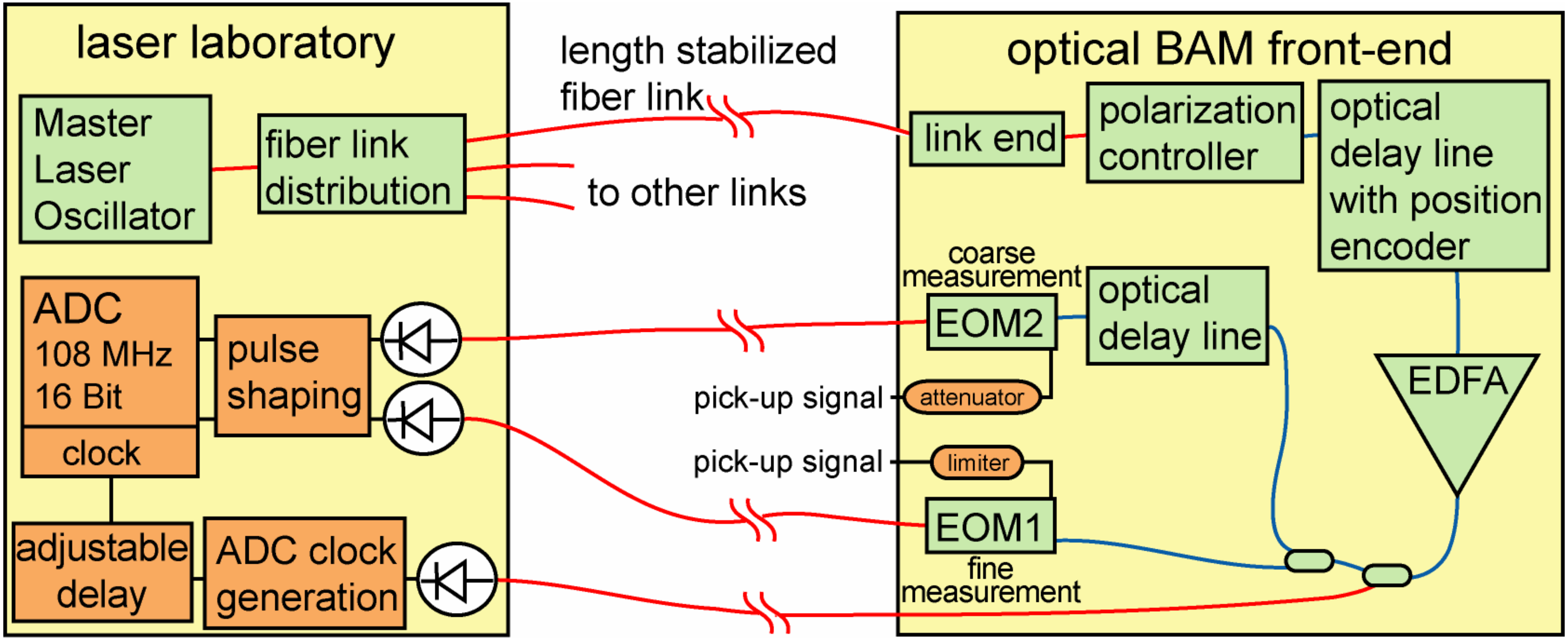




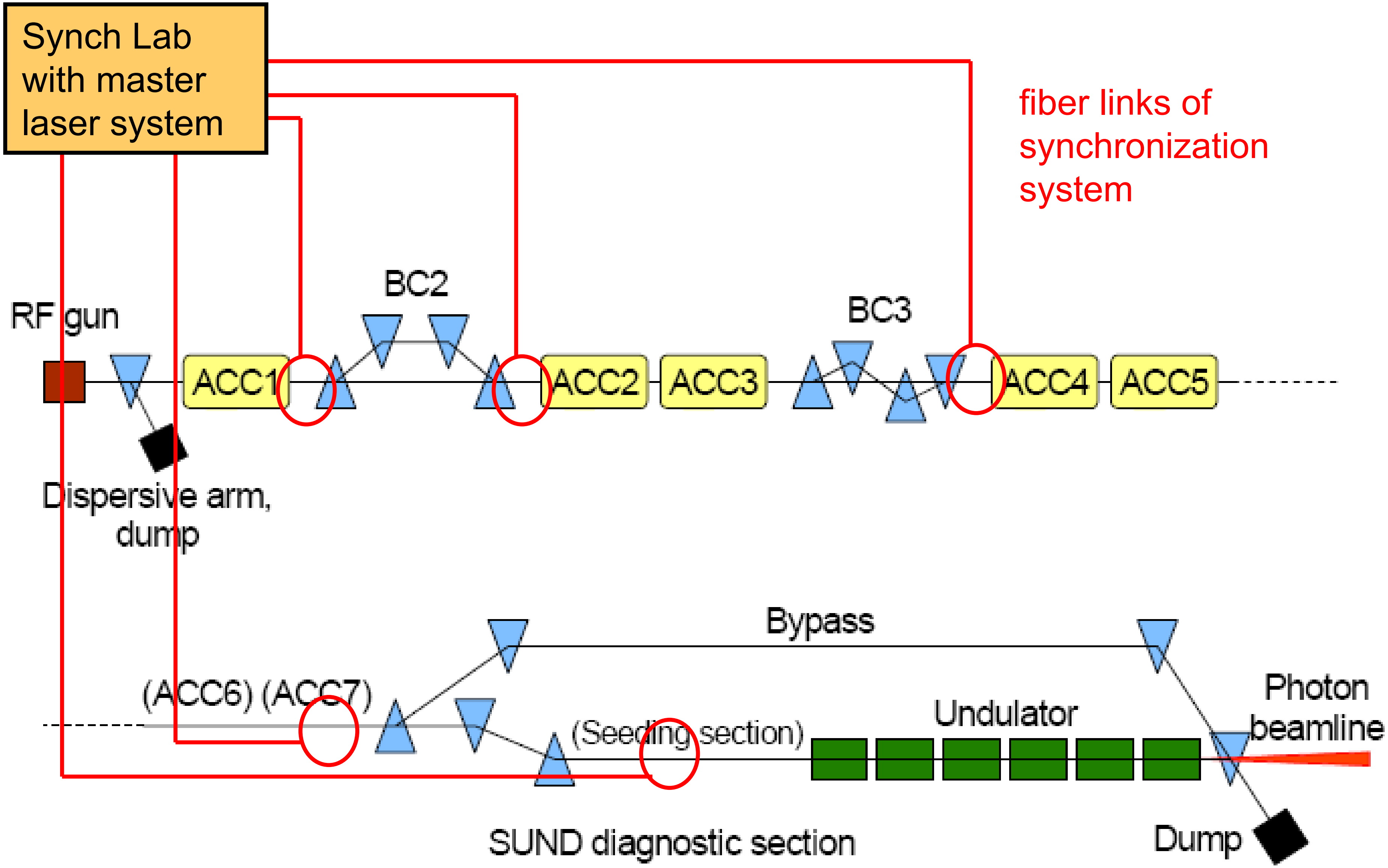
The timing information of the electron bunch is transferred into a laser amplitude modulation. This modulation is measured with a photo detector and sampled by a fast ADC.



Bunch arrival time monitor (BAM)
Schematic setup

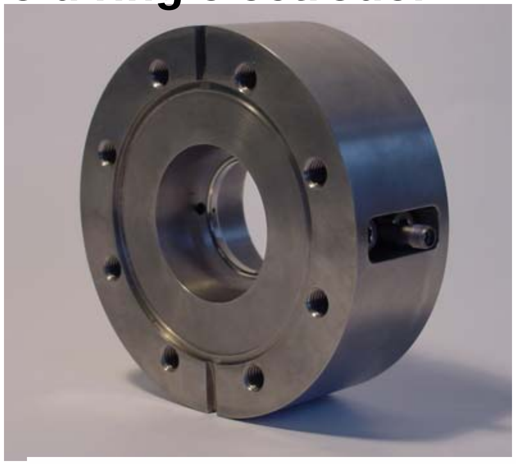


Bunch arrival time monitor (BAM)
Positions of the BAMs in the FLASH linac

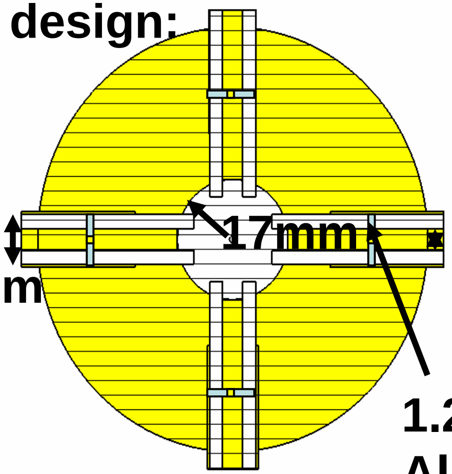


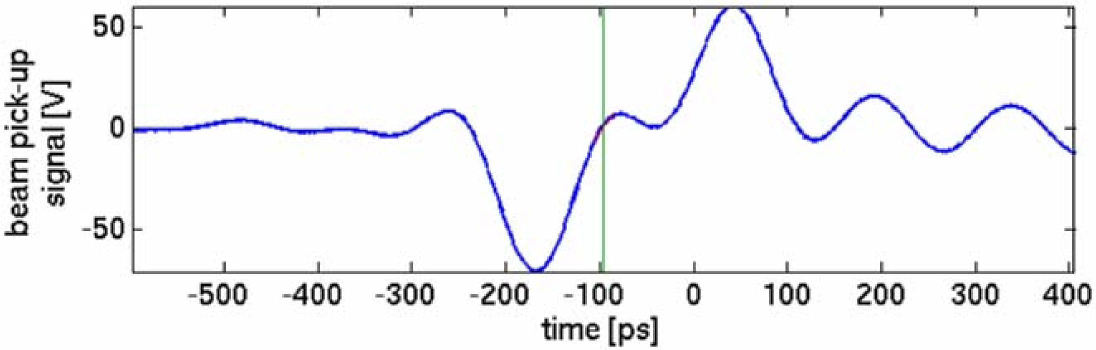
During last summer, a new beam pick-up (design: K. Hacker) was installed instead of the ring electrodes to improve the pick-up performance.

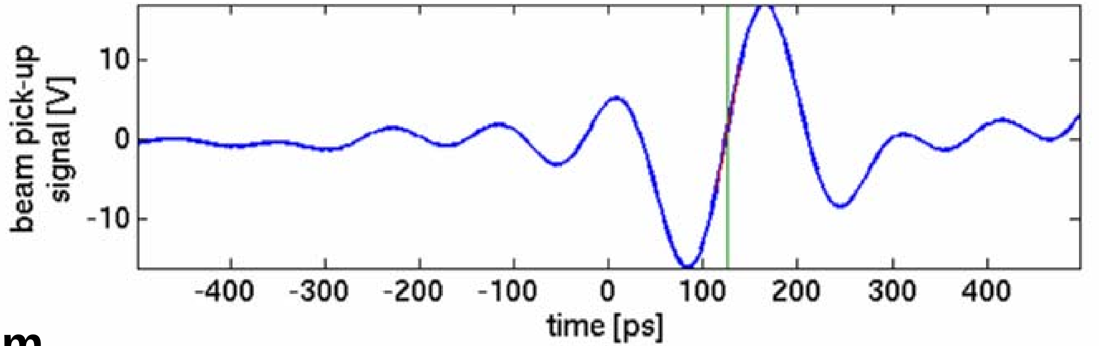
old ring electrode:



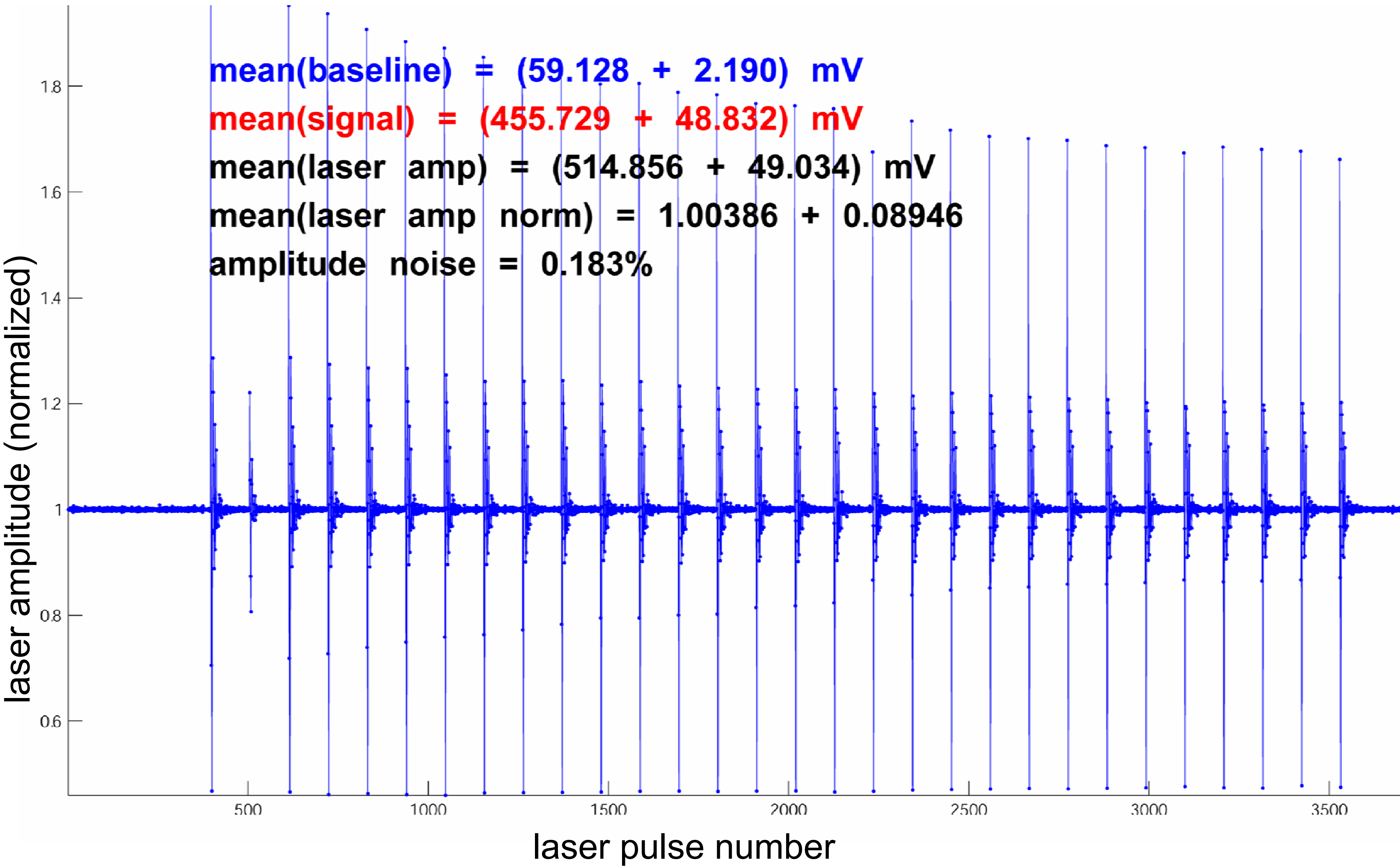
new design:





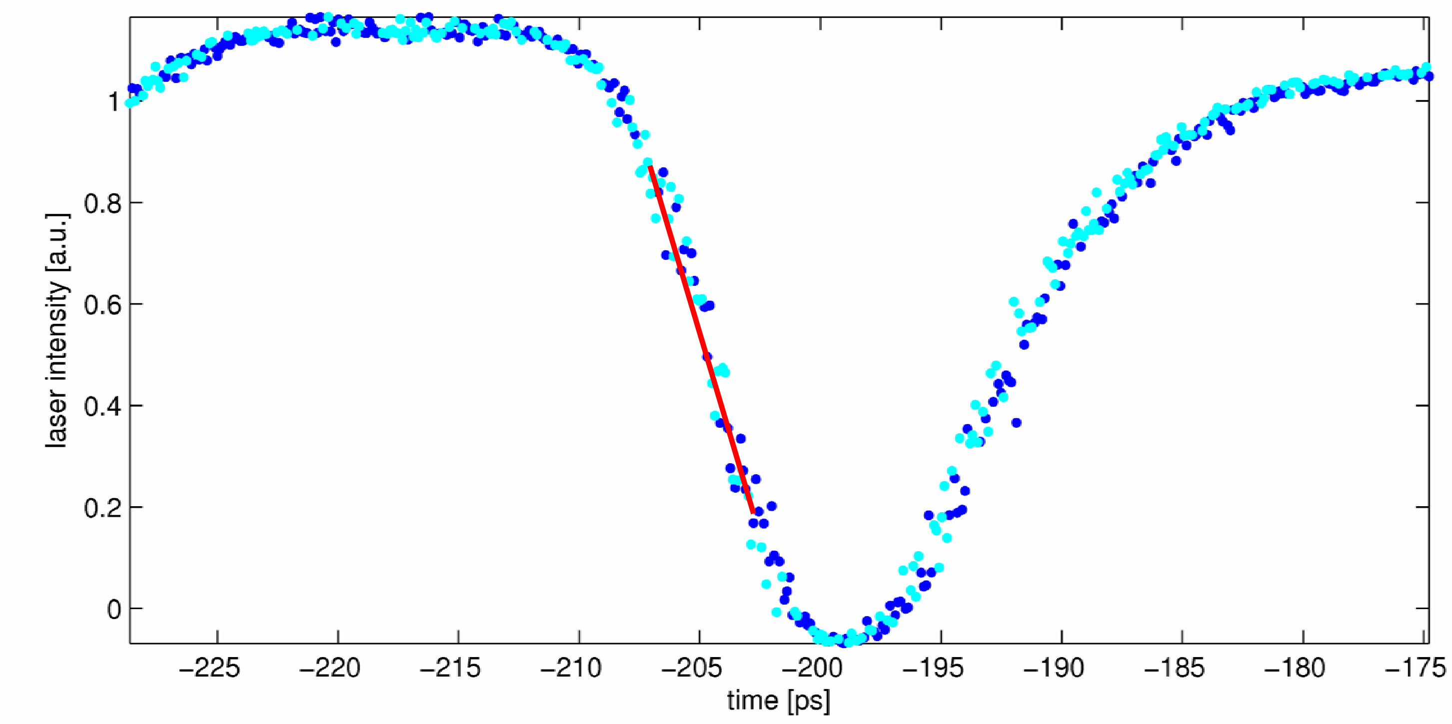


BAM signals



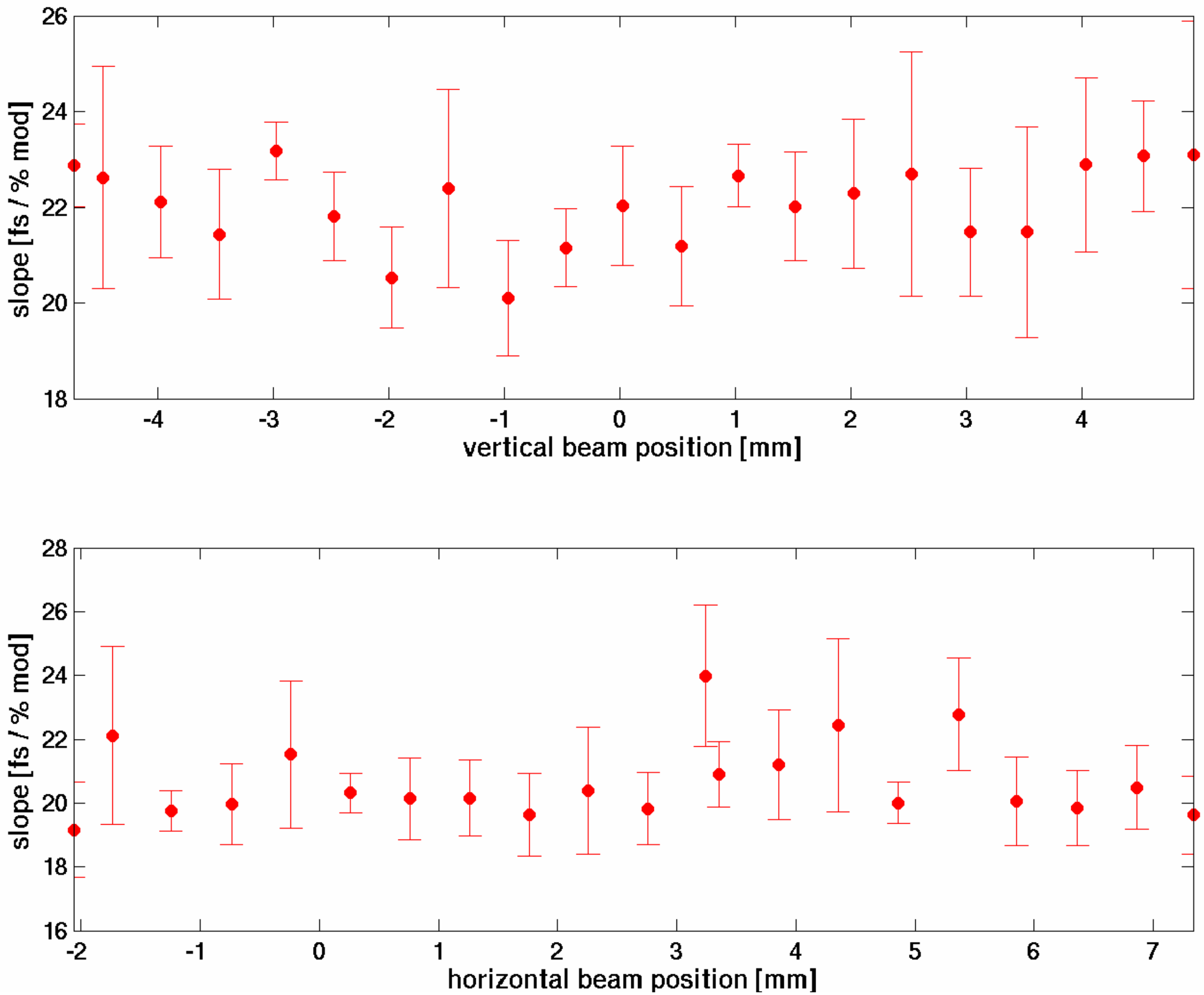
mean(baseline) = (59.128 + 2.190) mV
mean(signal) = (455.729 + 48.832) mV
mean(laser amp) = (514.856 + 49.034) mV
mean(laser amp norm) = 1.00386 + 0.08946
amplitude noise = 0.183%
laser amplitude (normalized)
1.8
1.6
1.4
1.2
1
0.8
0.6
500
1000
1500
2000
2500
3000
3500
laser pulse number

The laser pulses are scanned over the beam pick-up signal to map it onto the laser amplitude. The slope at the zero-crossing is used for the measurement. A calibration run can be made "online" and a continuous calibration update is foreseen in case operation conditions are changed (already implemented in DOOCS server).



(slope measured with old beam pick-up)

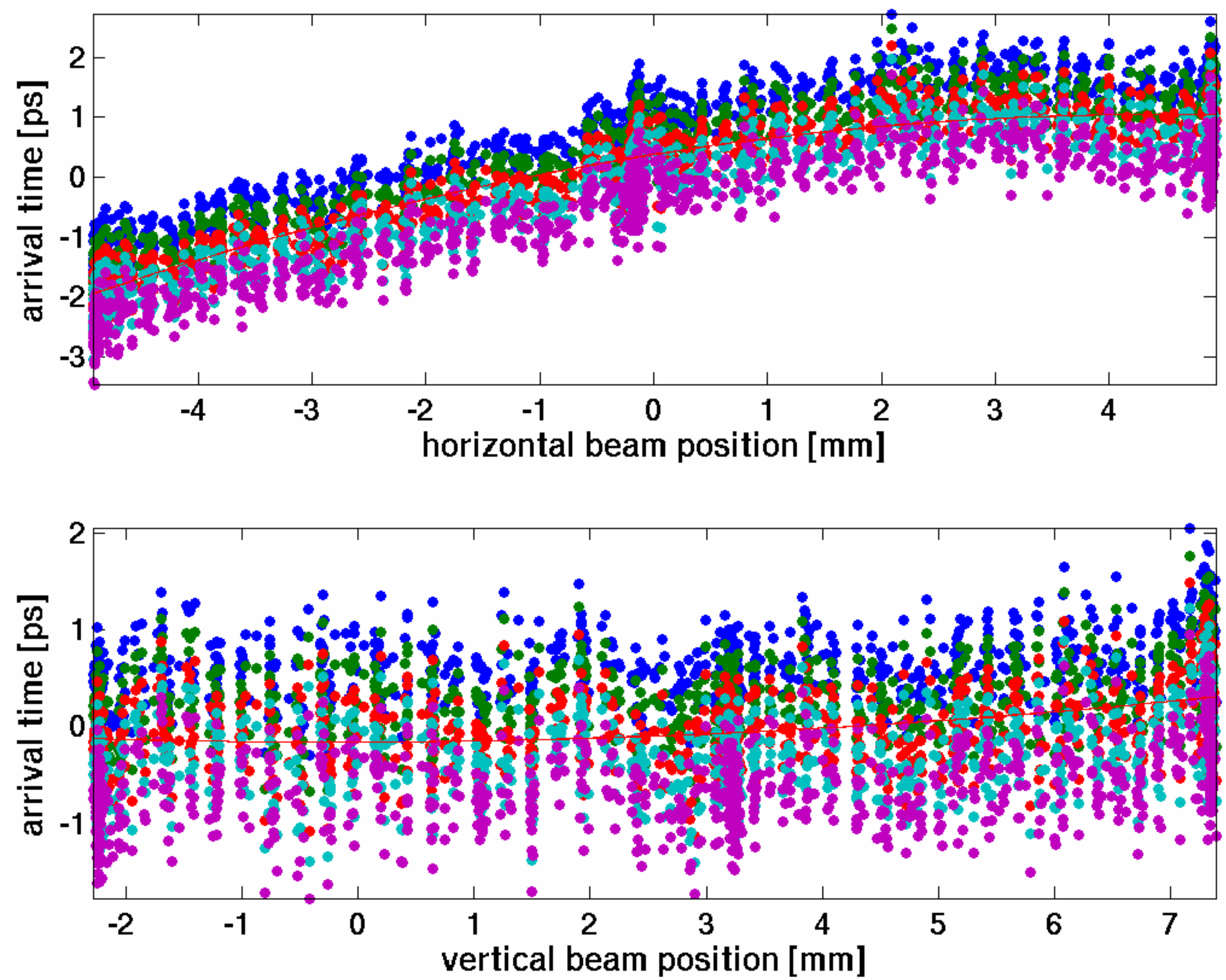
Bunch arrival time monitor (BAM)
Dependence of the pick-up signal slope on the beam position



There is basically no dependence!

Bunch arrival time monitor (BAM)
Dependence of the pick-up zero-crossing on the beam position

horizontal channels combined:

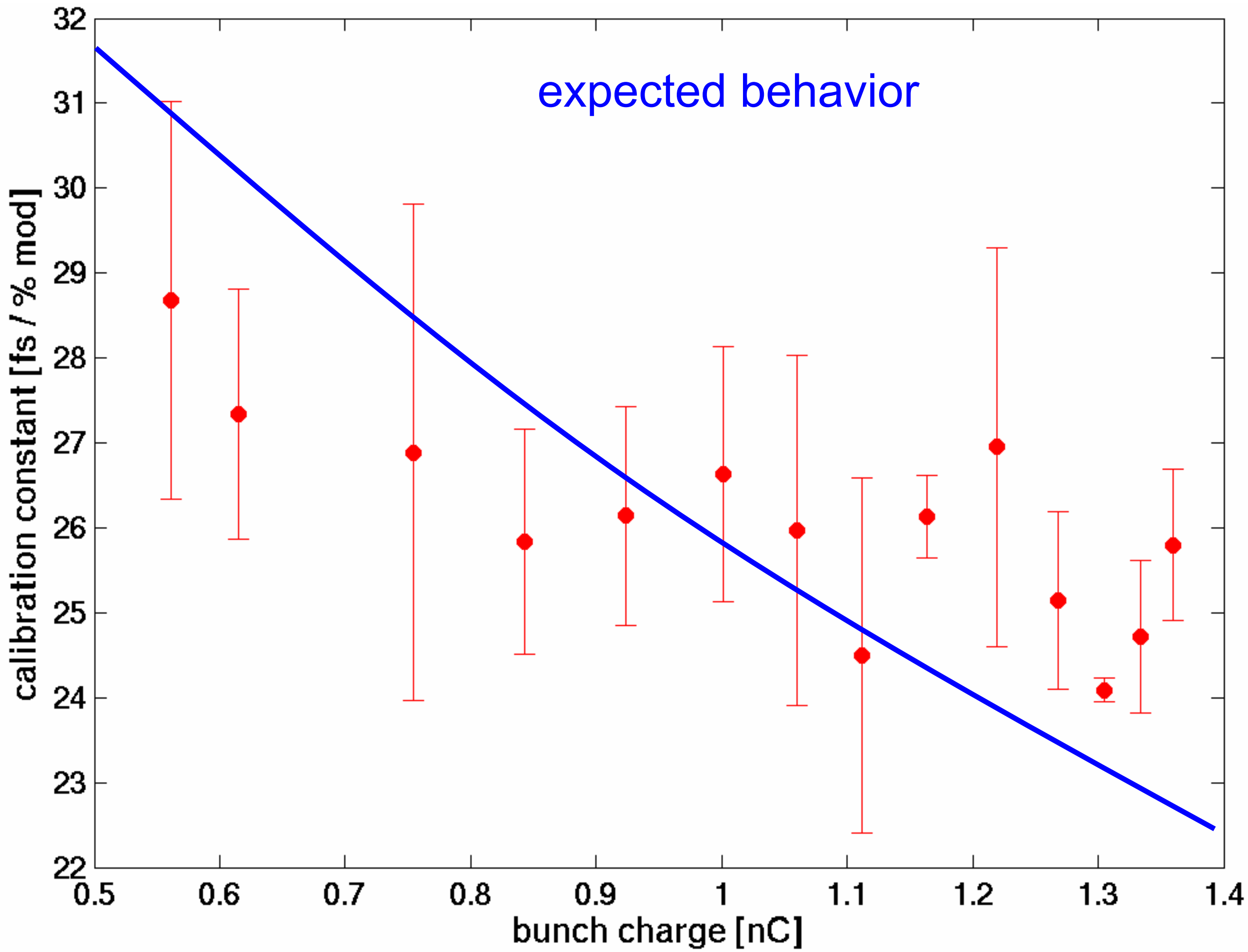


Symmetric curve with zero slope at y = 0 expected!

possible reasons:

- misalignment of BPM 16ACC7
- misalignment of BAM 18ACC7 and OTR chamber
- different coupling efficiency of different pick-up electrodes

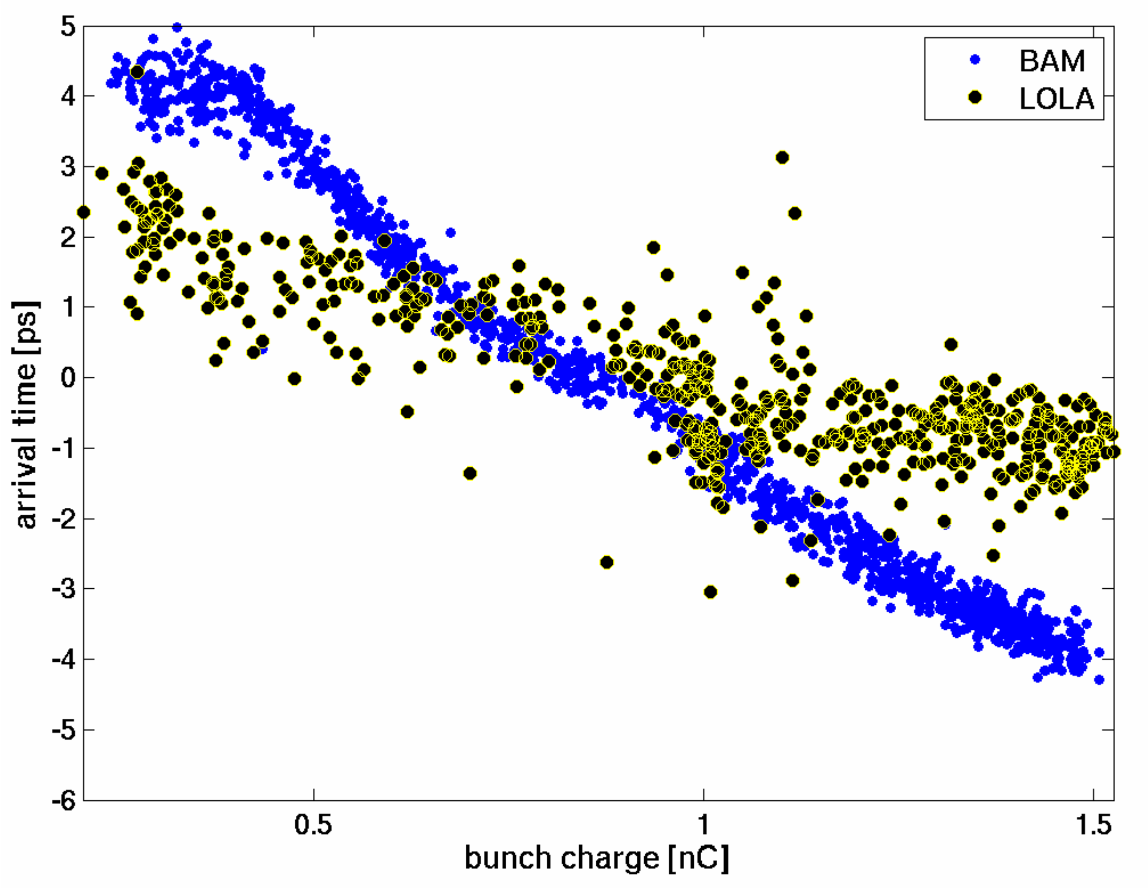
Dependence of the pick-up signal slope on the bunch charge



Slope does not get steeper with increasing charge!

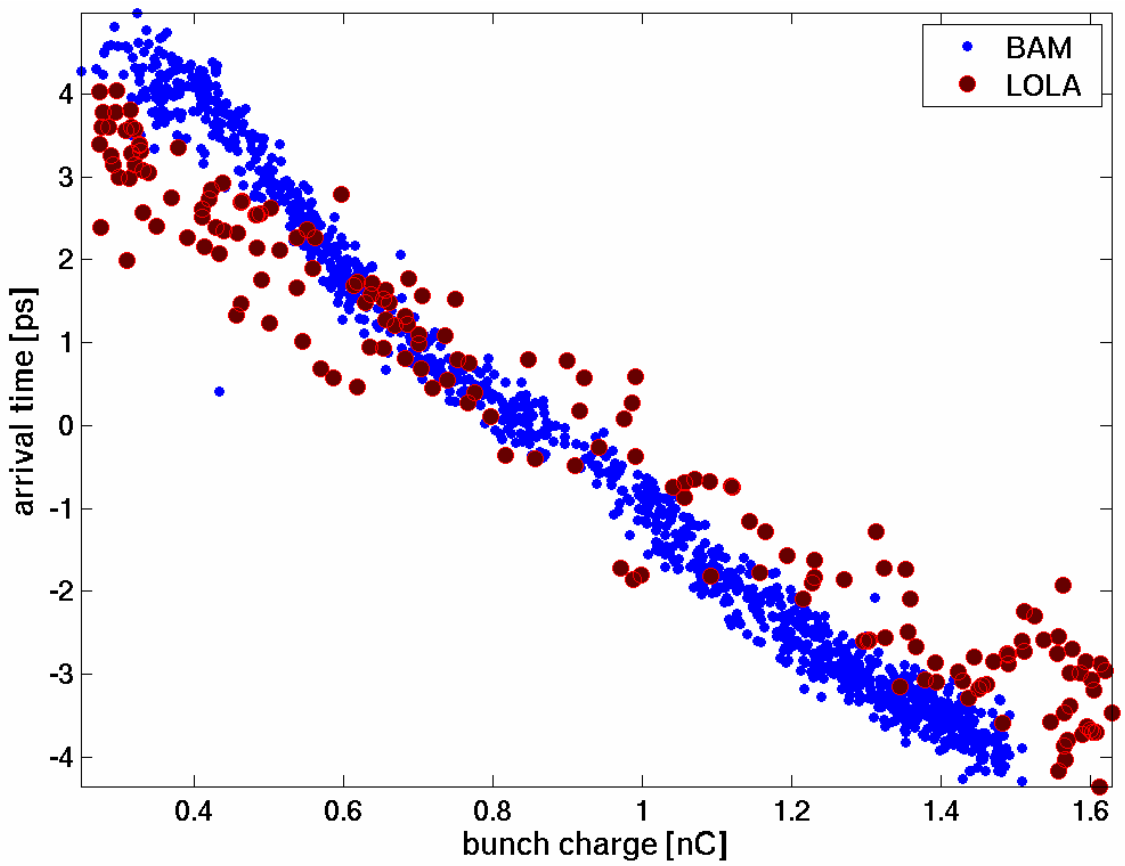
Dependence of the measured bunch arrival time on the charge

orbit feedback switched on



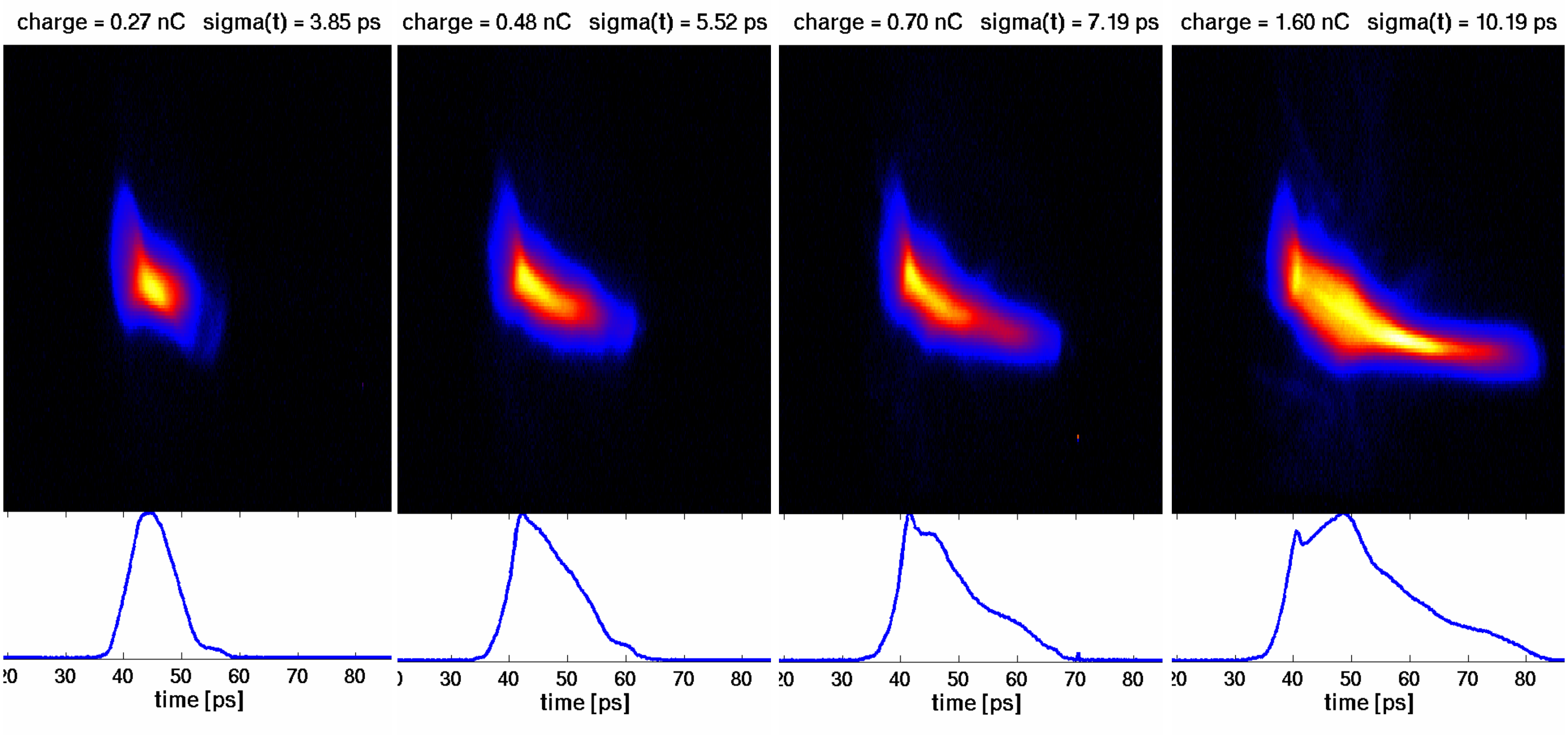
Arrival time dependence on the bunch charge is much higher for the BAM than for LOLA!

orbit feedback switched off



Do the BPMs have a charge dependence?

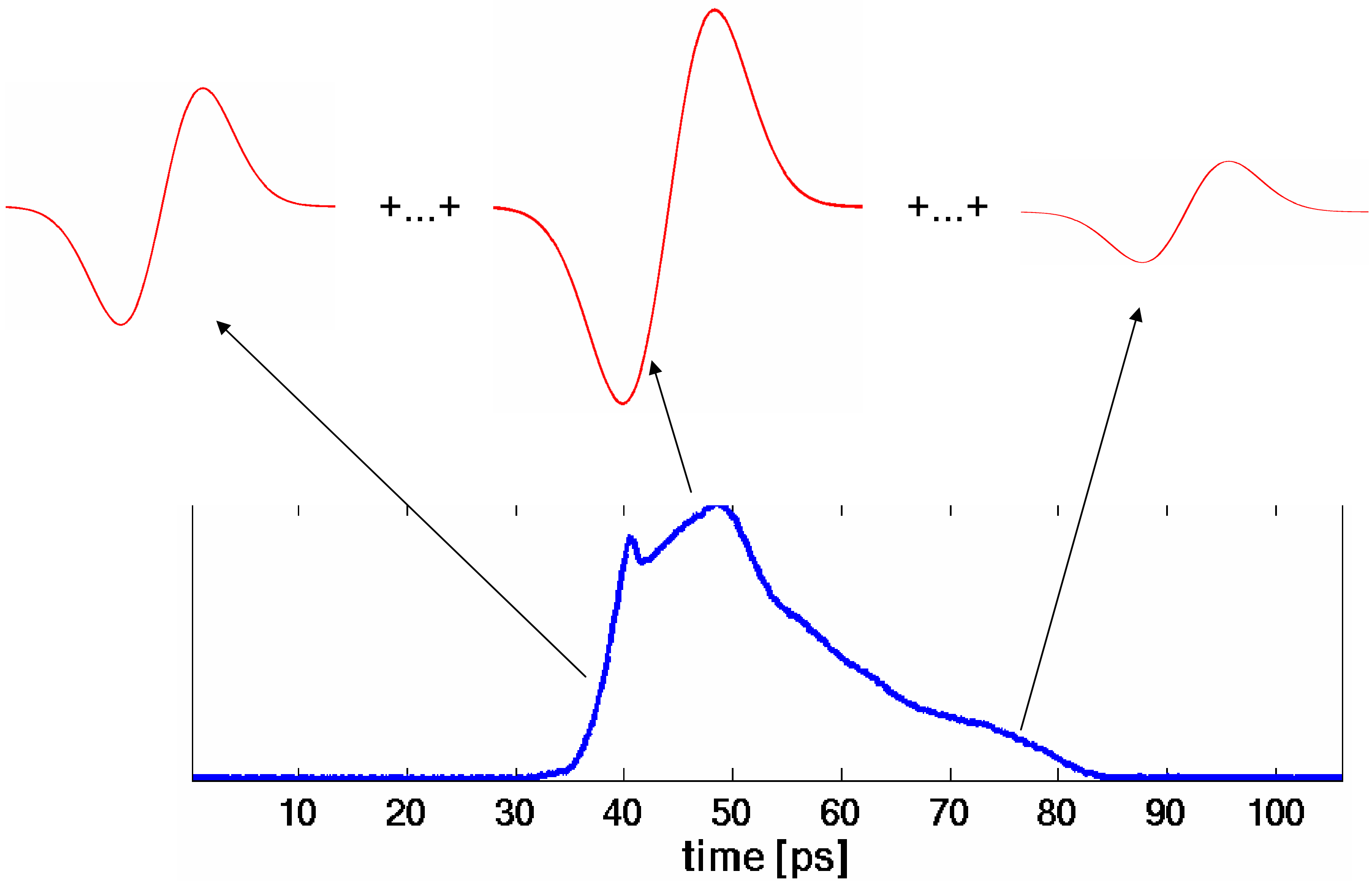
Change of the bunch length with charge (on-crest)



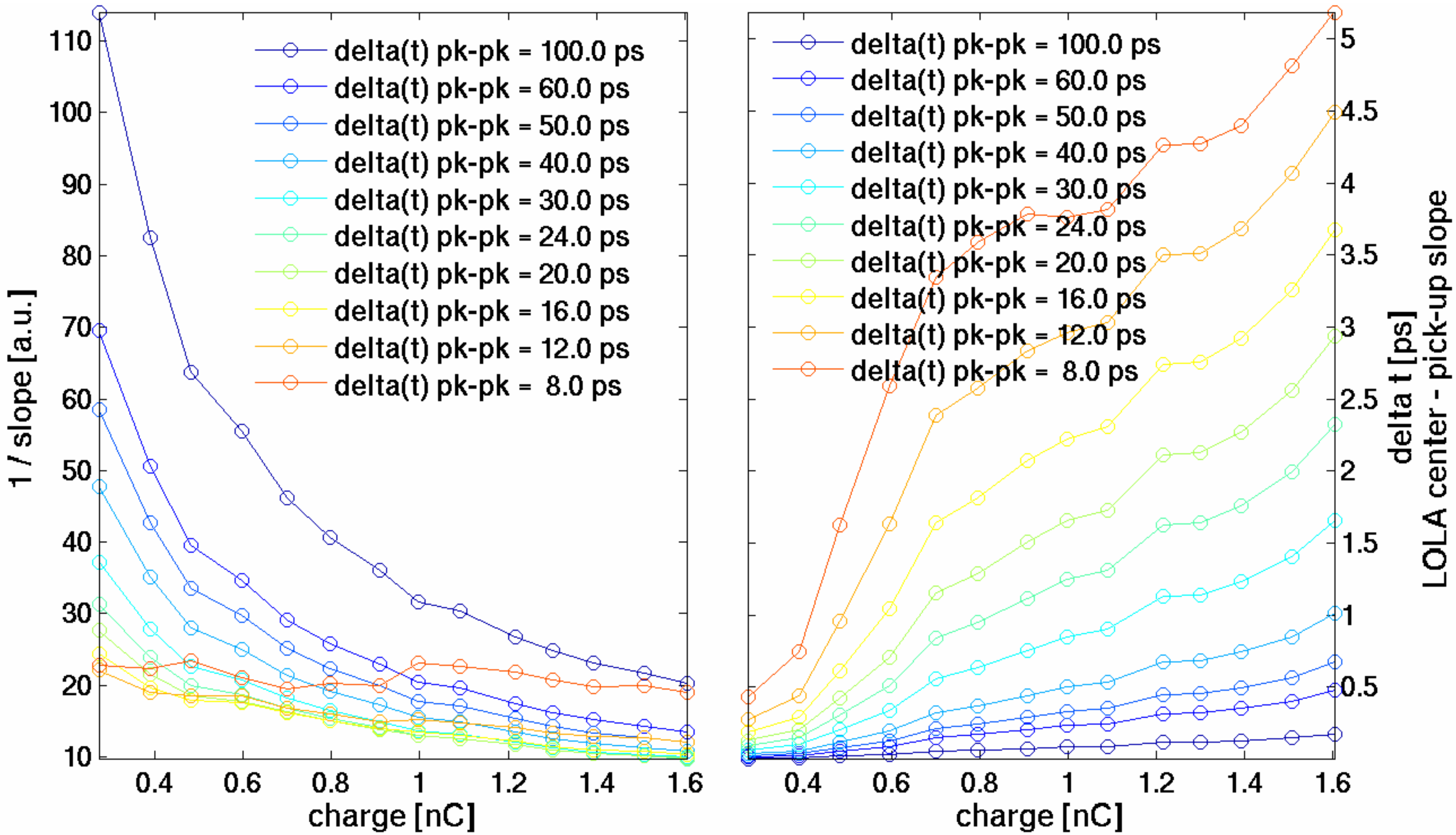
The bunch length is changed almost by a factor of three!
The longitudinal pulse shape is changed significantly!
→ Intra bunch train charge feedback needed.

Simple model to understand the BAM charge dependence

Superposition of "wavelets" for each longitudinal slice.
Free parameter: wavelet duration.



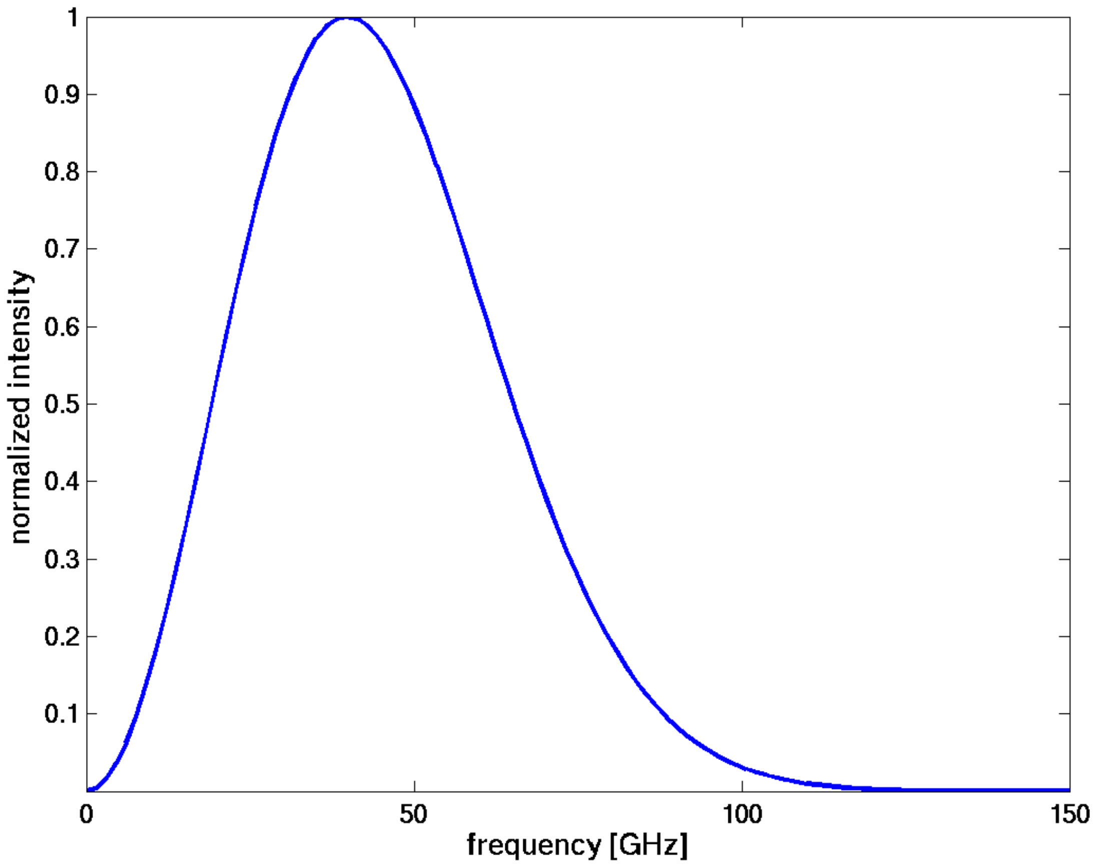
Bunch arrival time monitor (BAM)
Simple model to understand the BAM charge dependence



For a compressed bunch, the dependency is strongly suppressed.

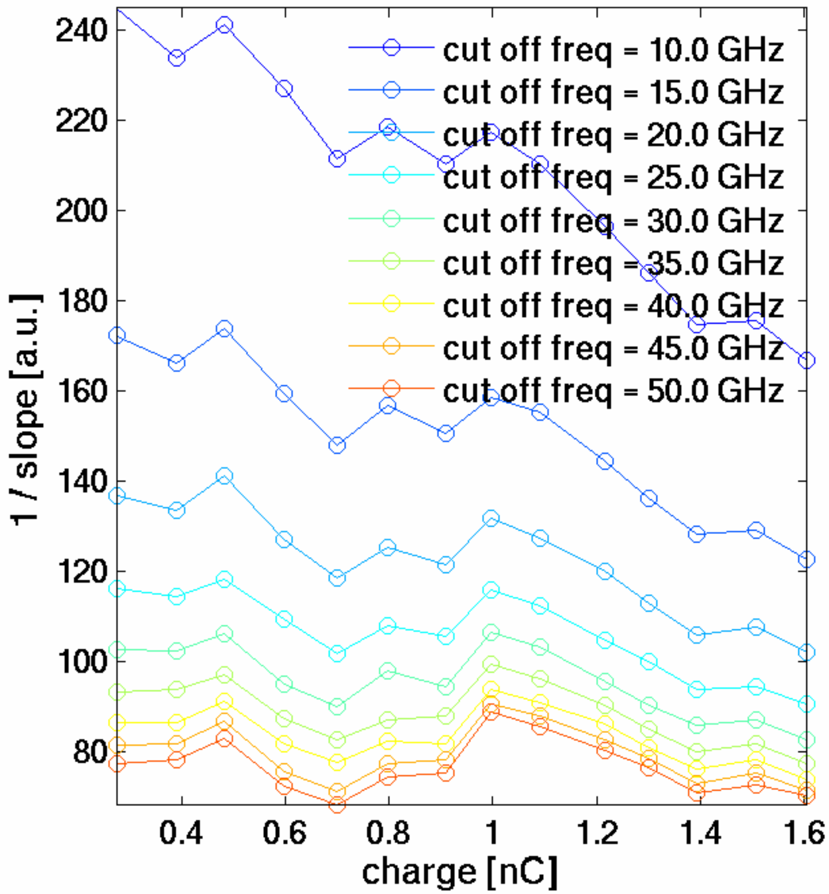
The previous considerations seem to explain the charge dependence…

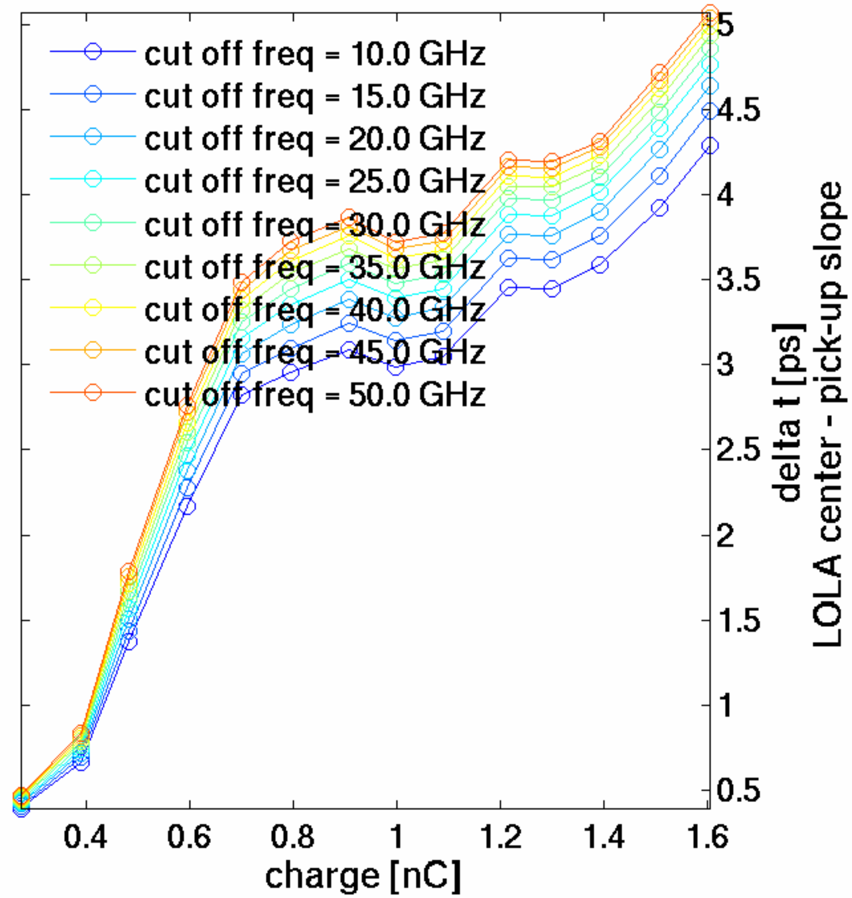
BUT: This is the frequency spectrum of the shortest wavelet:
(bandwidth of EOM: 20 GHz)



Bunch arrival time monitor (BAM)
Bandwidth of pick-up and EOM?

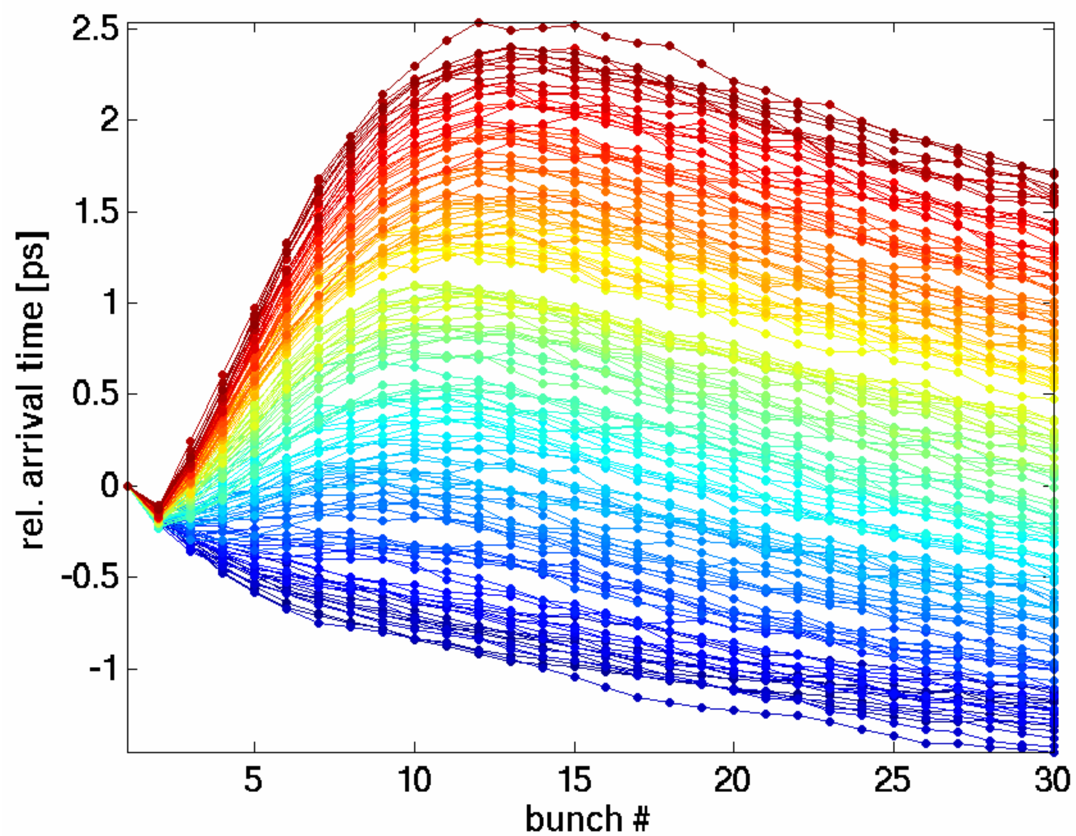
Expansion of the model by a low pass filter.
Behavior of the BAM can still be described by the model.
(wavelet pkpk ~ 6 ps)



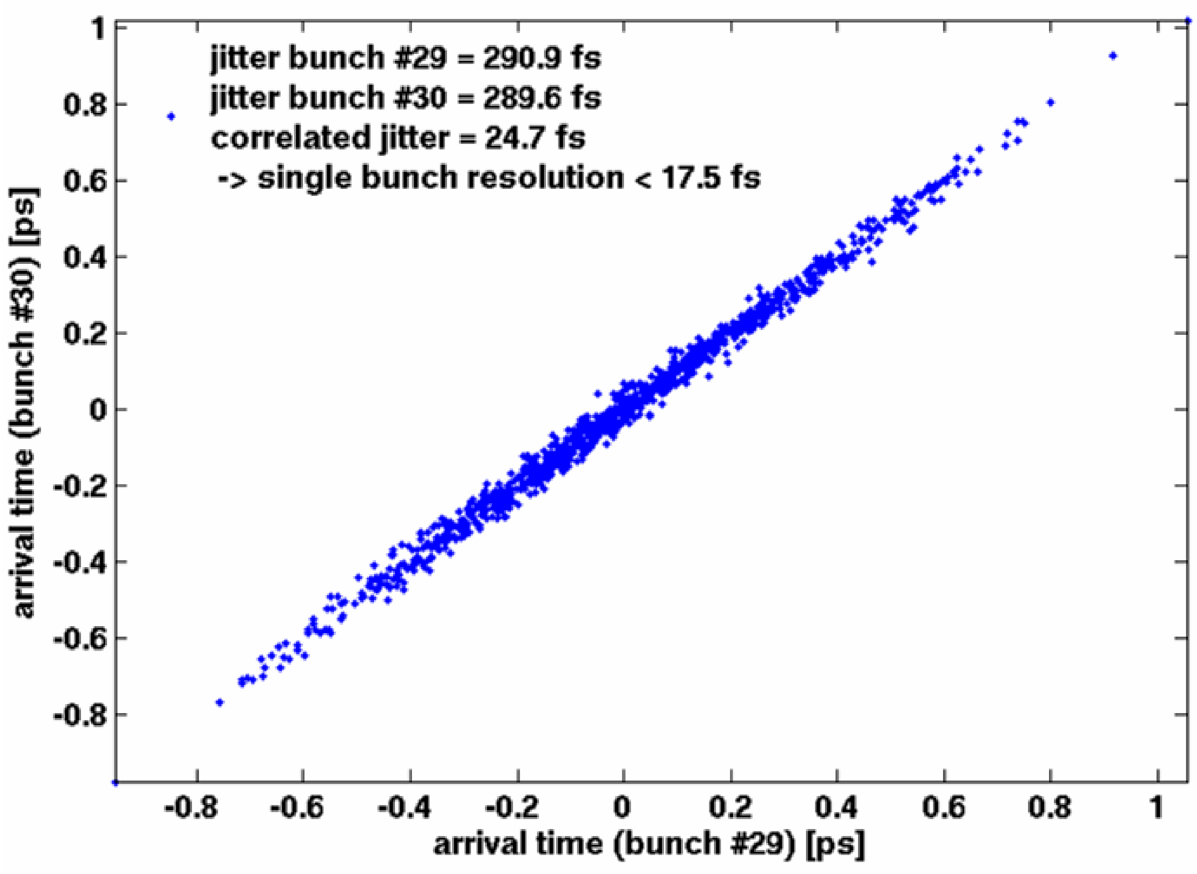


Goal: generate and compensate arrival time slopes with the beam loading amplitude of ACC1

The different colors represent different settings of the beam loading compensation.

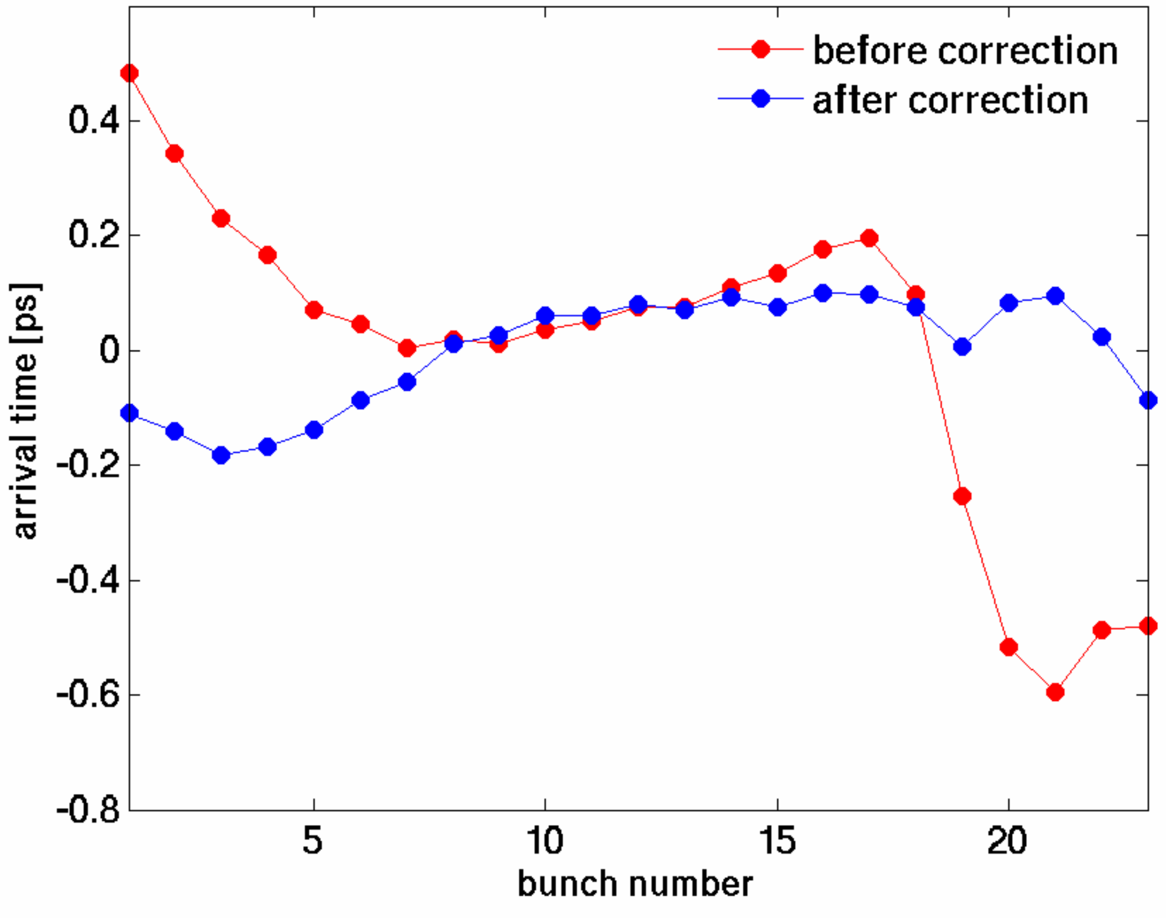


An upper limit for the BAM resolution can be estimated by correlating the arrival time of two adjacent bunches in the bunch train:

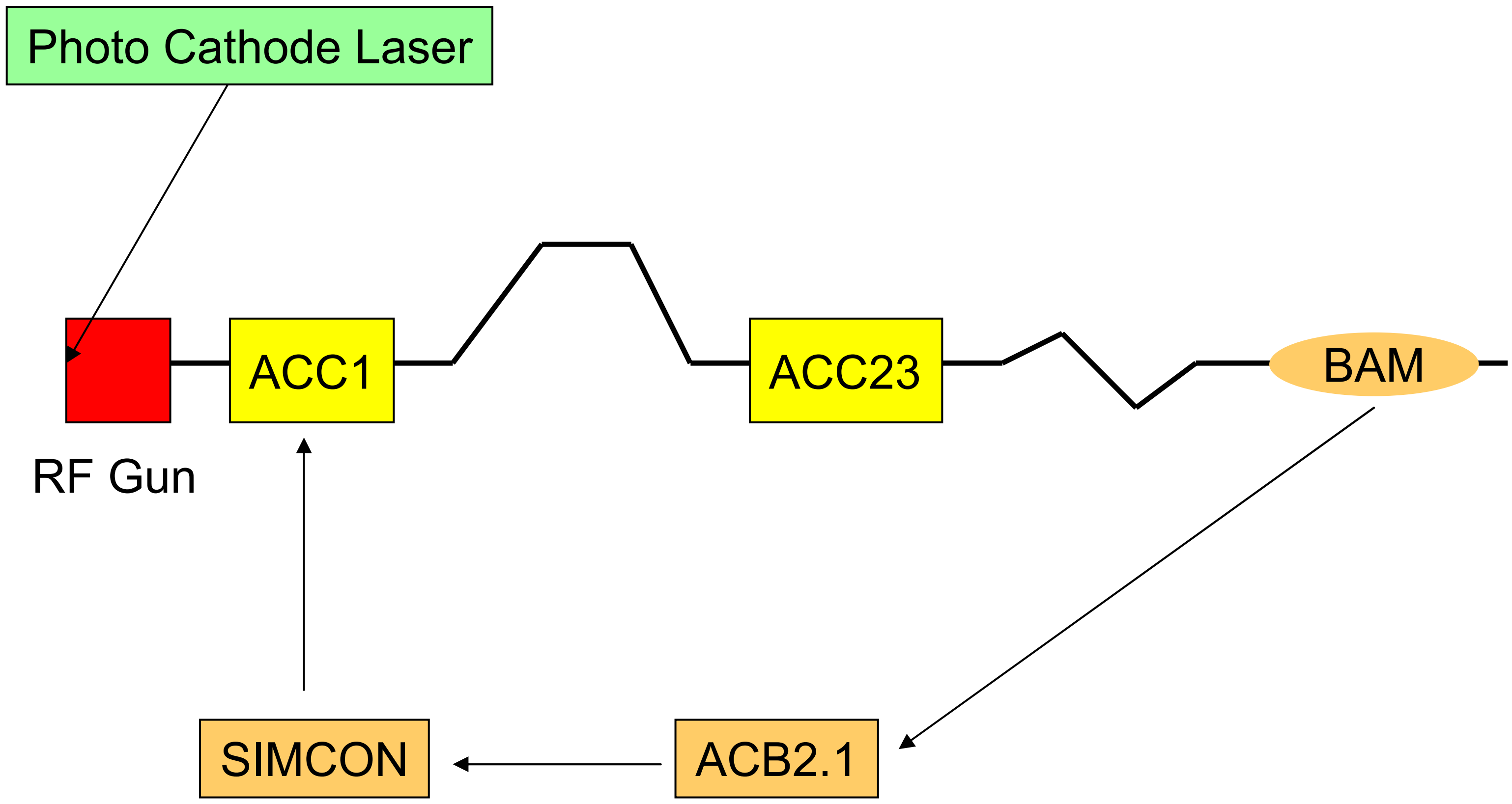


The resolution estimated from the laser amplitude noise and the slope steepness is well below 10 fs.

Arrival time flattened by applying arrival time readings to ACC1 amplitude set point tables.



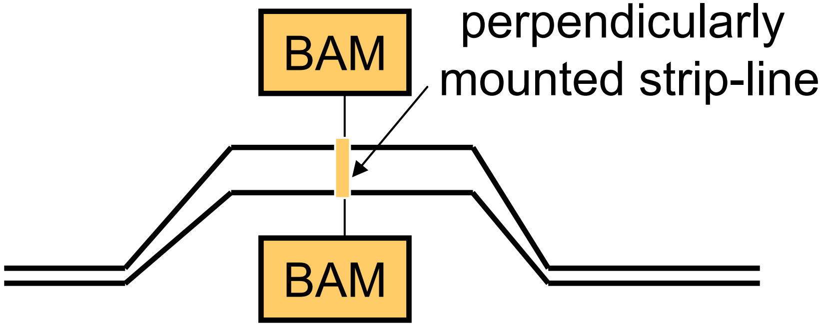
Next step: intra bunch-train arrival time feedback



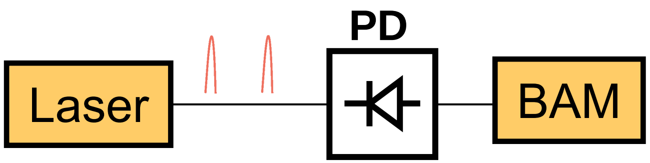
Bunch arrival time monitor (BAM)
Other applications of the BAM

The bunch arrival time monitors can be used for many different kinds of diagnostics, e.g.:

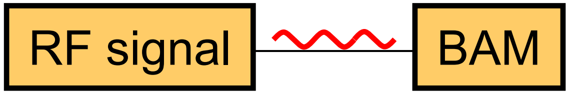
- Beam position measurement as difference of two arrival time measurements



- Laser timing measurement by sampling of photo detector signals

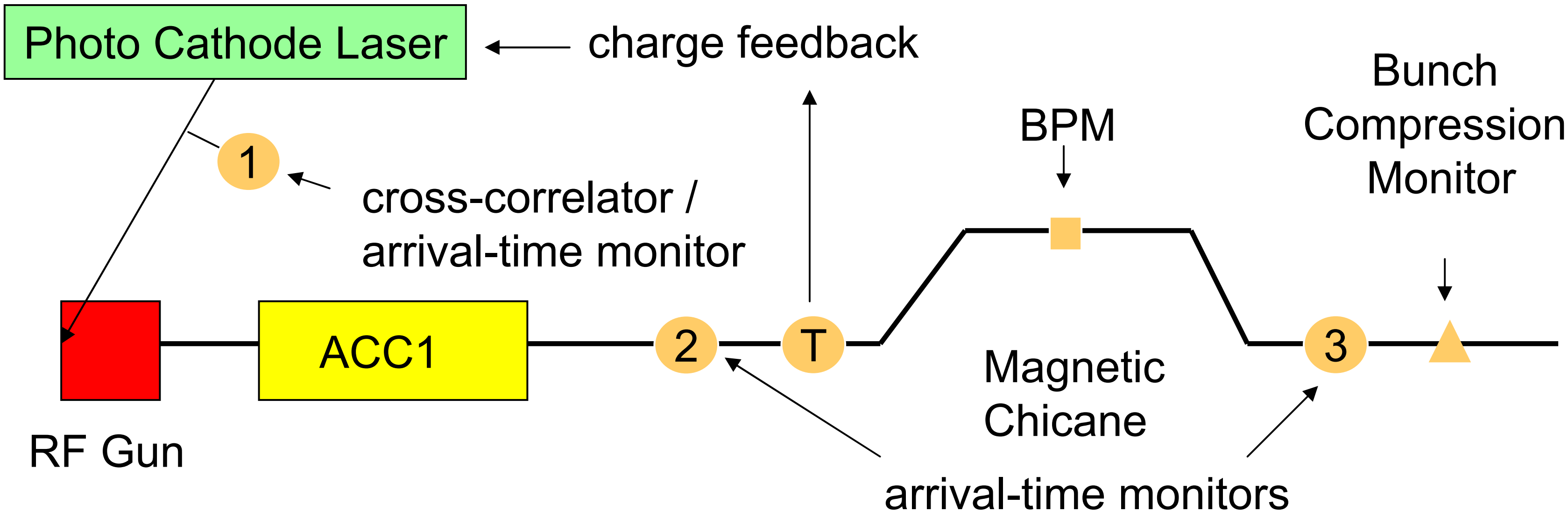


- Phase and amplitude measurements of RF signals



- …

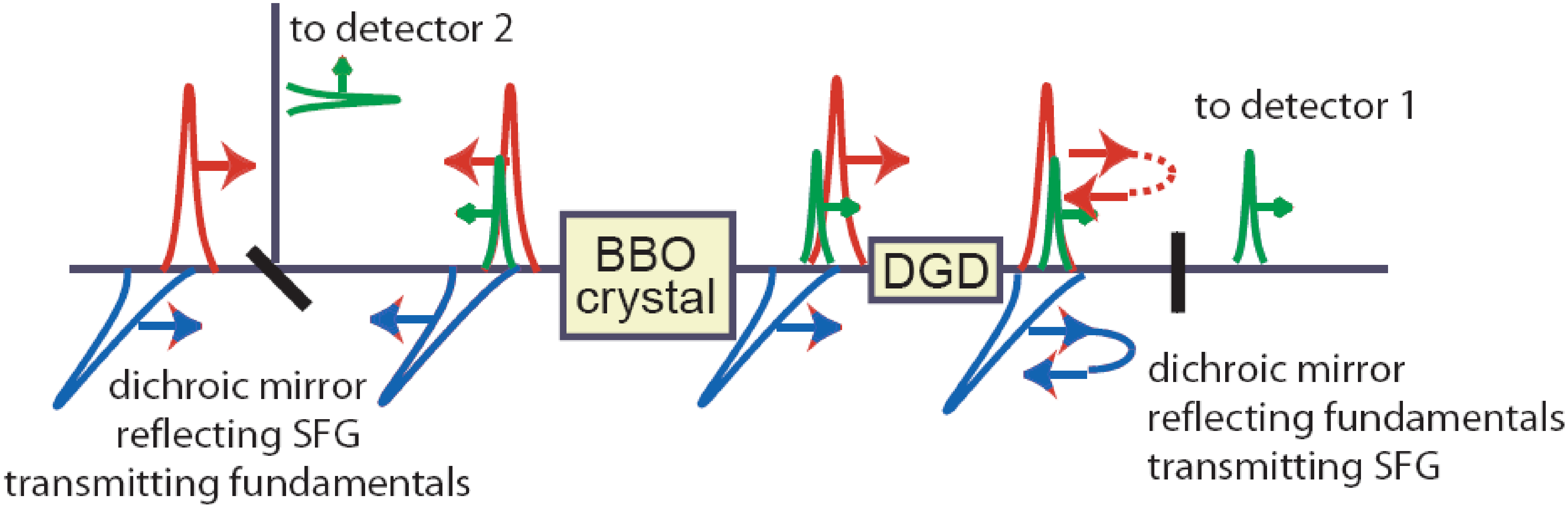
Outlook: complete longitudinal feedback



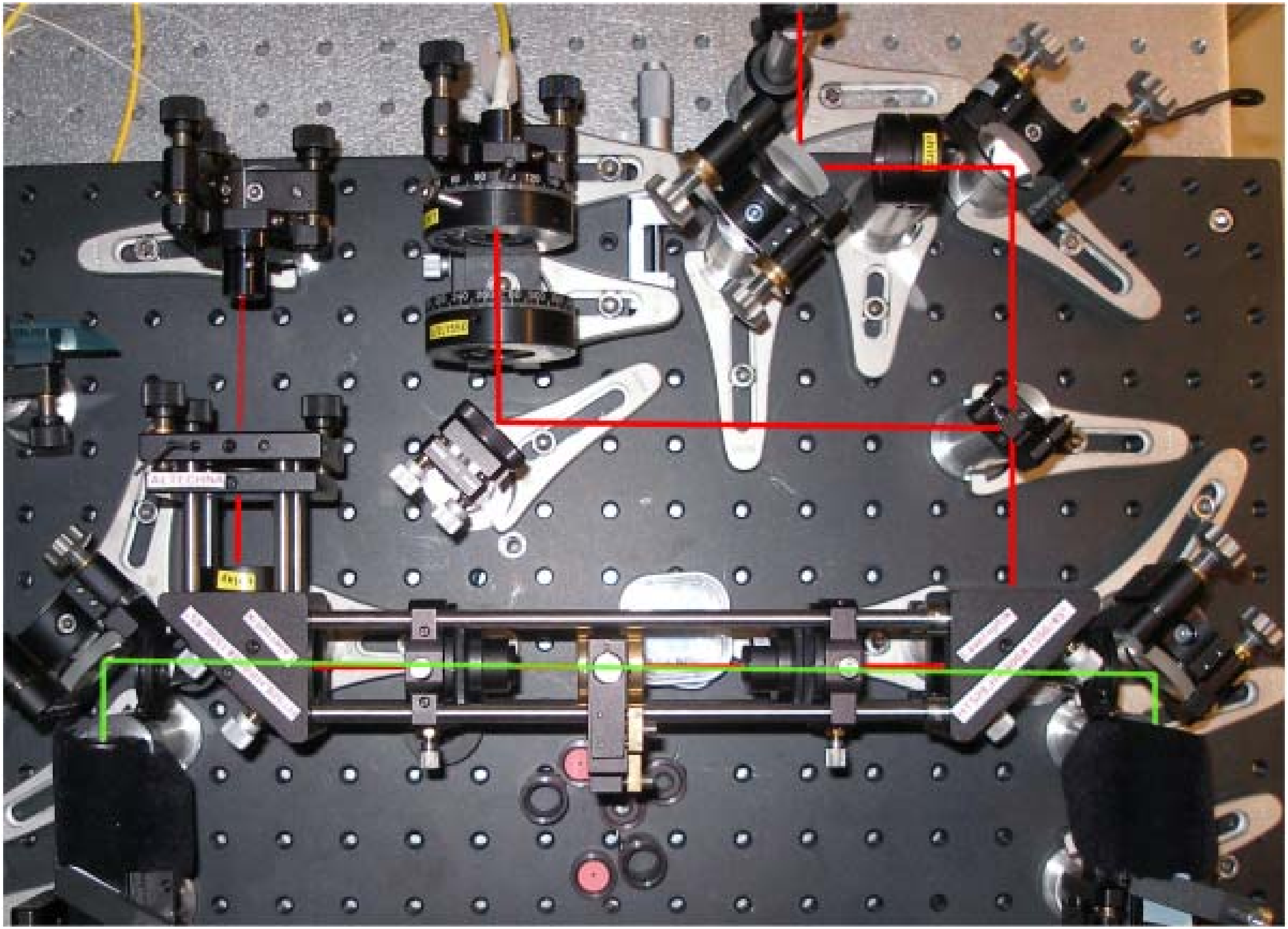
Detection of main arrival-time jitter sources

- Arrival time of photo cathode laser pulses **(CC / 1st arrival time monitor)**
- Phase of RF gun **(difference between 1st and 2nd arrival time monitor)**
- Amplitude of ACC1 **(BPM in magnetic chicane)**
- Phase of ACC1 **(Bunch Compression Monitor)**
- Arrival time of pump-probe laser **(cross-correlation with timing system)**

A similar scheme as for the fiber link cross-correlator will be used:

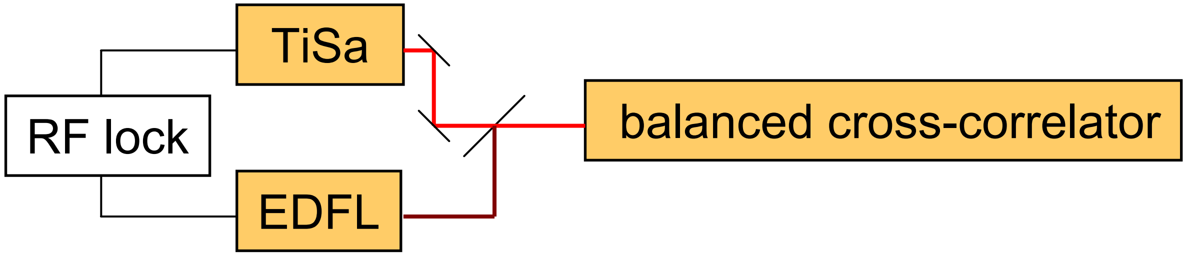


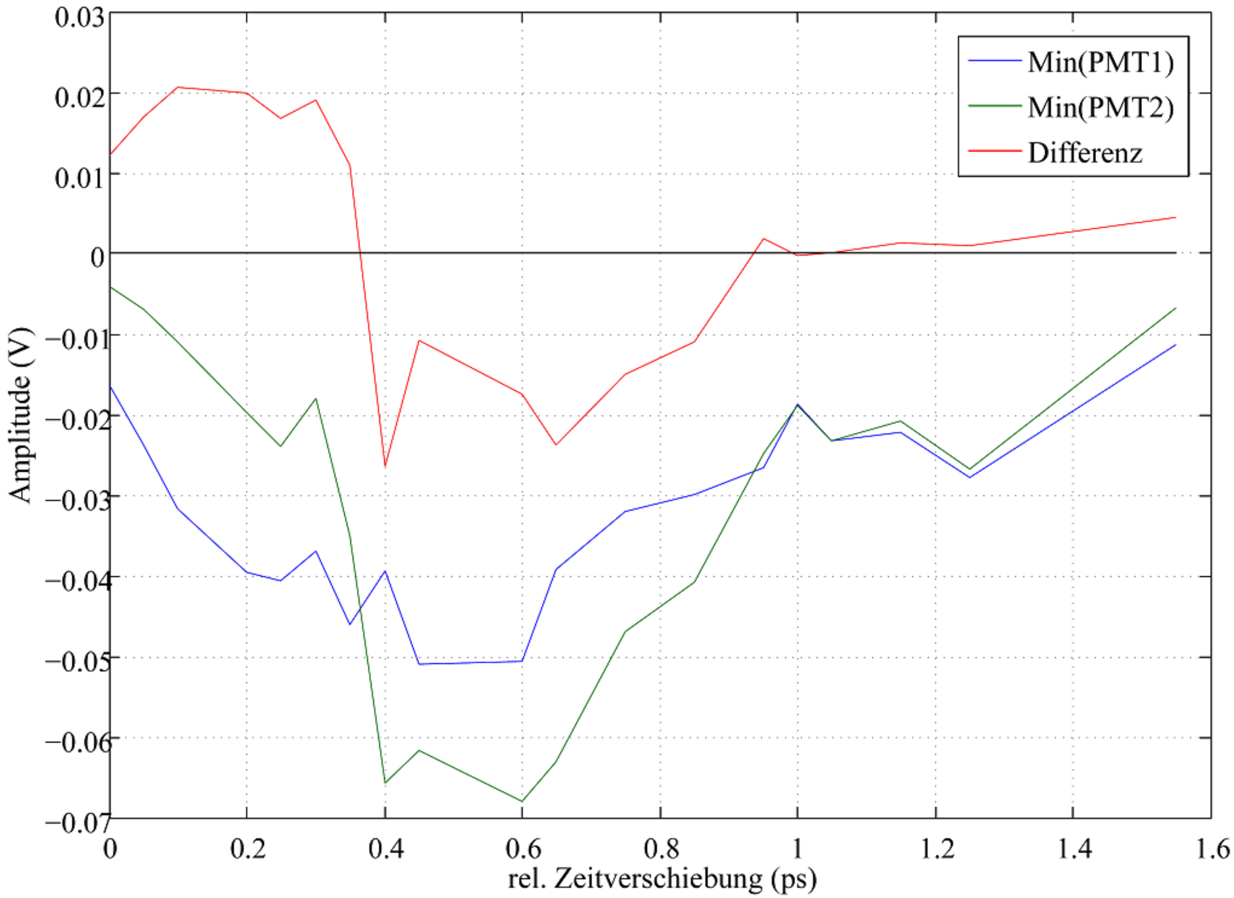
Locking of external lasers
First setup



Courtesy of S. Schulz, V. Arsov

First signal

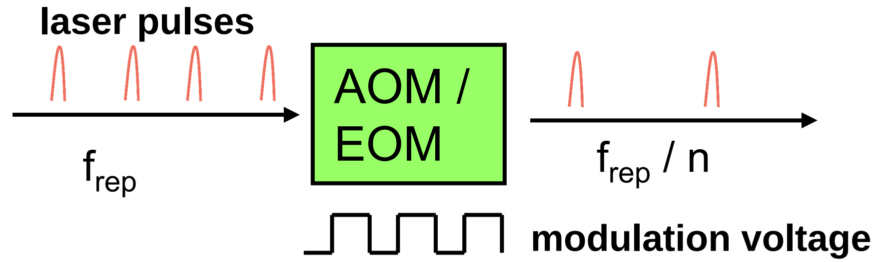




Courtesy of S. Schulz, V. Arsov

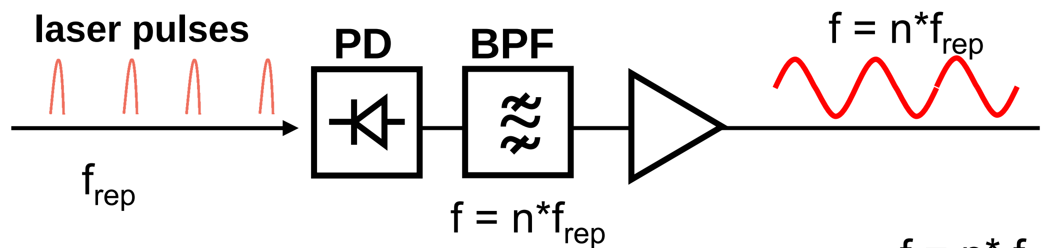
Laser to RF conversion
Possible schemes

Optical division of distributed frequency



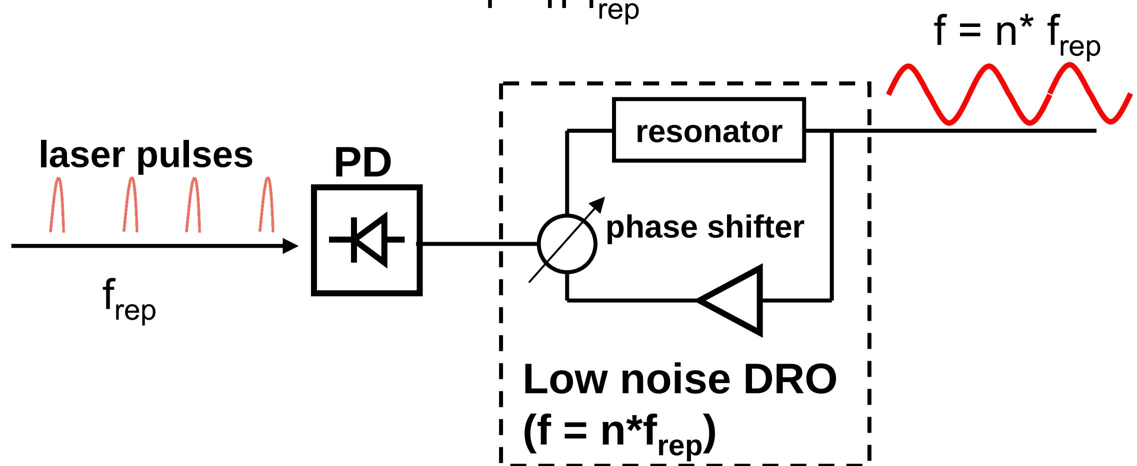
Direct conversion with PD

– temperature drifts
– AM to PM conversion*
– noise limitation due to low power in spectral line of PD output

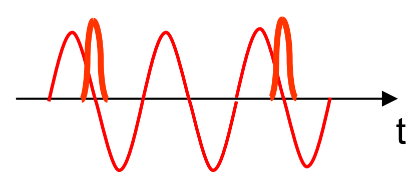


Injection Locking

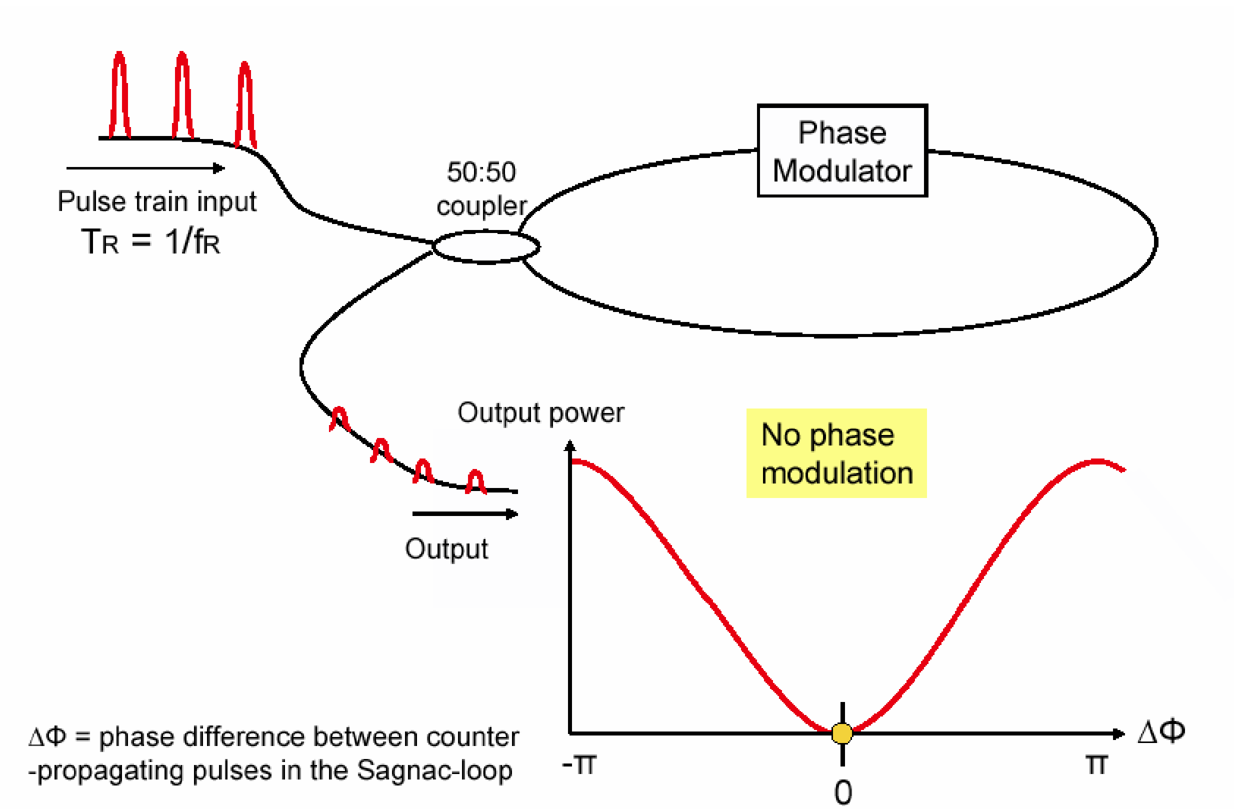
– temperature drifts of PD
– AM to PM conversion of PD*
+ DRO determines high frequency noise
+ entire photo detector signal used



(*) typical AM to PM conversion: 1-10ps/mW



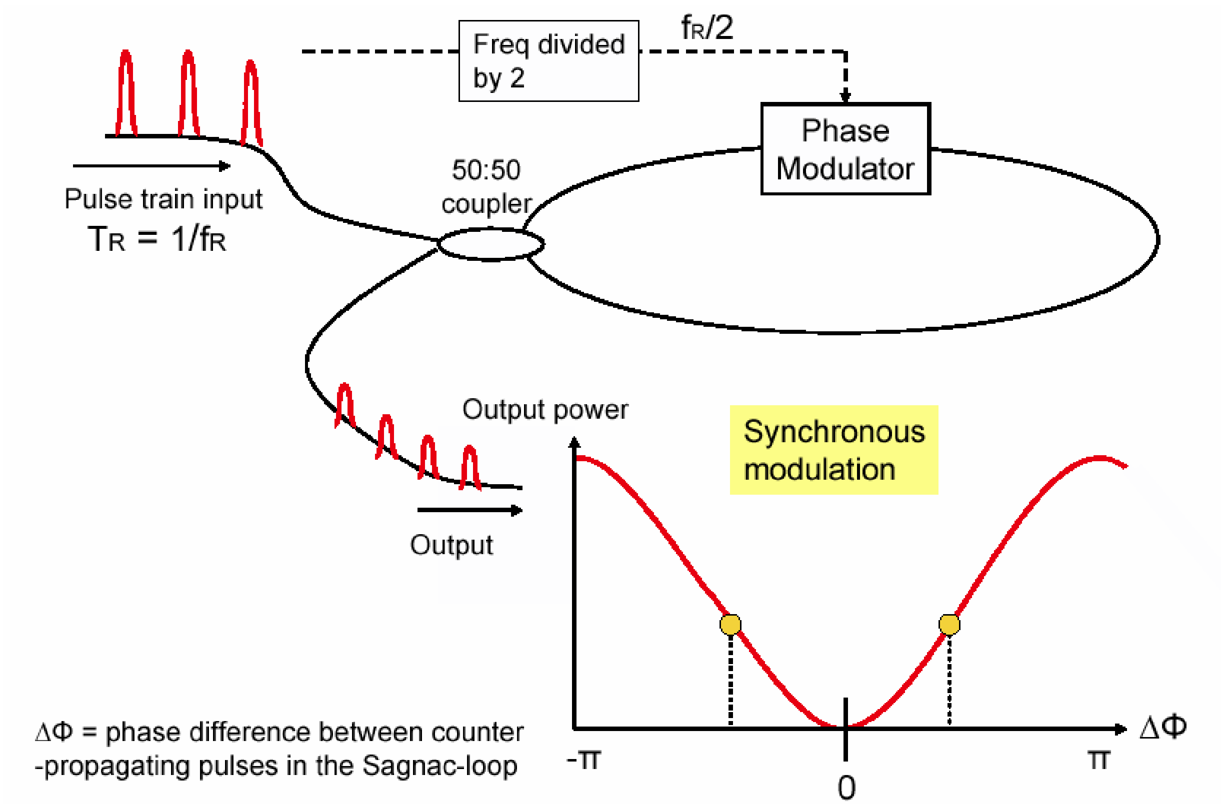
Phase detection in the optical domain:

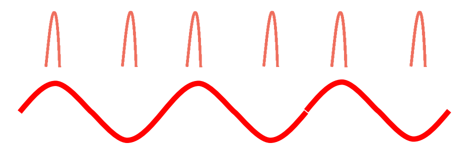


Courtesy of J. Kim

Laser to RF conversion
Sagnac loop

Phase detection in the optical domain:

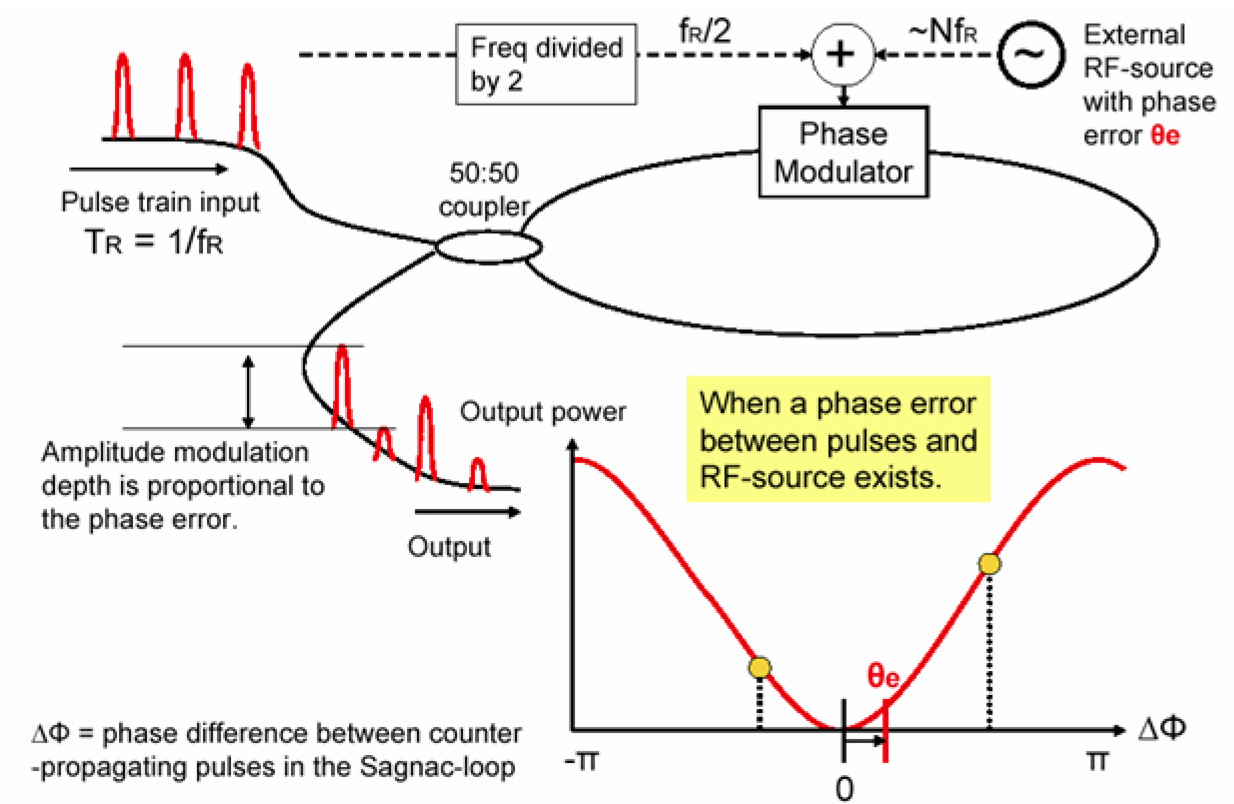




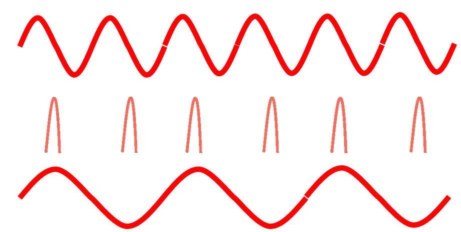
modulation voltage: f_{rep} / 2

Courtesy of J. Kim

Phase detection in the optical domain:



VCO signal to stabilize ($n*f_{rep}$)

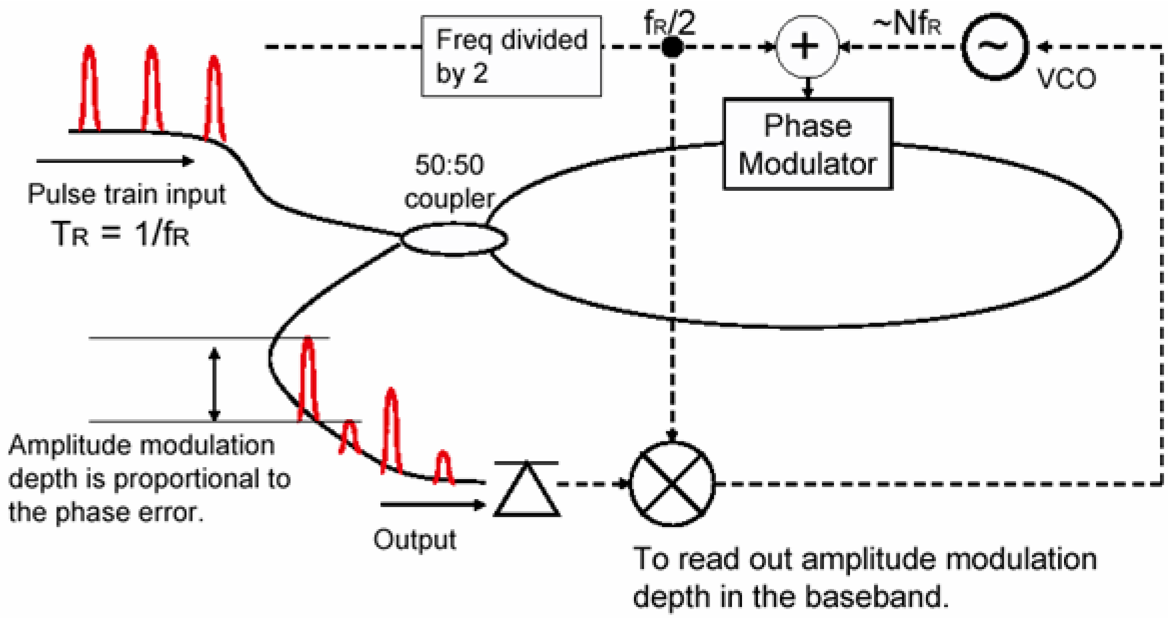


modulation voltage: f_{rep} / 2

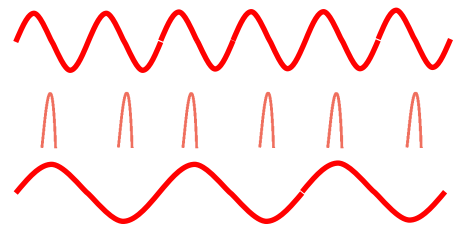
Courtesy of J. Kim

Laser to RF conversion
Sagnac loop

Phase detection in the optical domain:



VCO signal to stabilize ($n*f_{rep}$)



modulation voltage: f_{rep} / 2

First results with a DRO frequency of 10 GHz are very promising (< 10 fs drift over 12h, J. Kim et. al.).
Next step: Transition to 1.3 GHz DRO.

Courtesy of J. Kim

Conclusion

- Most subsystems have been prototyped and proven to have a resolution / stability of ~ 10 fs.
- A complete system consisting of a fiber laser, a fiber link and a bunch arrival time monitor is running and provides the expected resolution
- The ultimate machine stabilization will be done using beam based measurements.

Next steps:

- Consistency studies:
  - comparison measurement of two BAMs
  - comparison measurement BAM ↔ EO
- Implementation of arrival time feedback
- Upgrade of synchronization system to reach more end-stations

We would like to thank J. Szewinski for his support of ACB2.1, MCS4 for their help with all kinds of controls, and the technicians of the group FLA for their great work.

Thank you for your attention!