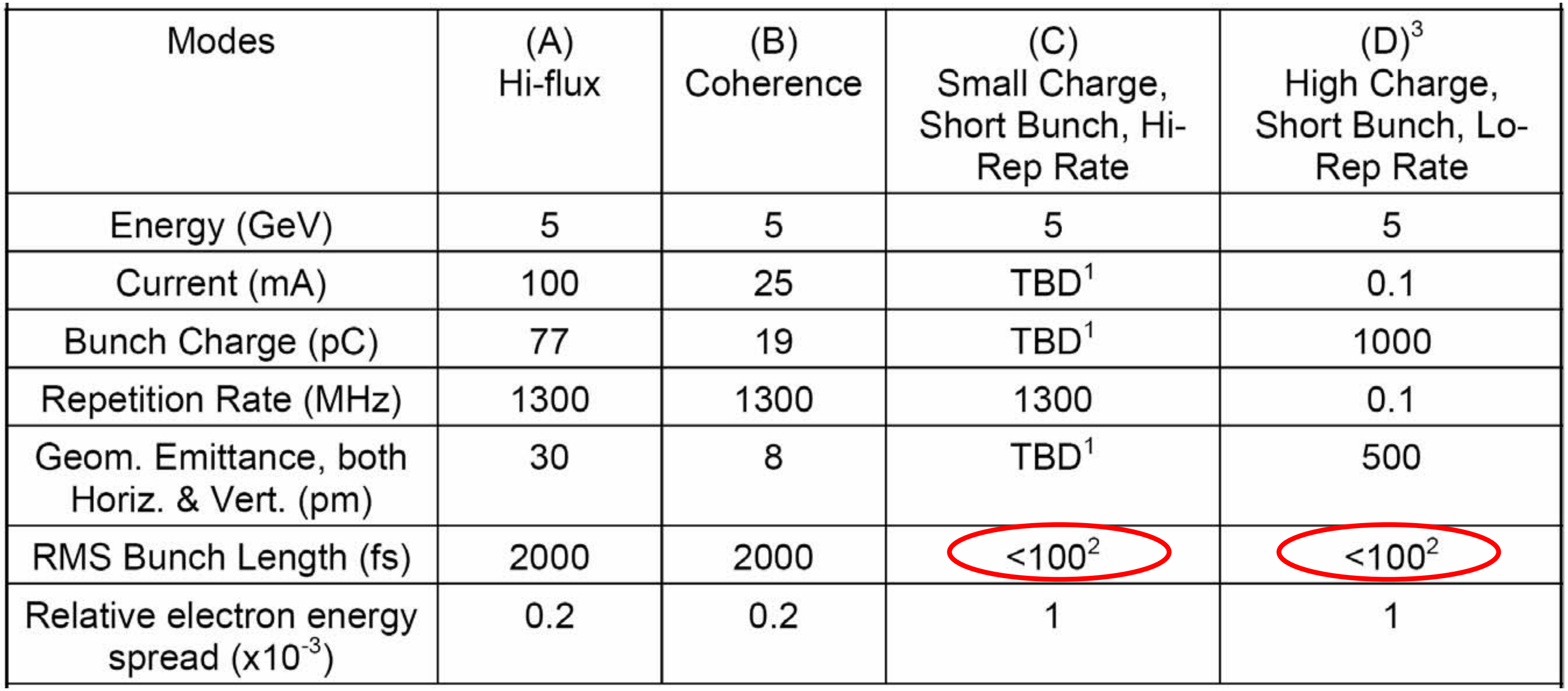
Bunch Arrival Synchronization

- Arrival time detector overview
- Optical synchronization system using a pulsed reference laser
  - Distribution system
  - Synchronization of laser oscillators
  - Measurement and generation of RF signals
  - Arrival time detector
- Sources for arrival time changes
  - Arrival time stabilization at FLASH
- Summary of arrival time detectors

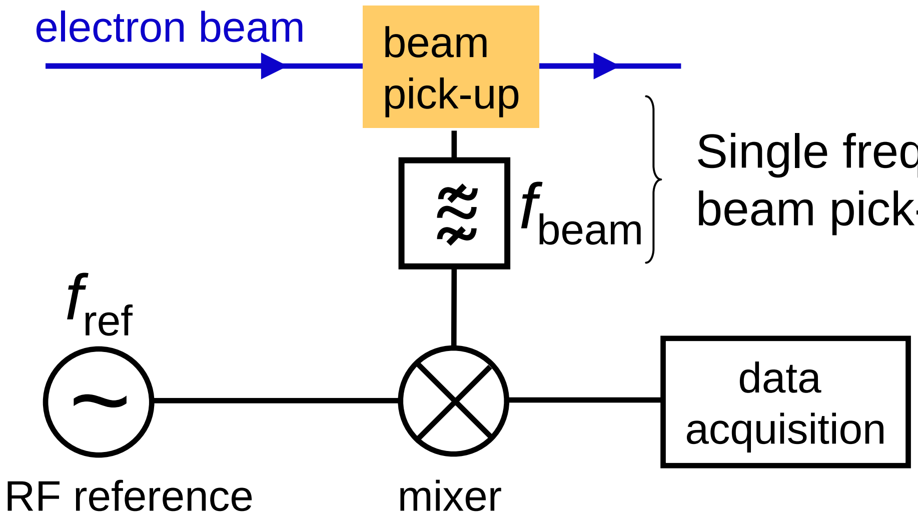
ERL requirements



Modes	(A) Hi-flux	(B) Coherence	(C) Small Charge, Short Bunch, Hi-Rep Rate	(D)[3] High Charge, Short Bunch, Lo-Rep Rate
Energy (GeV)	5	5	5	5
Current (mA)	100	25	TBD[1]	0.1
Bunch Charge (pC)	77	19	TBD[1]	1000
Repetition Rate (MHz)	1300	1300	1300	0.1
Geom. Emittance, both Horiz. & Vert. (pm)	30	8	TBD[1]	500
RMS Bunch Length (fs)	2000	2000	<100[2]	<100[2]
Relative electron energy spread (x10^{-3})	0.2	0.2	1	1

In short pulse modes, an electron bunch arrival time stability of 10 fs is required.

Arrival time detection by RF methods
Simplified principle



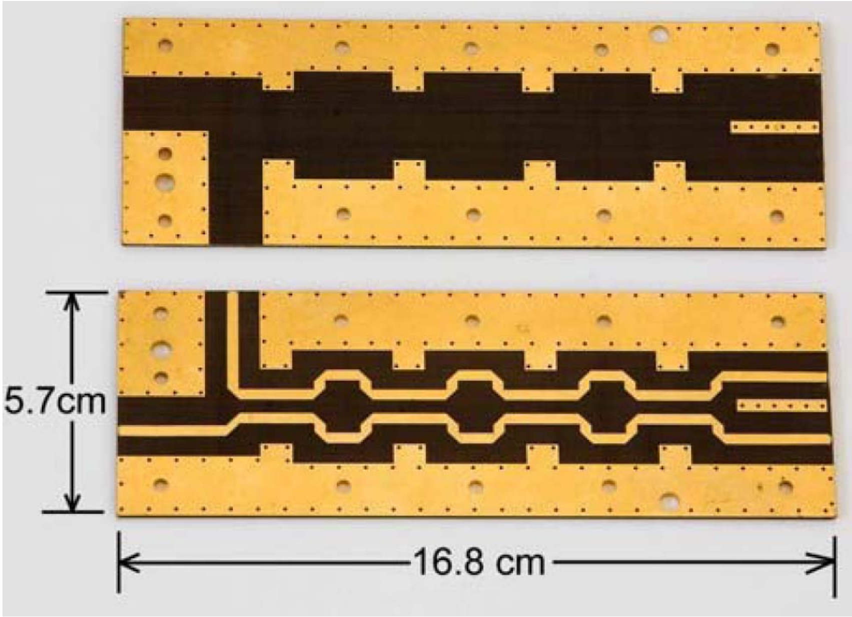
Single frequency generation by beam pick-up + filter or cavity

Measurement of beam phase relative to RF reference

+ relative simple setup
+ high resolution possible at high frequencies
+ single bunch measurement possible
  demonstrated at 2 ns bunch spacing (J. Fox et al.)

- long-term stability hard to achieve
  - band pass filter / cavity and mixer tend to drift
  - drift free generation of high frequency reference signal is challenging
- no information on bunch shape

Arrival time detection by RF methods
PEP-II / ALS / BESSY / PLS system

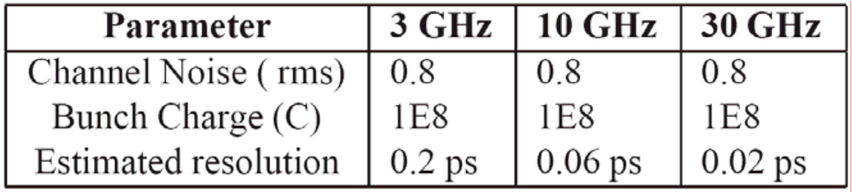


Planar stripline circuit band-pass filter

- generates 4 cycle output signal at 2856 MHz from a button BPM signal
- Finite time response allows for single bunch detection at small bunch spacings (here: 2 ns)

Single shot resolution: 200 fs.

Estimated resolutions for a higher frequency design:

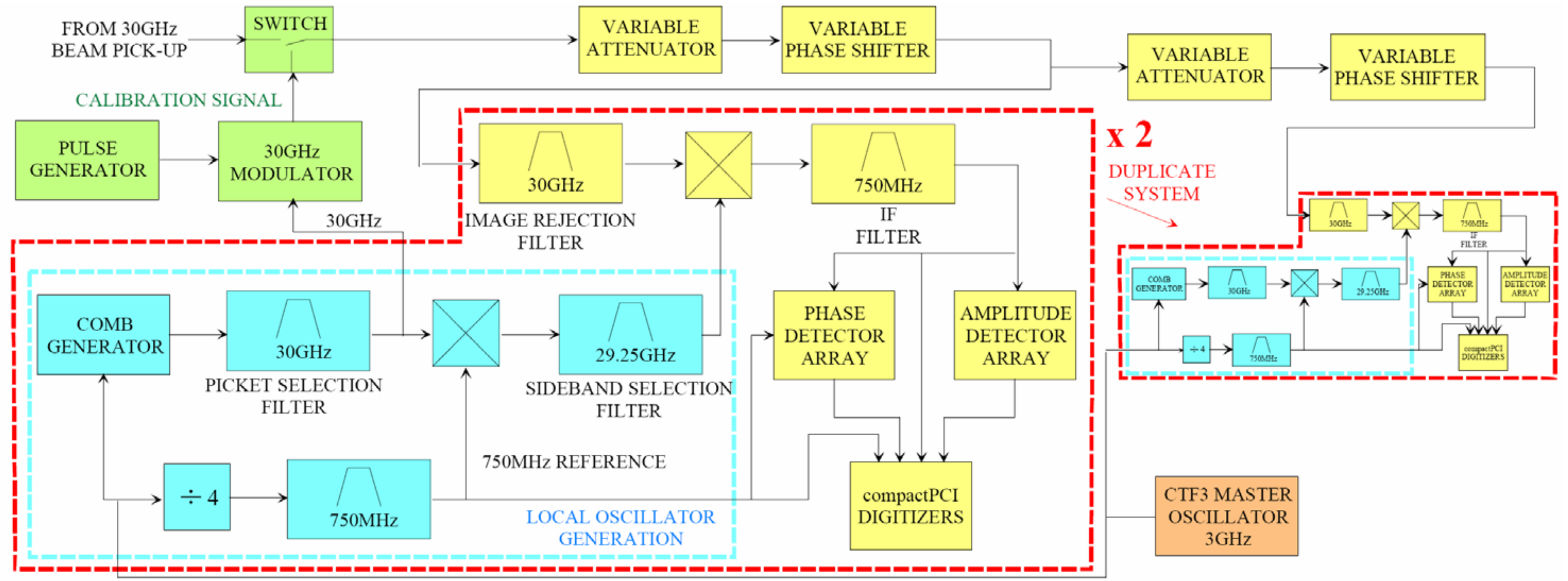


Parameter	**3 GHz**	**10 GHz**	**30 GHz**
Channel Noise (rms)	0.8	0.8	0.8
Bunch Charge (C)	1E8	1E8	1E8
Estimated resolution	0.2 ps	0.06 ps	0.02 ps

bunch charge: 10 nC
ERL: 0.077 nC

Courtesy of J. Fox (SLAC), et al.

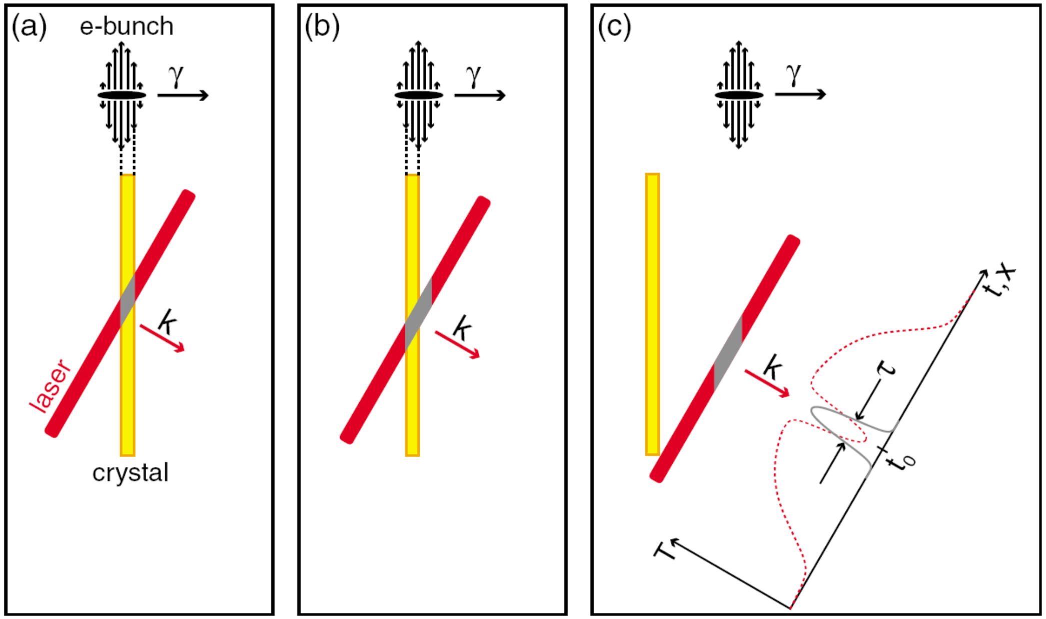
Arrival time detection by RF methods
CLIC system



- detection scheme at 30 GHz
- less than 10 fs resolution in 250 MHz bandwidth
- bunch spacing: 333 ps

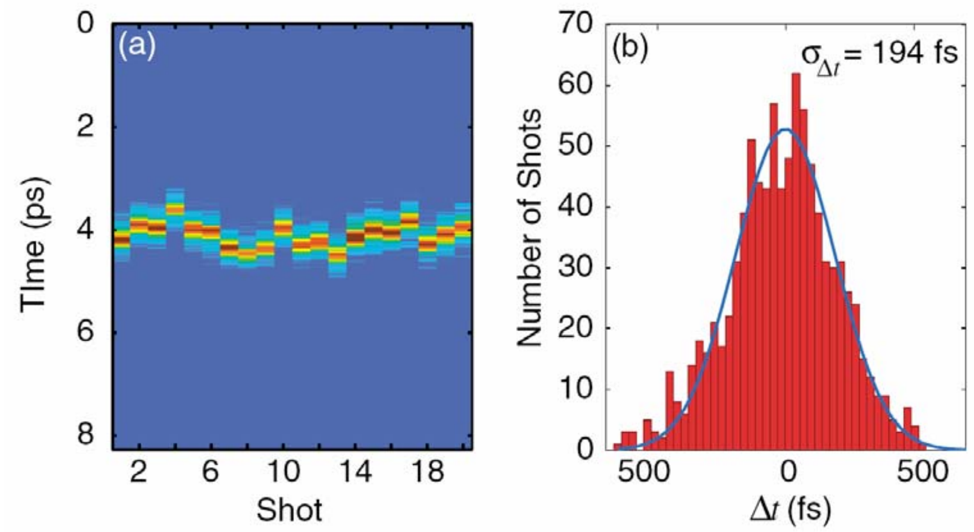
Courtesy of A. Andersson, J.P.H. Sladen (CERN)

Electro-optical arrival time detection: Spatial mapping



Detection of electron arrival time with respect to reference beam.

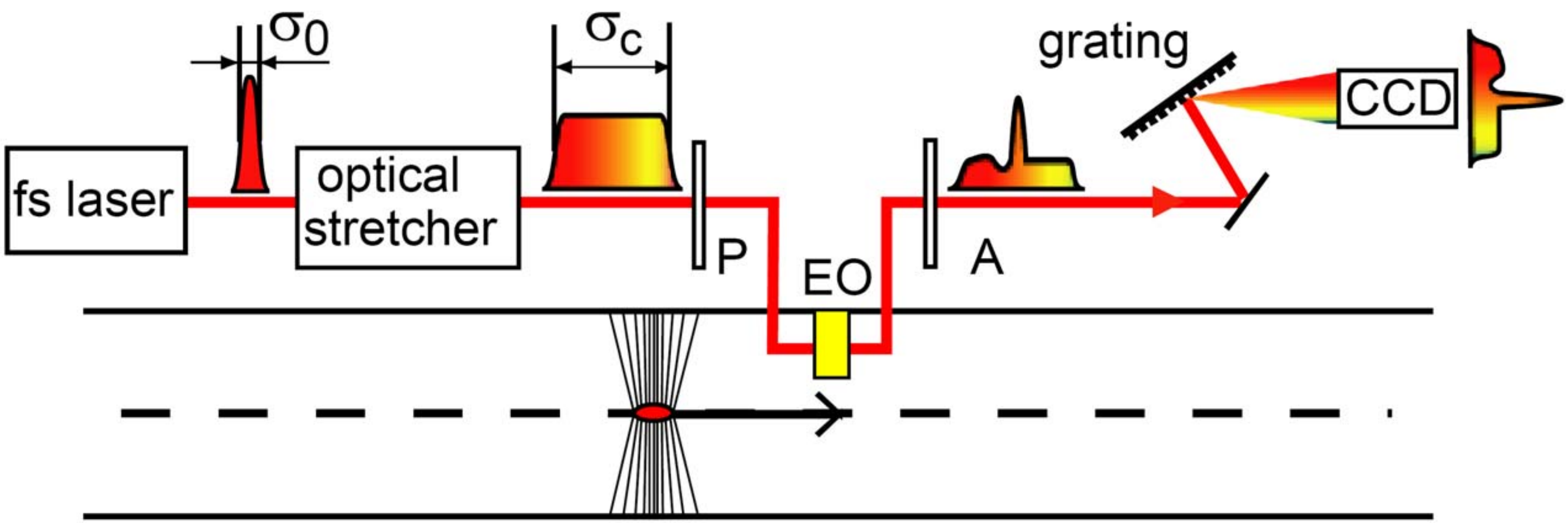
- Mapping of electron bunch profile into polarization of a short laser pulse using an electro-optical crystal.
- Different arrival times correspond to different spatial positions of the laser pulse.

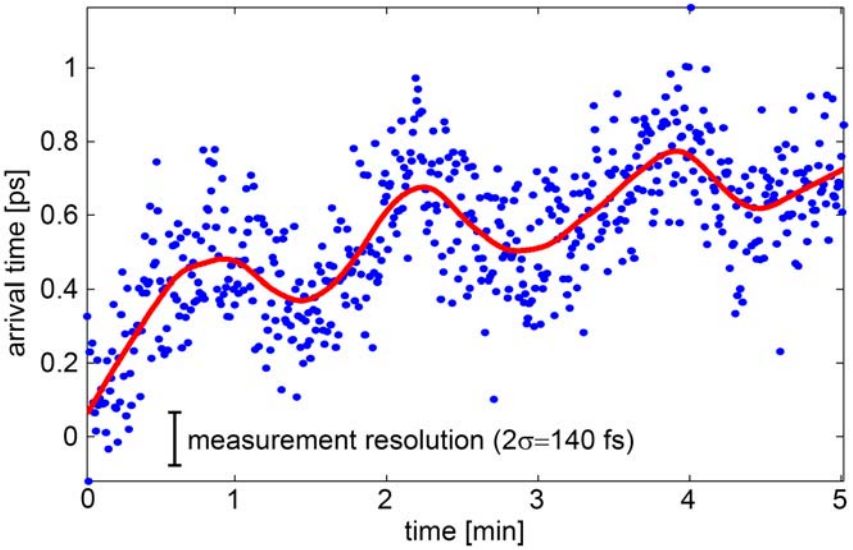


- 30 fs resolution for bunch centroid
- single bunch measurement
- sample rate limited by readout system (and laser repetition rate)
- Bunch profile information available

Courtesy of A. Cavalieri

Electro-optical arrival time detection: Spectral decoding



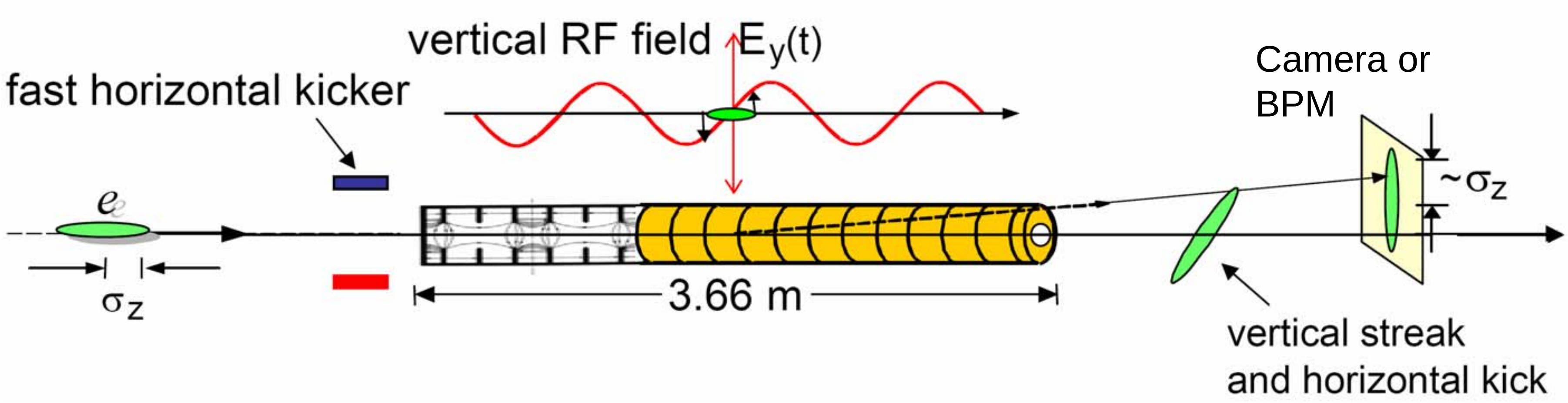


- Mapping of electron bunch profile into optical spectrum of a broad-band laser pulse using an electro-optical crystal.

Similar performance as previous scheme.

Courtesy of G. Berden et al. (FELIX)

Arrival time measurement with a transverse deflecting structure



Measurement of the bunch arrival time with respect to the RF field in the cavity

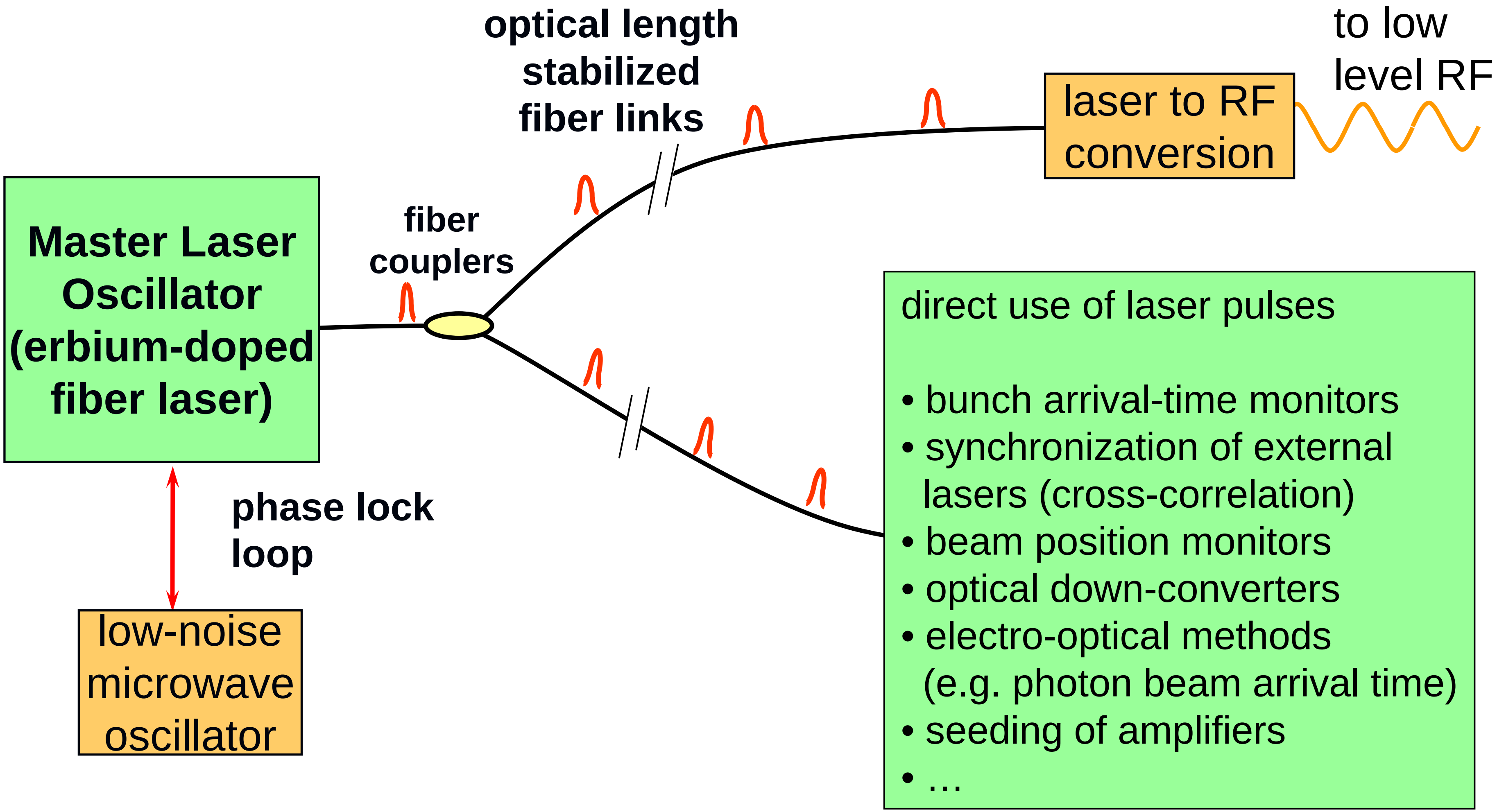
- \+ highest temporal resolution of the discussed methods (sub 20 fs within the longitudinal profile)
- \+ single shot detection possible
- \+ small bunch spacing possible when paired with BPM readout system

- \- Streaked bunches are lost
- o Knowledge of the timing of the cavity RF field determines arrival time resolution

„Synchronization“ of arrival time monitors

- „Single frequency detection“
  - provide stable RF signal with respect to reference
  - phase detection of RF signal with respect to reference
- Electro-optical methods with external lasers
  - synchronize laser to reference
- Transverse deflecting cavity
  - provide stable RF signal with respect to reference
  - phase detection of RF signal with respect to reference

Layout of the optical synchronization system at FLASH



Master Laser Oscillator (erbium-doped fiber laser)

fiber couplers

optical length stabilized fiber links

laser to RF conversion

to low level RF

phase lock loop

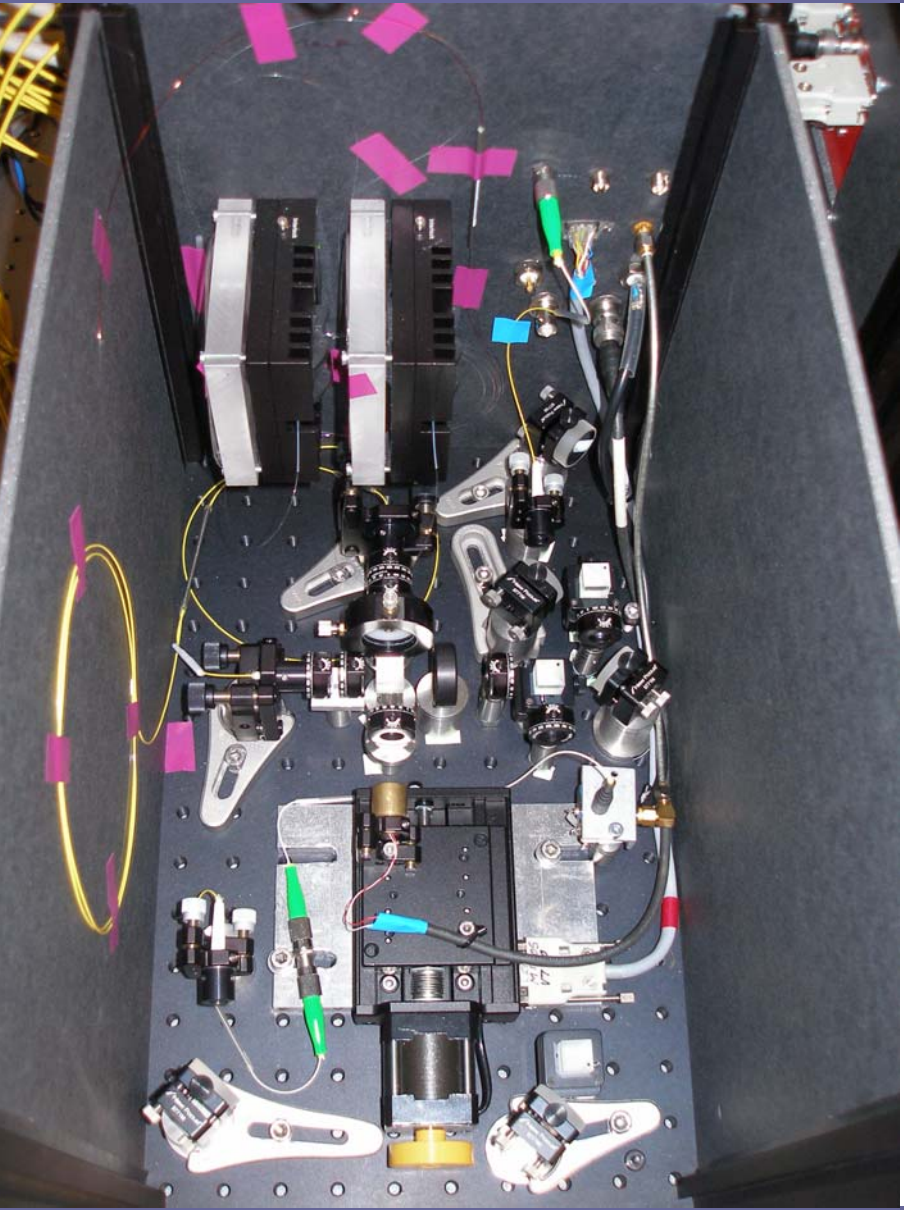
low-noise microwave oscillator

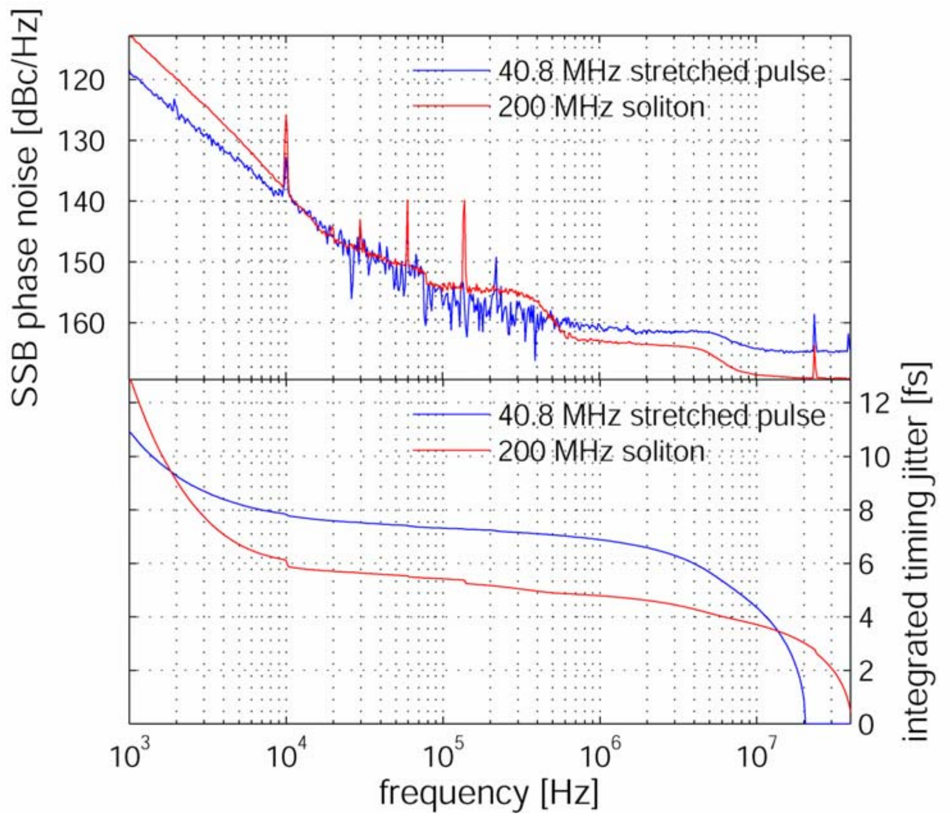
direct use of laser pulses

- bunch arrival-time monitors
- synchronization of external lasers (cross-correlation)
- beam position monitors
- optical down-converters
- electro-optical methods (e.g. photon beam arrival time)
- seeding of amplifiers
- …

Development in collaboration with MIT (F.X. Kaertners group)

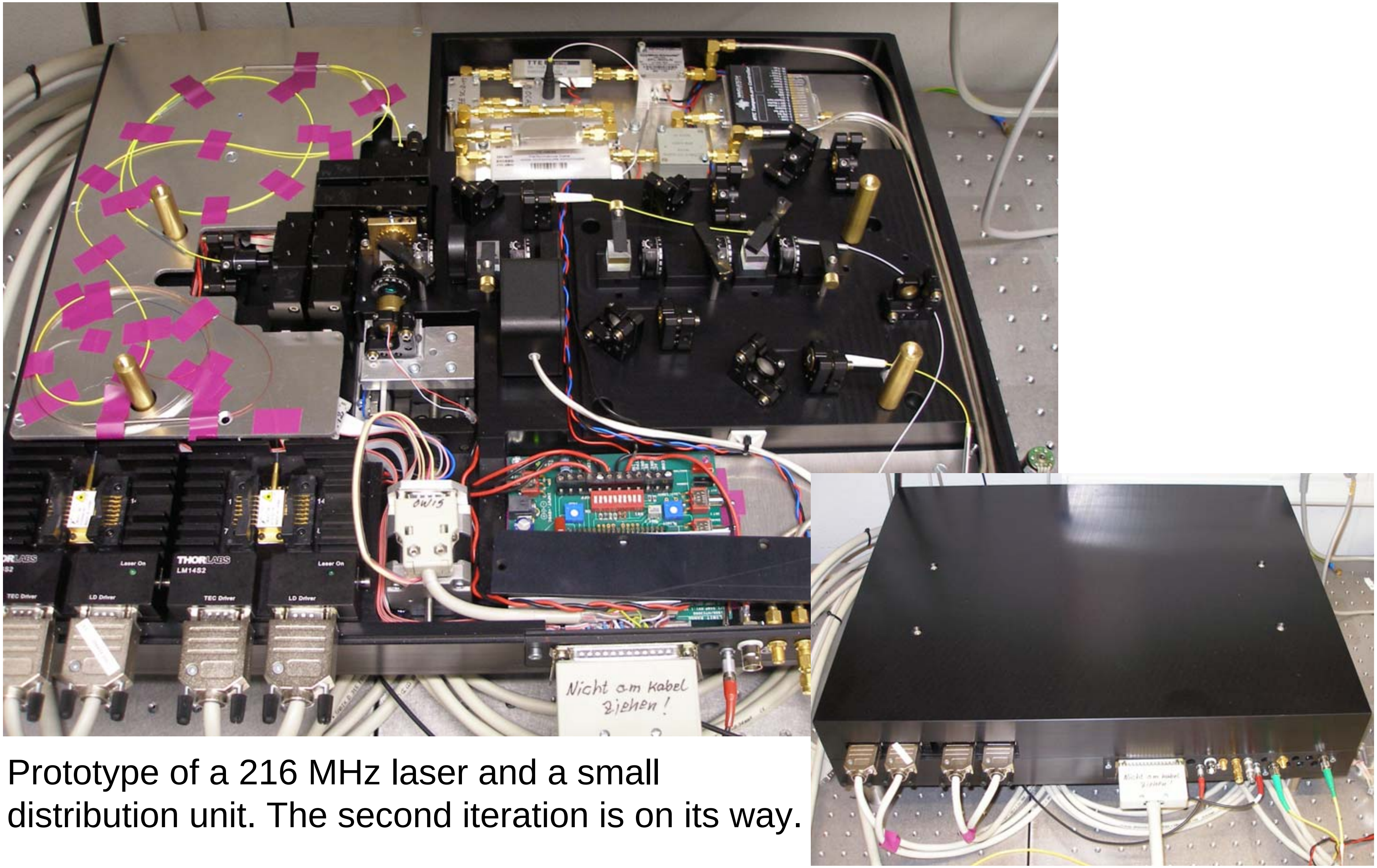
The fiber laser system





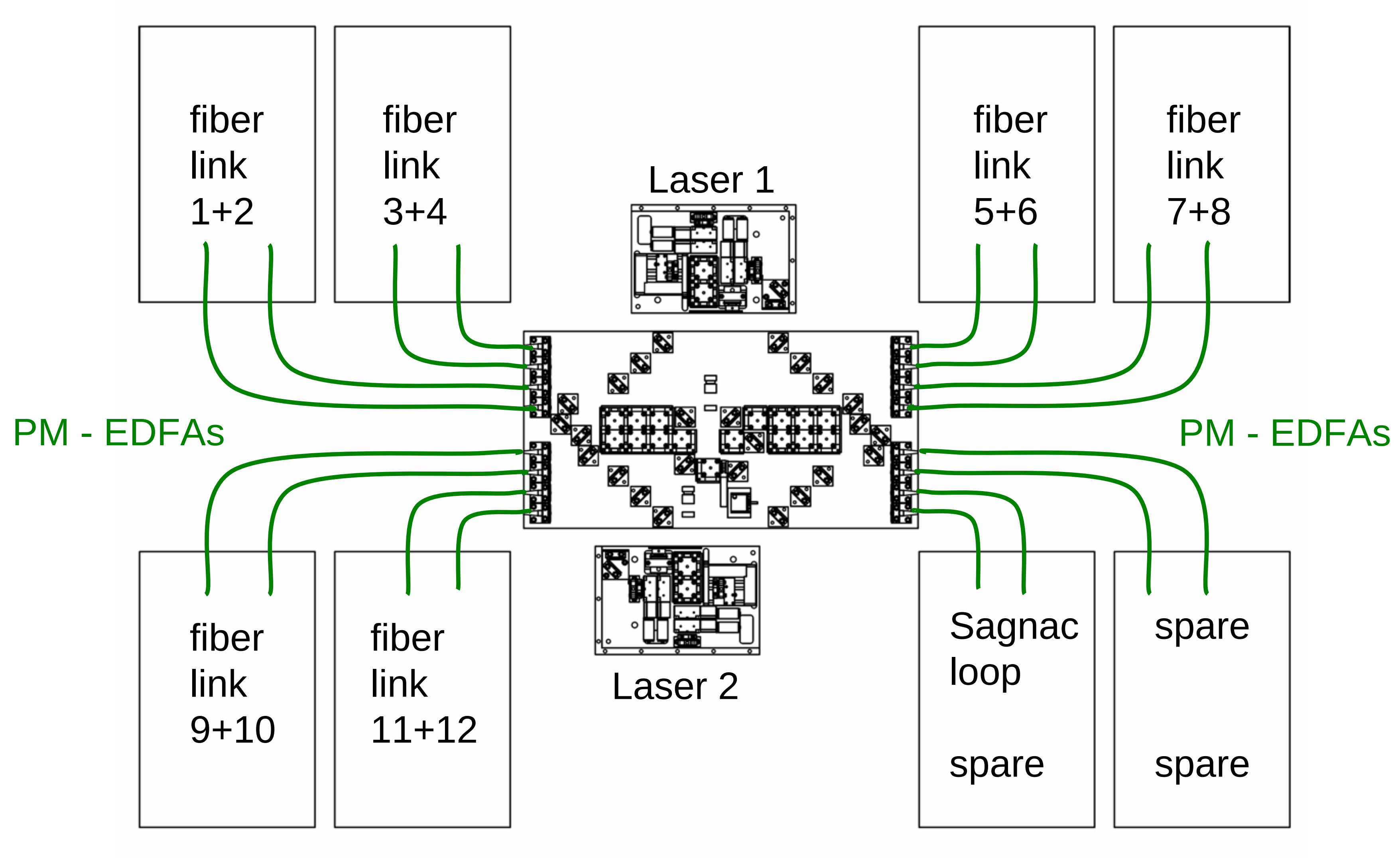
A low noise, Erbium-doped, modelocked, 216 MHz soliton laser is used as the timing reference for the accelerator.

First prototype of a 216 MHz laser

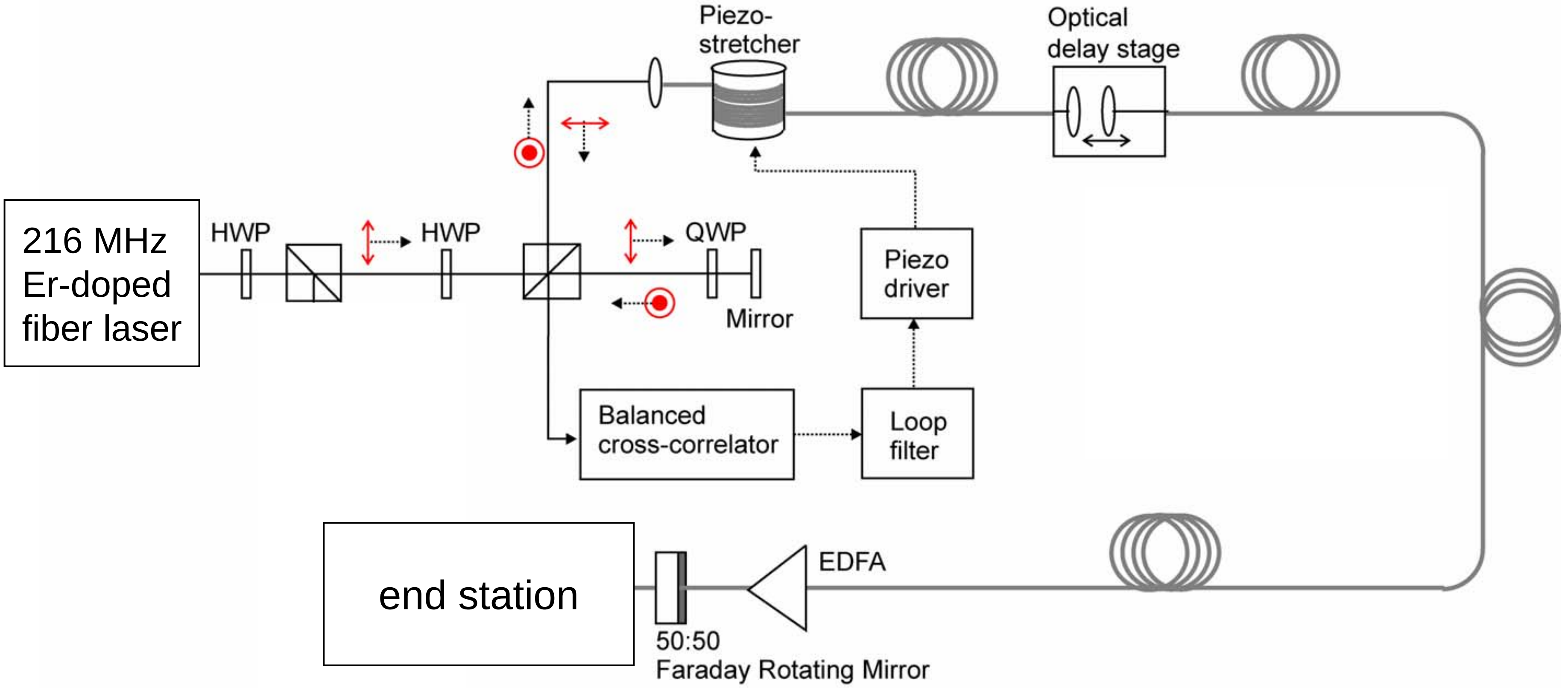


Prototype of a 216 MHz laser and a small distribution unit. The second iteration is on its way.

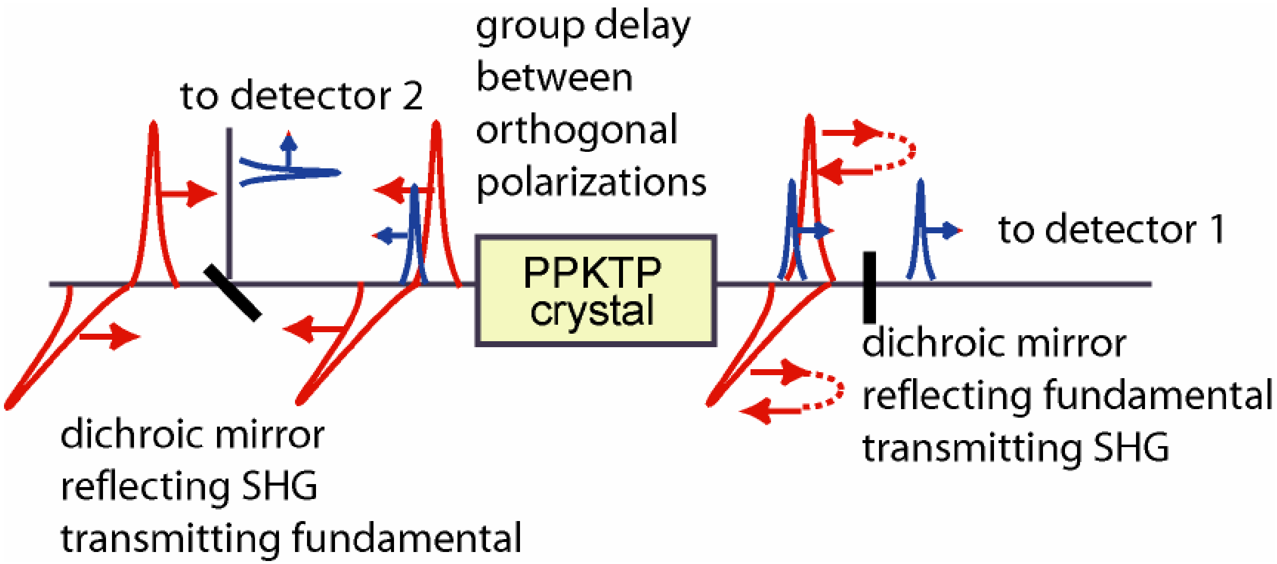
Laser distribution unit
Schematic layout

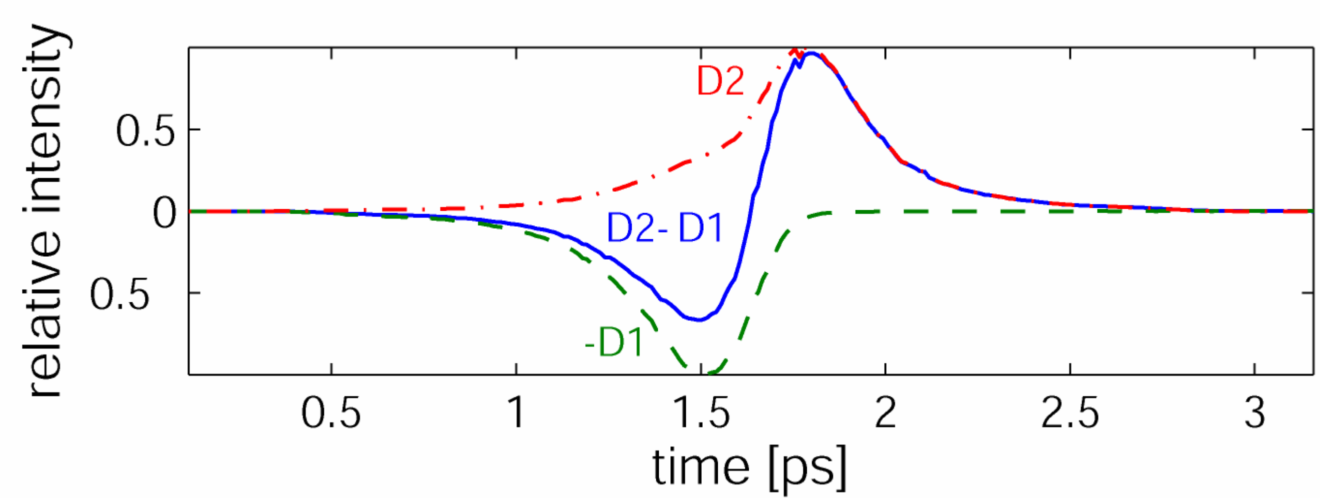


Fiber link stabilization: Schematic setup



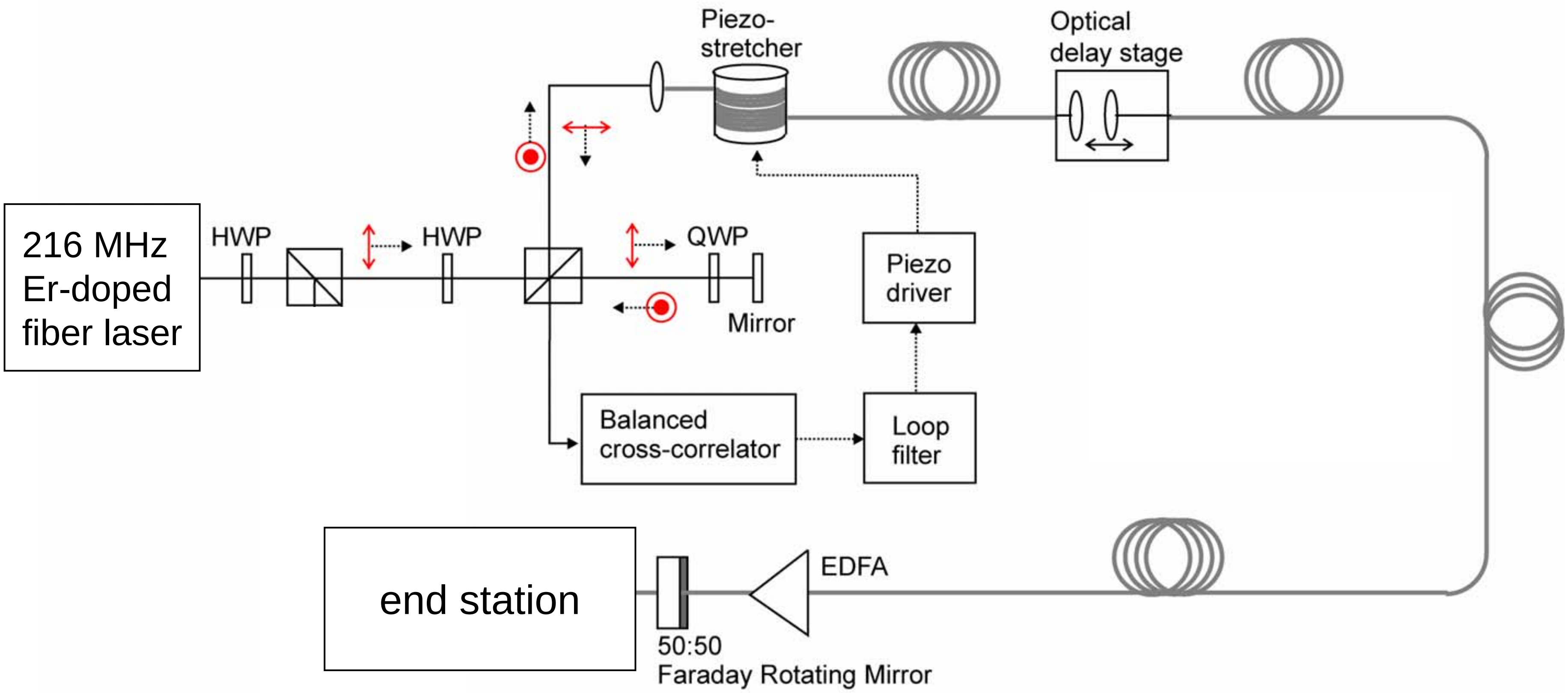
Fiber link stabilization:
Balanced optical cross-correlator



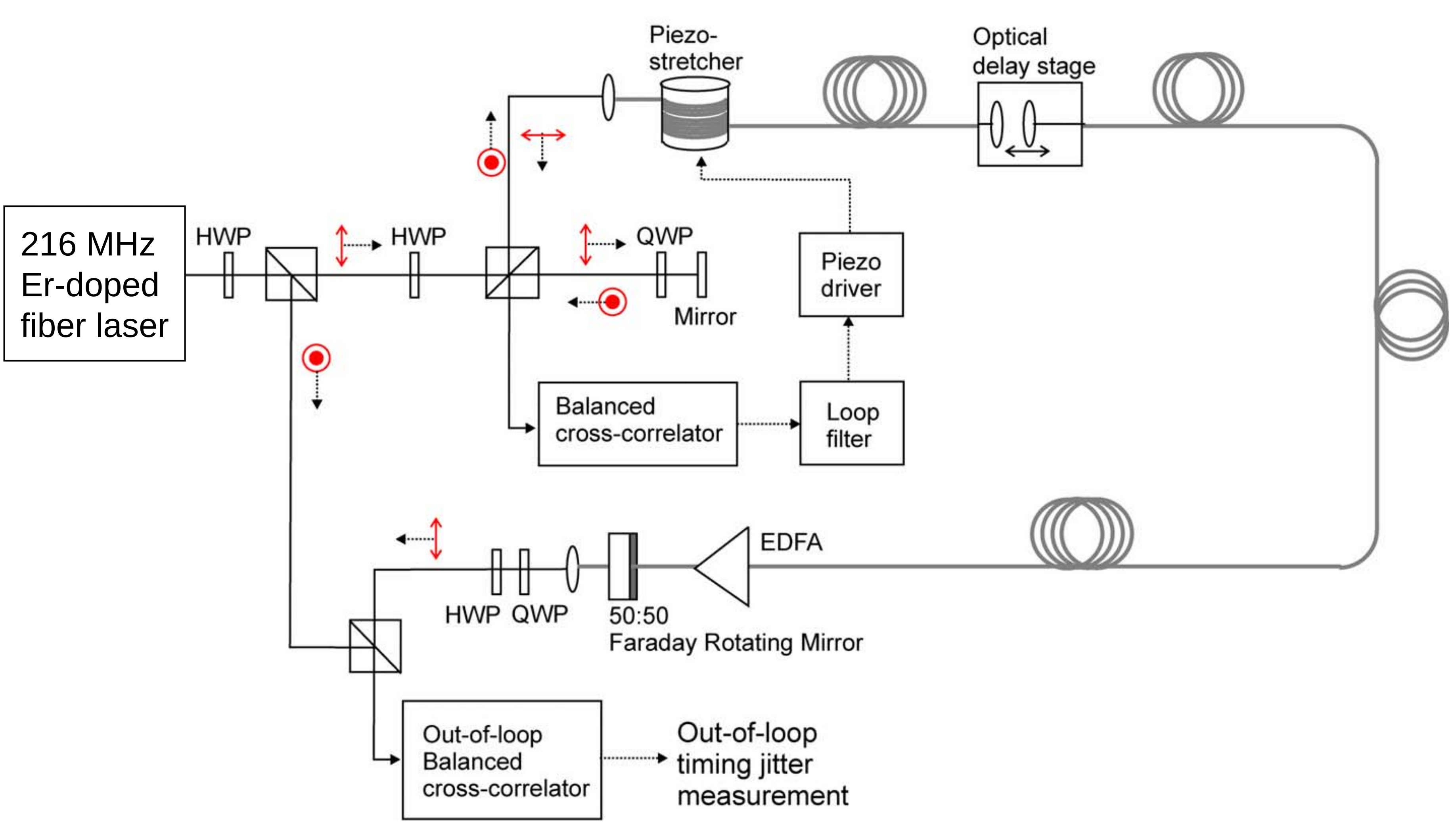


Development in collaboration with MIT

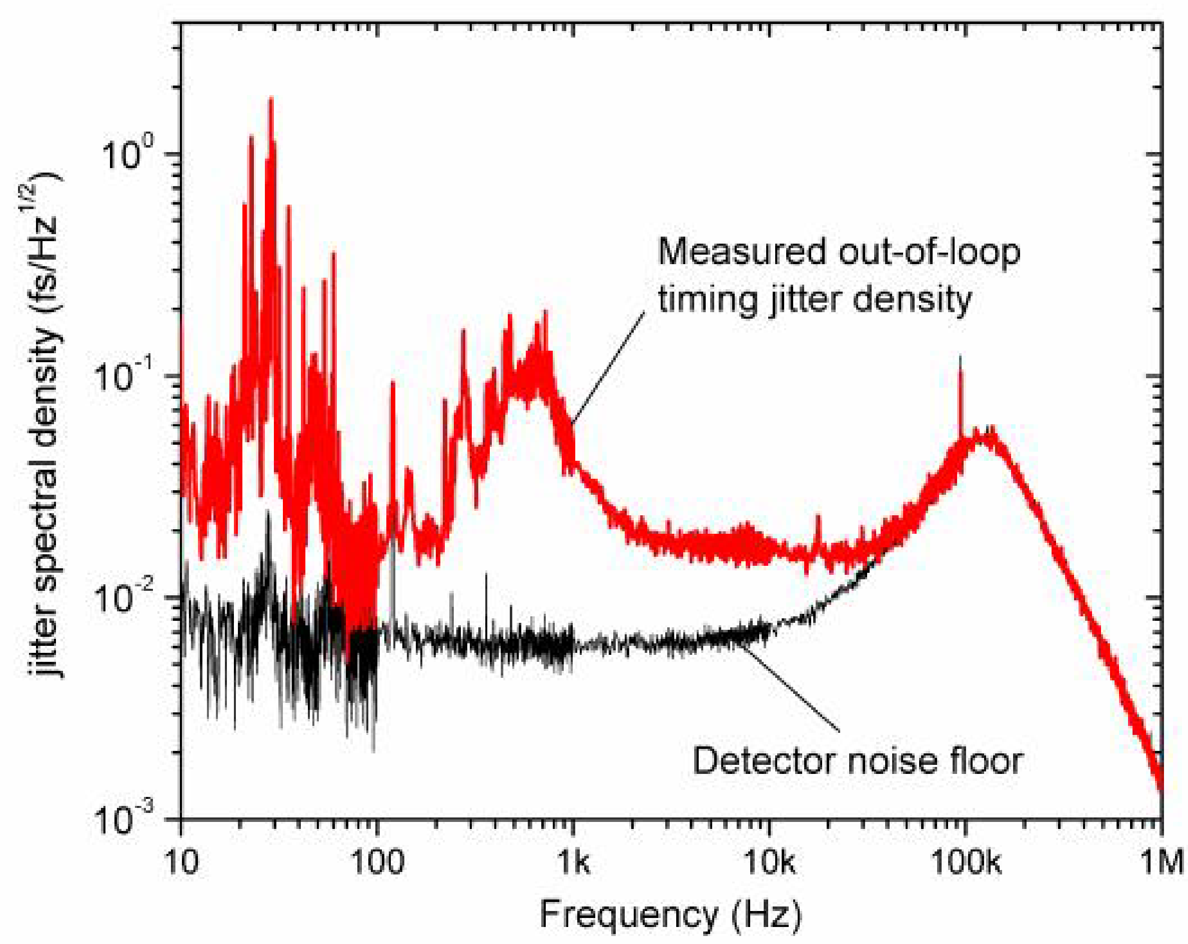
Fiber link stabilization: Schematic setup



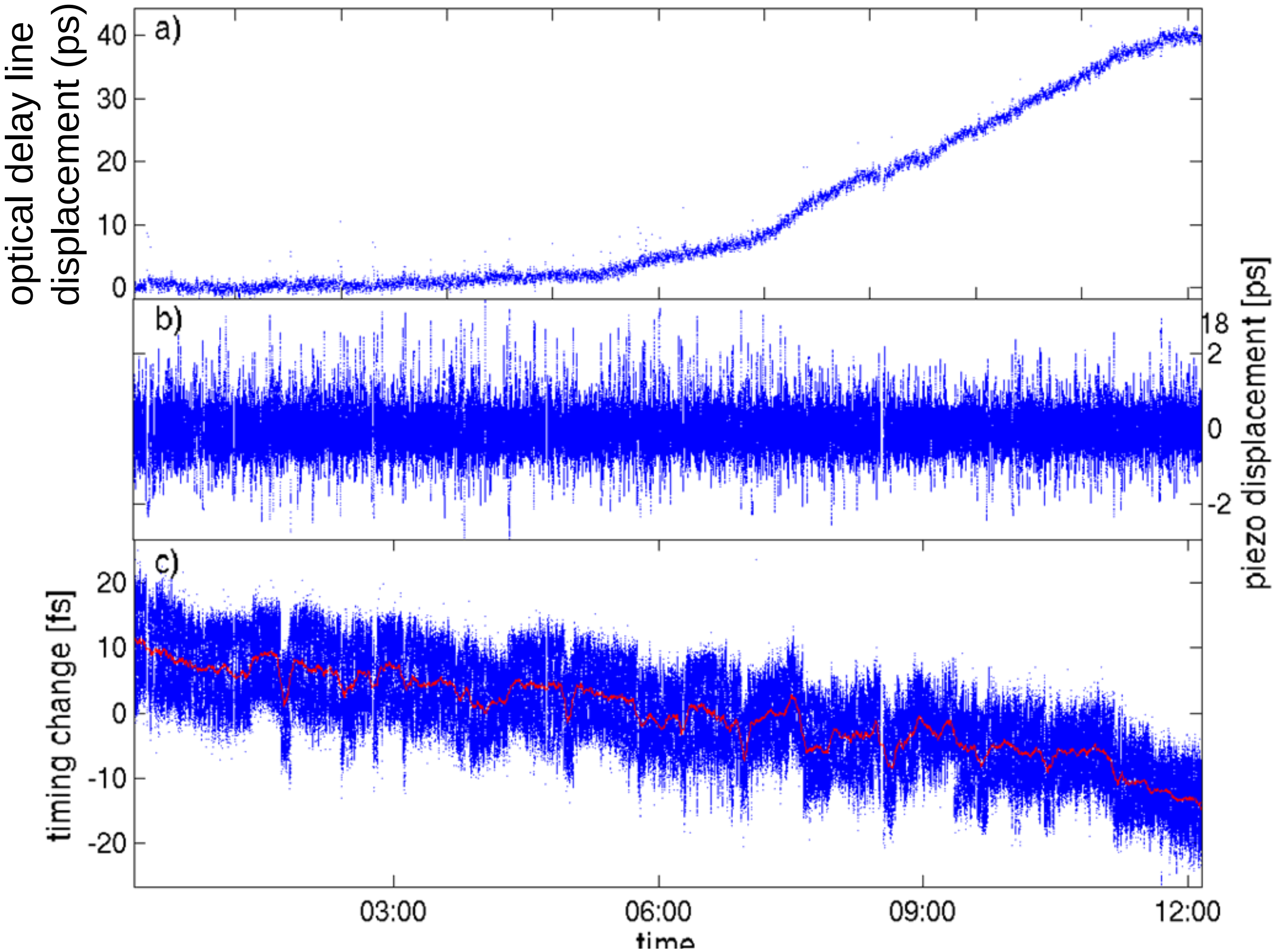
Fiber link stabilization:
Schematic setup to determine fiber link stability



Fiber link stabilization
Frequency distribution of fiber link timing changes

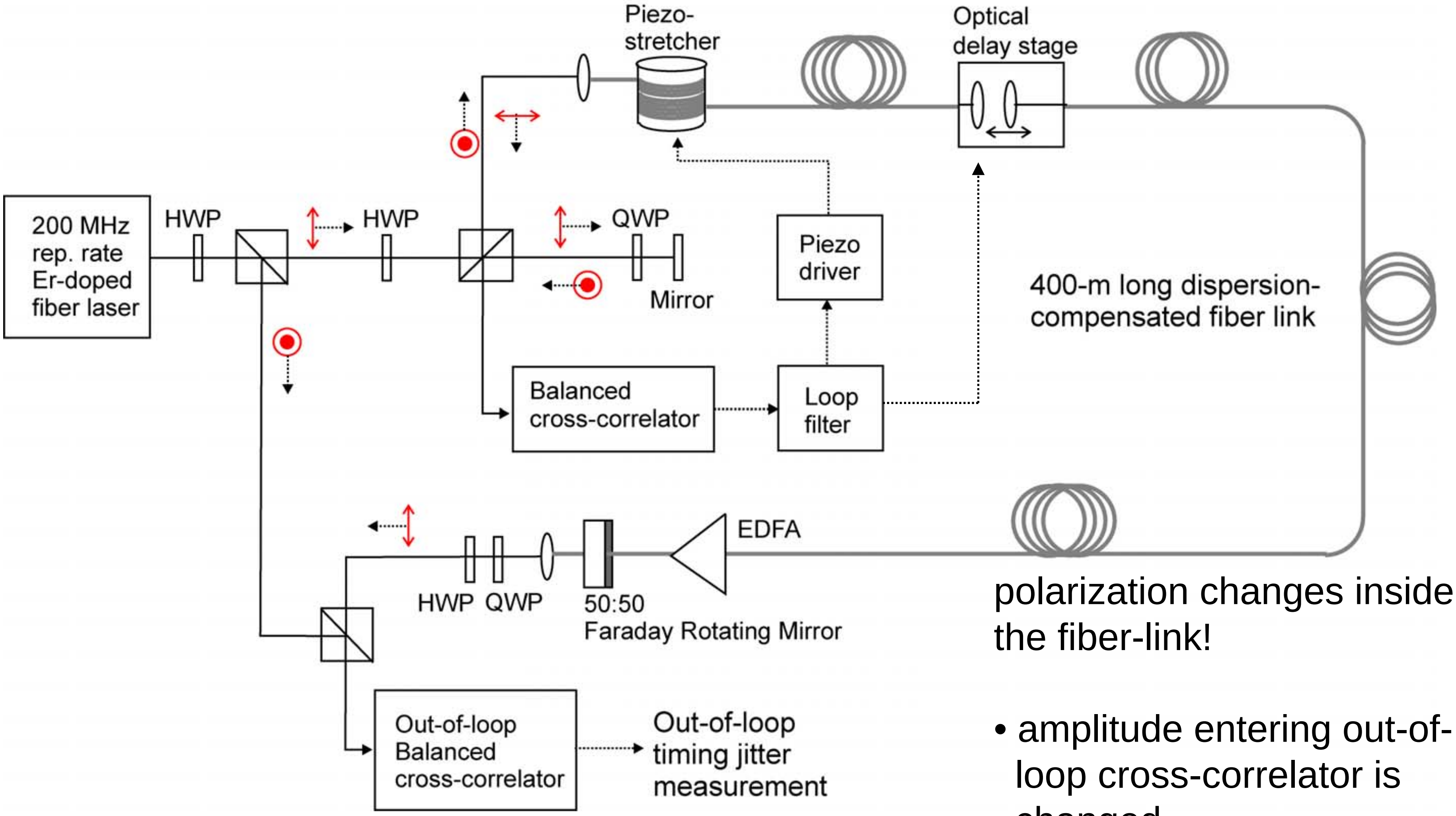


Fiber link stabilization
Long term stability



rms timing jitter over 2 minutes: (4.4 ± 1.1) fs
timing drift over 12 hours: 25 fs (rms over this time: 7.5 ± 1.8 fs)
measurement bandwidth: 200 kHz

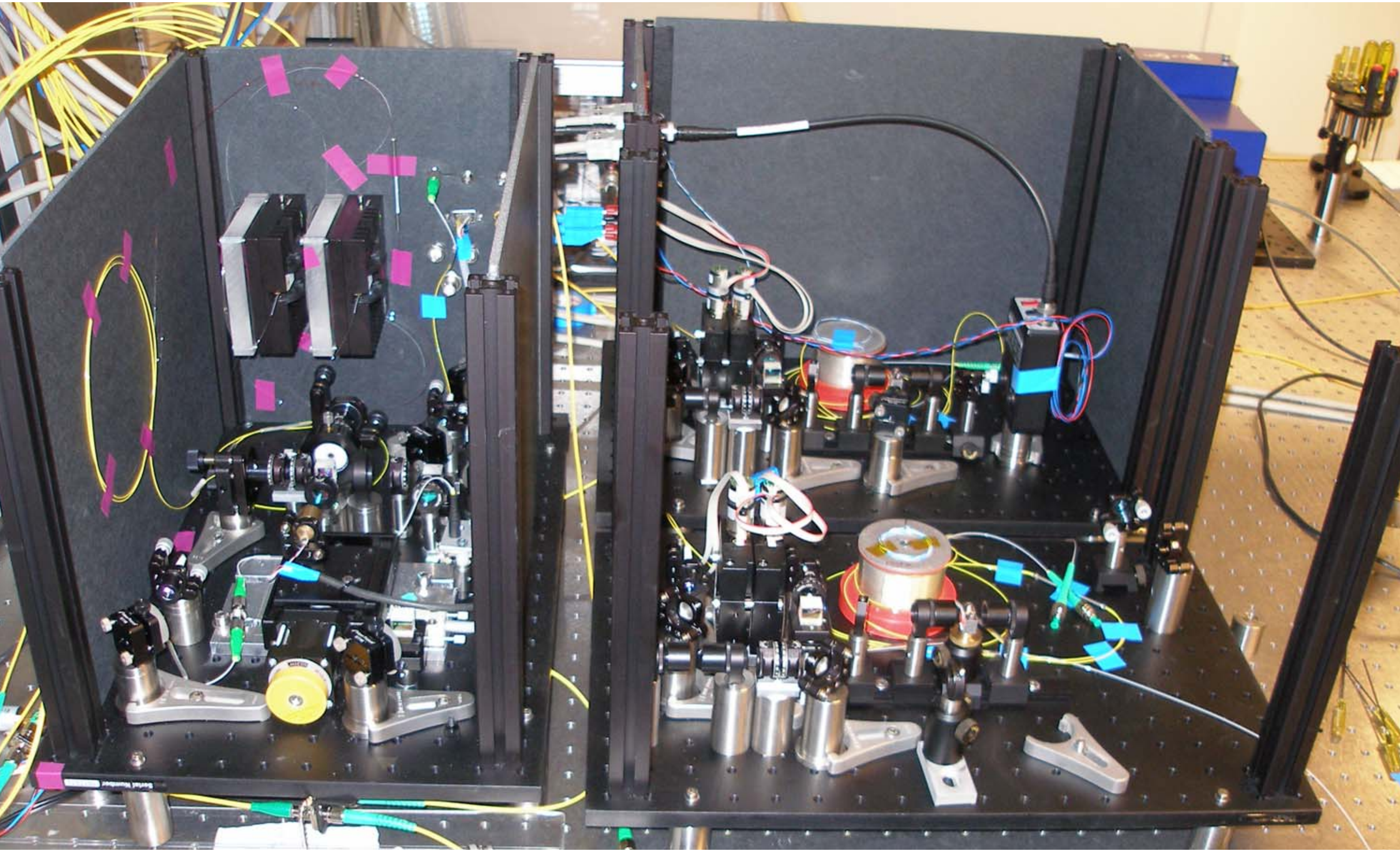
Fiber link stabilization
Timing drift a measurement artifact?



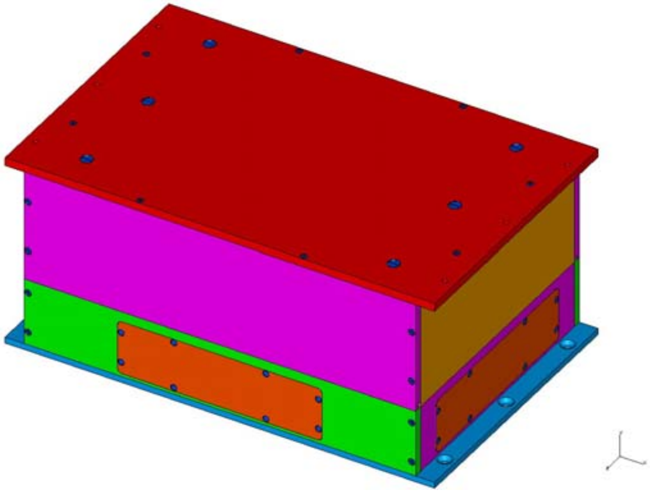
polarization changes inside the fiber-link!

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

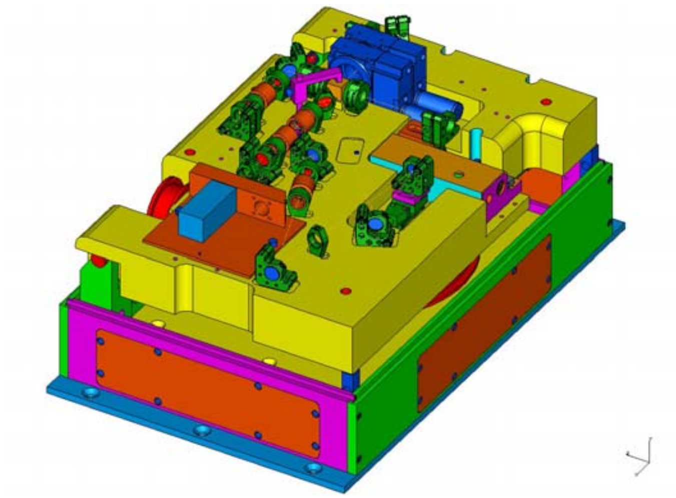
Prototypes of master laser and fiber link stabilization

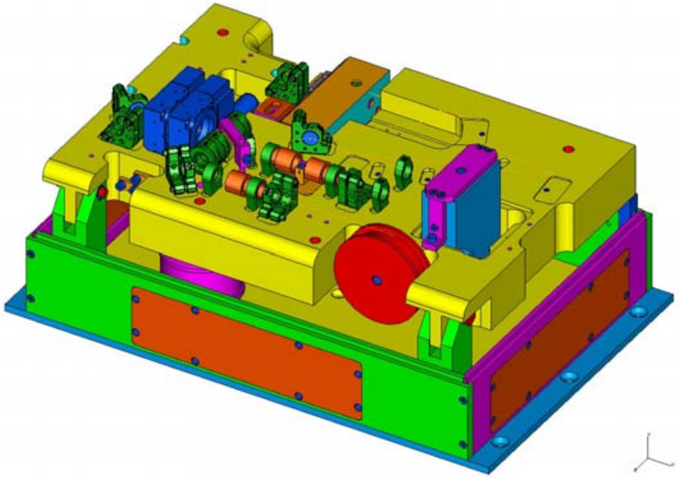


Fiber link stabilization
Mechanical design



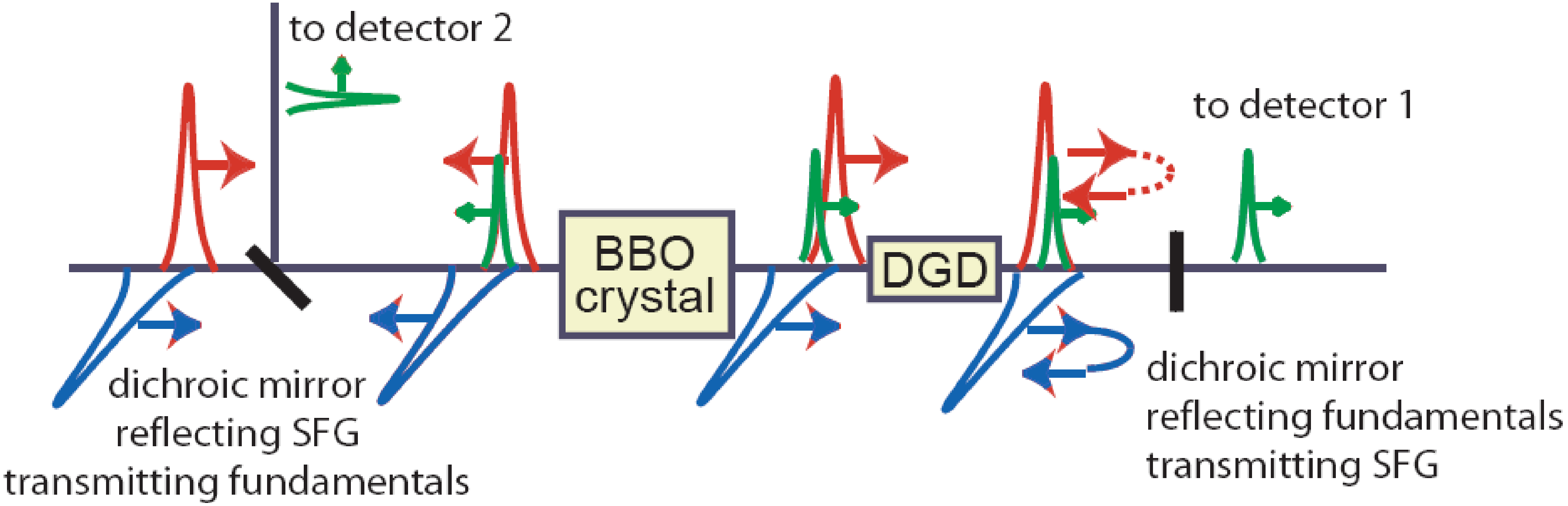
Construction of fiber link mechanics together with K. Jähnke (DESY).
Installation: summer 2008.





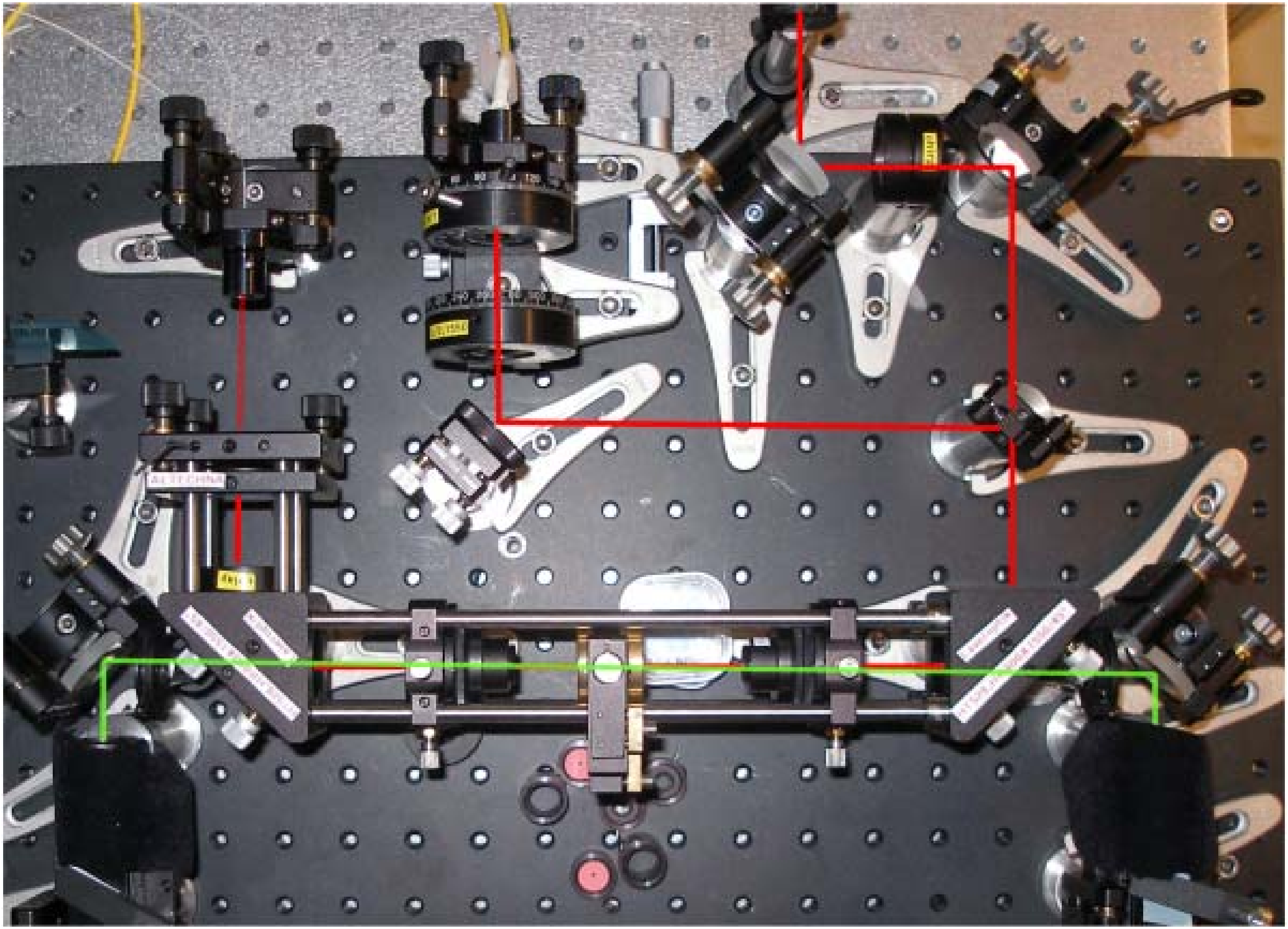
Locking of external lasers
Scheme of optical cross-correlator

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



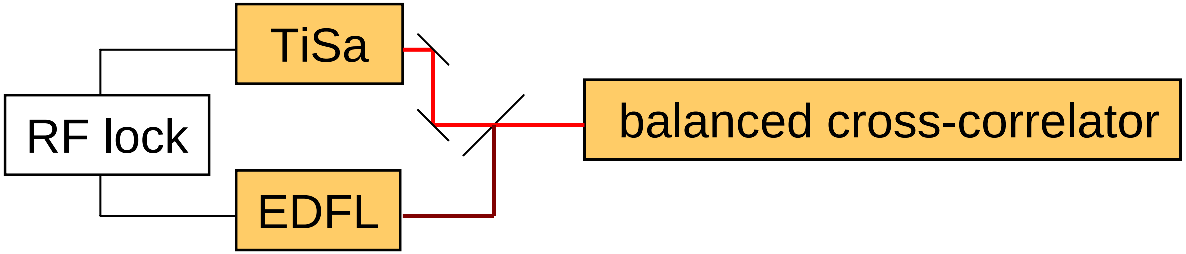
DGD: differential group delay

Locking of external lasers
First setup



Courtesy of S. Schulz, V. Arsov

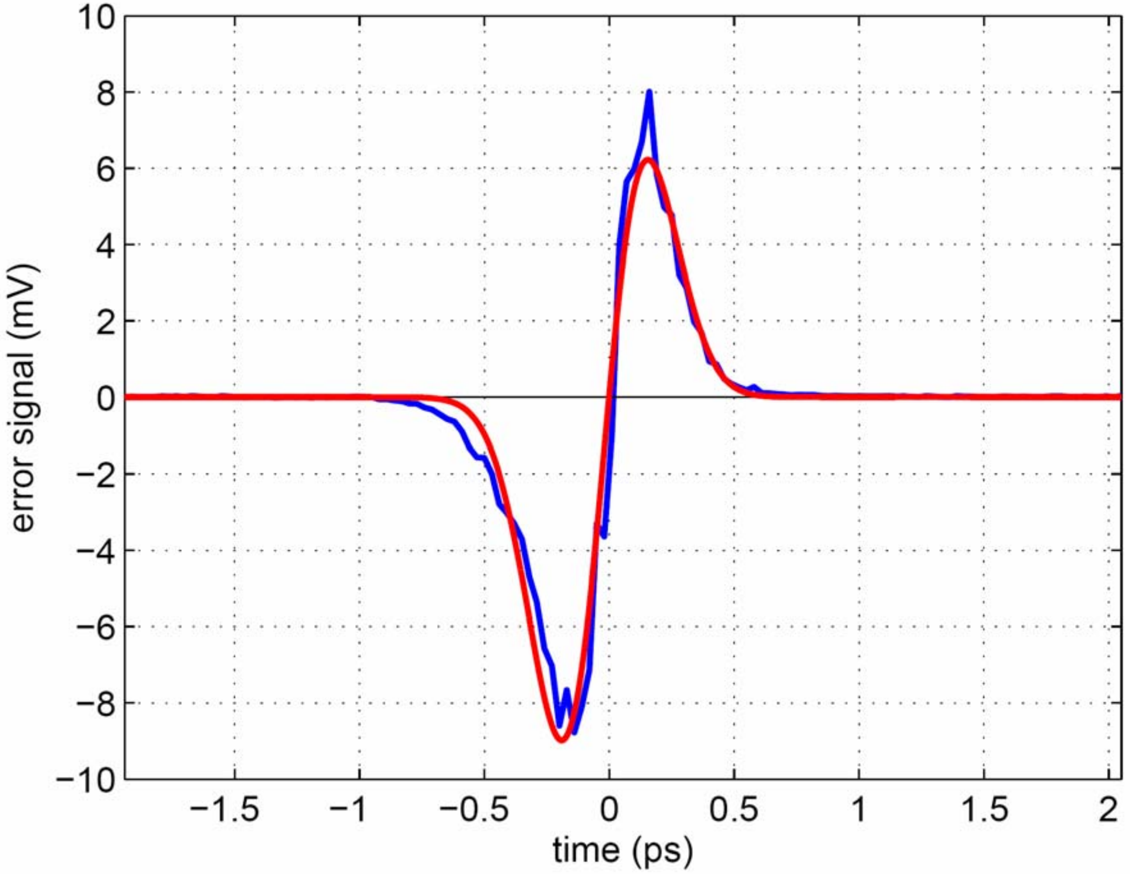
Locking of external lasers
First signal


RF lock

TiSa

EDFL

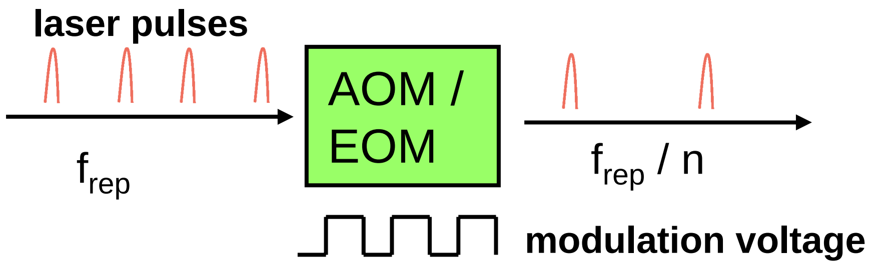
balanced cross-correlator



Courtesy of S. Schulz, V. Arsov

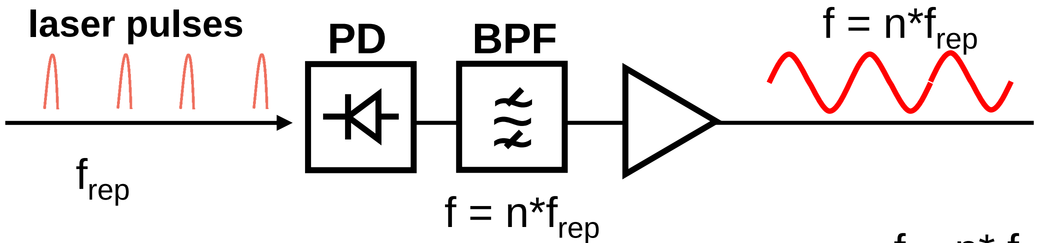
Laser to RF conversion
Possible schemes

Optical division of distributed frequency



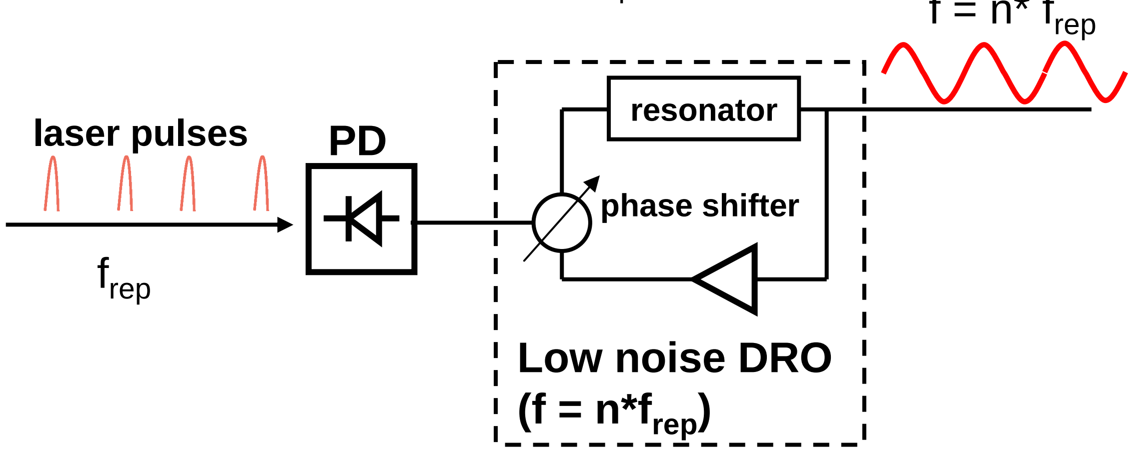
Direct conversion with PD

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

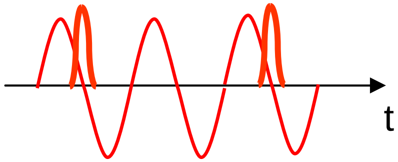


Injection Locking

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

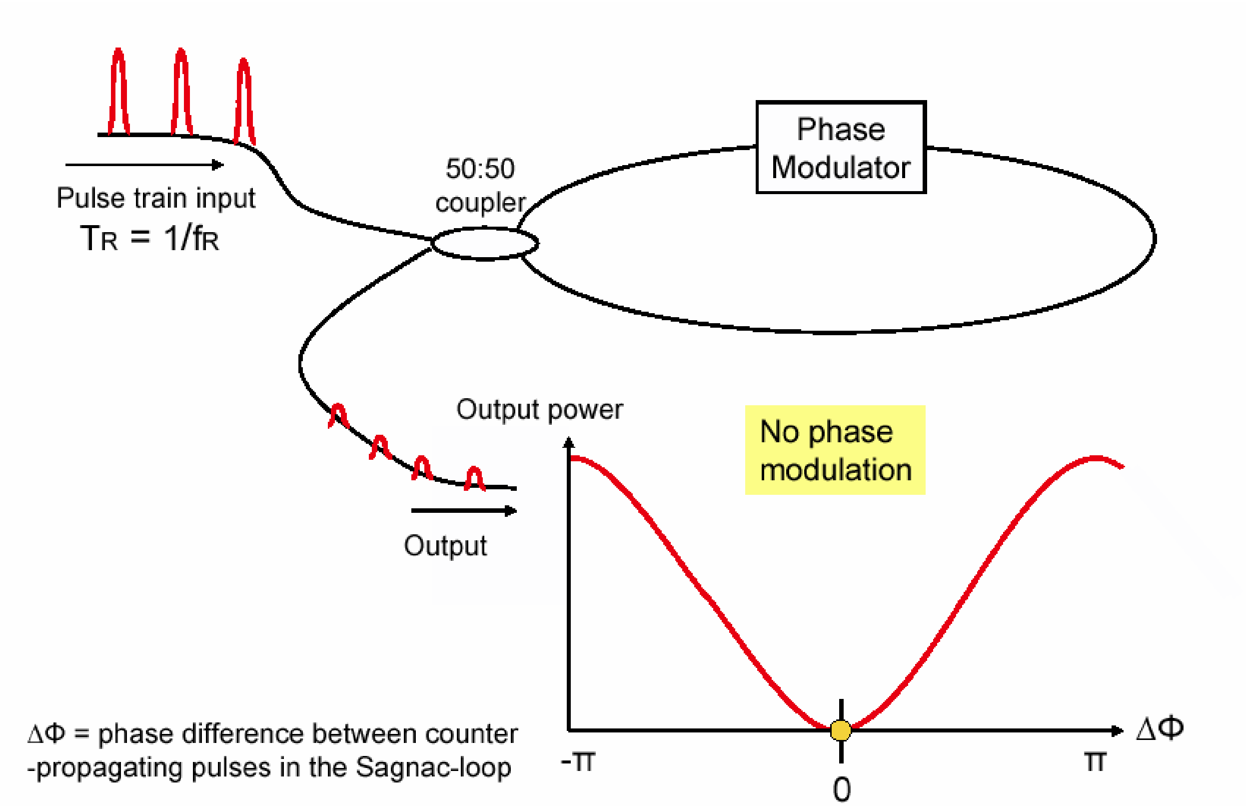


(*) typical AM to PM conversion: 1-10ps/mW



RF extraction and measurement with a Sagnac loop interferometer

Phase detection in the optical domain:

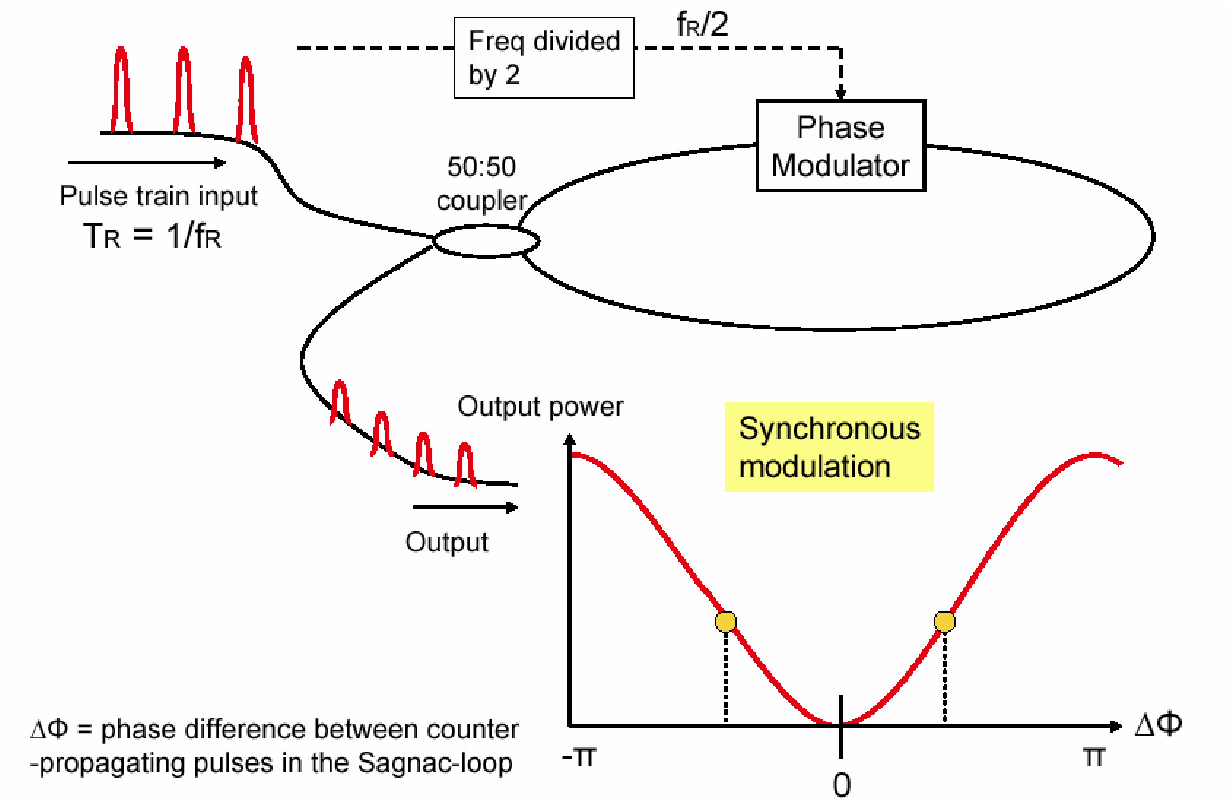


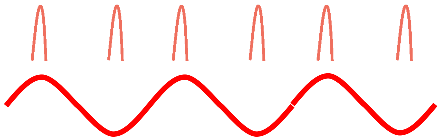
ΔΦ = phase difference between counter -propagating pulses in the Sagnac-loop

Courtesy of J. Kim (MIT)

RF extraction and measurement with a Sagnac loop interferometer

Phase detection in the optical domain:



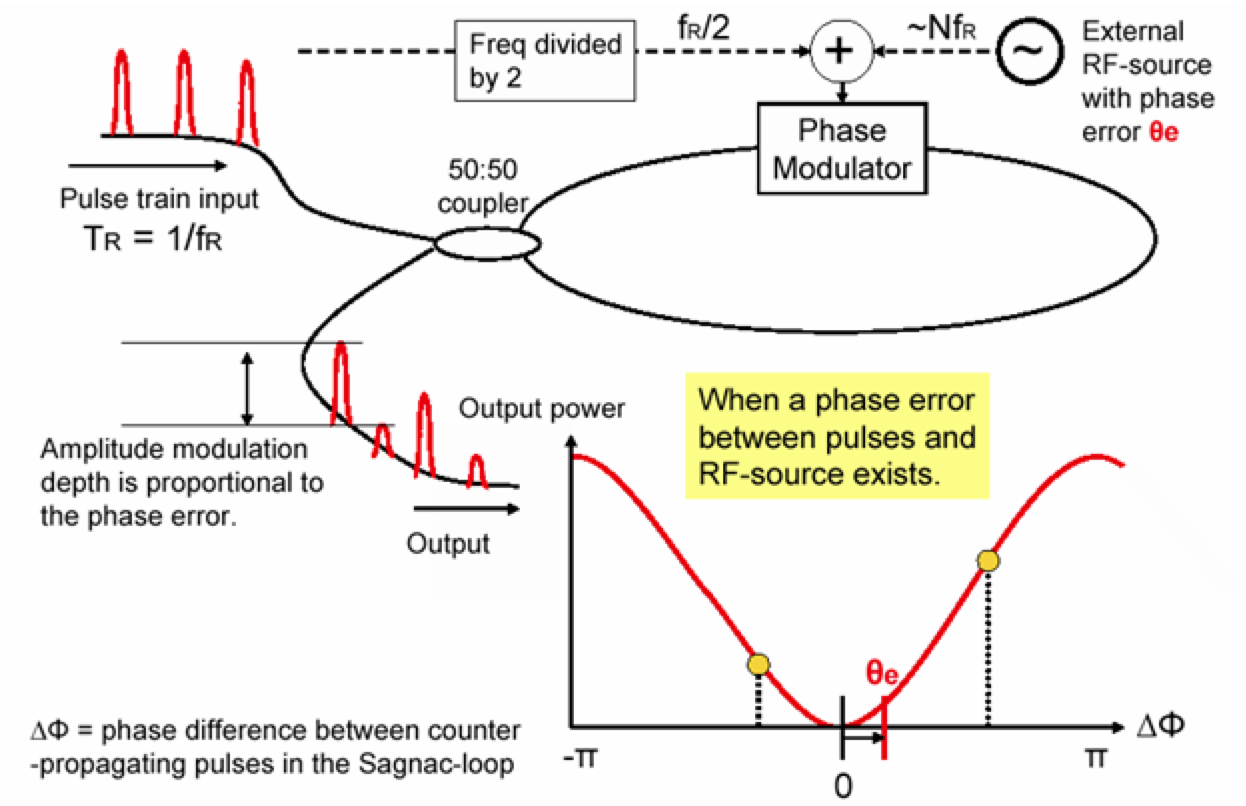


modulation voltage: f_{rep} / 2

Courtesy of J. Kim (MIT)

RF extraction and measurement with a Sagnac loop interferometer

Phase detection in the optical domain:

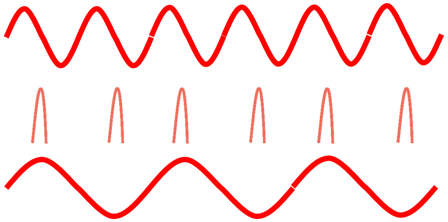


Amplitude modulation depth is proportional to the phase error.

When a phase error between pulses and RF-source exists.

ΔΦ = phase difference between counter -propagating pulses in the Sagnac-loop

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

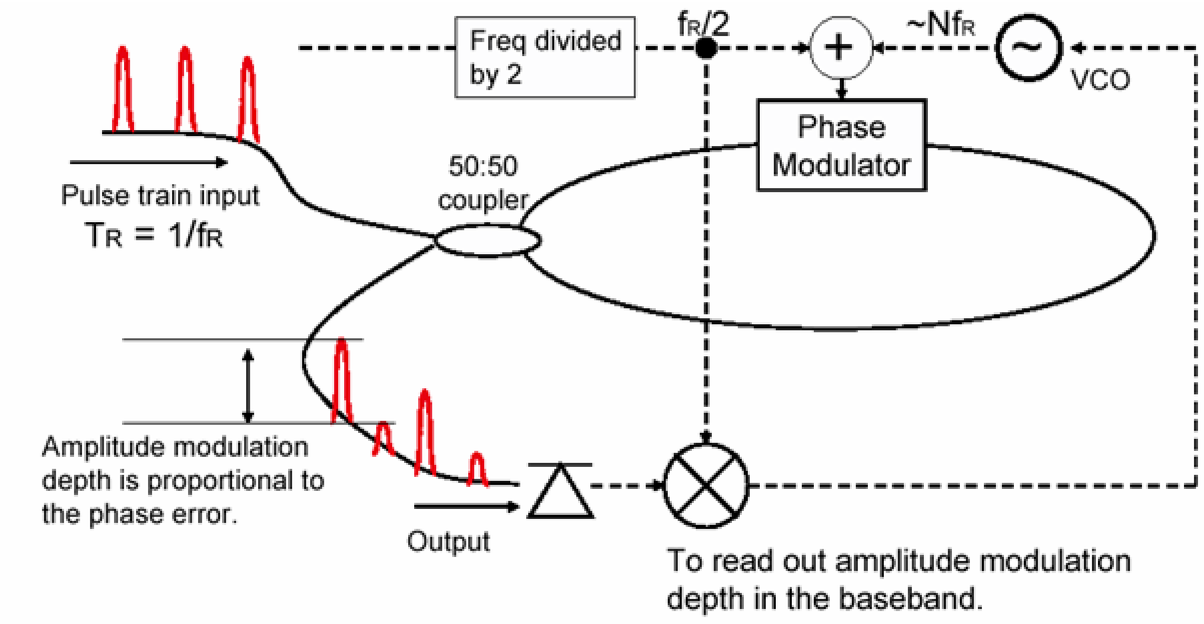


modulation voltage: $f_{rep} / 2$

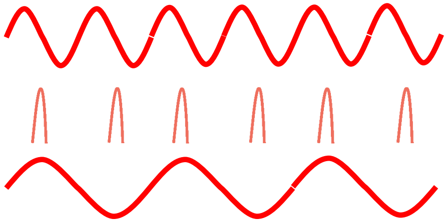
Courtesy of J. Kim (MIT)

RF extraction and measurement with a Sagnac loop interferometer

Phase detection in the optical domain:



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

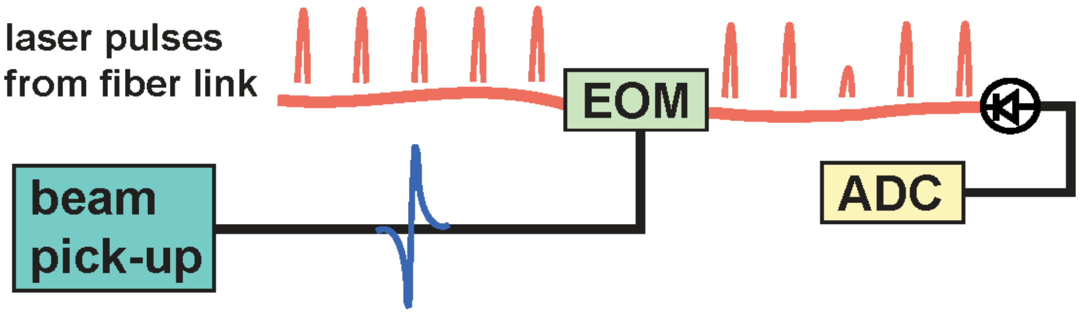


modulation voltage: $f_{rep} / 2$

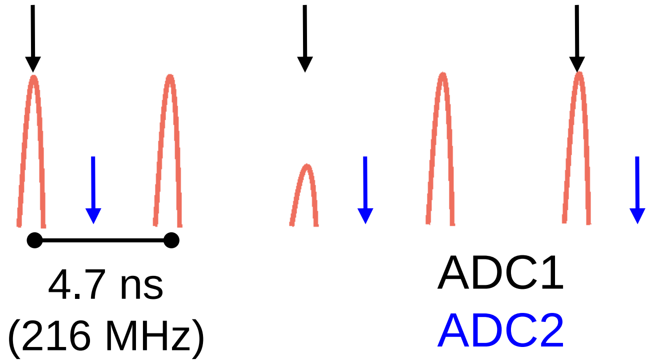
First results with a DRO (dielectric resonance oscillator) frequency of 10 GHz are very promising (6.8 fs over 10 h). Next step: Transition to 1.3 GHz DRO.

Courtesy of J. Kim (MIT)

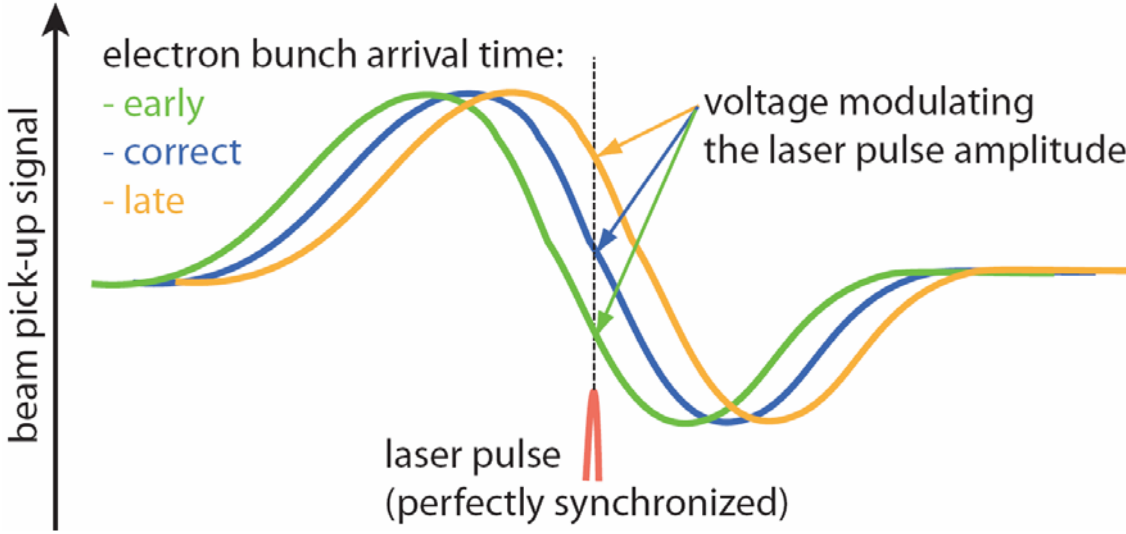
Bunch arrival time monitor (BAM)
Detection principle



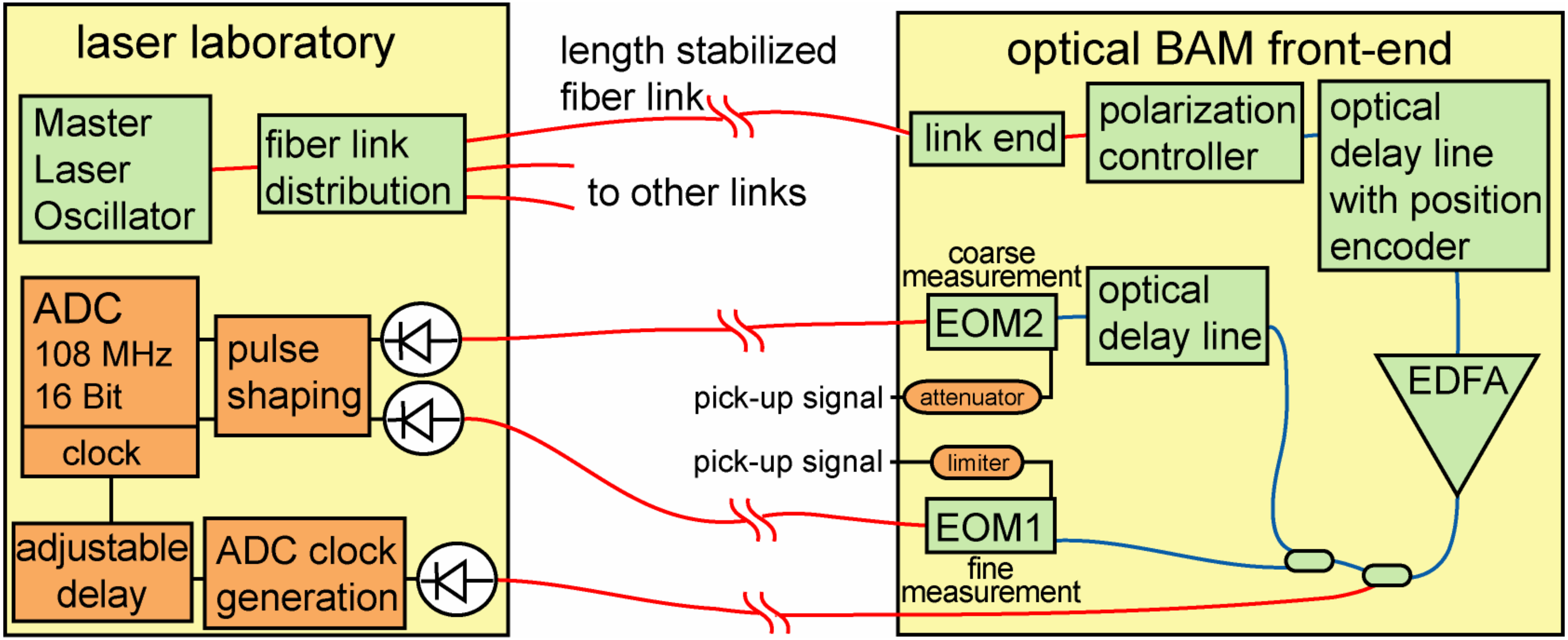
sampling times of ADCs



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.



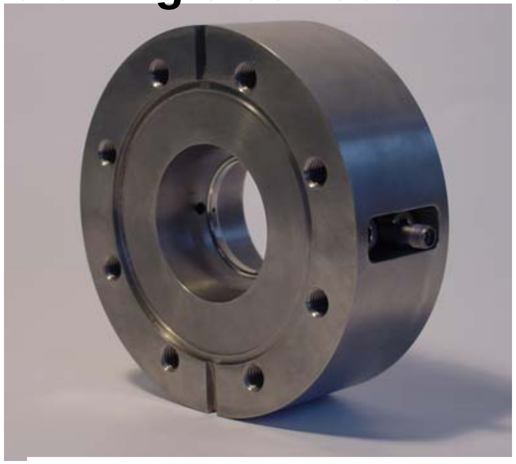
Bunch arrival time monitor (BAM)
Schematic setup



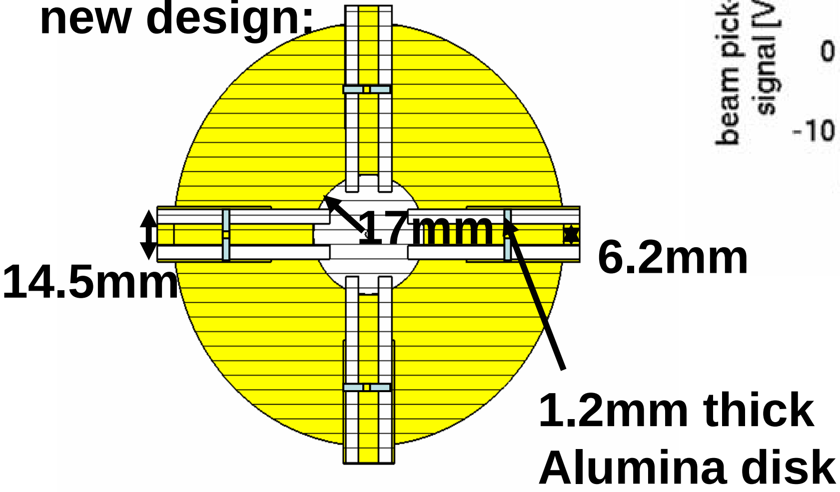
Bunch arrival time monitor (BAM)
Beam pick-up

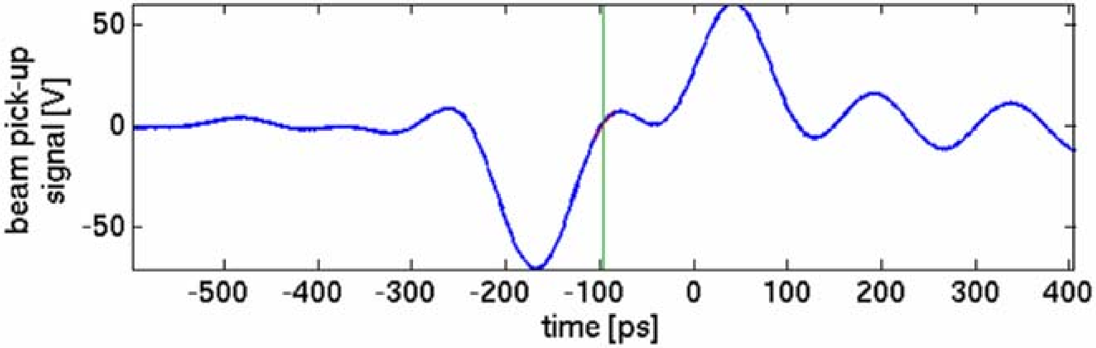
During last summer, a new beam pick-up (design: K. Hacker) was installed instead of ring electrodes to improve the pick-up performance.

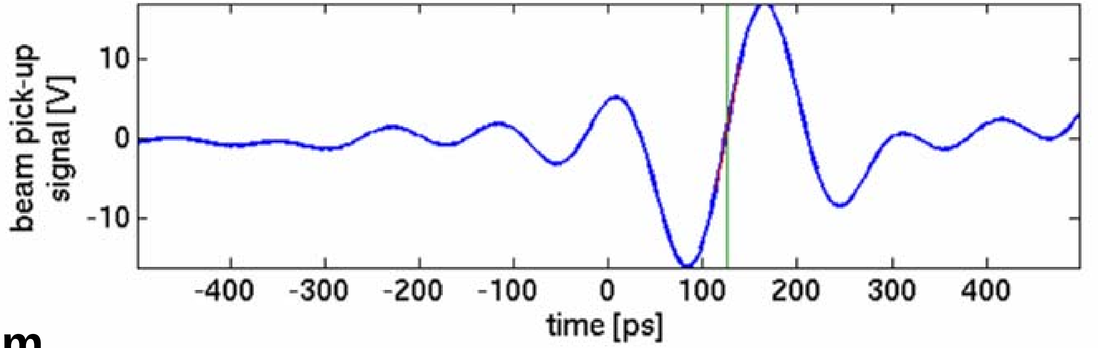
old ring electrode:



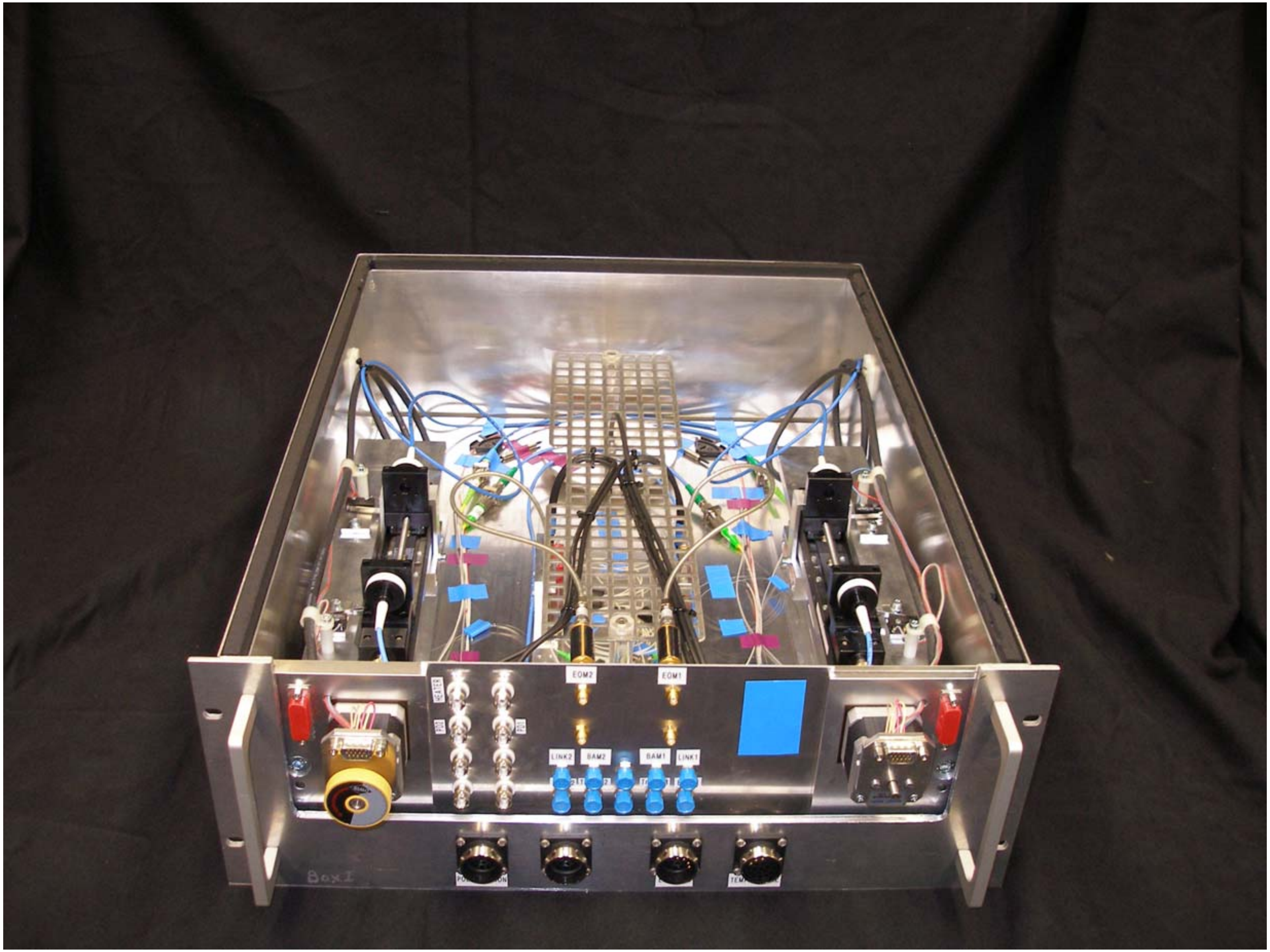
new design:







BAM

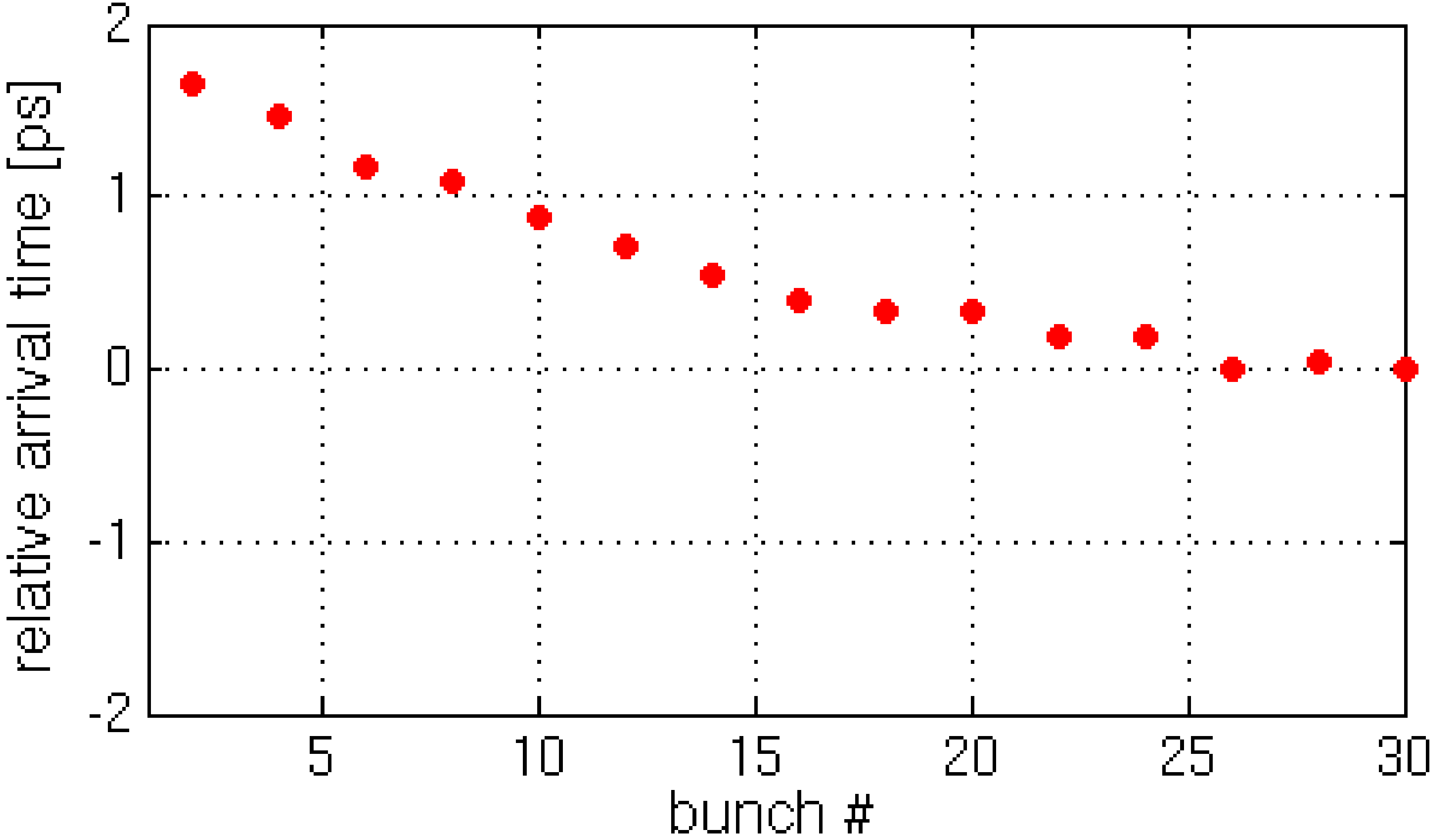


BAM

BAM-P II-0157 KLASSE II
KNALLKÖRPER PYRO CRACKER 440
Gegenstand auf den Boden legen, am äußersten Ende der Zündschnur anzünden und sich rasch entfernen. Nach dem Anzünden nicht in der Hand halten! Nur im Freien verwenden!
Abgabe an Personen unter 18 Jahren verboten!
Abgabe nur in ungeöffneter Originalpackung erlaubt!
Import: JECO 27502 Brhv. Tel.0471/393-0 Hersteller: YLH
Herstellungsstätte: KWANGCHOW/VR CHINA
Bruttogewicht : 40 g
112

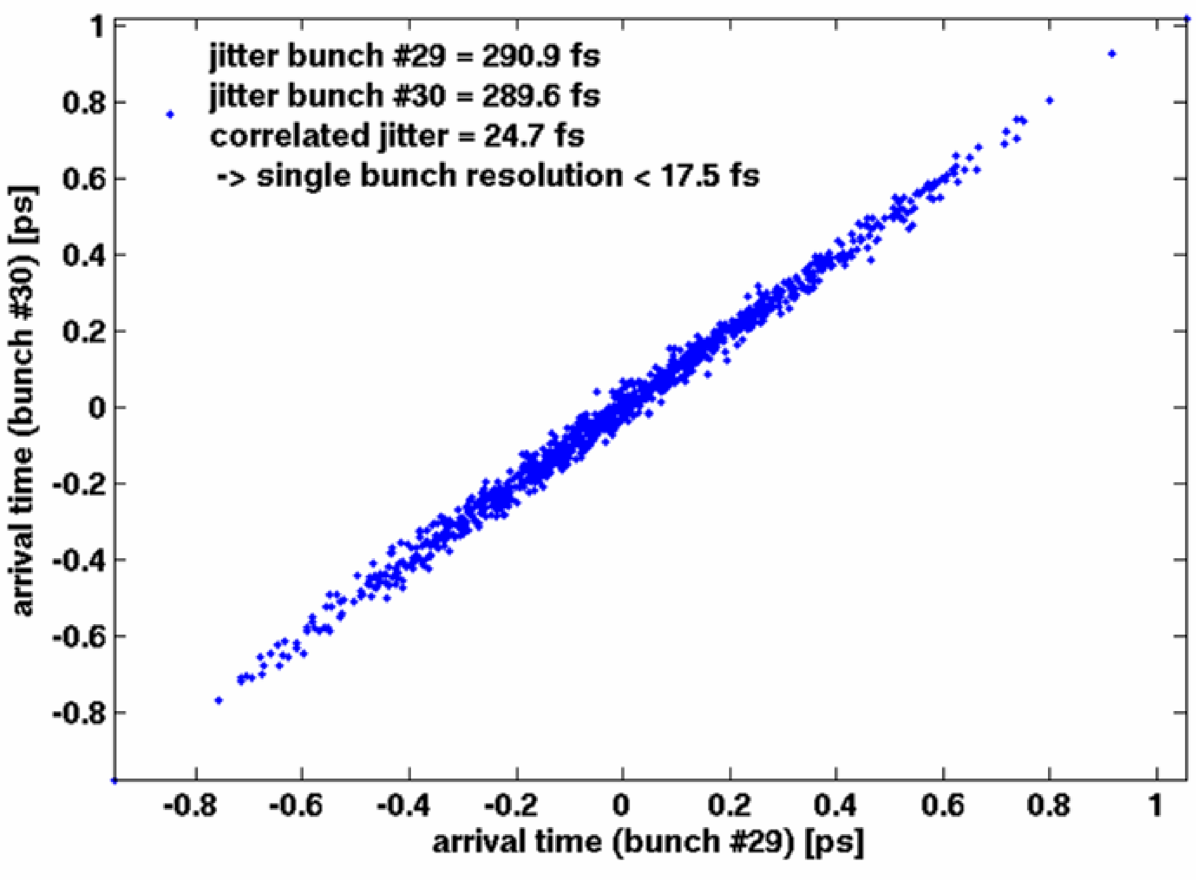
www.Feuerwerk-Fanpage.de
© Florian Rommerskirchen

Bunch arrival time monitor (BAM)
shot-to-shot fluctuations and intra bunch train pattern



Bunch arrival time monitor (BAM)
BAM resolution

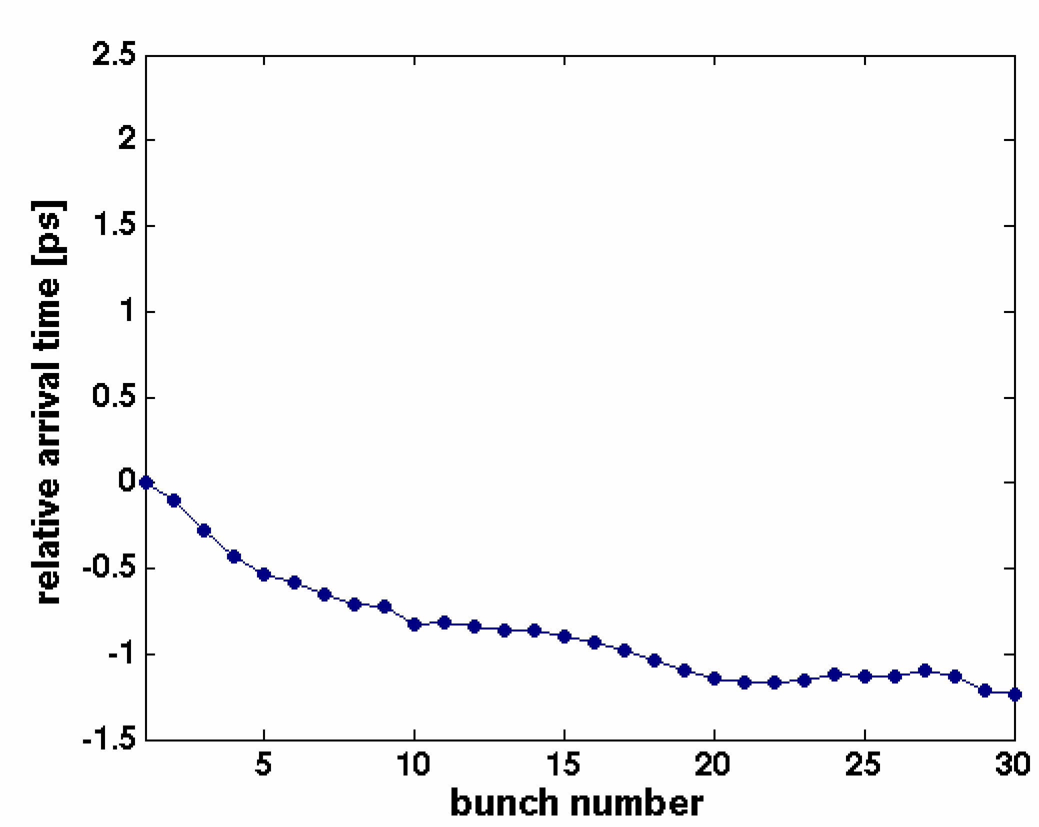
An upper limit for the BAM resolution can be estimated by correlating the arrival time of two adjacent bunches in the bunch train:



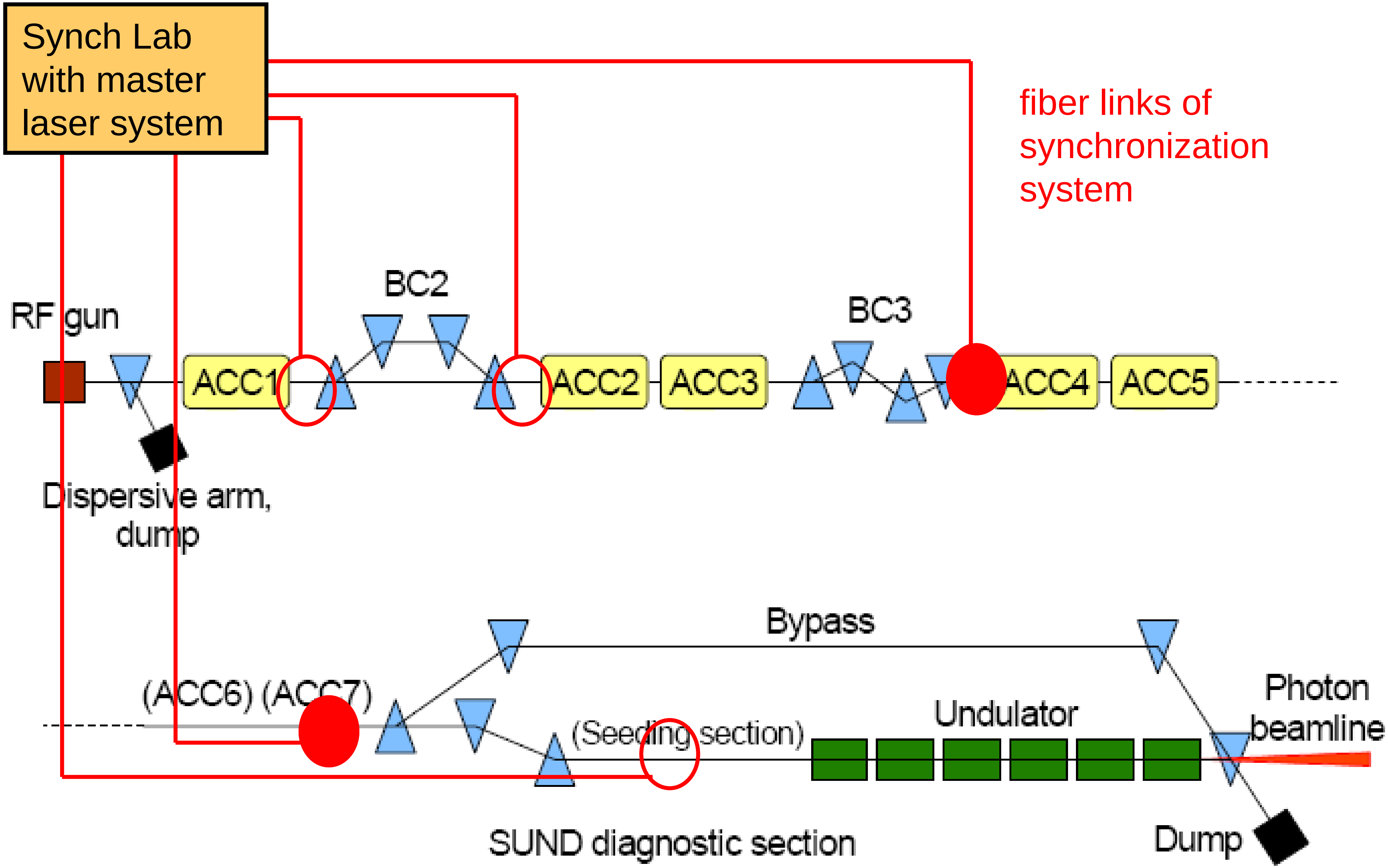
The resolution estimated from the laser amplitude noise and the slope steepness is about 5-6 fs.

Bunch arrival time monitor (BAM)
Arrival time manipulation over the bunch train

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



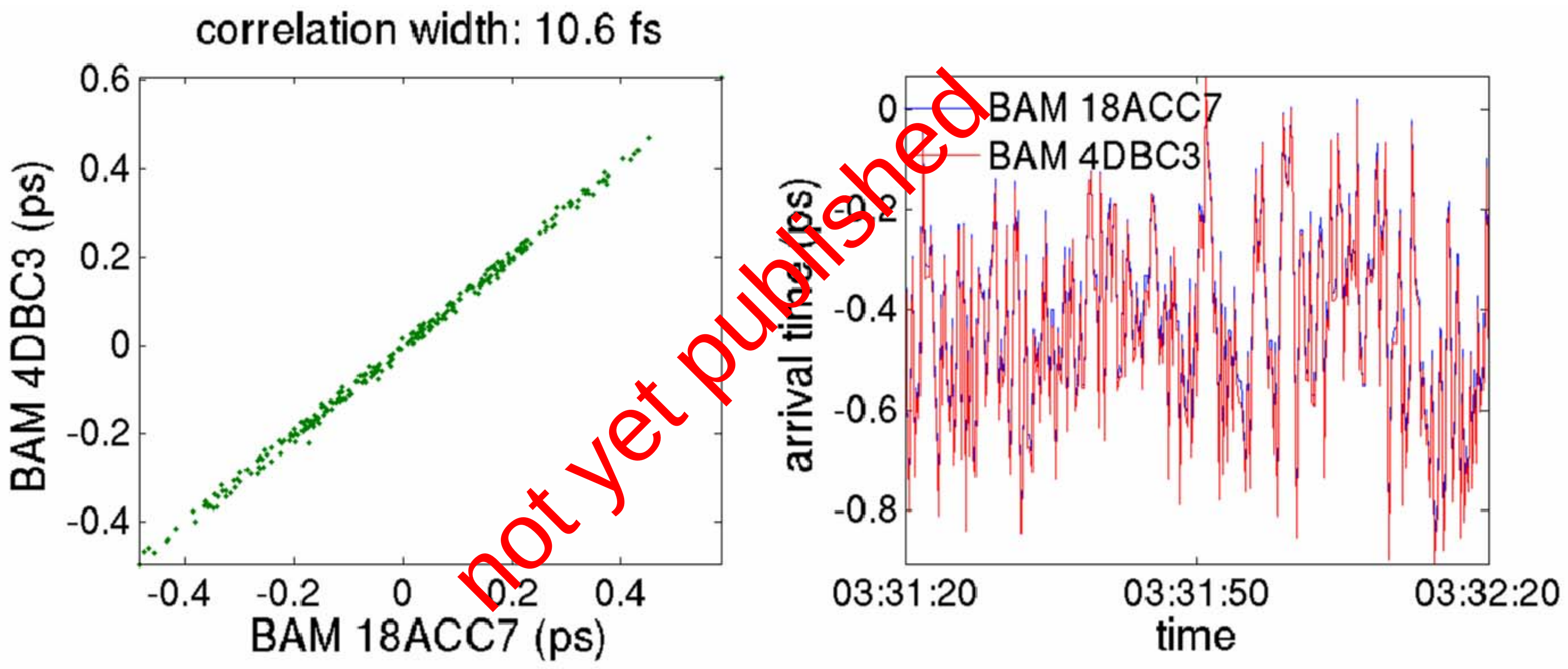
Bunch arrival time monitor (BAM)
Positions of the BAMs in the FLASH linac



Synch Lab with master laser system

fiber links of synchronization system

Arrival time correlation between two BAMs

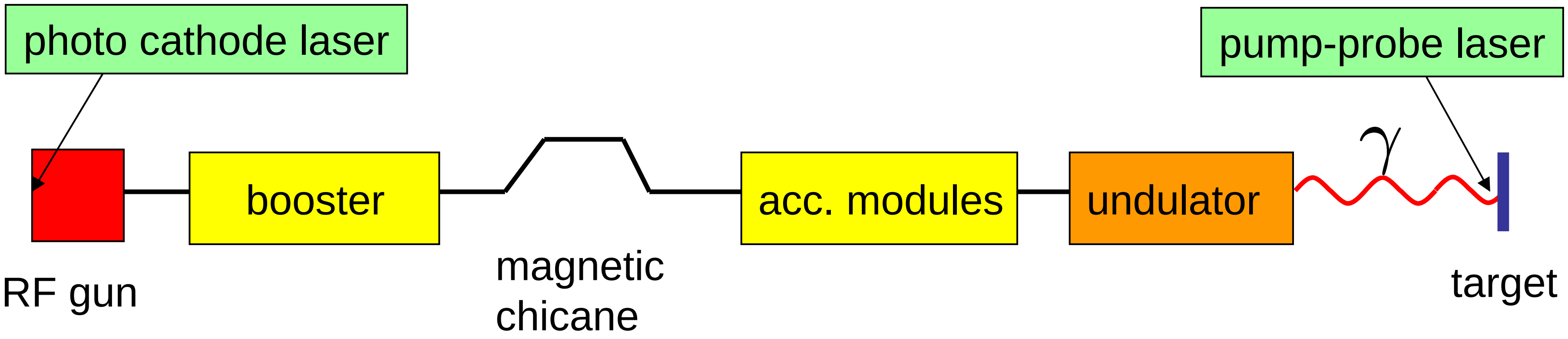


Arrival time measurement with two BAMs, separated by 60 m drift space.
Arrival time difference contains:

- high frequency laser noise (~1.7 MHz – 216 Mhz)
- two fiber link stabilizations
- two BAMs

Single bunch resolution of entire measurement chain: 7.5 fs (rms)
300 shots in 60 seconds

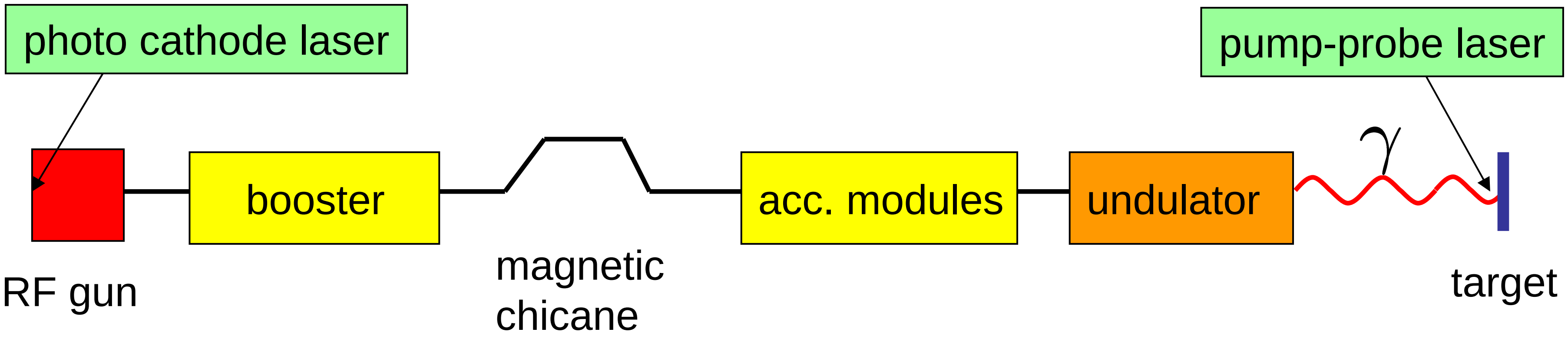
Timing changes in a FEL



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

Timing changes in a FEL



timing jitter behind chicane

RF amplitude changes

RF phase changes

reduction of incoming timing jitter due to compression

$$\Sigma_t^2 \approx \left(\frac{R_{56}}{c_0}\frac{\sigma_A}{A}\right)^2 + \left(\frac{C-1}{C}\right)^2\left(\frac{\sigma_\phi}{2\pi f_{RF}}\right)^2 + \left(\frac{1}{C}\right)^2\Sigma_{i,t}^2$$

RF requirements for 10 fs arrival time stability at FLASH:

phase stability	< 0.005° @ 1.3 GHz (= 10 fs)
amplitude stability	< 1.6 * 10^{-5}

Bunch arrival time monitor (BAM)
intra bunch-train arrival time feedback

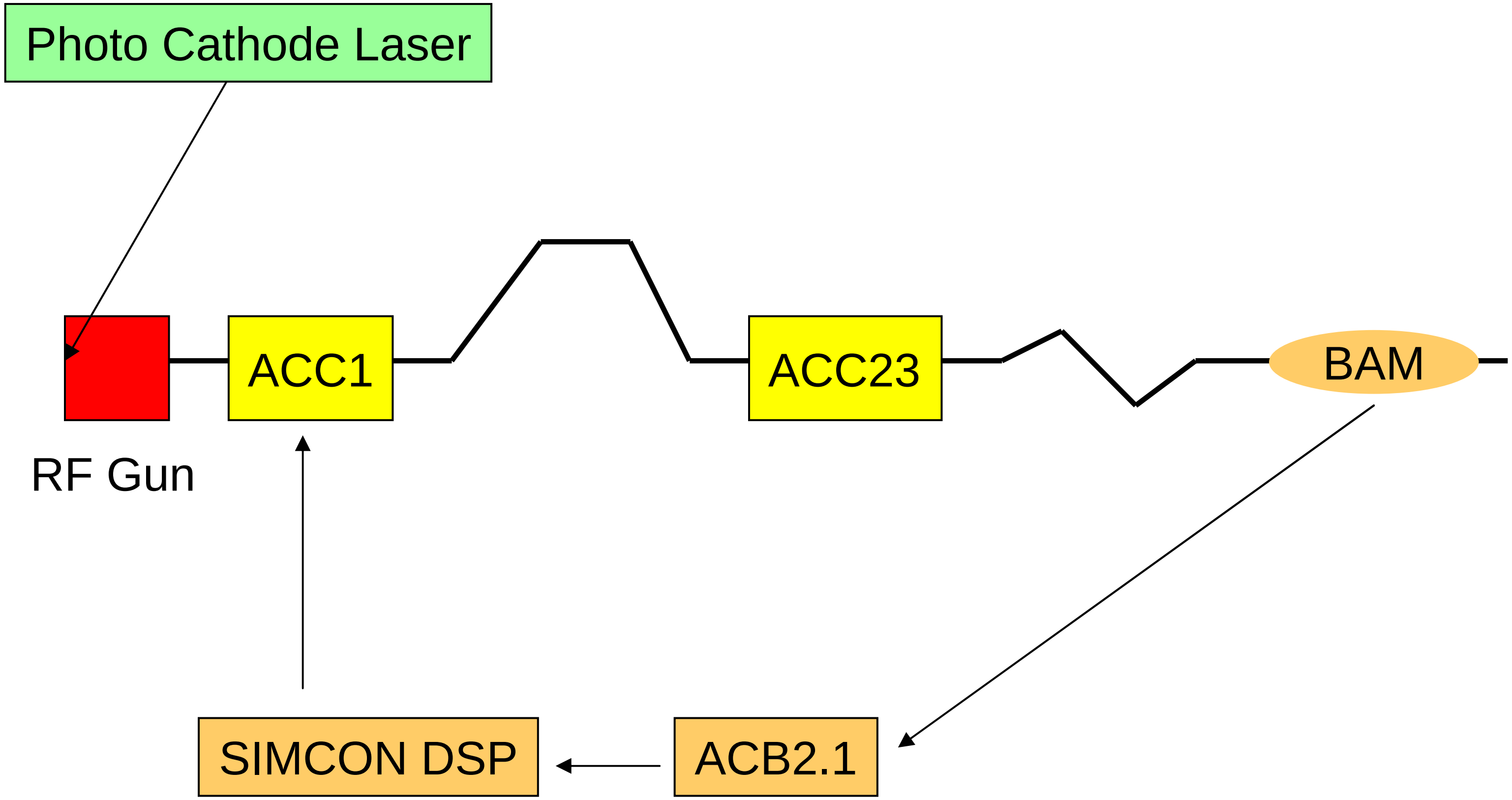


Photo Cathode Laser

ACC1

ACC23

BAM

RF Gun

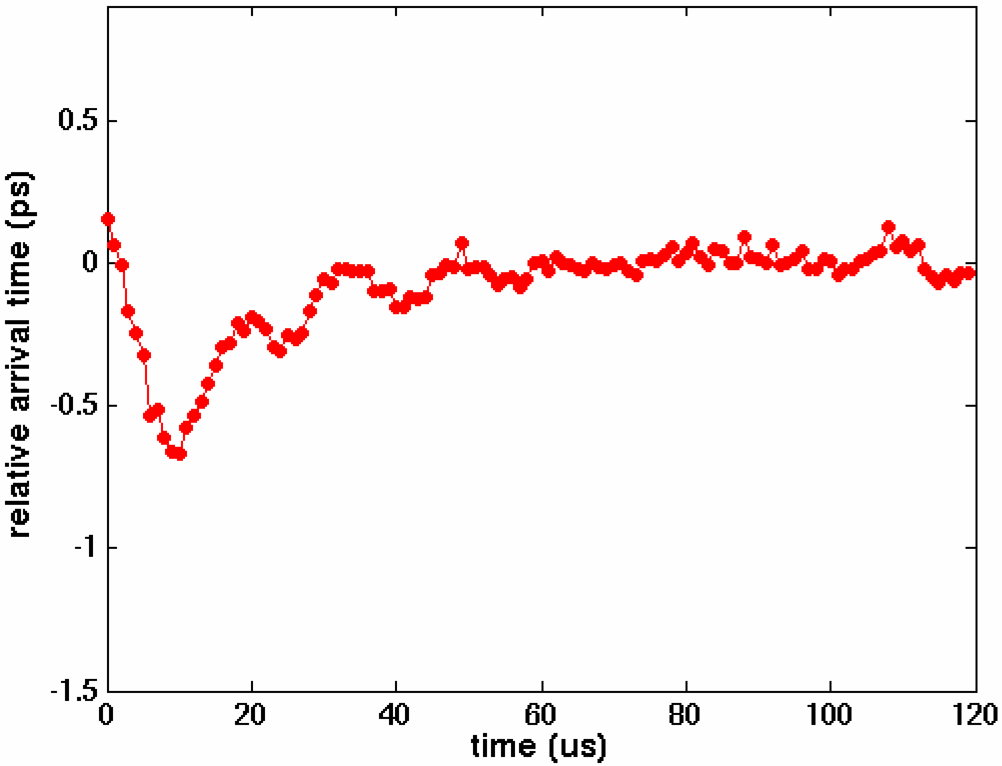
SIMCON DSP

ACB2.1

Digital cavity
Controller board
FPGA + DSP
Rocket IO

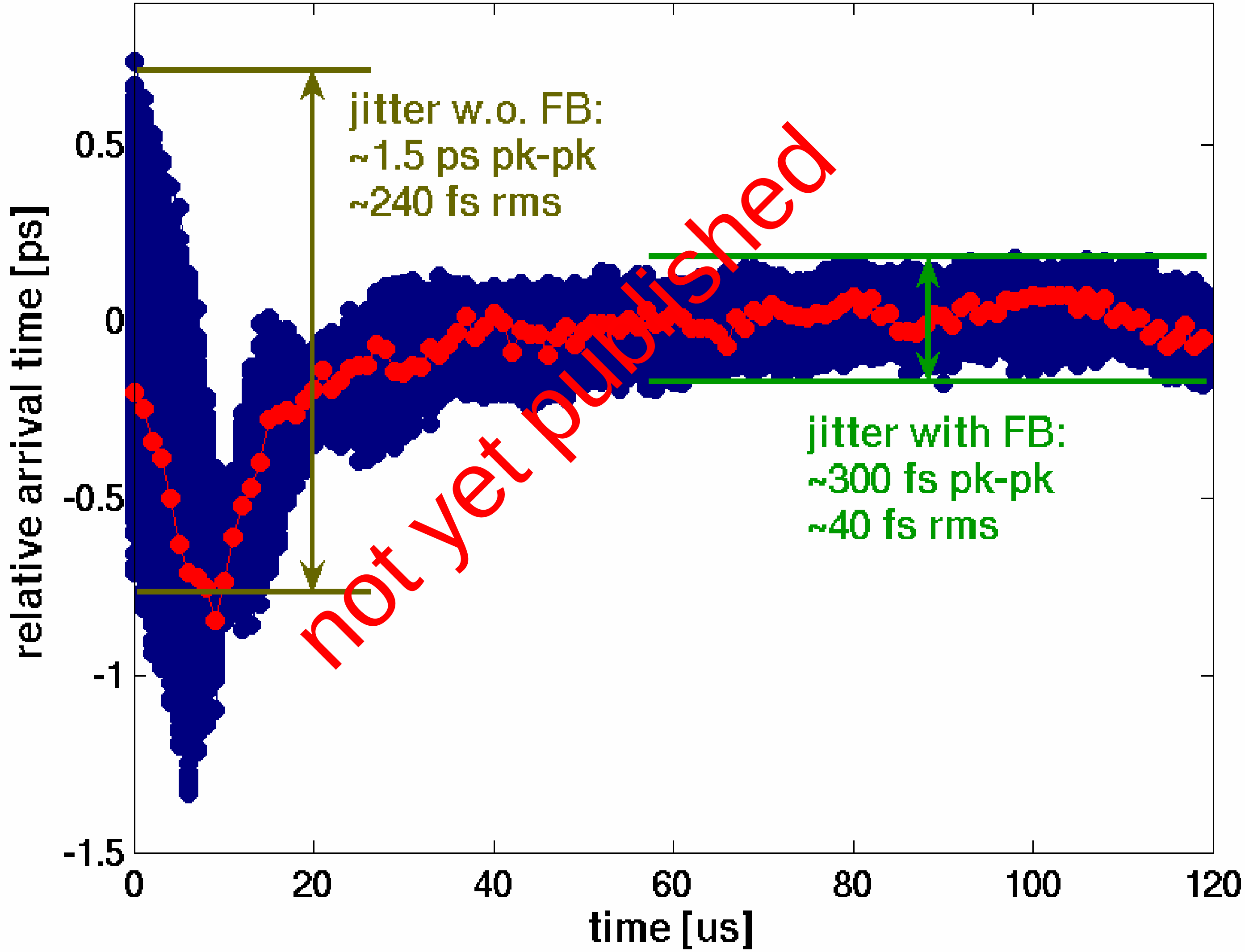
4 channel 108 MHz ADC board
16 bit resolution
FPGA for data processing
Rocket IO

Bunch arrival time monitor (BAM)
intra bunch-train arrival time feedback



Bunch arrival time monitor (BAM)
intra bunch-train arrival time feedback

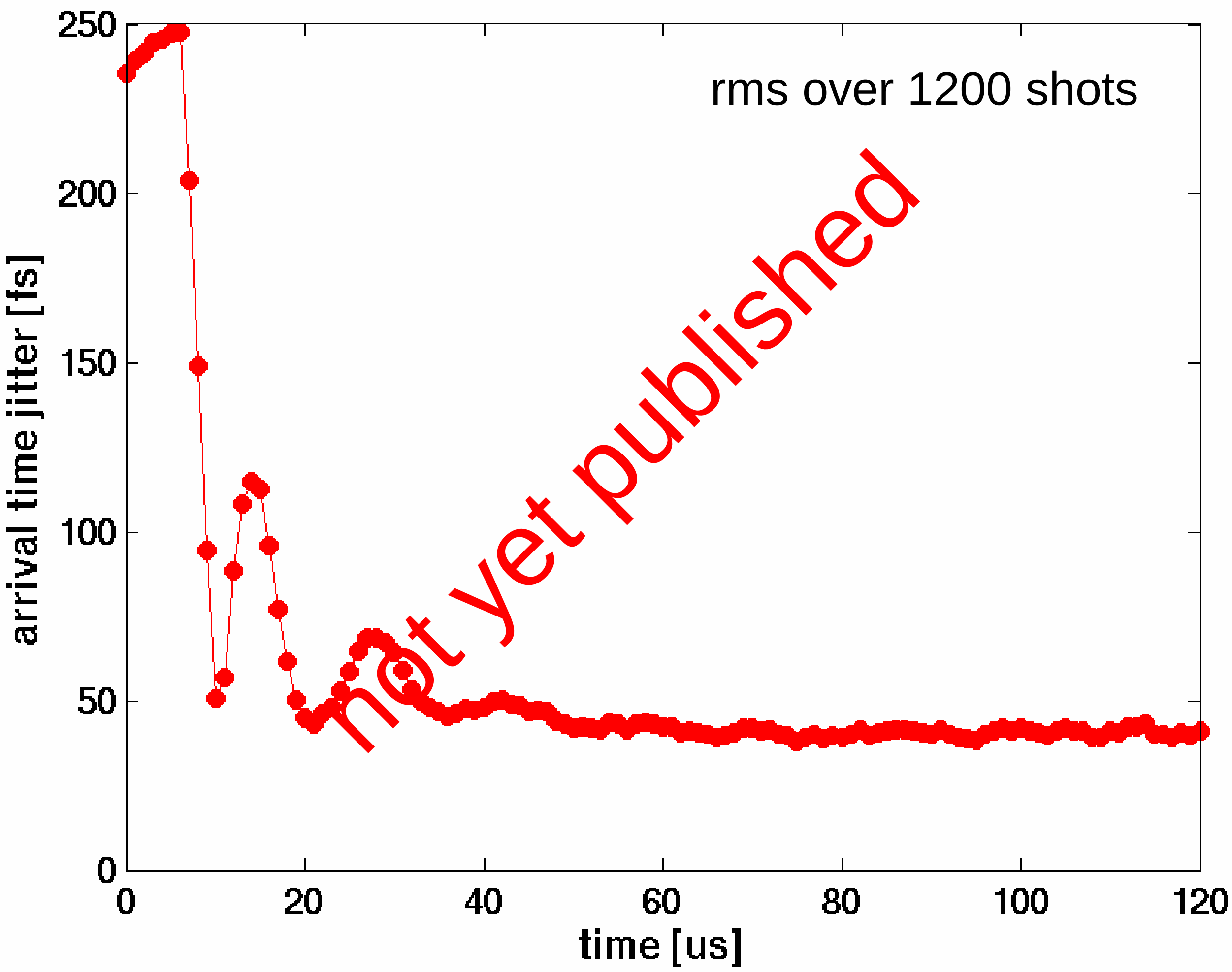
arrival time for 1200 shots:



jitter w.o. FB:
~1.5 ps pk-pk
~240 fs rms

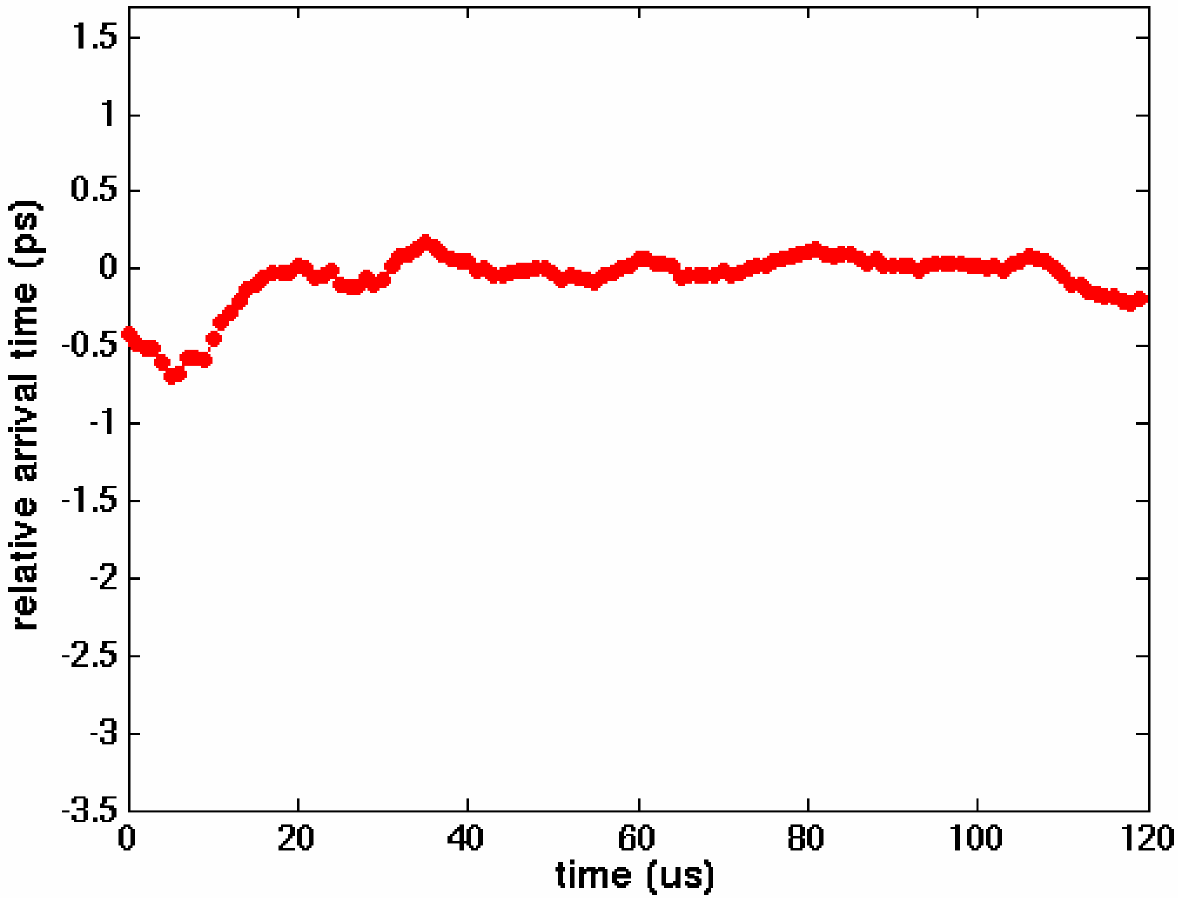
jitter with FB:
~300 fs pk-pk
~40 fs rms

Bunch arrival time monitor (BAM)
intra bunch-train arrival time feedback

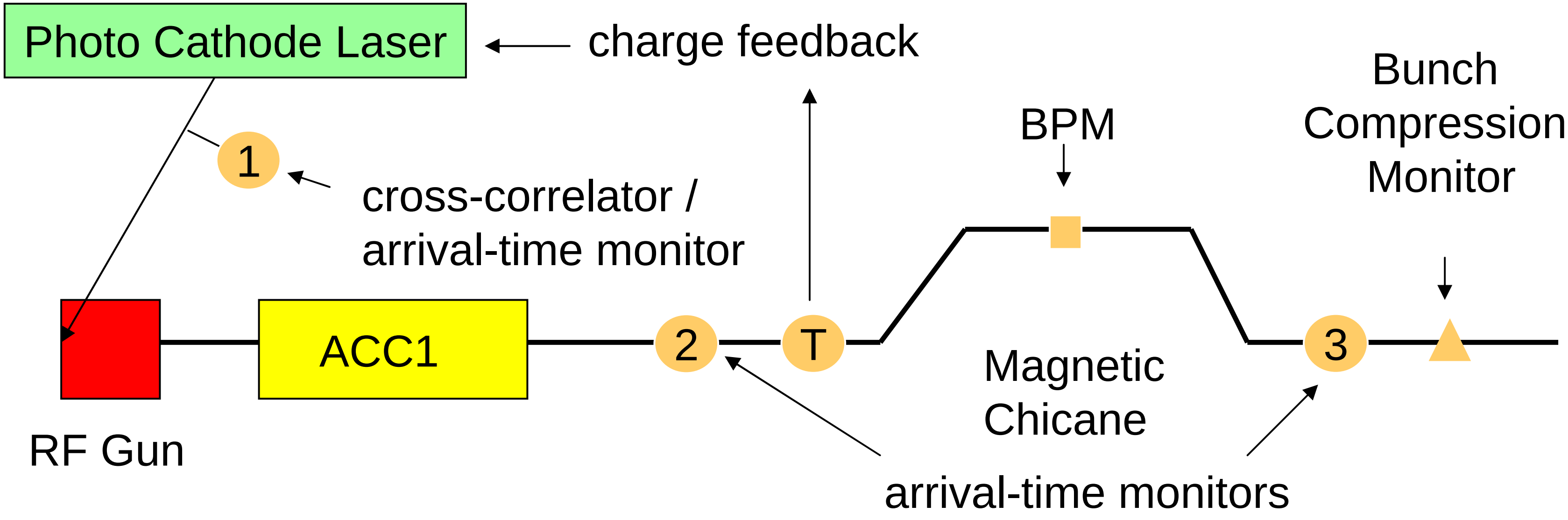


Bunch arrival time monitor (BAM)
intra bunch-train arrival time feedback

Generation of well defined arrival time slopes over the bunch train:
(this allows complete pump-probe experiments within a single bunch train)



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 lasers **(cross-correlation with timing system)**

Summary of bunch arrival time detectors

measurement bandwidth →

	RF mixing	„BAM“	„EO“	TDS
single shot	yes	yes	yes	yes
sample rate	GHz	~200 MHz	~10 – 100 kHz	GHz
pros	- no optics - simple setup - easy and fast data processing	- high resolution - easy and fast data processing - absolute reference - drift free	- high resolution - profile information - drift free	-highest resolution profile information
cons	- may drift - single shot resolution - no profile infos	- no profile infos - small bunch spacing requires fast pick-up	- complicated - slow data acquisition - data processing	-expensive -invasive -may drift
develop. for ERL	- pick-up - drifts	- pick-up	- fast detector - data processing	

Summary

- Four different schemes for the arrival time detection were discussed. None of these schemes meets all ERL requirements (i.e. 1.3 GHz data acquisition, low bunch charge).
- The reference signal and its distribution go hand in hand with the arrival-time detection.
- The timing stability of a machine depends sensitively on the design of the bunch compressor scheme.

Contributing People

V. Arsov, M. Felber, K. Hacker, F. Ludwig, B. Lorbeer, K. Matthiesen, H. Schlarb, B. Schmidt, A. Winter
(Deutsches Elektronen-Synchrotron)

S. Schulz, J. Zemella
(Universität Hamburg)

J. Kim, J. Cox, J. Chen, F.X. Kaertner
(Massachusetts Institute of Technology)

J. Szewinski
(Warsaw University of Technology Institute of Electronic Systems)

W. Jalmuzna
(Technical University of Lodz)

Thank you for your attention!