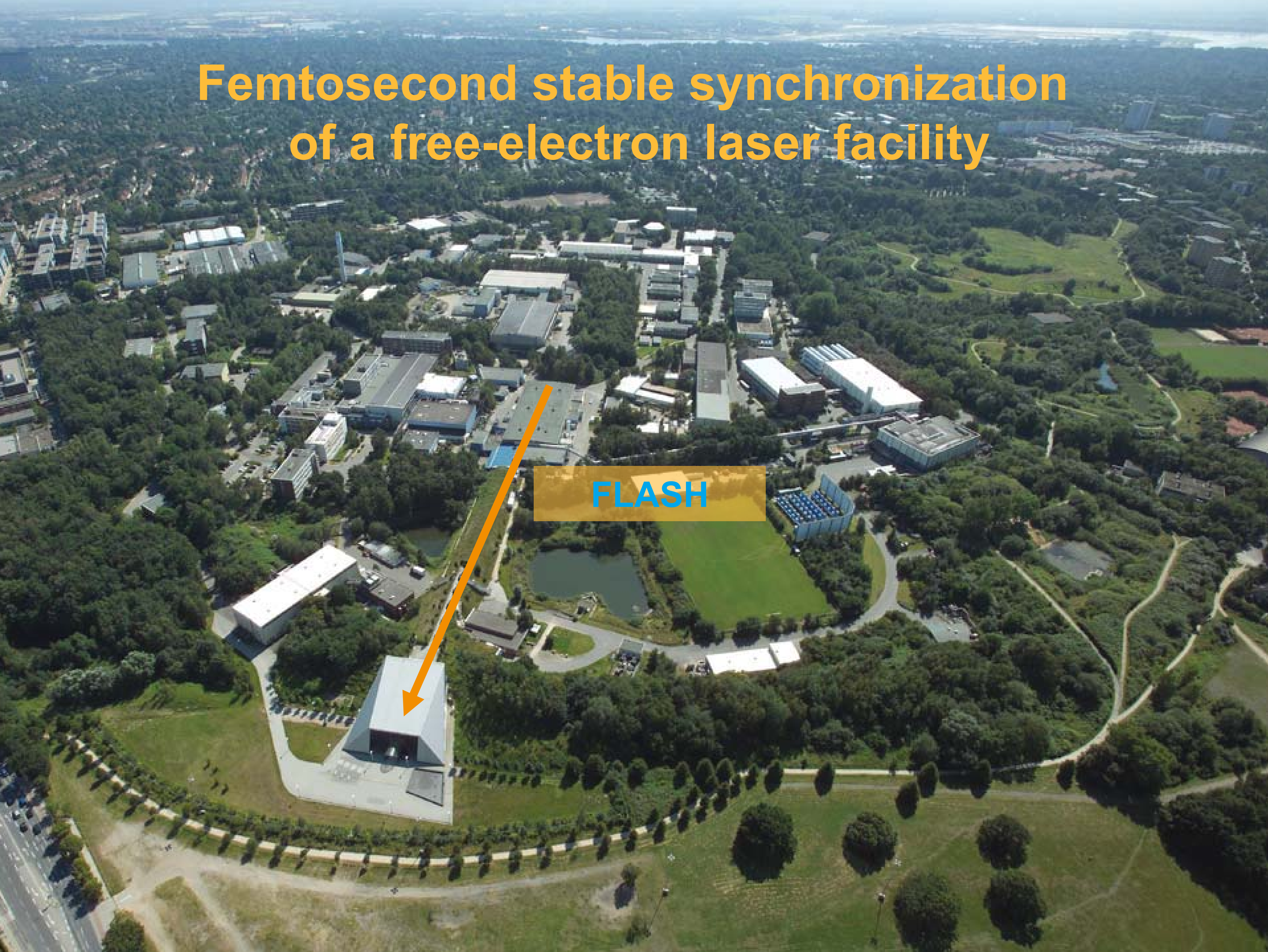
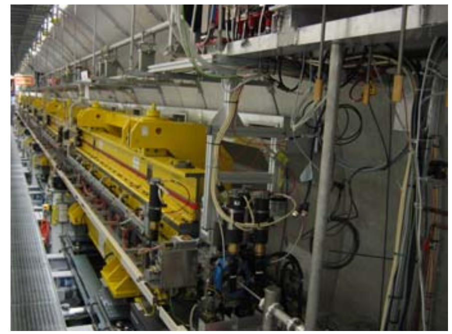
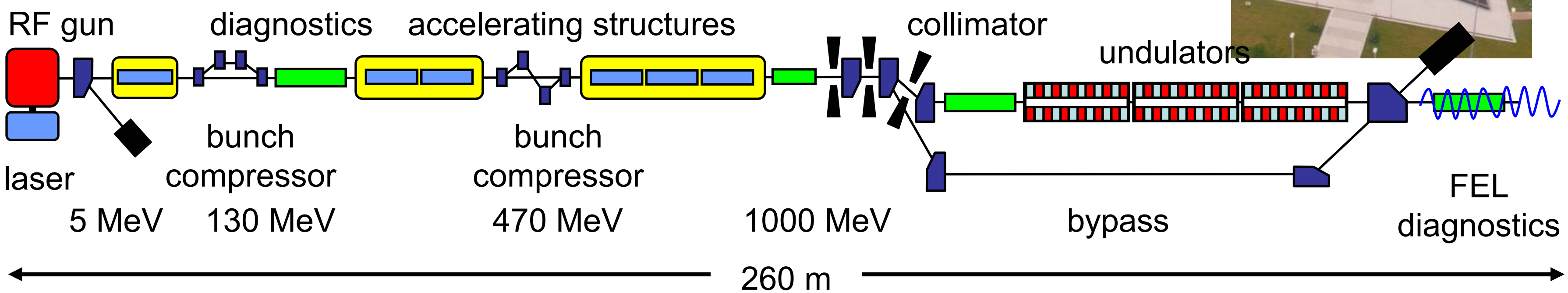

Femtosecond stable synchronization
of a free-electron laser facility
FLASH

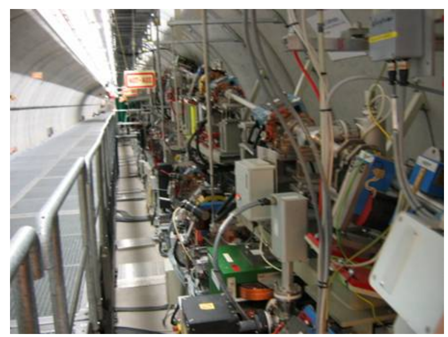
FLASH – The Free-electron Laser in Hamburg





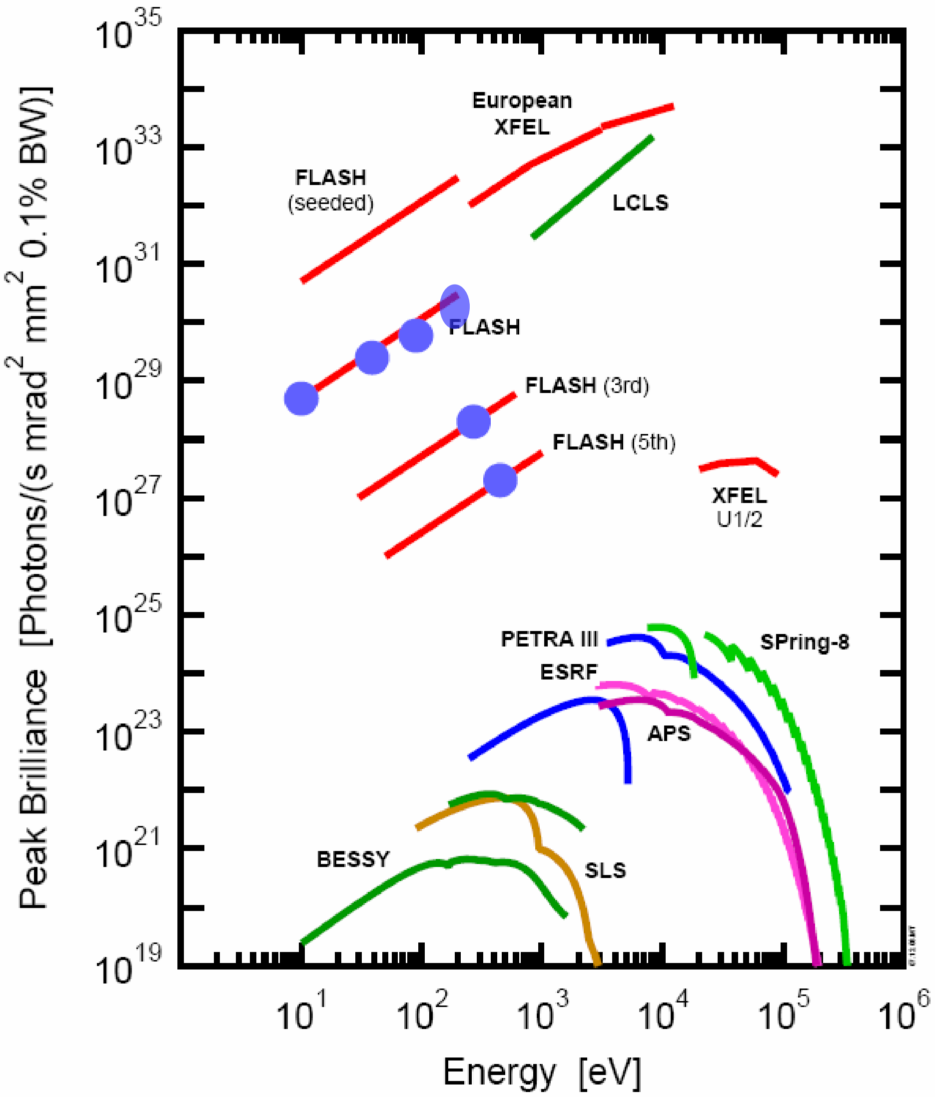








FLASH parameters

Para.	FLASH	XFEL
$\varepsilon_{x,y}$	2 μm	1.4 μm
I_{peak}	2.5 kA	5 kA
f_{rep}	1 (9)MHz	5 MHz
Q	1 nC	1 nC
E	1 GeV	17.5 GeV
RF	1.3/3.9GHz	1.3/3.9GHz
Δt	800μs	650μs
λ	6.5 – 45 nm	0.1 – 6.4 nm
σ_{photon}	< 10 fs	??

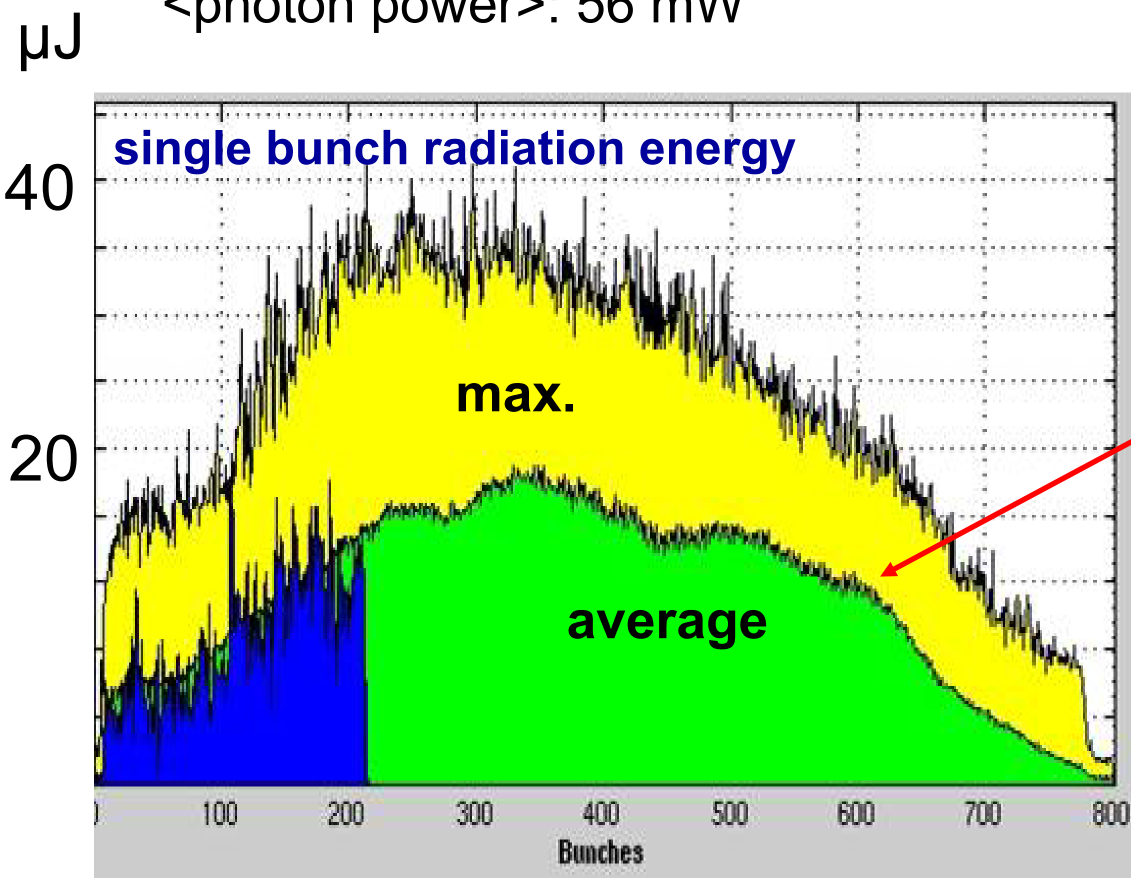


800 bunches

685 MeV (13.4 nm)

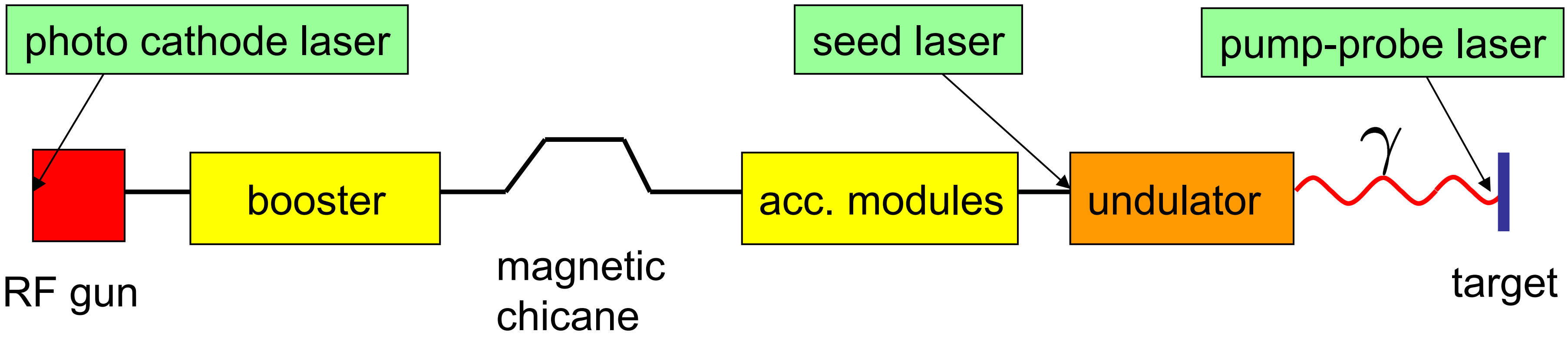
<electron beam power> : 2.7 kW

<photon power>: 56 mW



Systematic variation of SASE intensity over macro pulse!

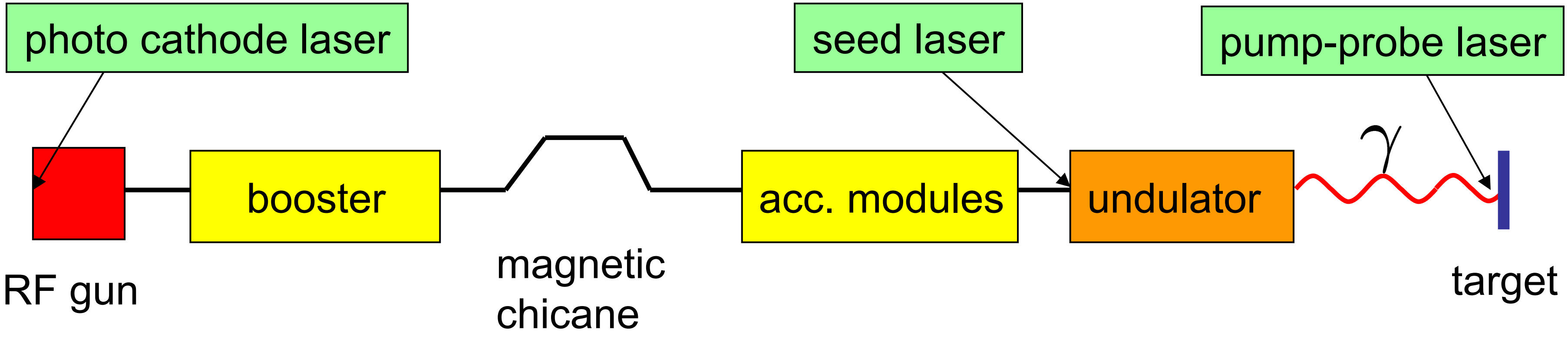
Timing changes in an FEL



Goal:
Synchronization of pump-probe laser pulses with FEL pulses to the femtosecond level

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 an FEL



timing jitter behind chicane

RF amplitude changes
FLASH: R_{56} = 180 (50) mm
XFEL: R_{56} = 100 (20) mm
LCLS: R_{56} = 36 (22) mm

RF phase changes

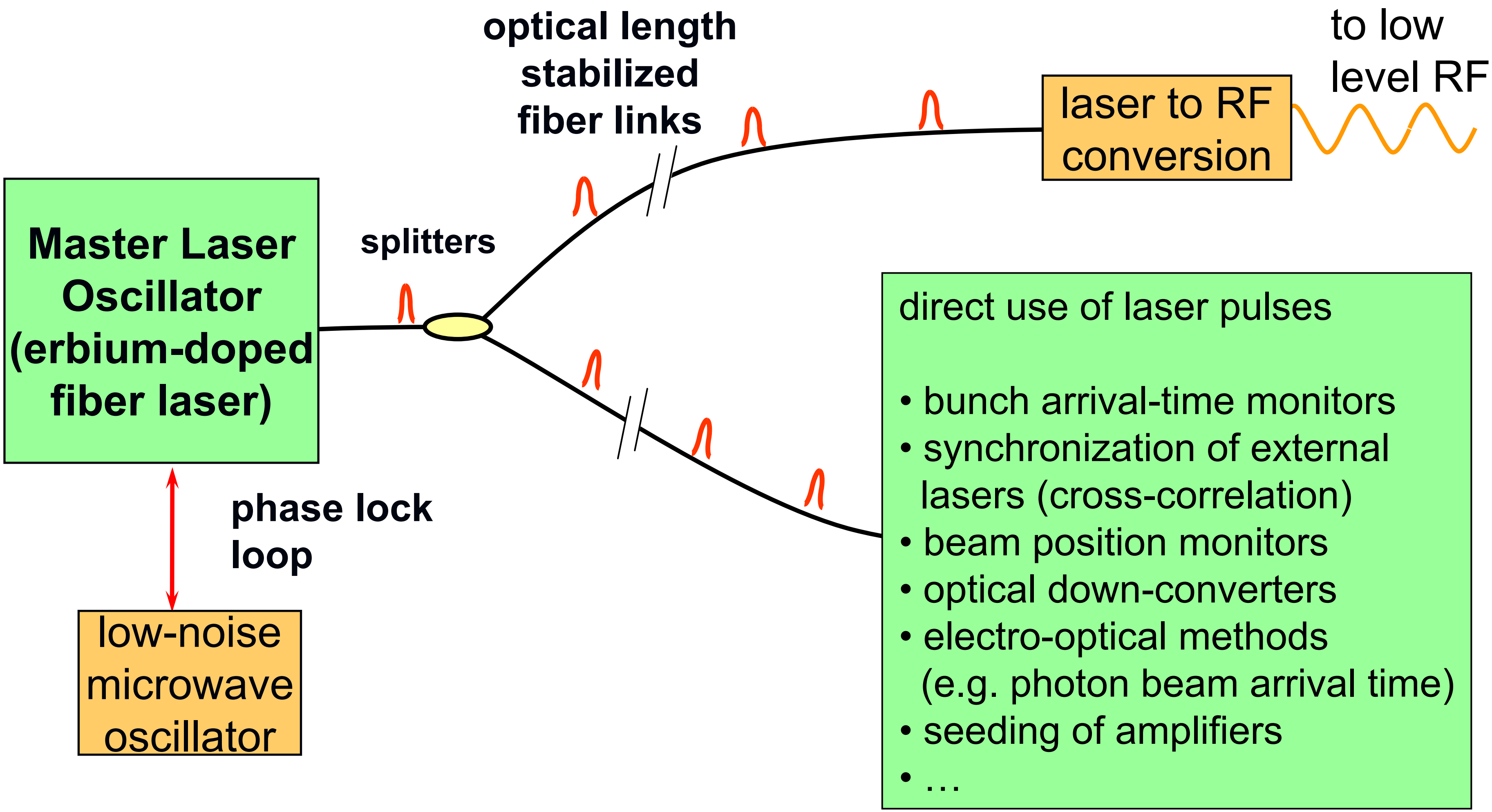
reduction of incoming timing jitter due to compression

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

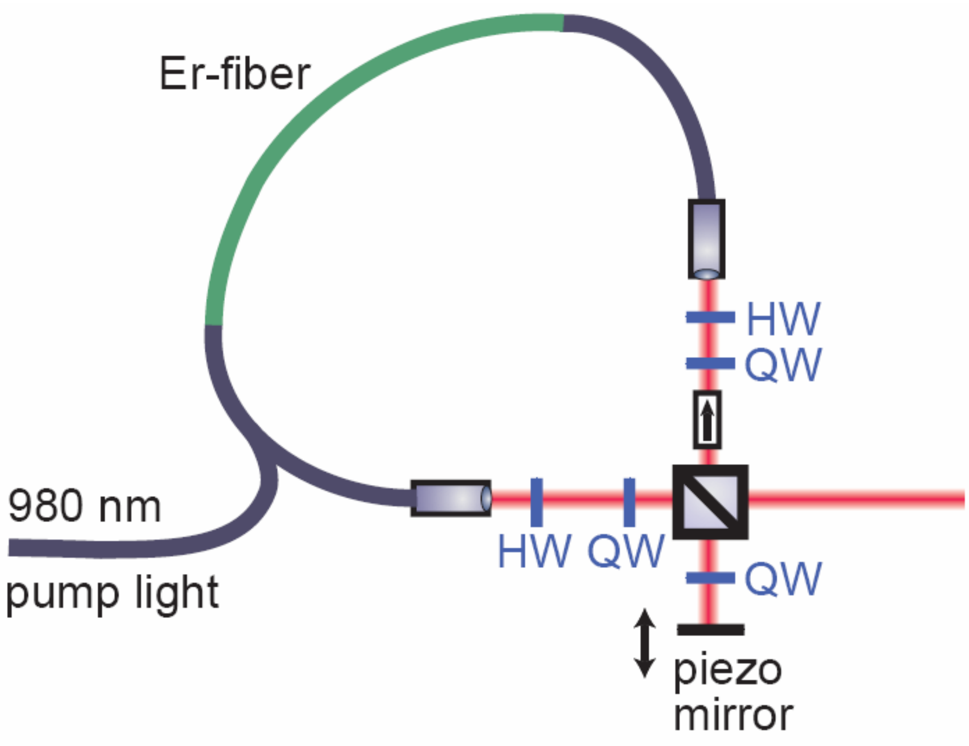
RF requirements for 10 fs arrival time stability at FLASH:

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

Schematic layout of the optical synchronization system



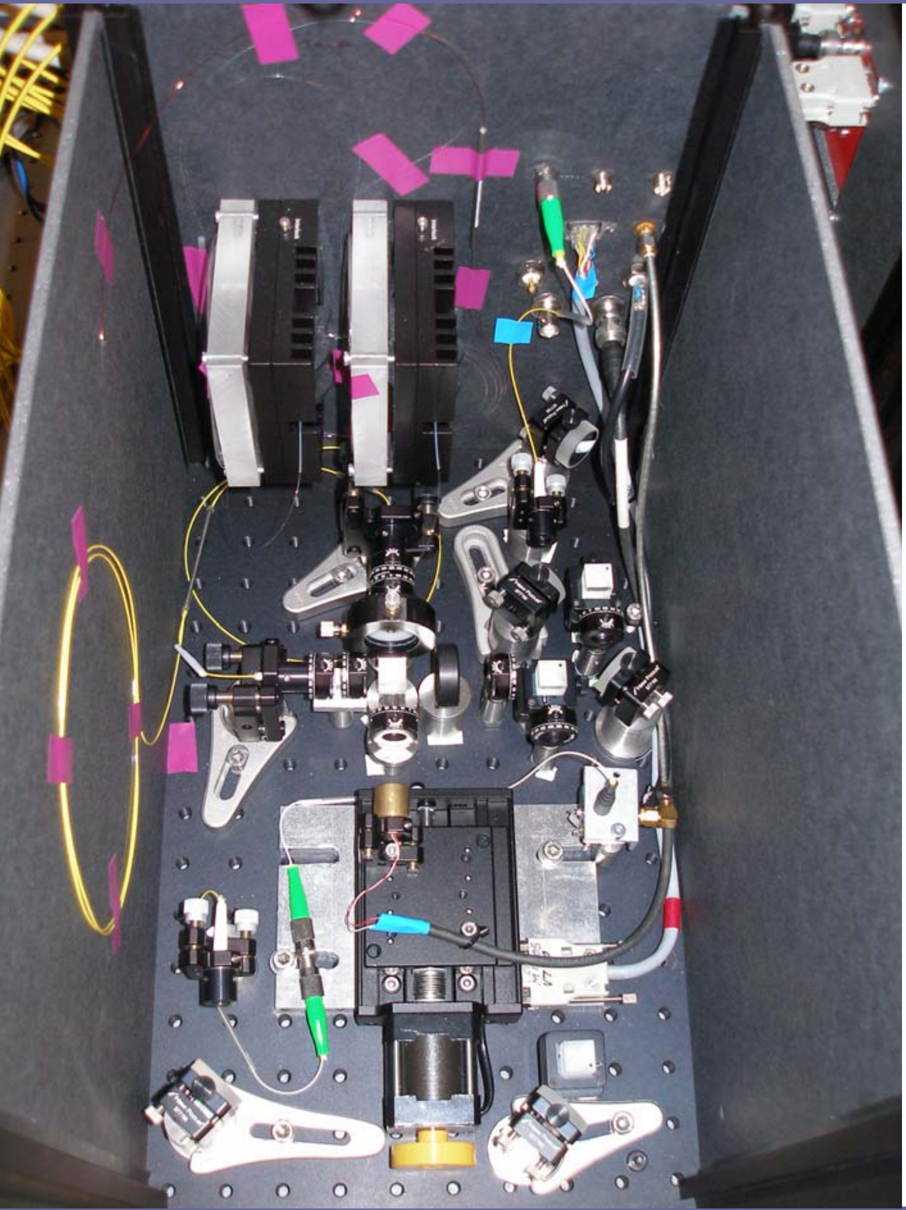
Distribution scheme originally proposed in J. Kim et al., FEL04 conference

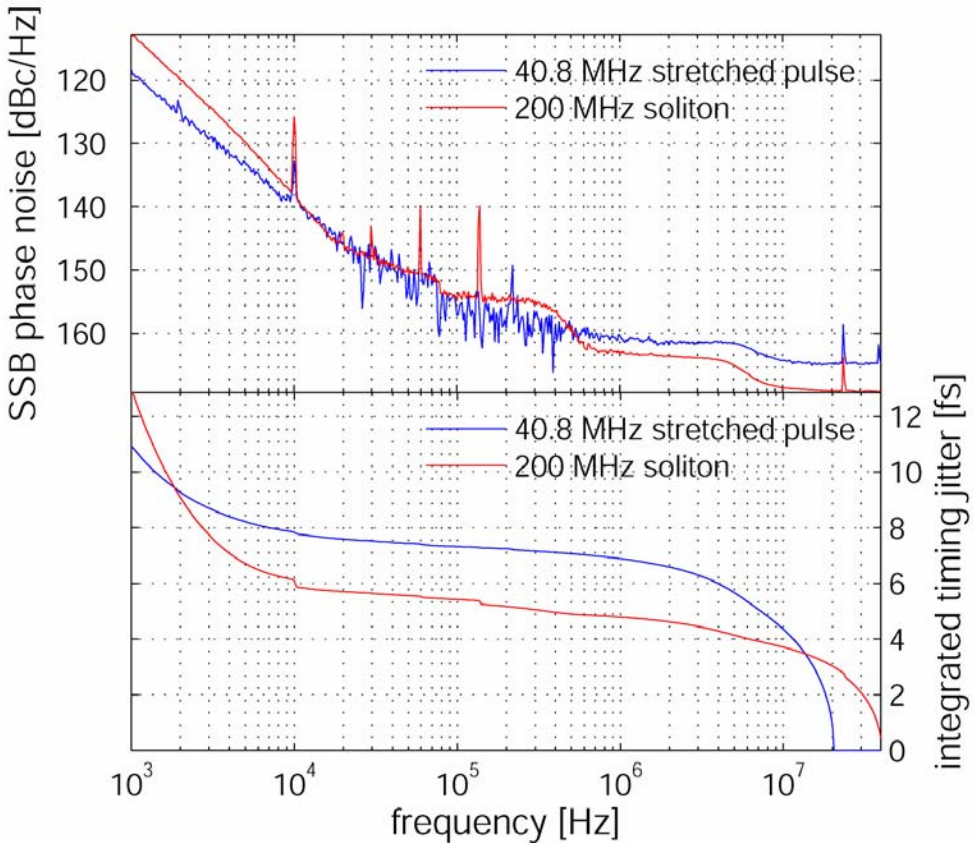


Original design:
J. Chen et. al., Opt. Lett. **32**, 1566-1568 (2007)

Modifications:

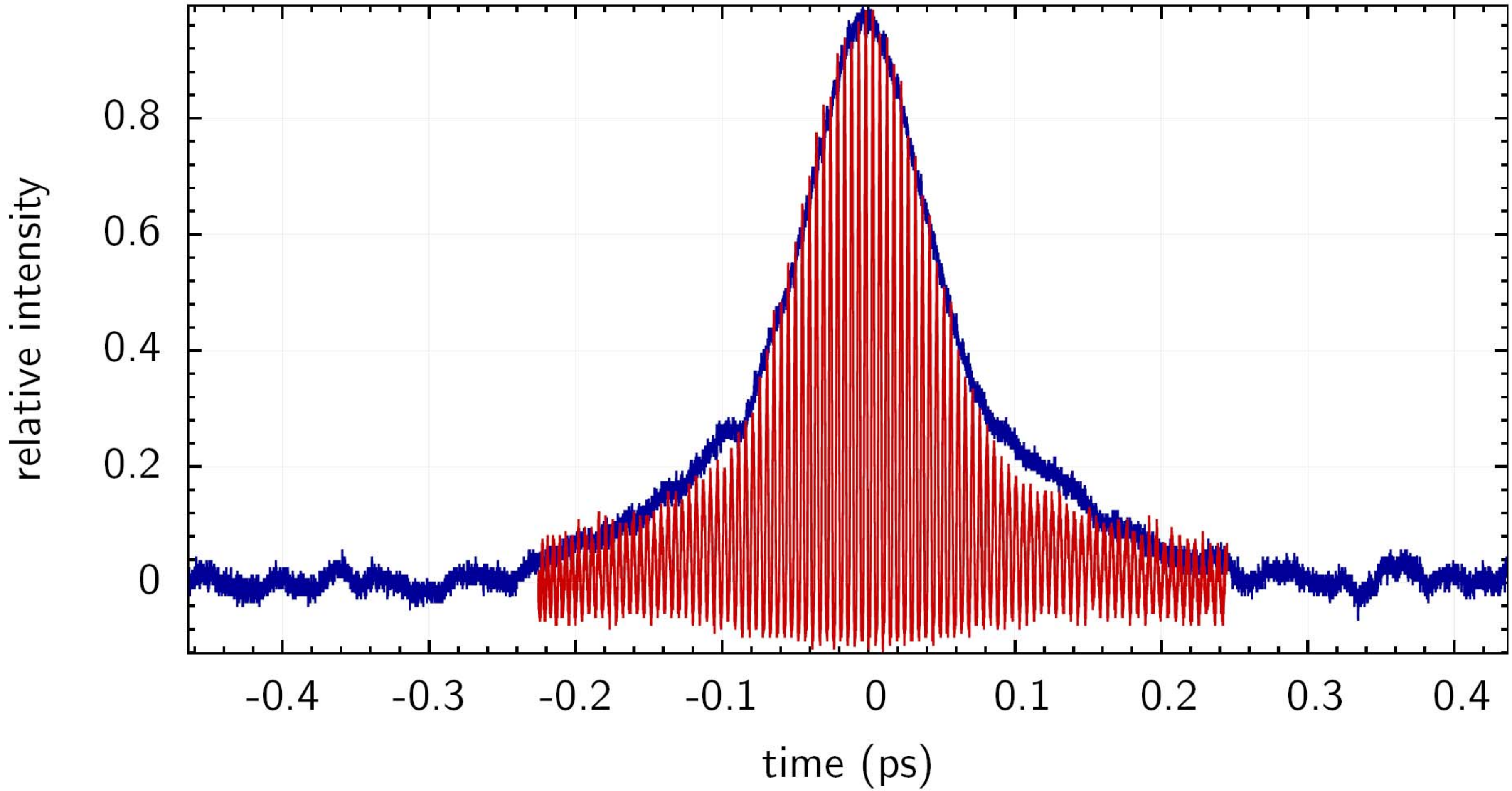
- sigma configuration to lock laser to machine reference
- 216 MHz repetition rate
- different dispersion
  - à shorter pulses
  - à higher output power





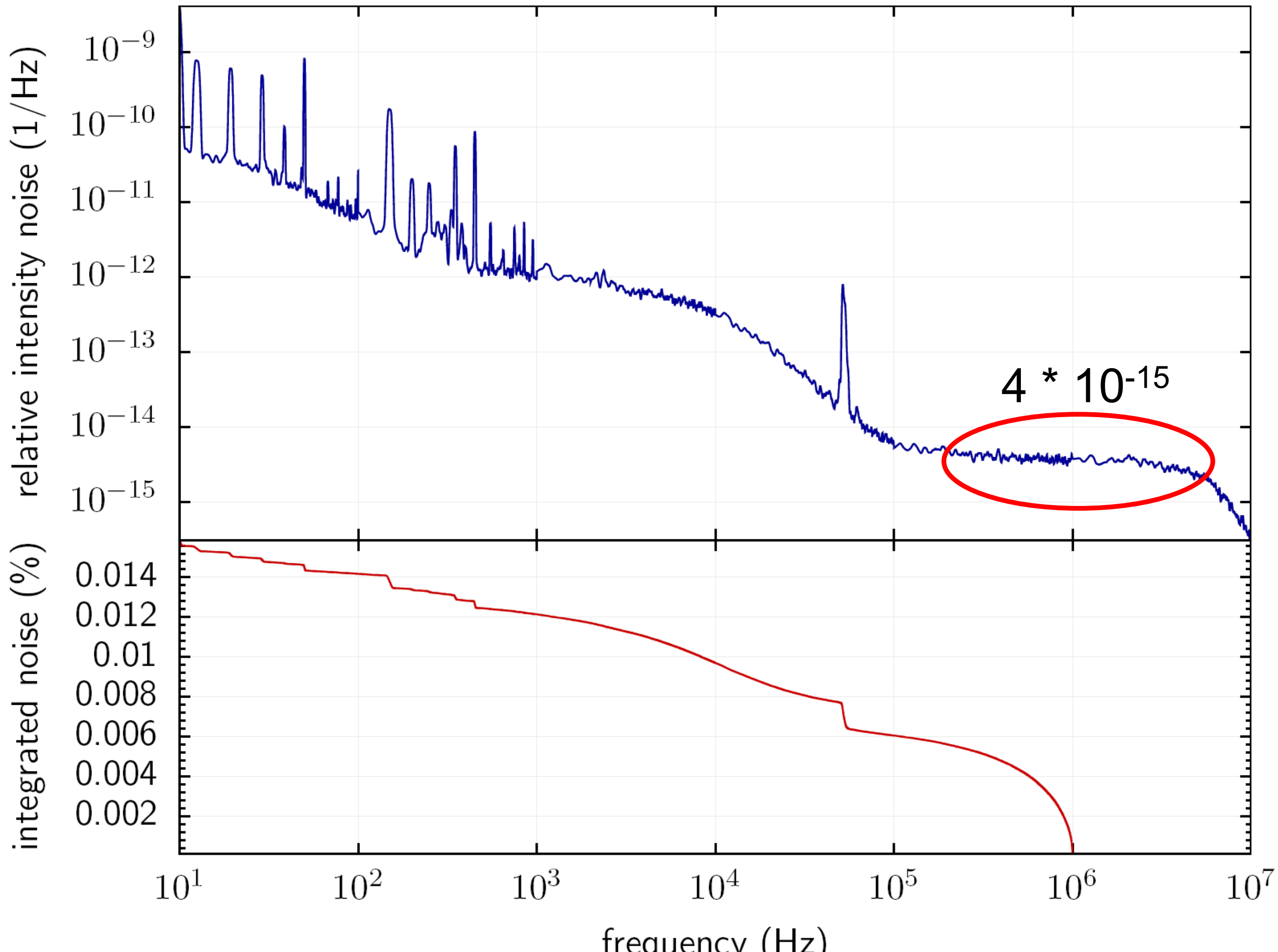
Integrated timing jitter:
< 6 fs [10kHz – 40 MHz]

laser pulse width: 75 fs (FWHM)

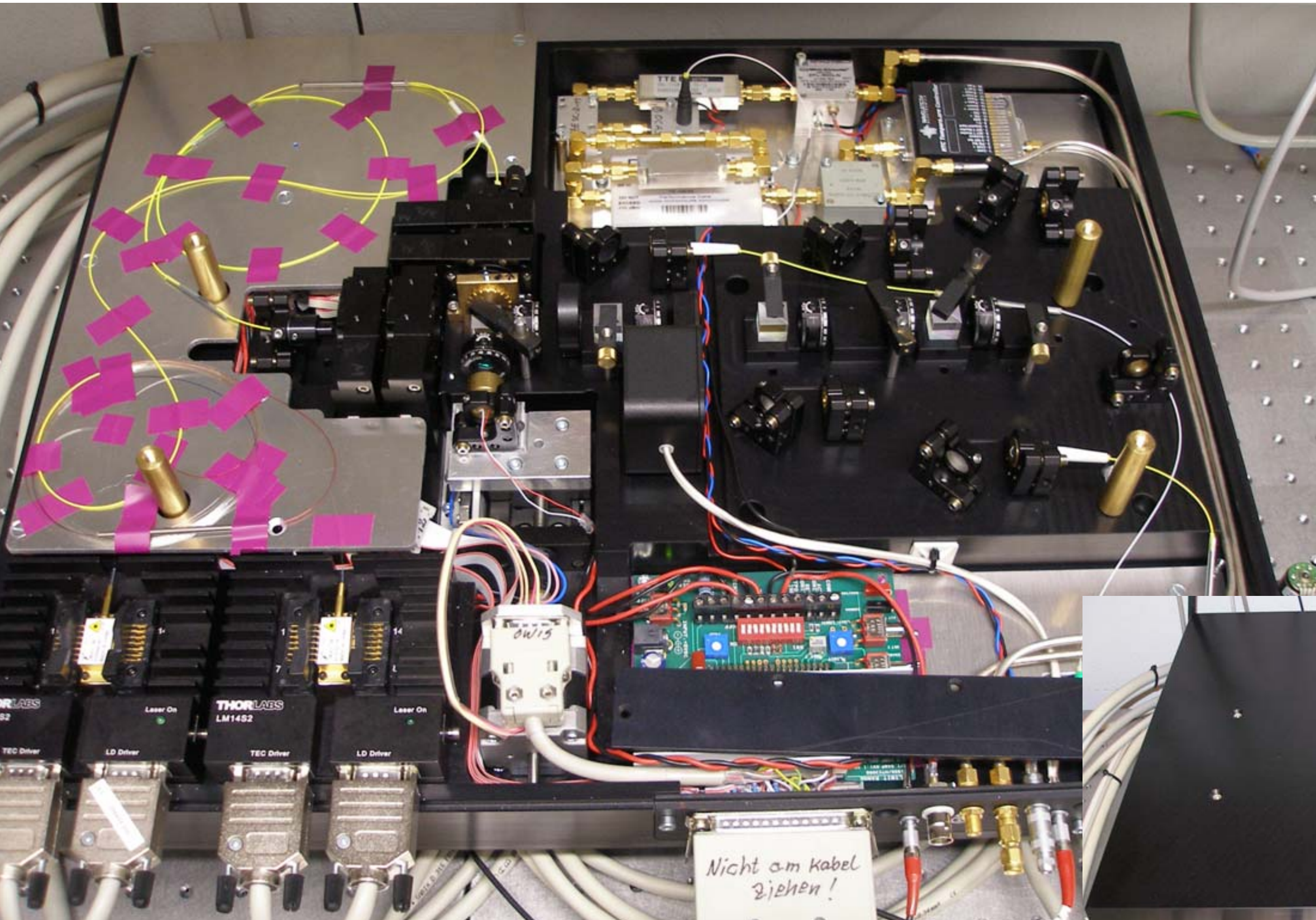


Timing reference laser of the facility

relative intensity noise: 0.016 % [10 Hz – 1MHz]

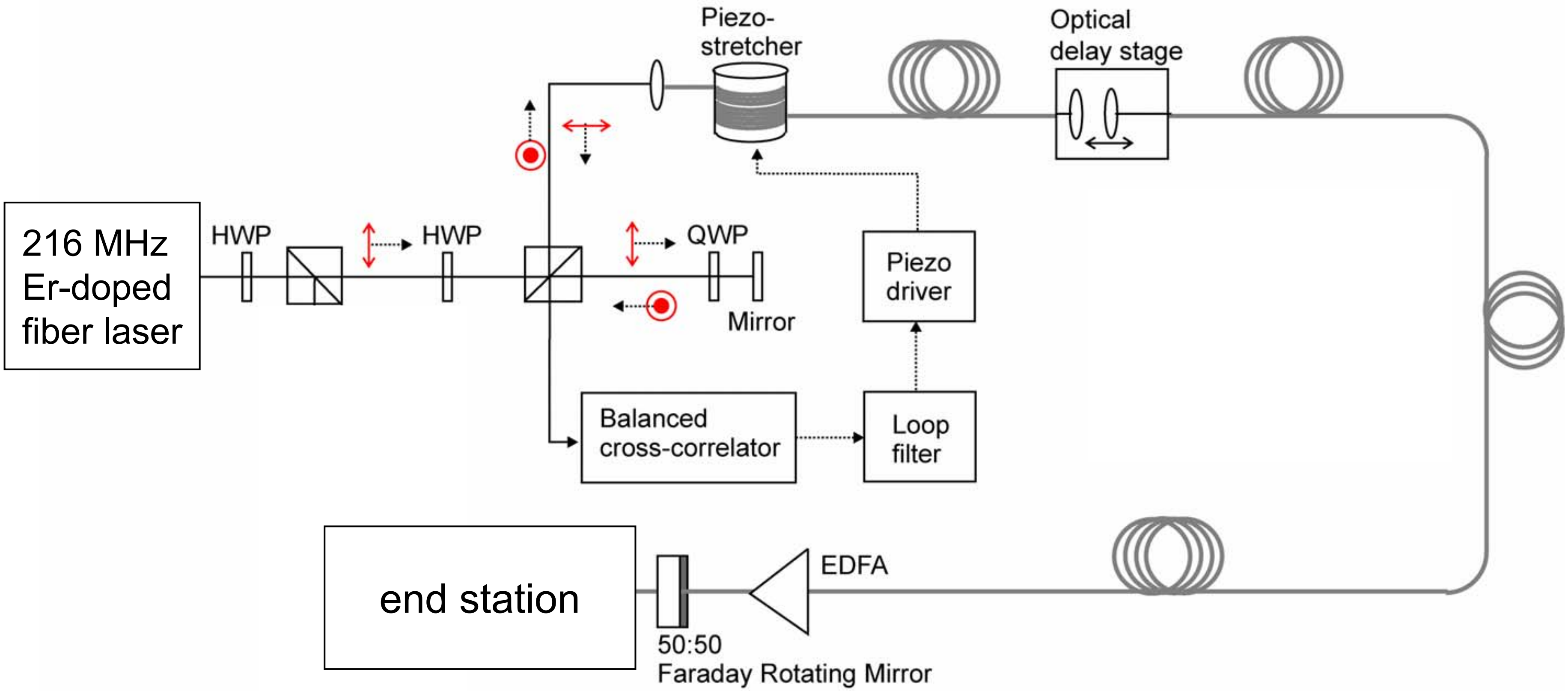


Timing reference laser of the facility



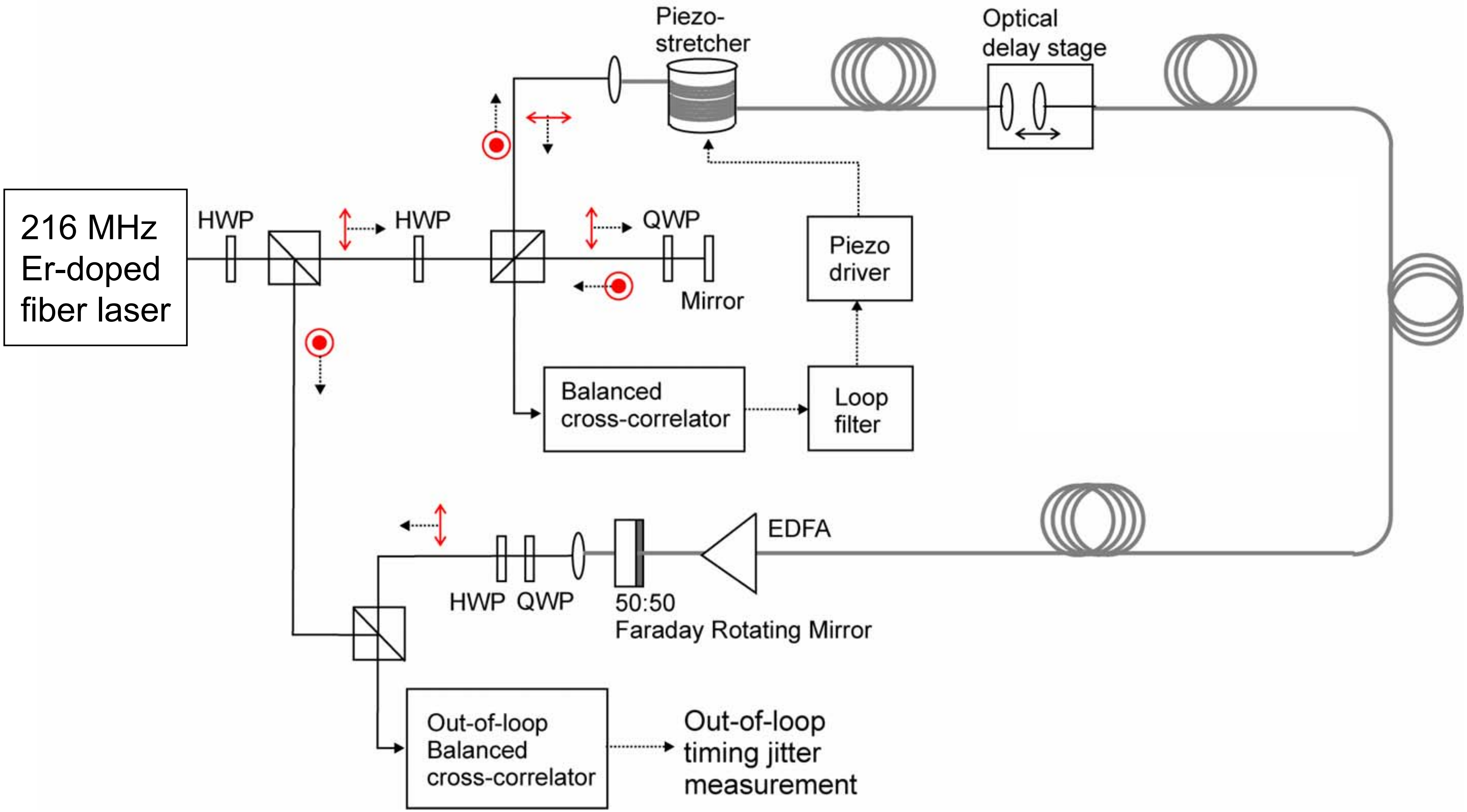
Prototype of a 216 MHz laser and a small distribution unit. An improved design is on its way.

Fiber link stabilization
Schematic setup



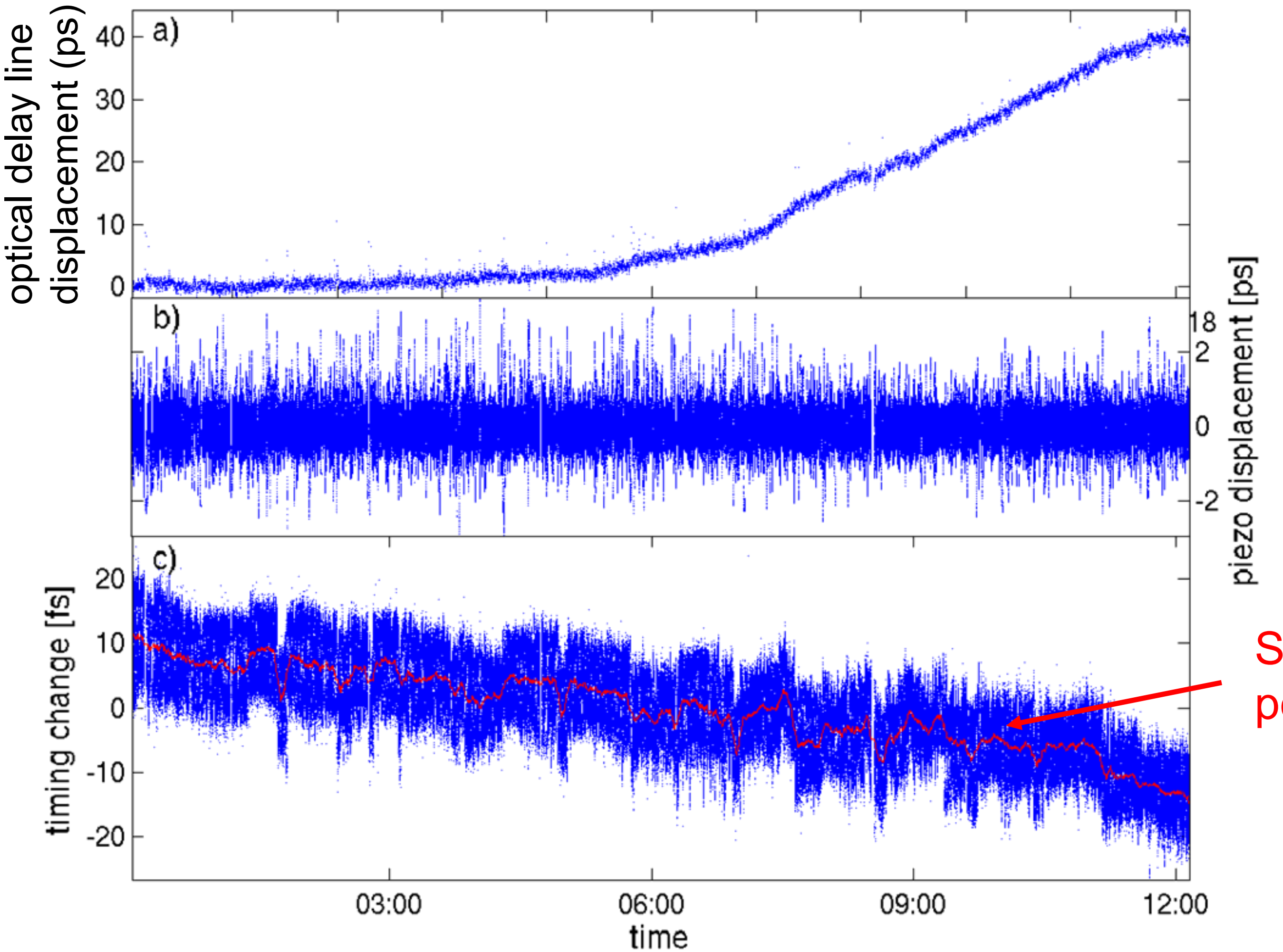
J. Kim et al., Opt. Lett. **32**, 1044-1046 (2007)

Schematic setup to determine fiber link stability



J. Kim et al., Opt. Lett. **32**, 1044-1046 (2007)

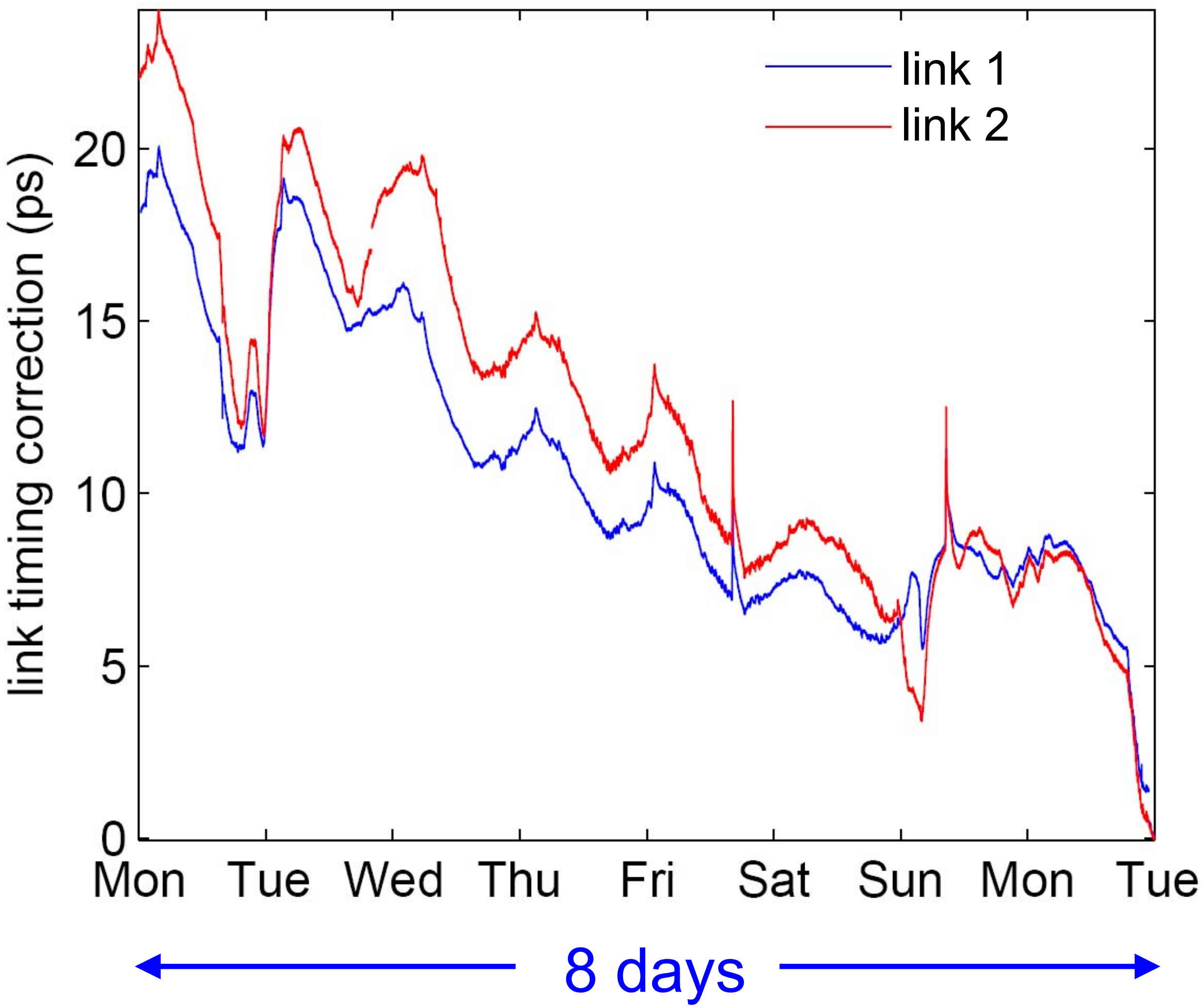
Long term stability of a 400 m long fiber link installed in an accelerator environment



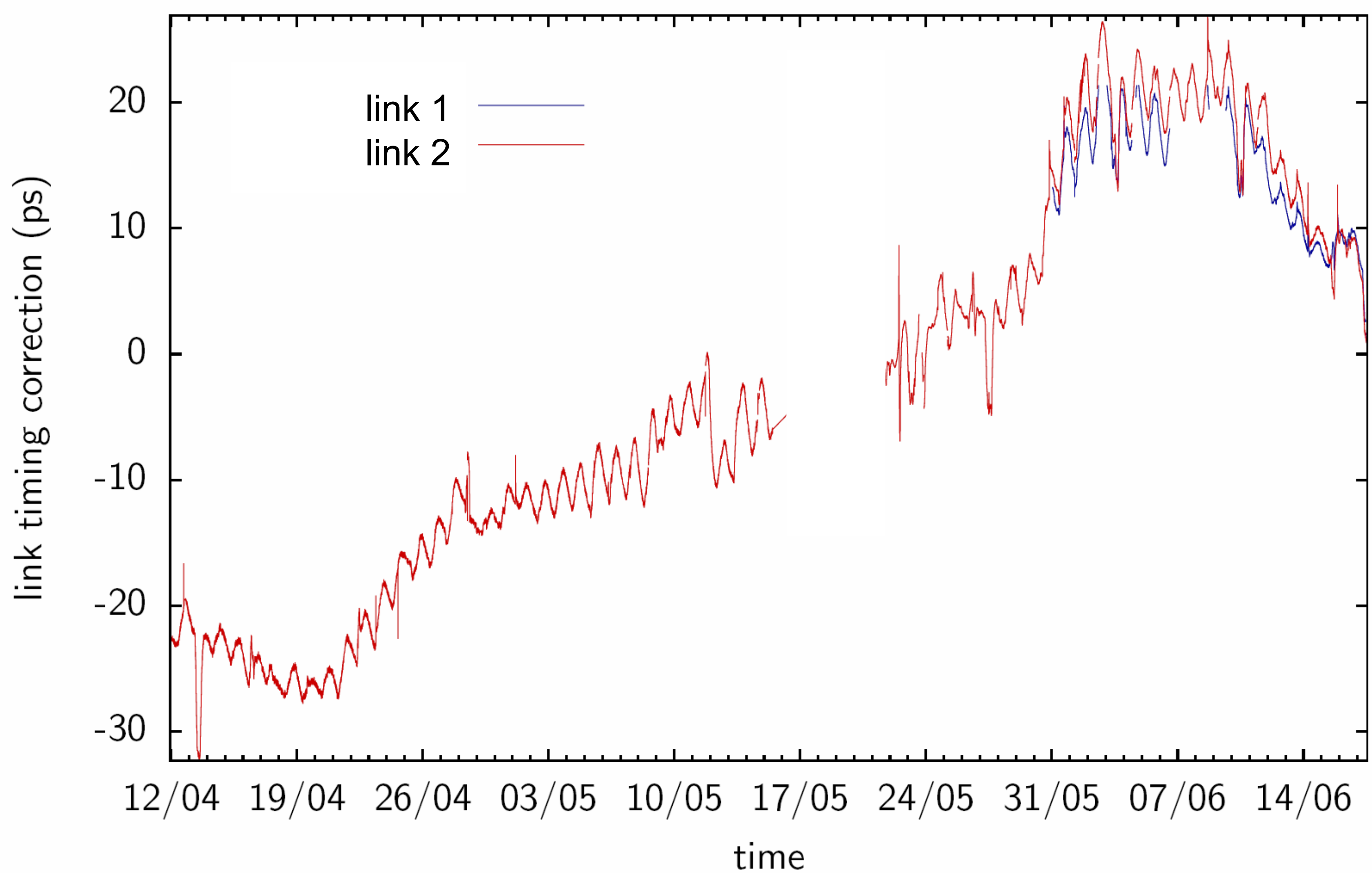
Slow timing drift: polarization artefact

rms timing jitter over 2 minutes: (4.4 ± 1.1) fs
rms timing jitter over 12 h: (7.5 ± 1.8) fs
measurement bandwidth: 200 kHz

First two fiber links installed at FLASH

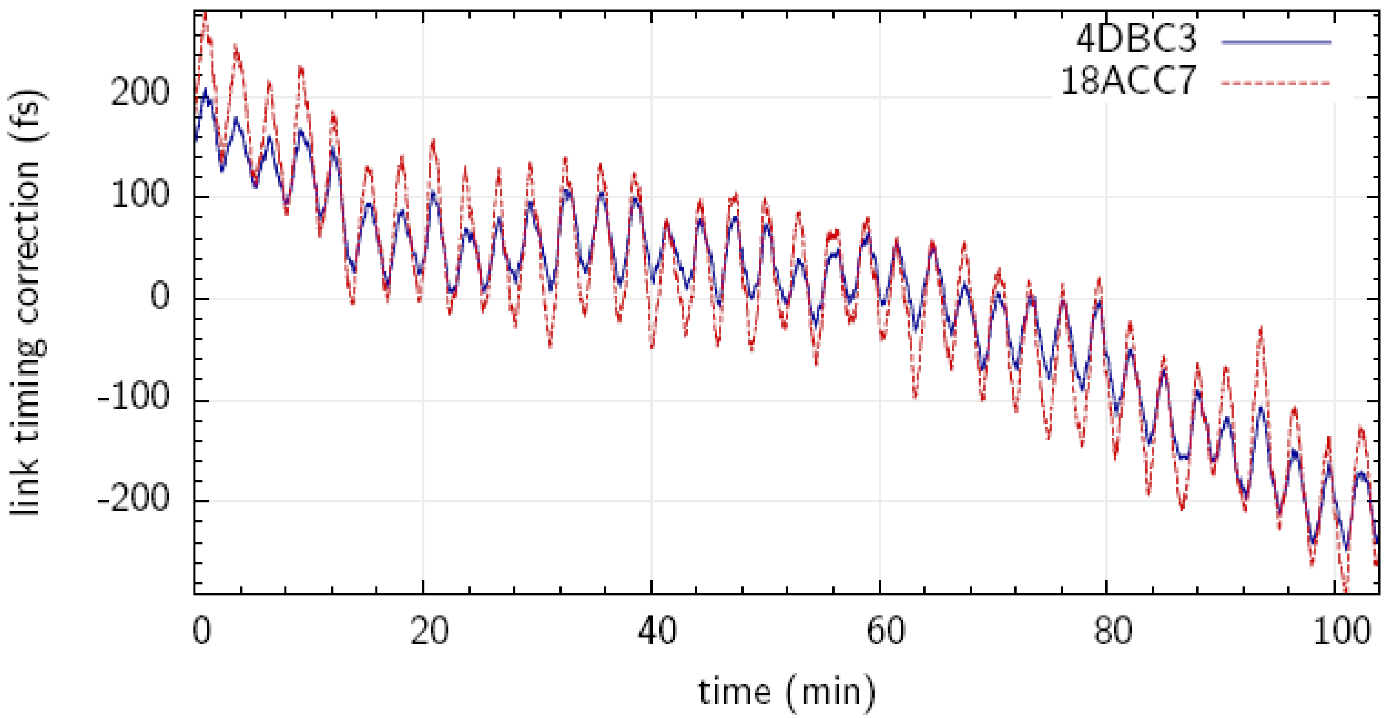


Fiber link stabilization
Long term timing correction



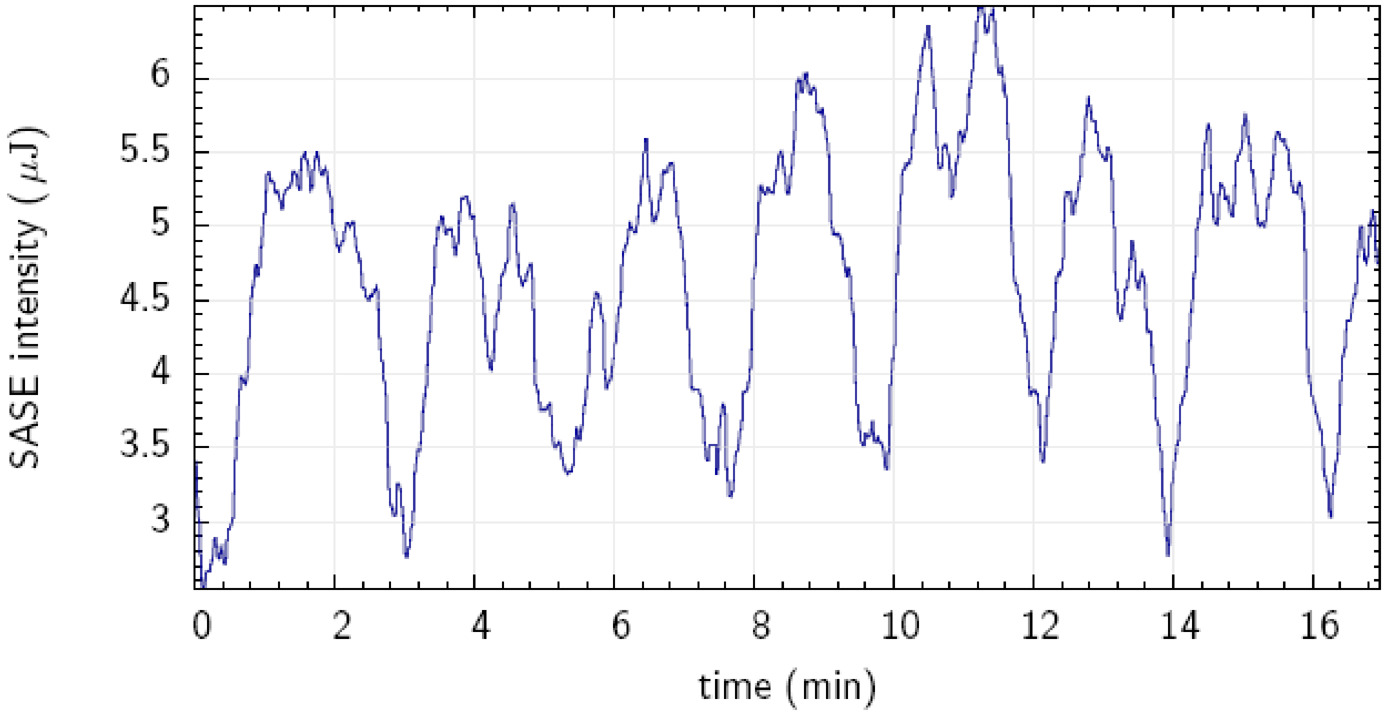
2 month

Lessons from fiber link timing changes



Oscillations of the fiber lengths with a period of about 3 minutes!

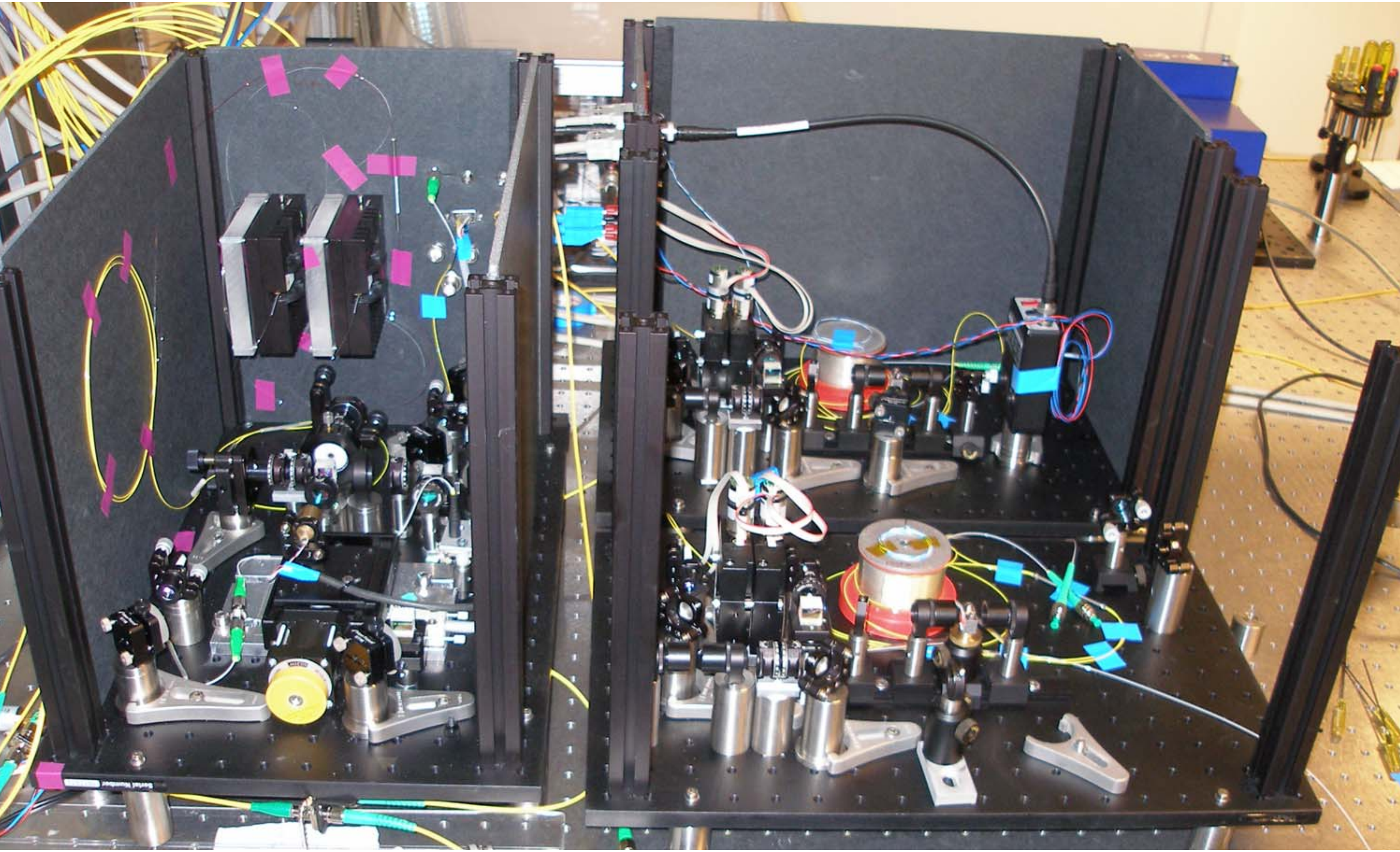
Lessons from fiber link timing changes



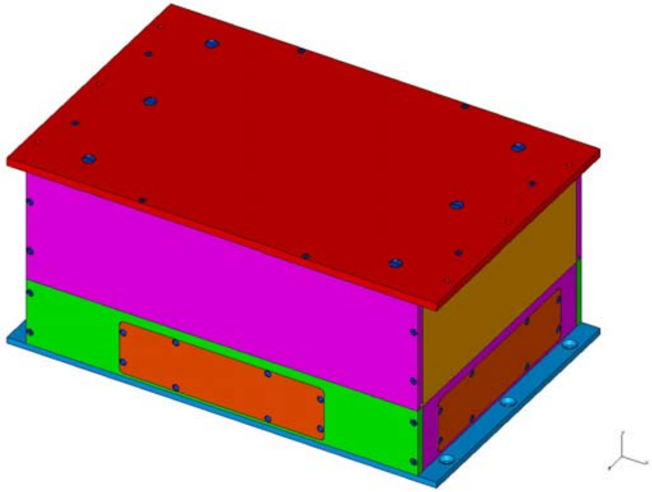
Oscillations of the fiber lengths with a period of about 3 minutes!

The Oscillation is also visible on the SASE signal
→ frequency change of microwave reference?!

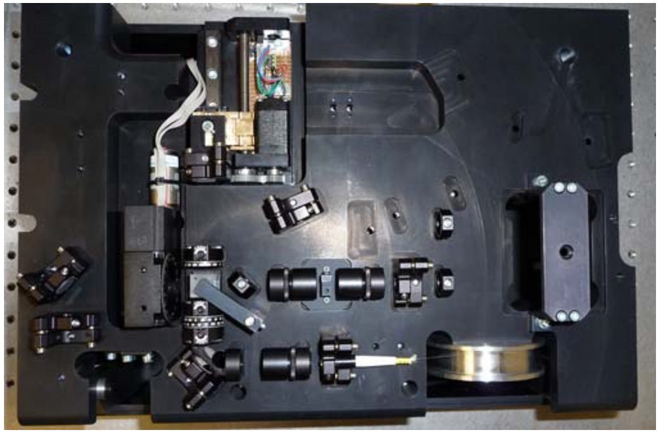
Prototypes of reference laser and fiber link stabilization

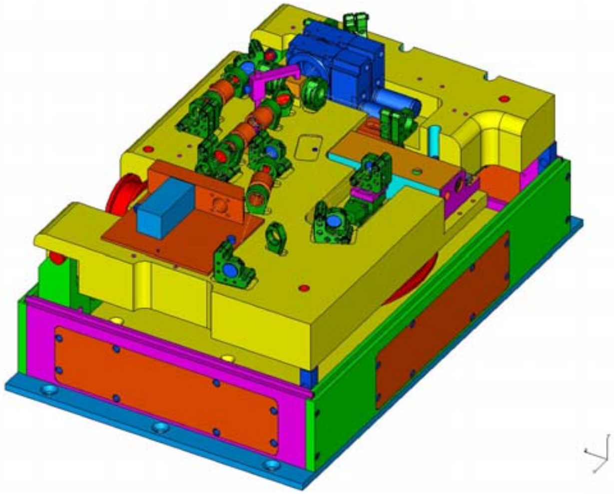


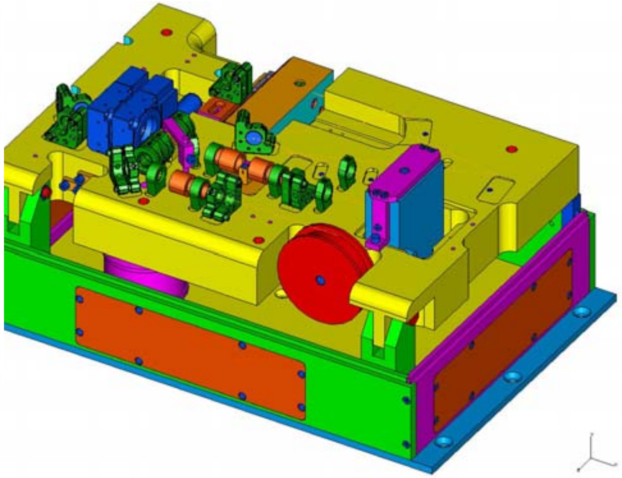
Fiber link stabilization
Engineered mechanical designs



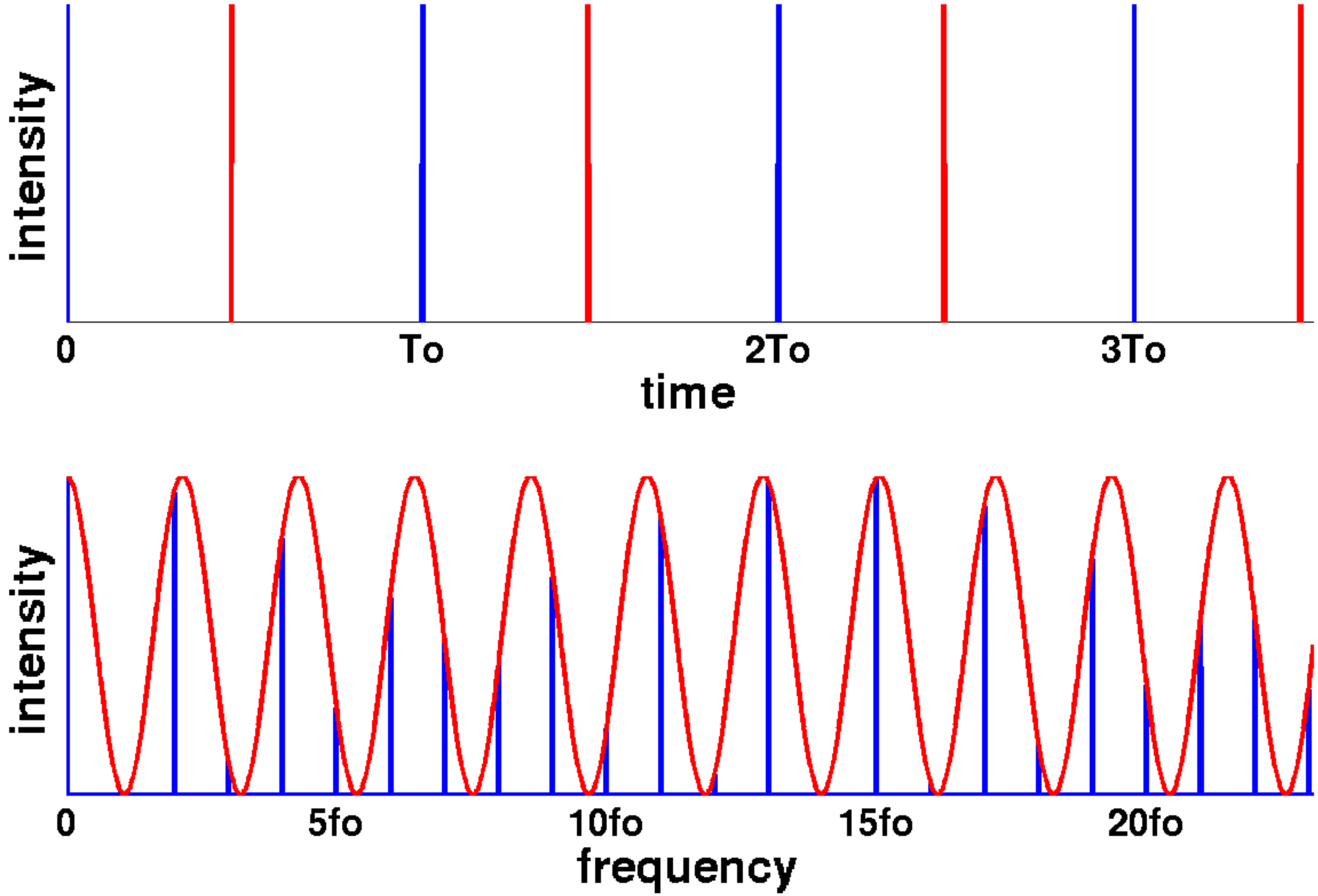
Installation November 2008.







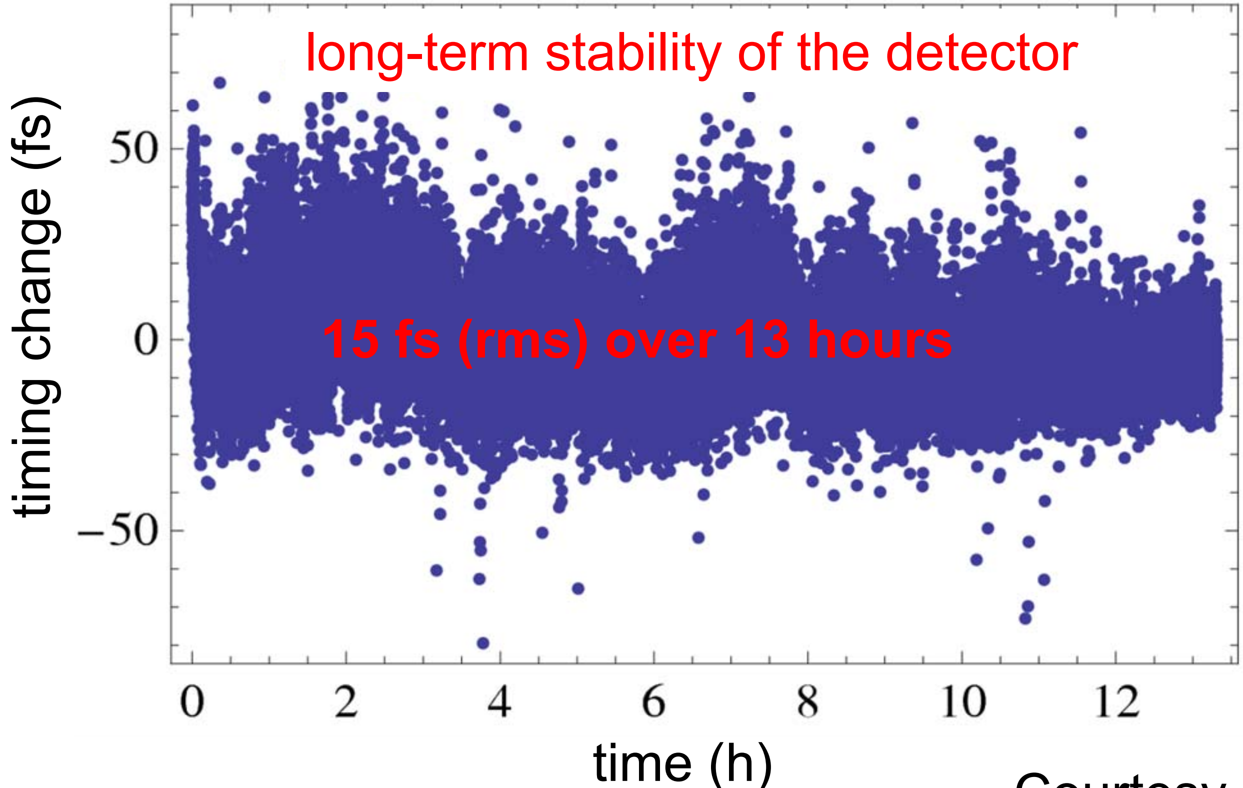
Cost-effective high resolution RF based timing detection



Cost-effective high resolution RF based timing detection

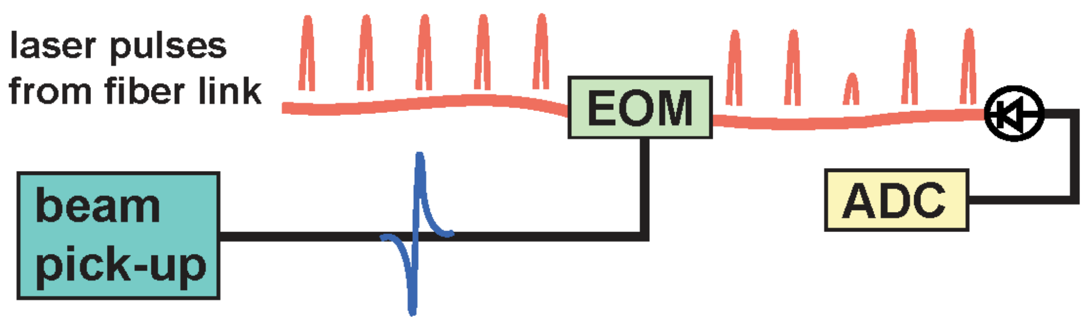
New detection scheme to measure the overlap between two optical pulse trains

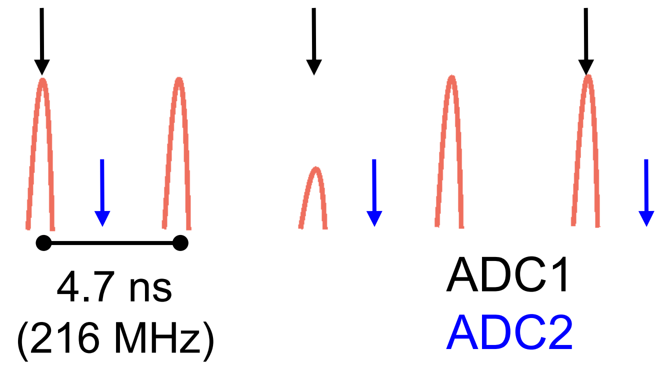
- RF based scheme using a single photo detector
- overcomes the phase drift problematic of conventional mixing schemes
- insensitive to changes of the optical input power



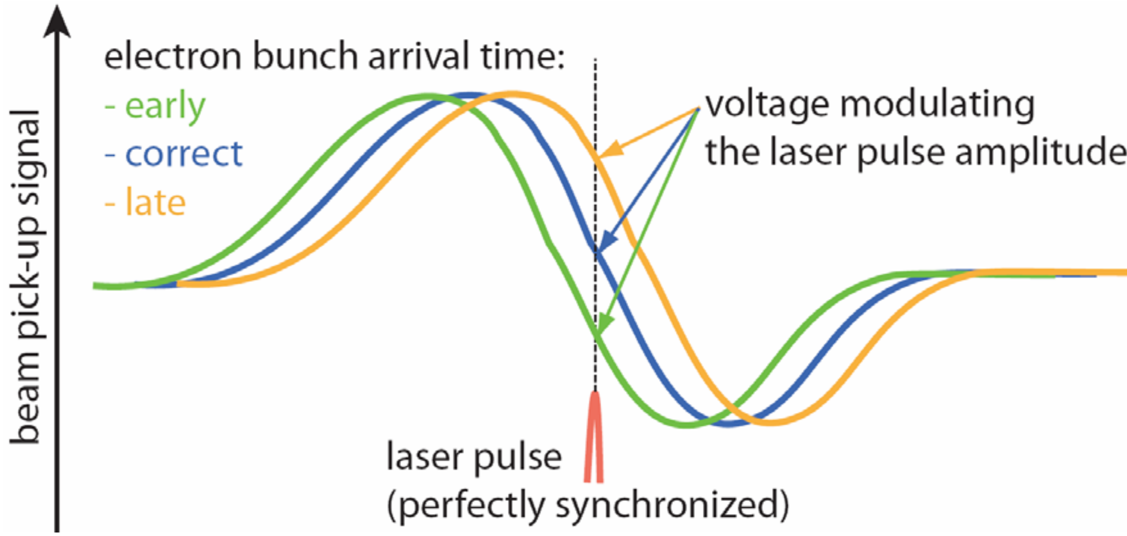
Courtesy of Johann Zemella

Bunch arrival time monitor (BAM) Detection principle



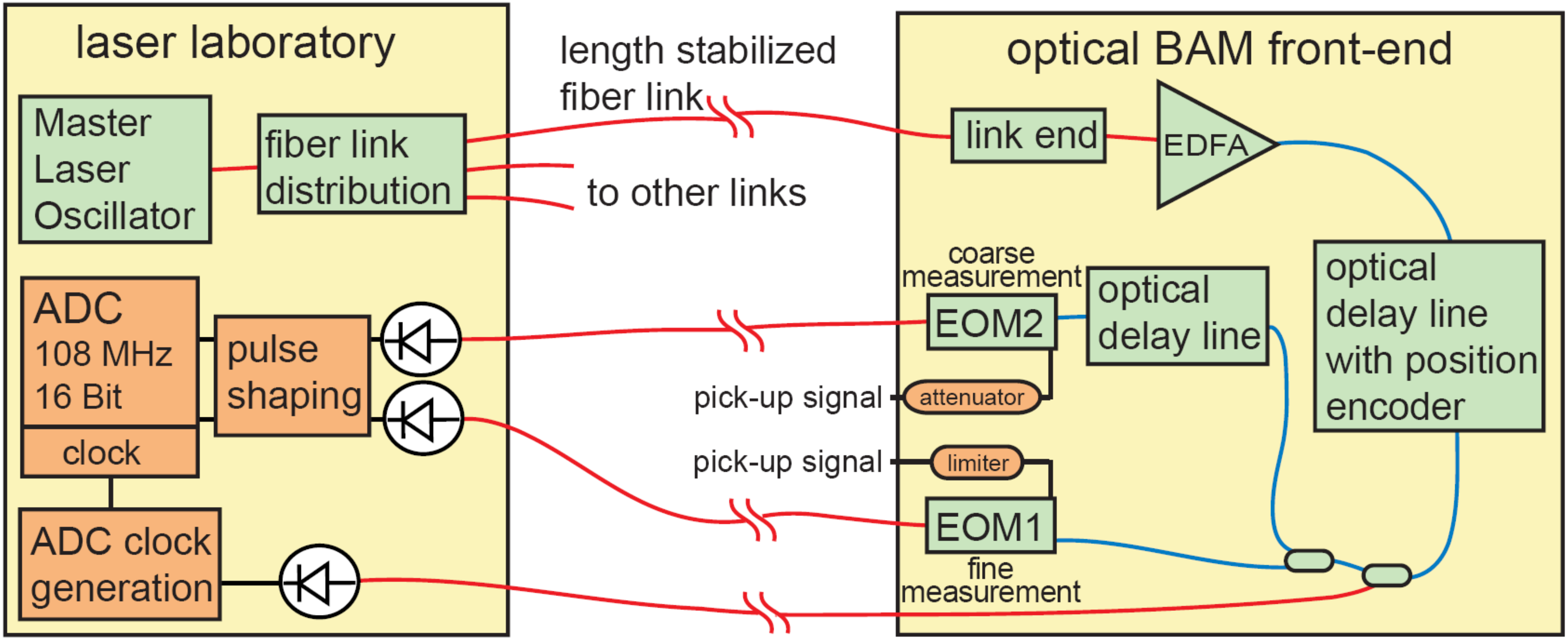


The timing information of the electron bunch is transferred into a laser amplitude modulation. This modulation is measured with a photo detector and sampled by a fast ADC.

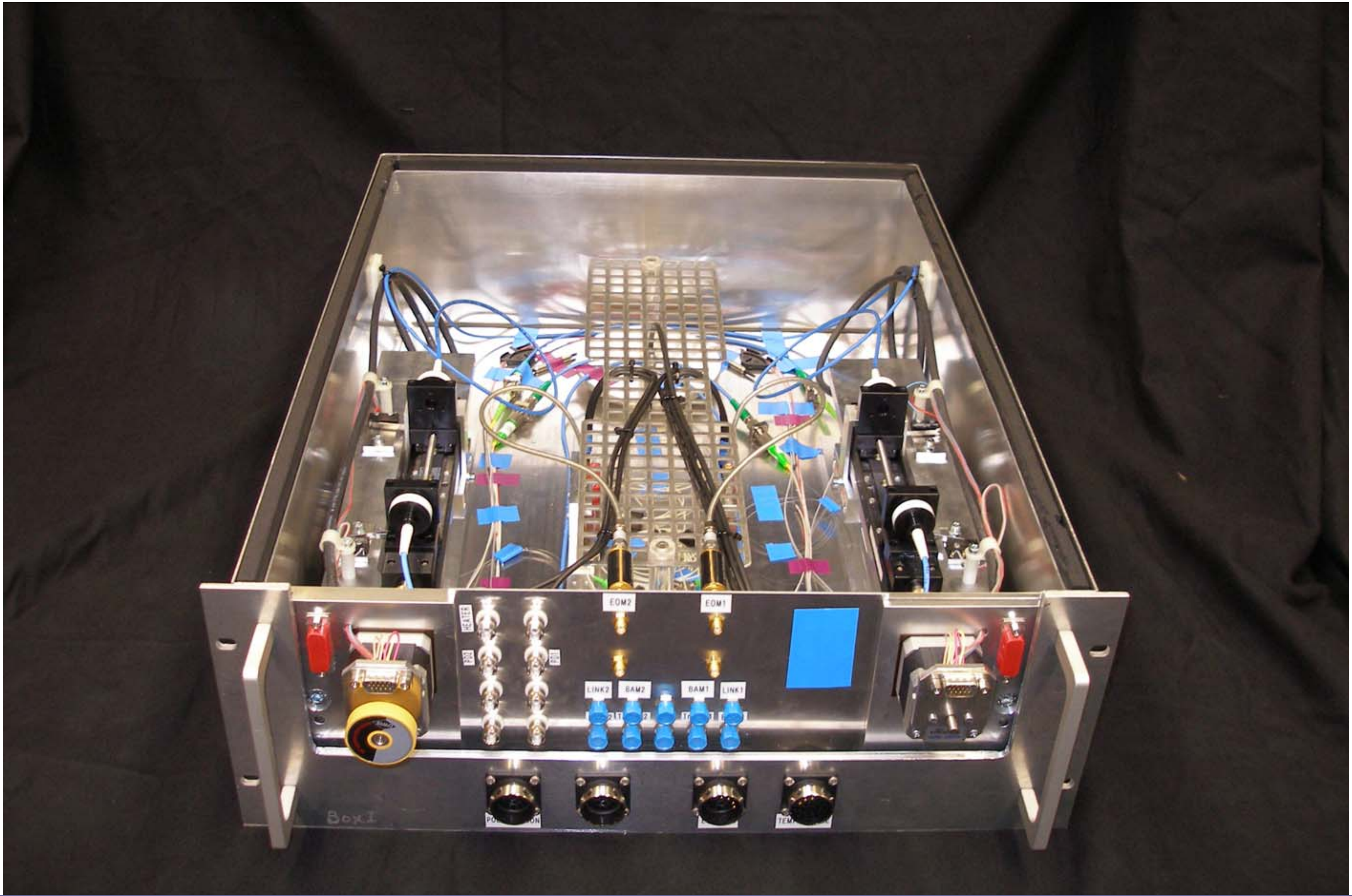


Bunch arrival time monitor (BAM)
Schematic setup

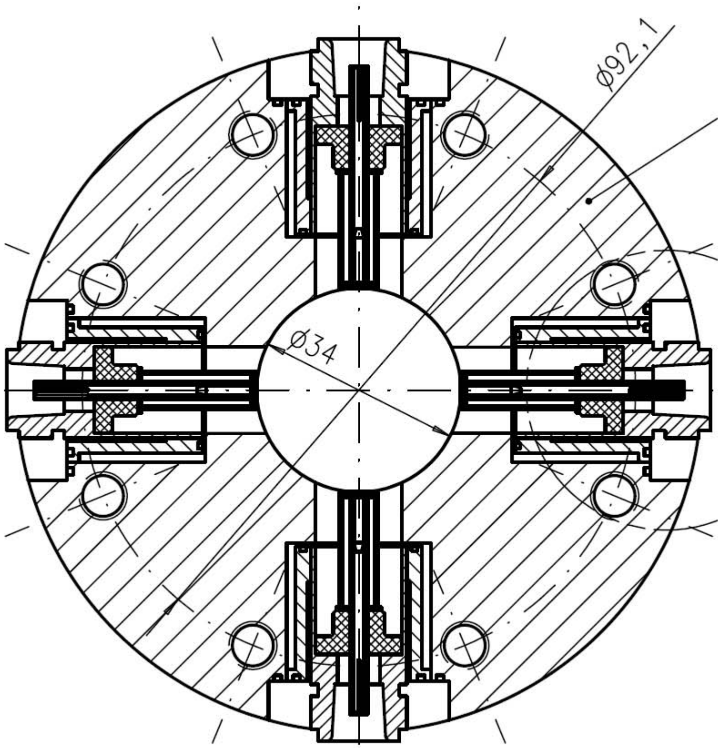
installed next to the beam line

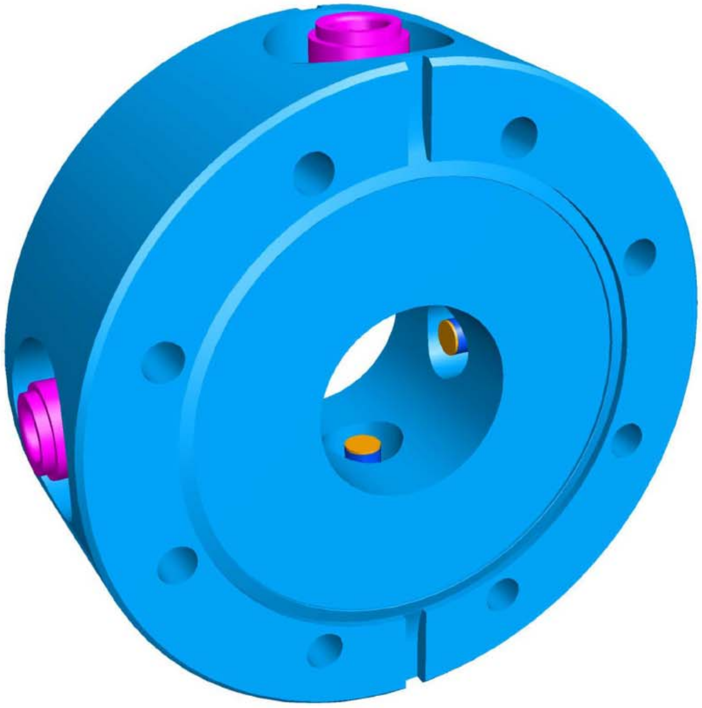


Bunch arrival time monitor (BAM)
First prototype

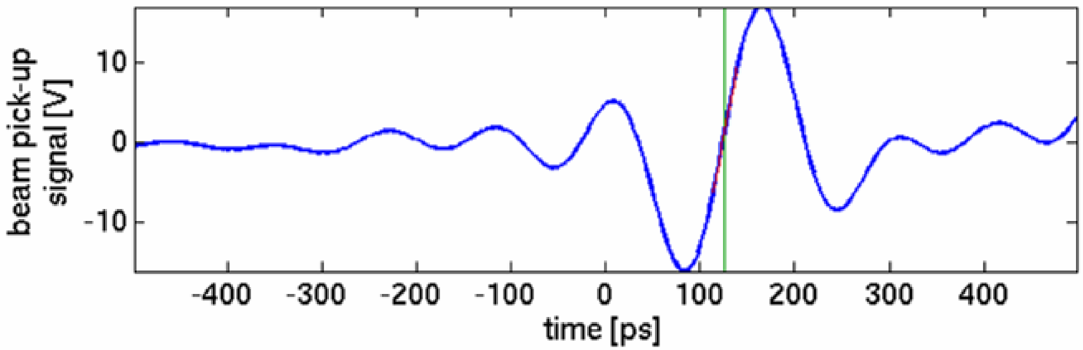


Bunch arrival time monitor (BAM)
Beam pick-up



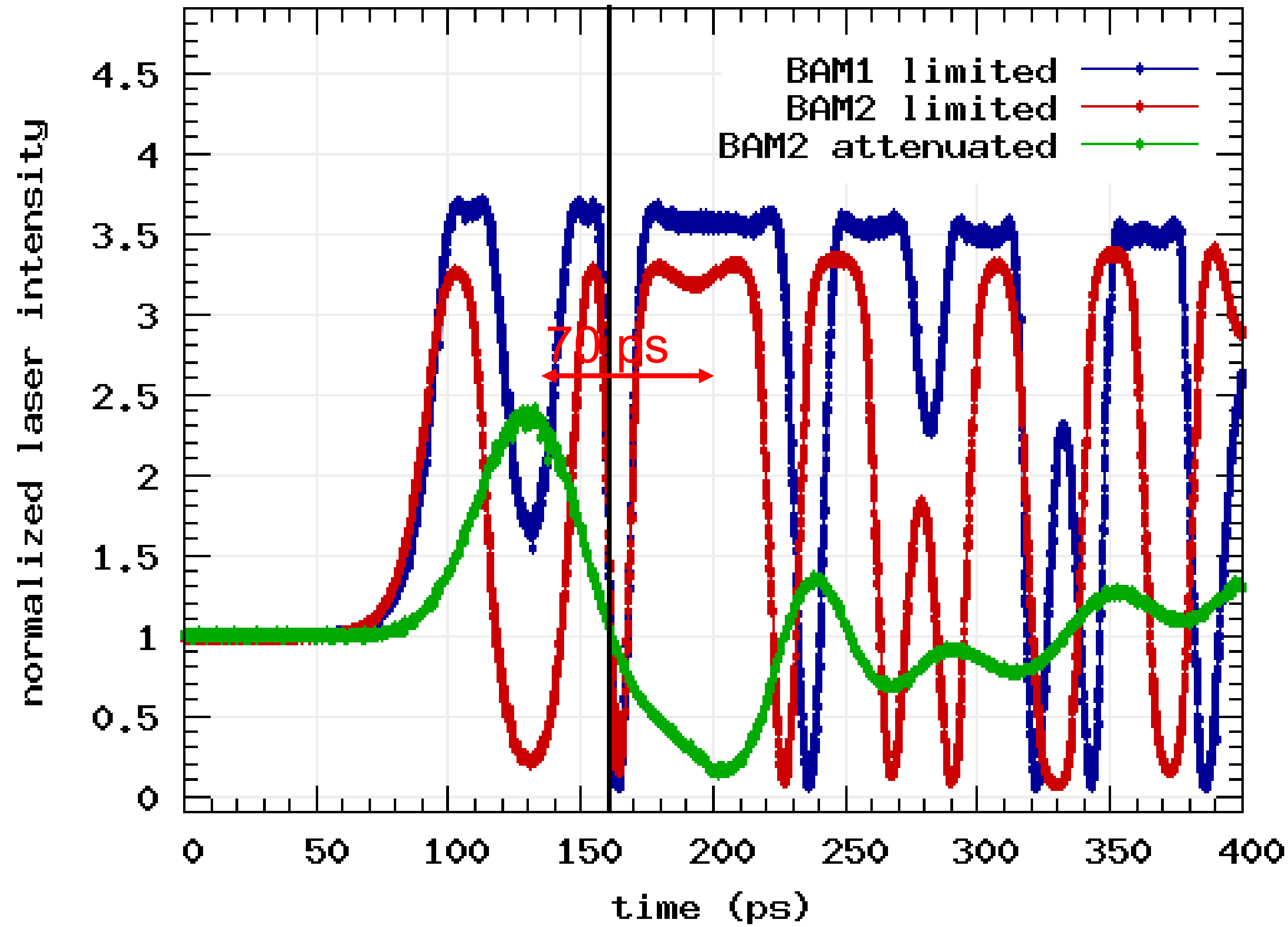


Design: K. Hacker

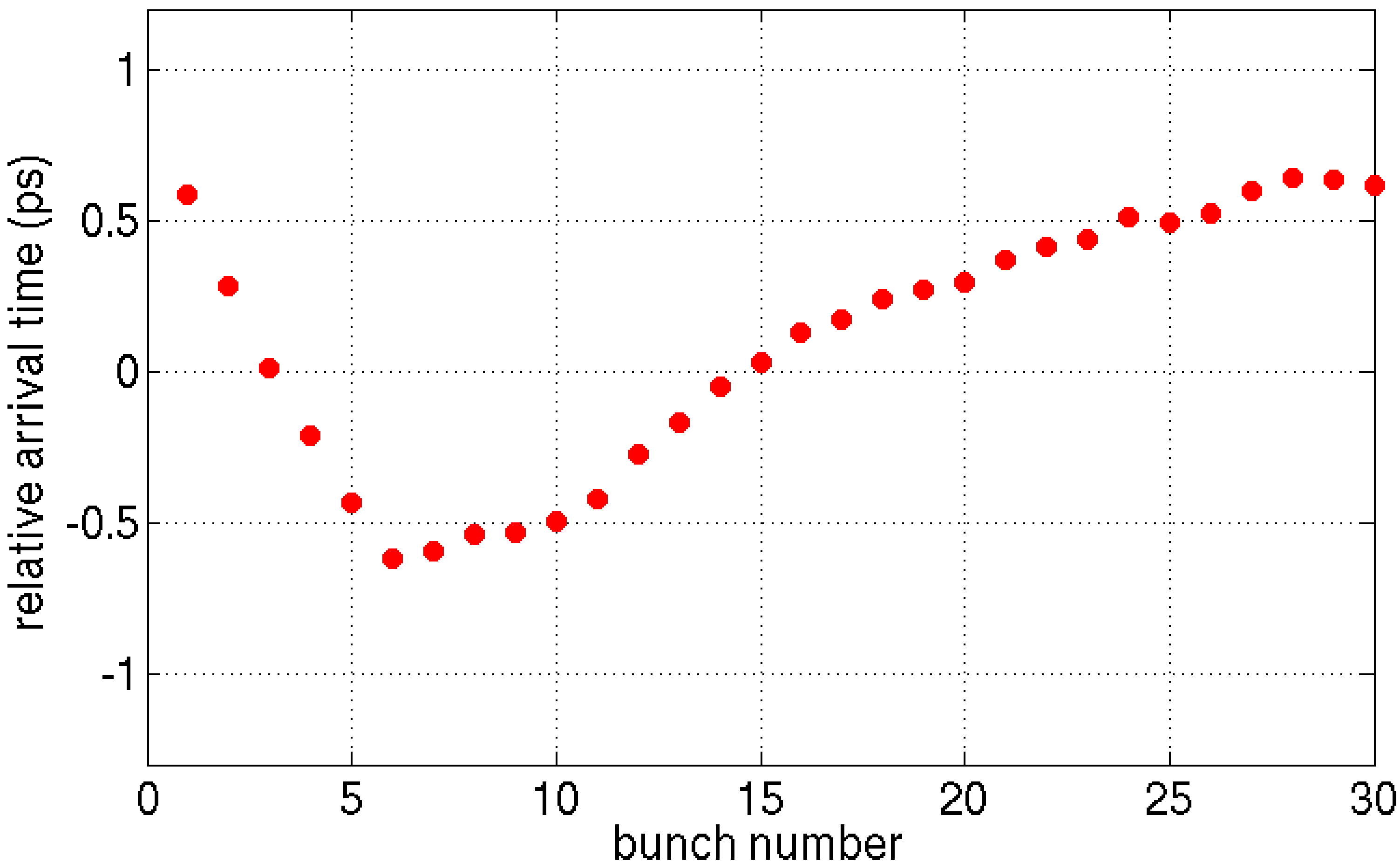


Scope trace measured with 8 GHz bandwidth

Bunch arrival time monitor (BAM)
Mapping of beam pick-up signal onto laser amplitude

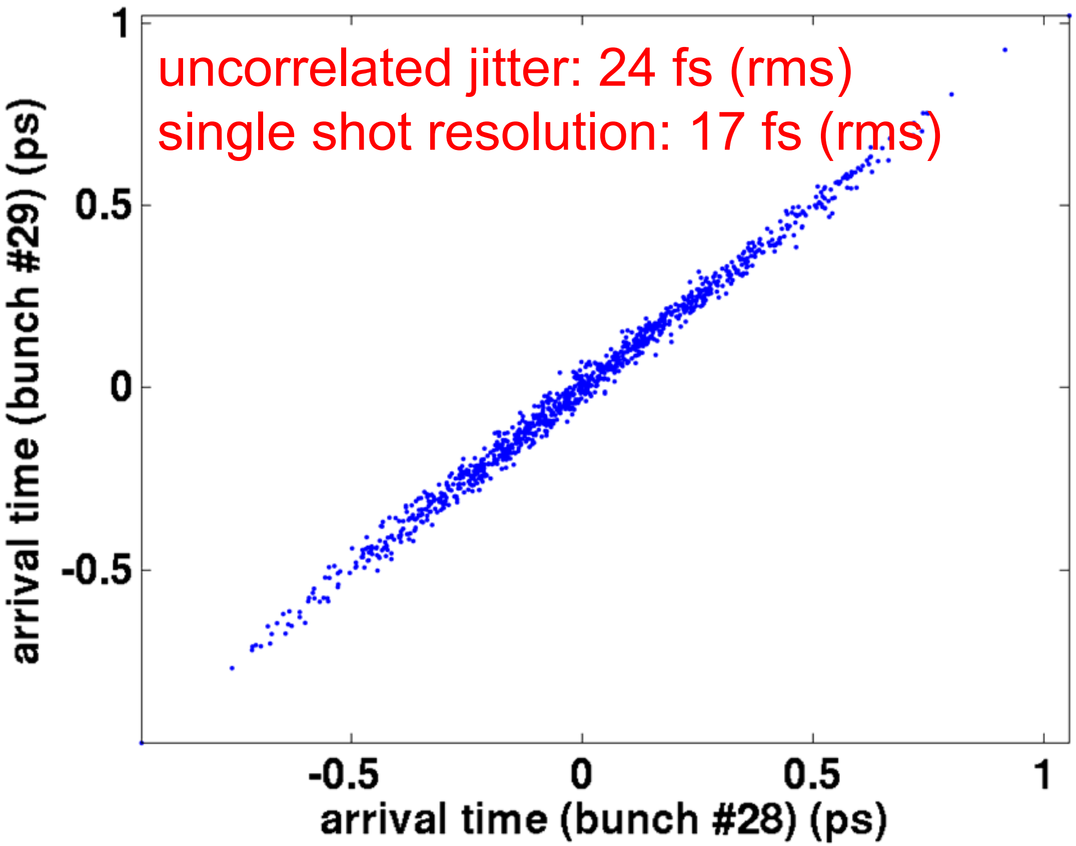


Shot-to-shot fluctuations and intra bunch train pattern



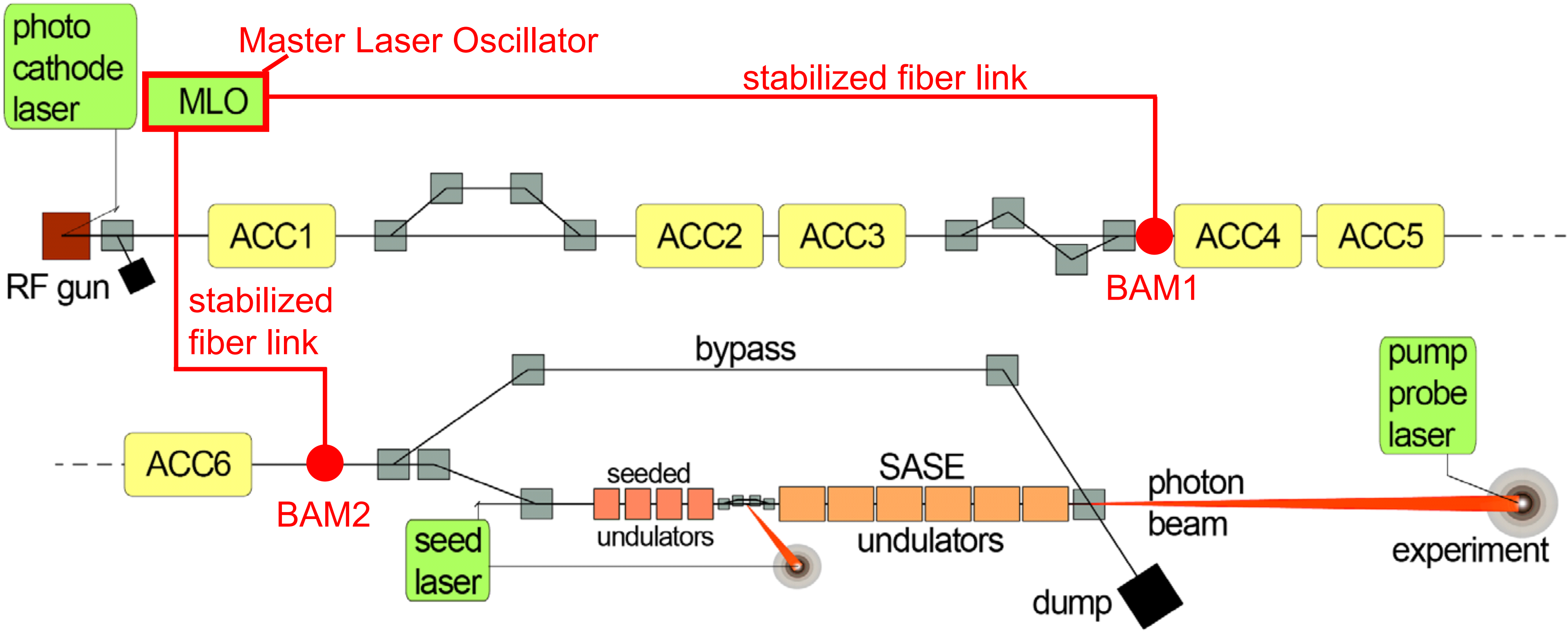
Bunch arrival time monitor (BAM)
Resolution

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 4-5 fs.

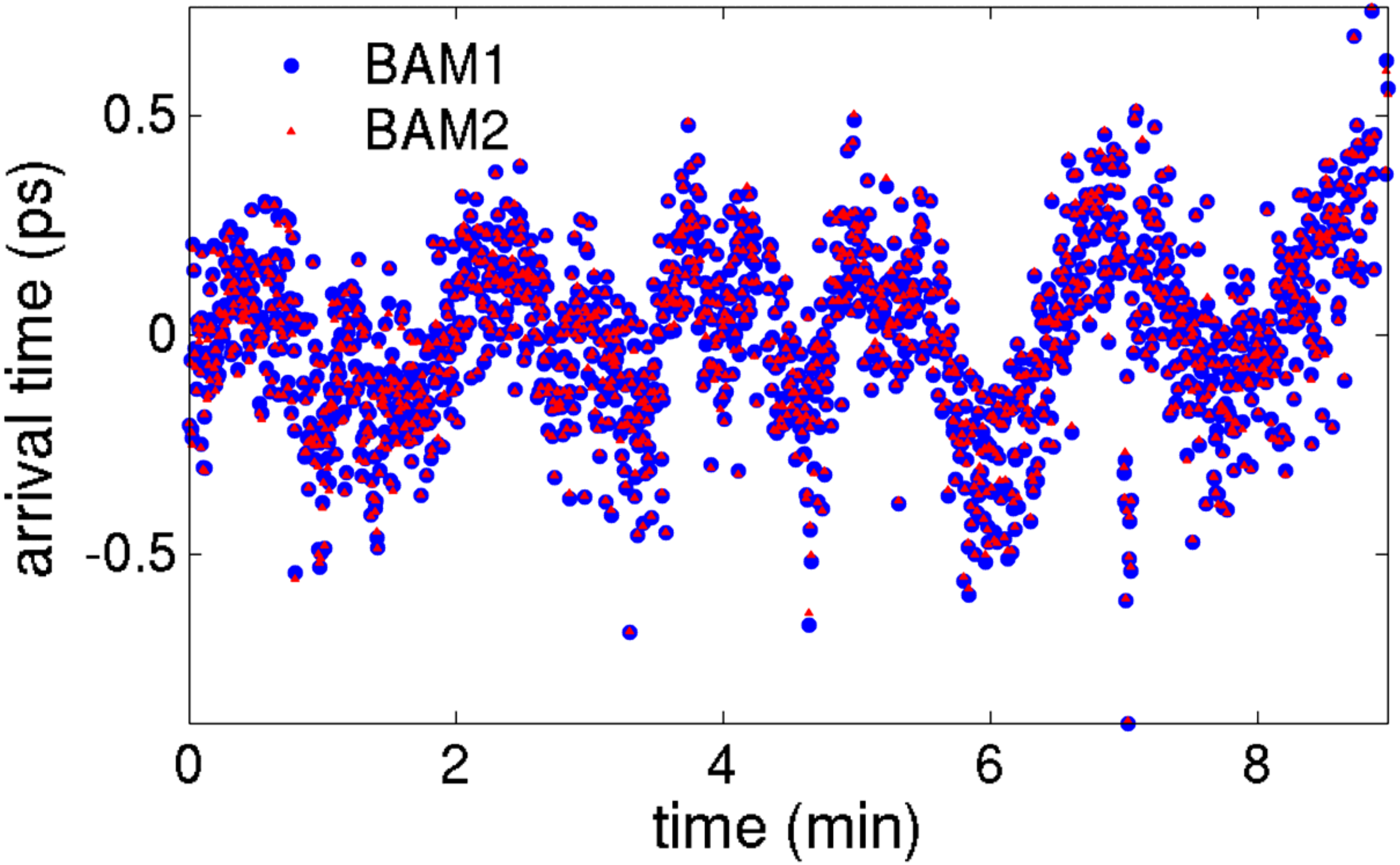
Bunch arrival time monitor (BAM) Resolution measurement



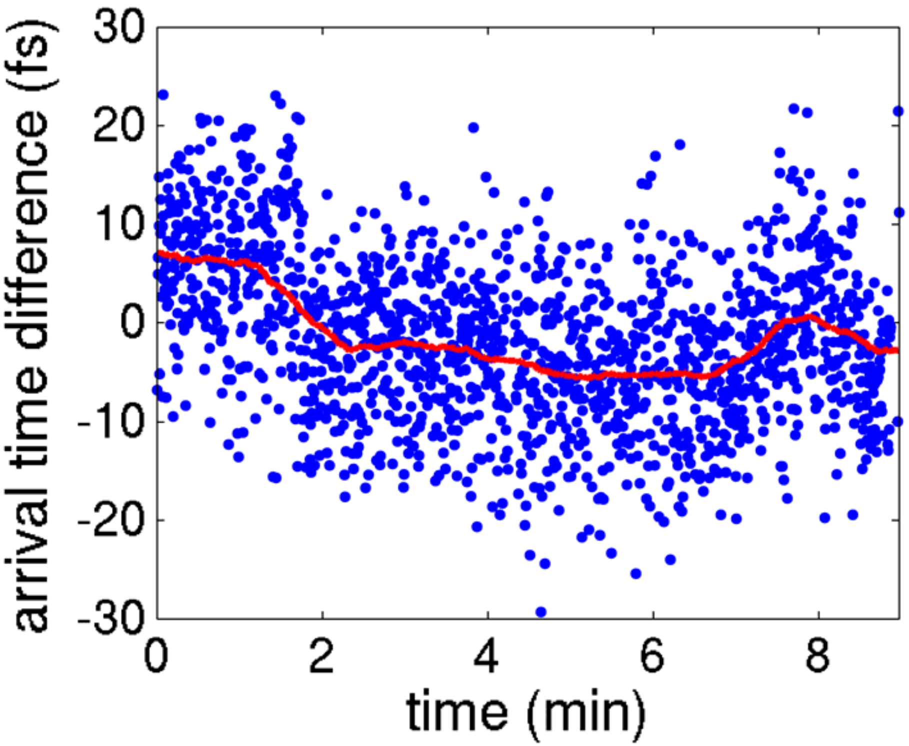
Two BAMs in a straight section are used to measure the arrival time of the same bunches

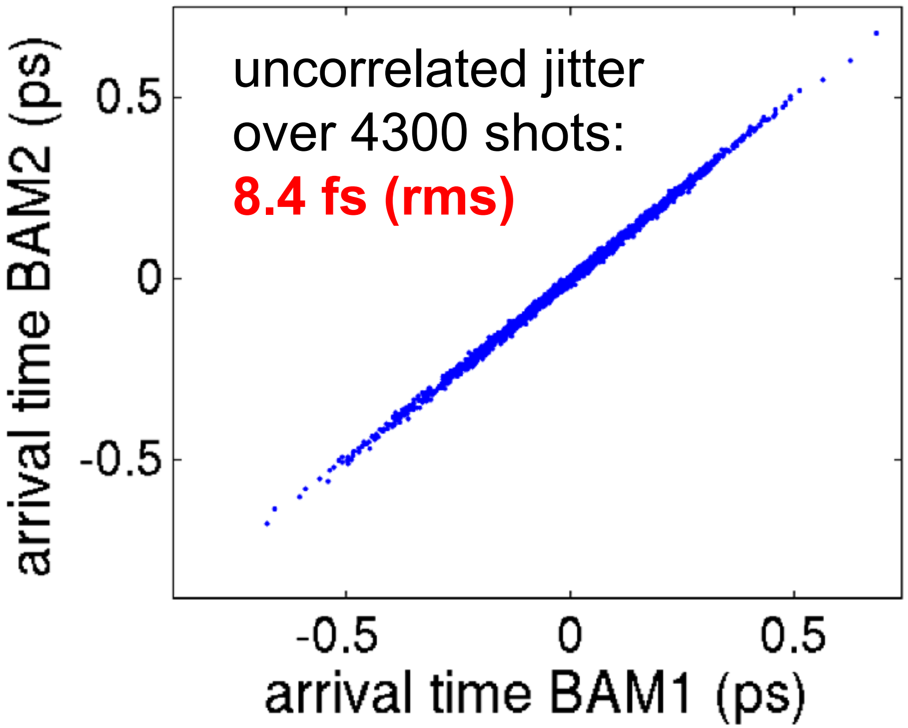
The BAMs are separated by 60 m.

Arrival time correlation between two BAMs



Arrival time correlation between two BAMs





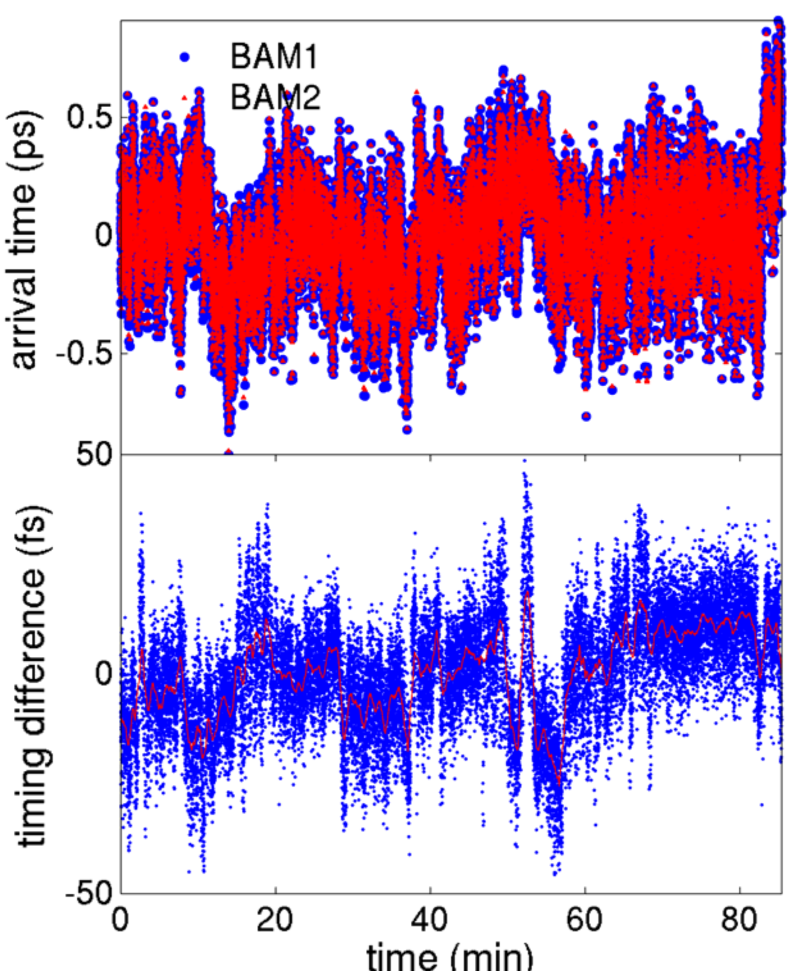
Arrival time difference contains:

- high frequency laser noise (~3 MHz – 108 MHz)
- stability of two fiber links
- two BAMs

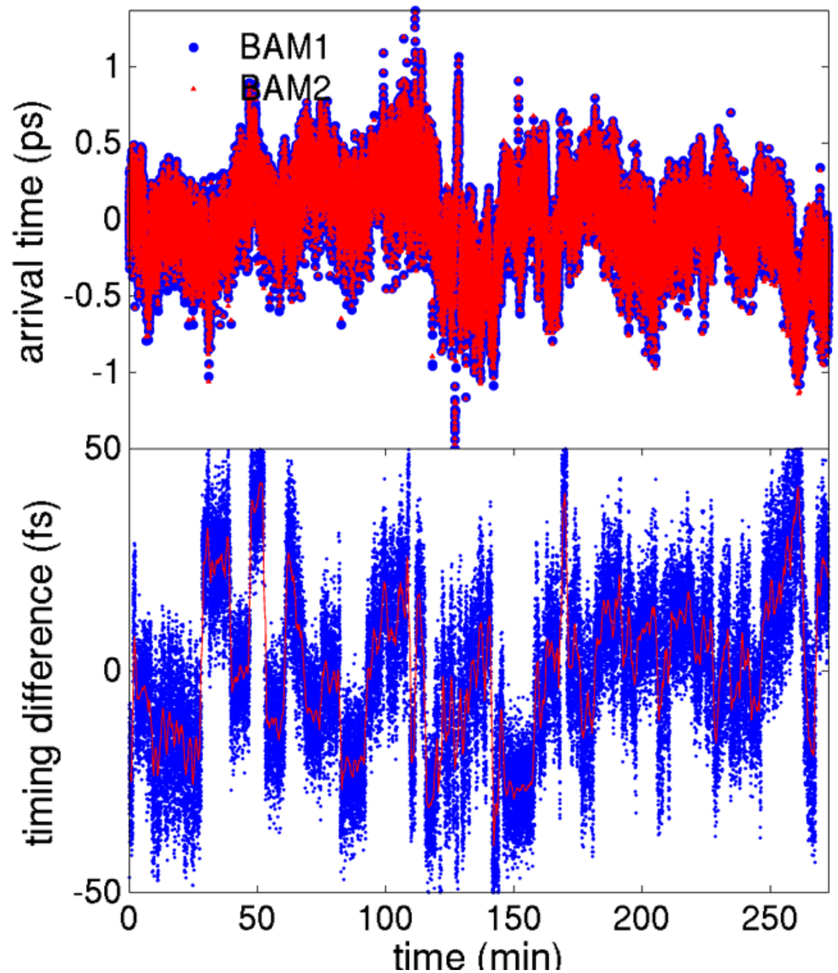
Single bunch resolution of entire measurement chain: **< 6 fs (rms)**

Arrival time correlation between two BAMs

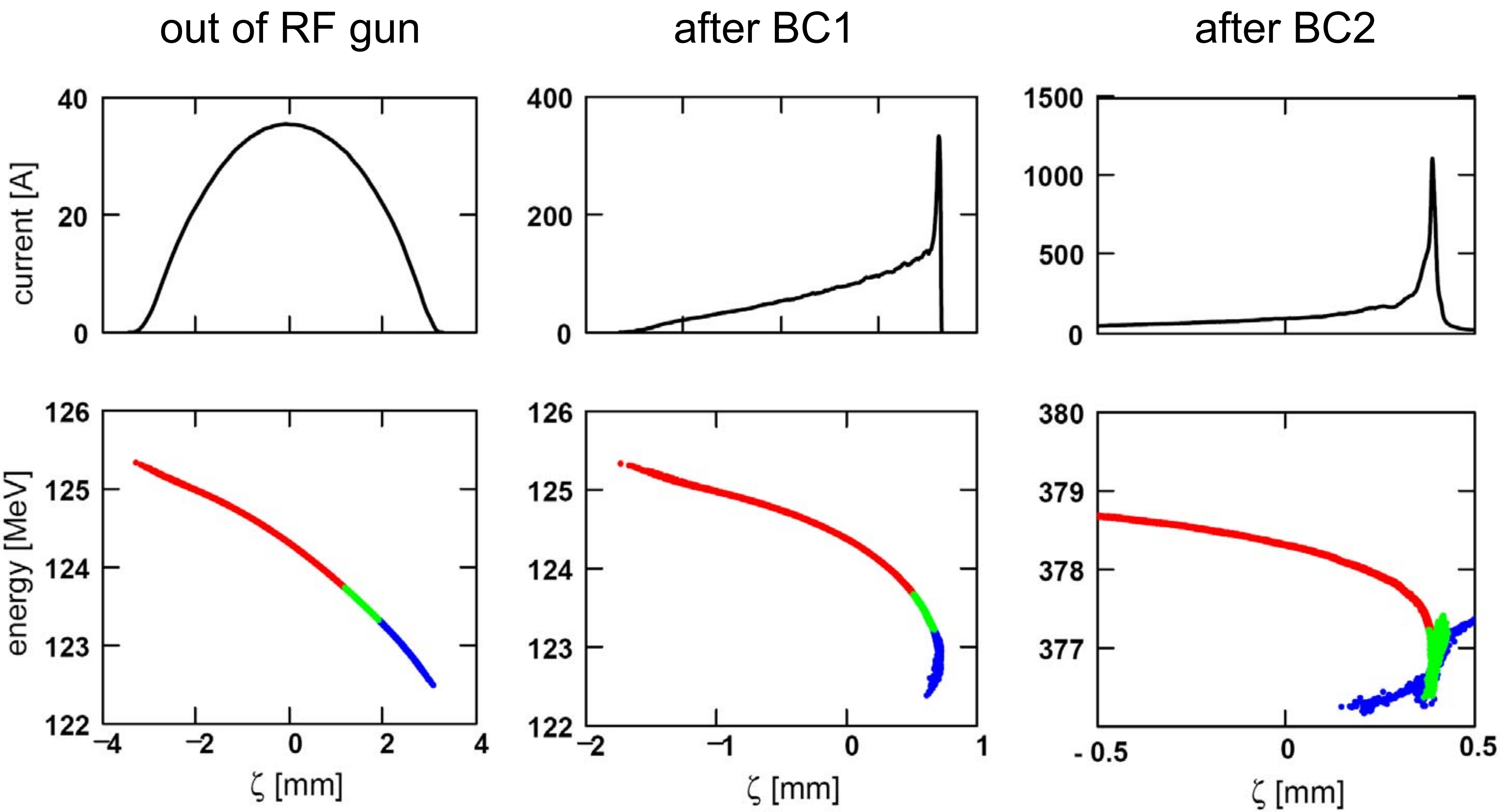
stability over 1.5 hours:
13.1 fs uncorrelated jitter
→ 9.3 fs resolution of a single BAM



stability over 4.5 hours:
19.4 fs uncorrelated jitter
→ 13.7 fs resolution of a single BAM

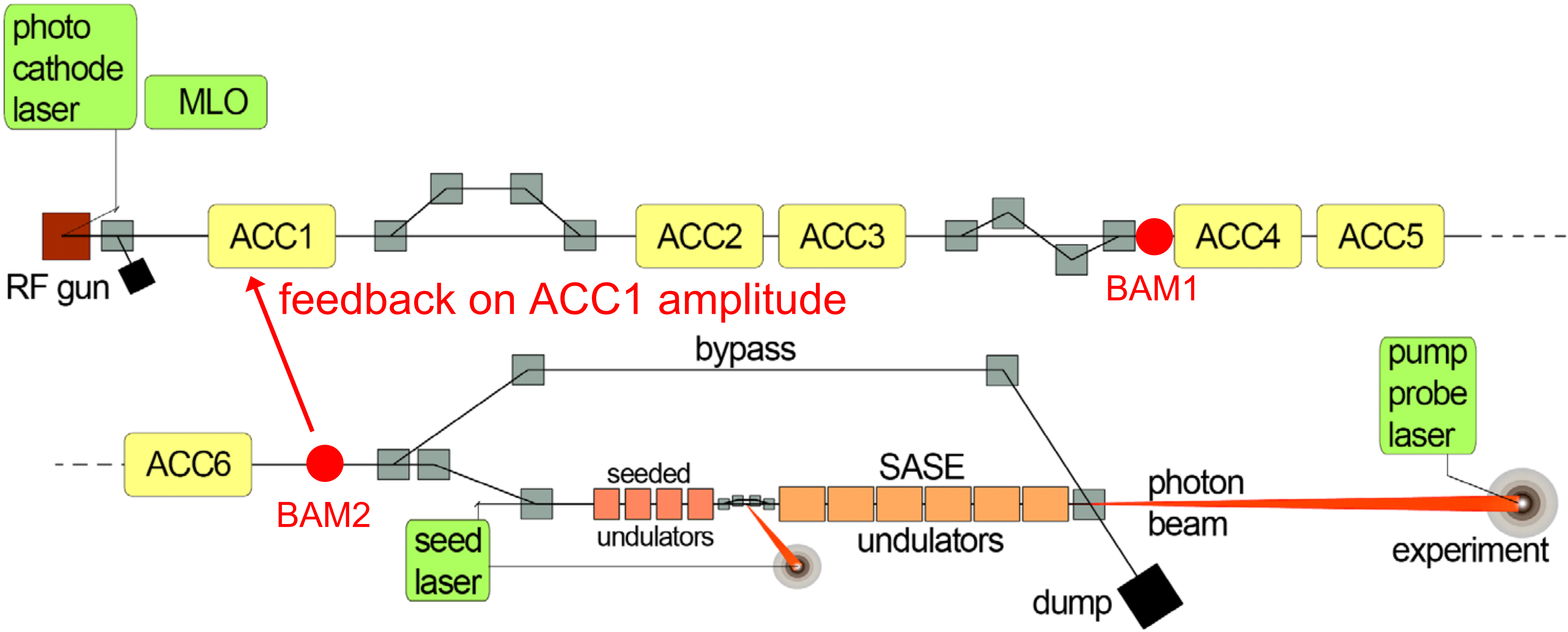


Longitudinal charge distribution

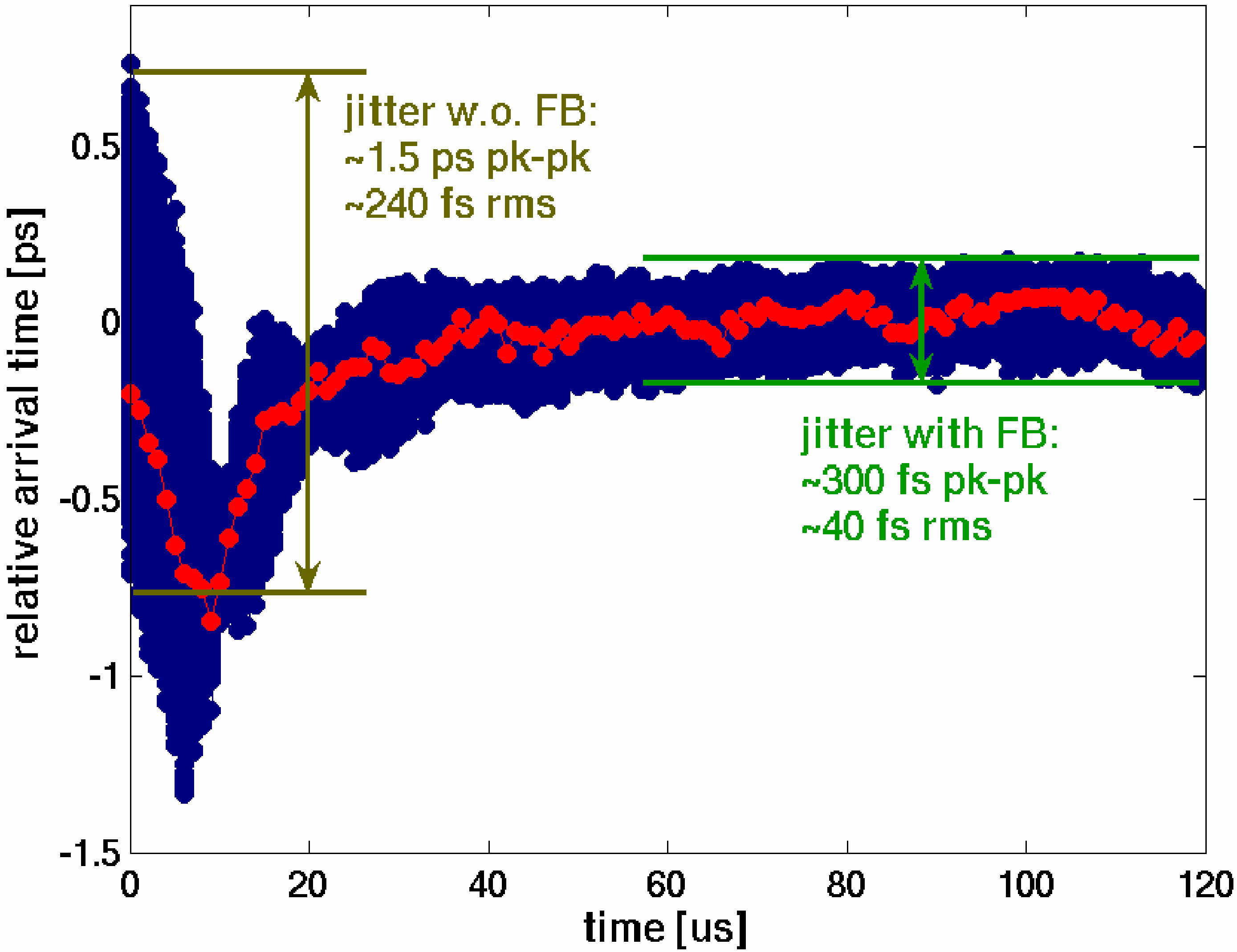


Courtesy of M. Dohlus

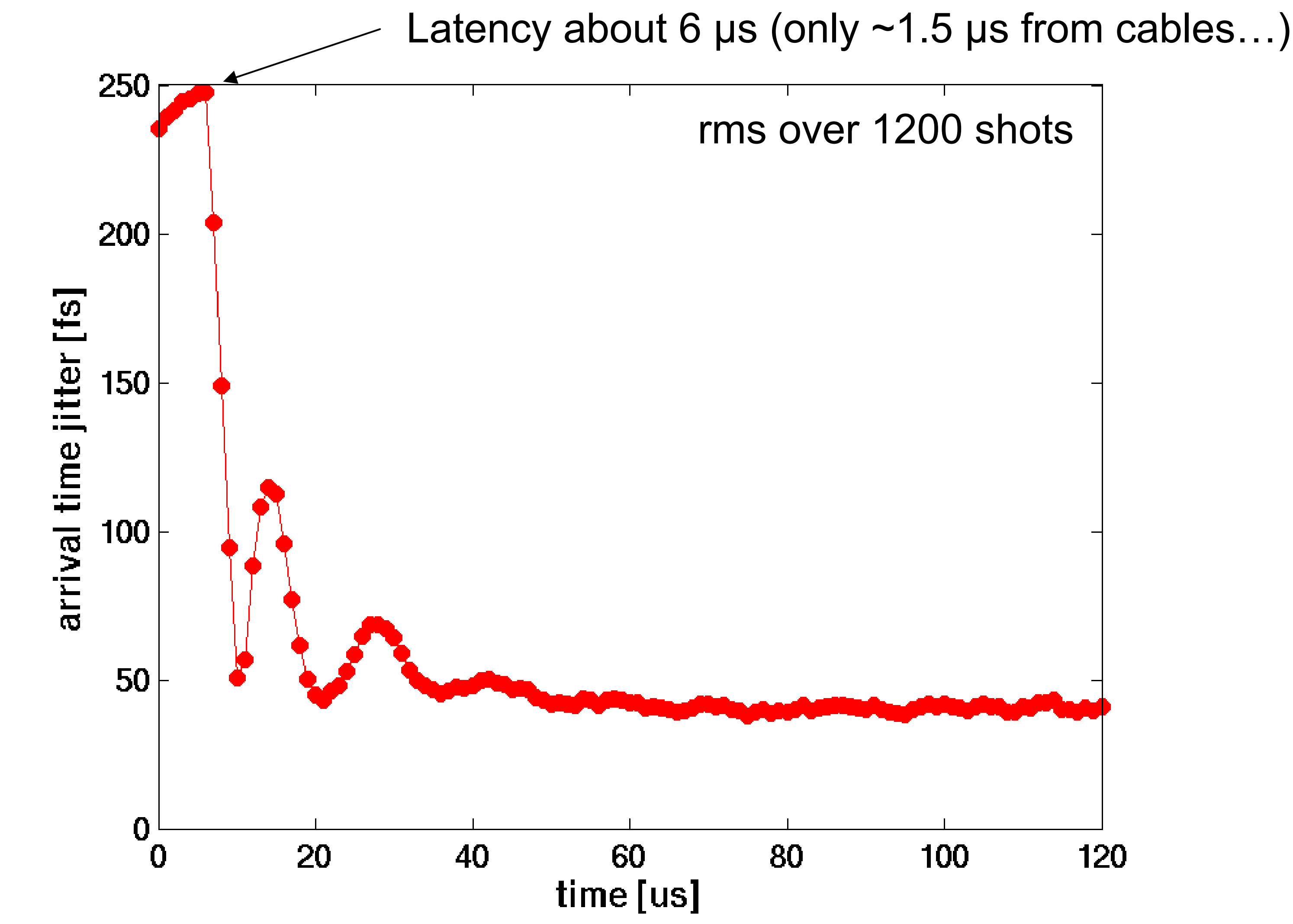
Arrival time feedback



1200 shots:

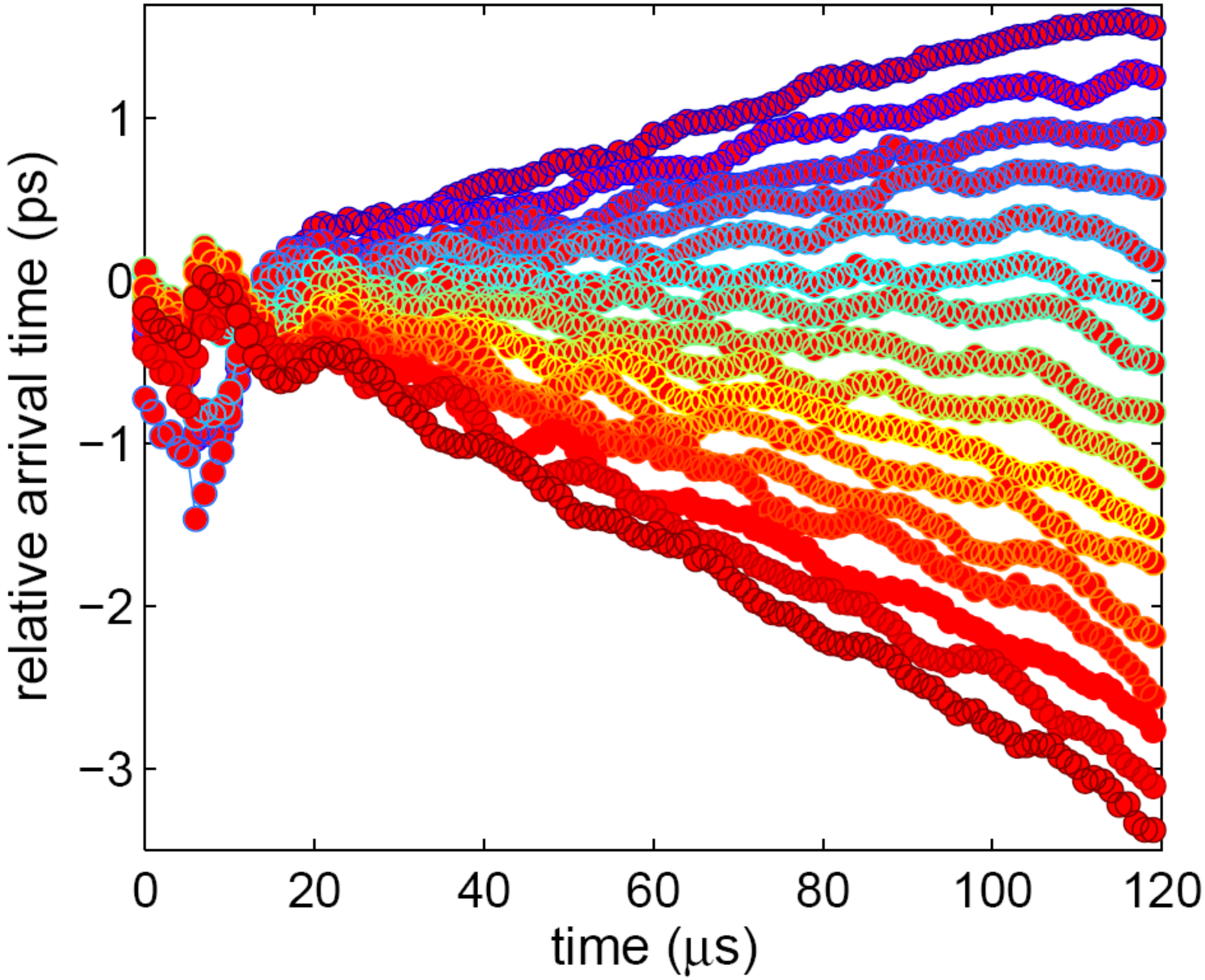

jitter w.o. FB:
~1.5 ps pk-pk
~240 fs rms
jitter with FB:
~300 fs pk-pk
~40 fs rms
relative arrival time [ps]
time [us]
0.5
0
-0.5
-1
-1.5
0
20
40
60
80
100
120

Intra bunch-train arrival time feedback

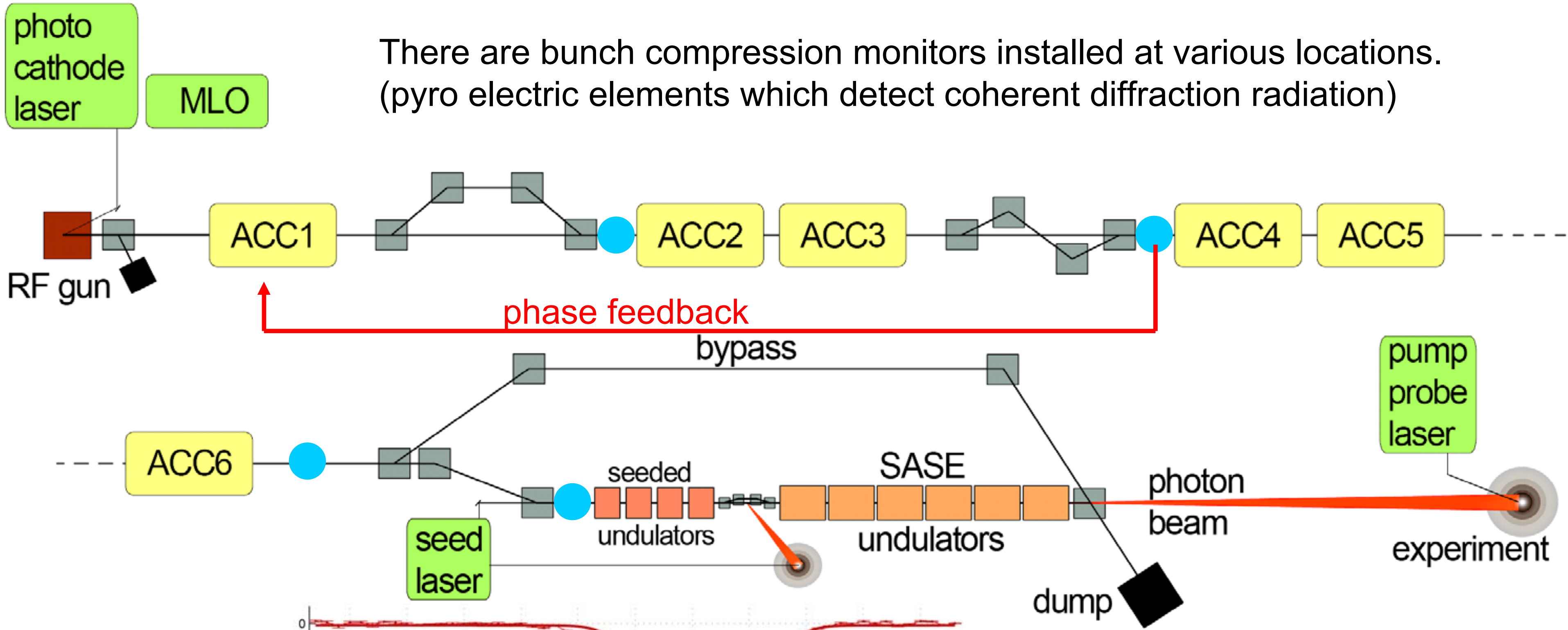


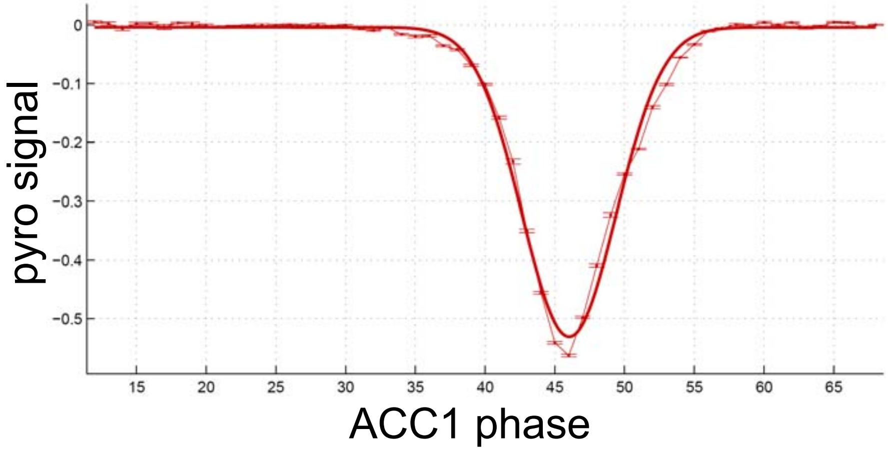
Intra bunch-train arrival time feedback

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



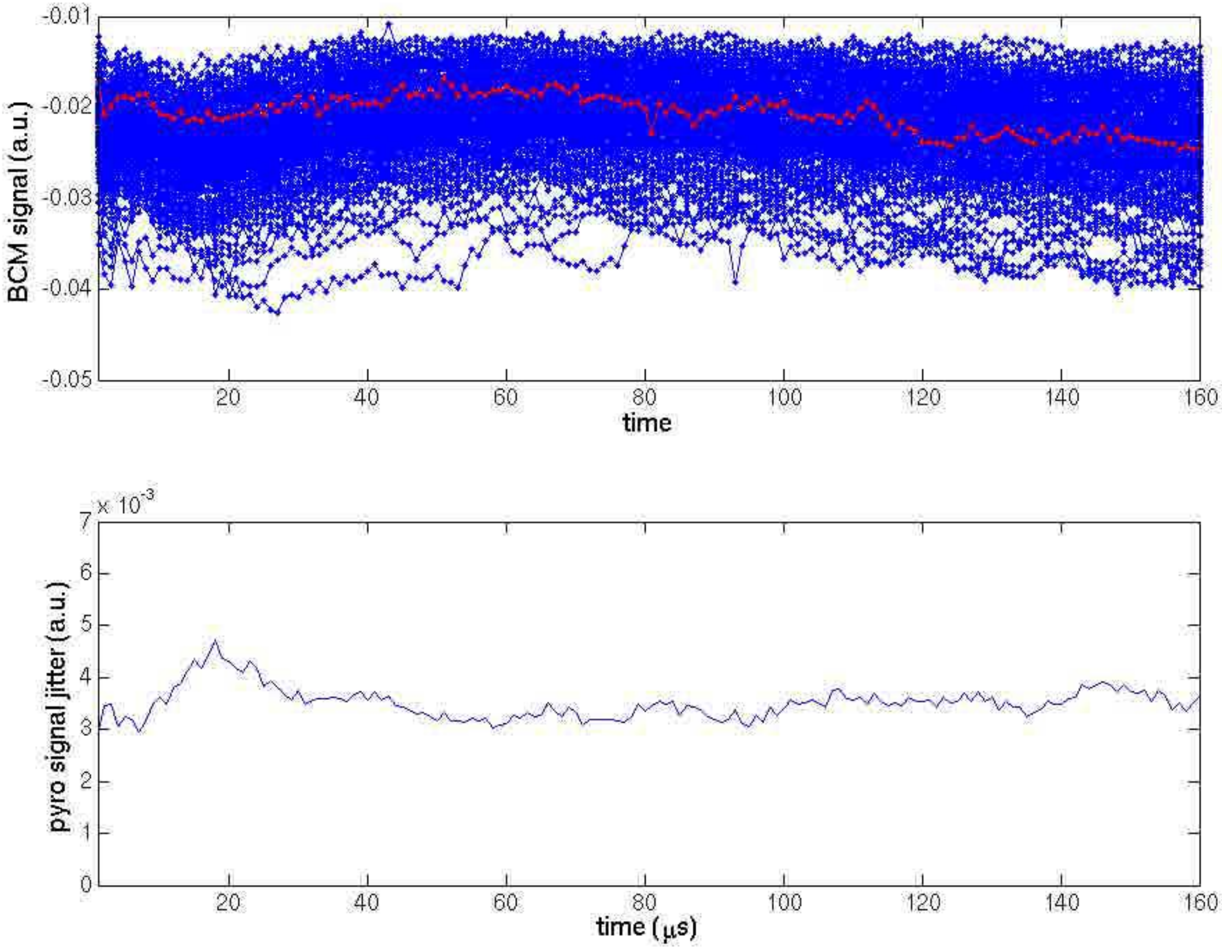
There are bunch compression monitors installed at various locations.
(pyro electric elements which detect coherent diffraction radiation)





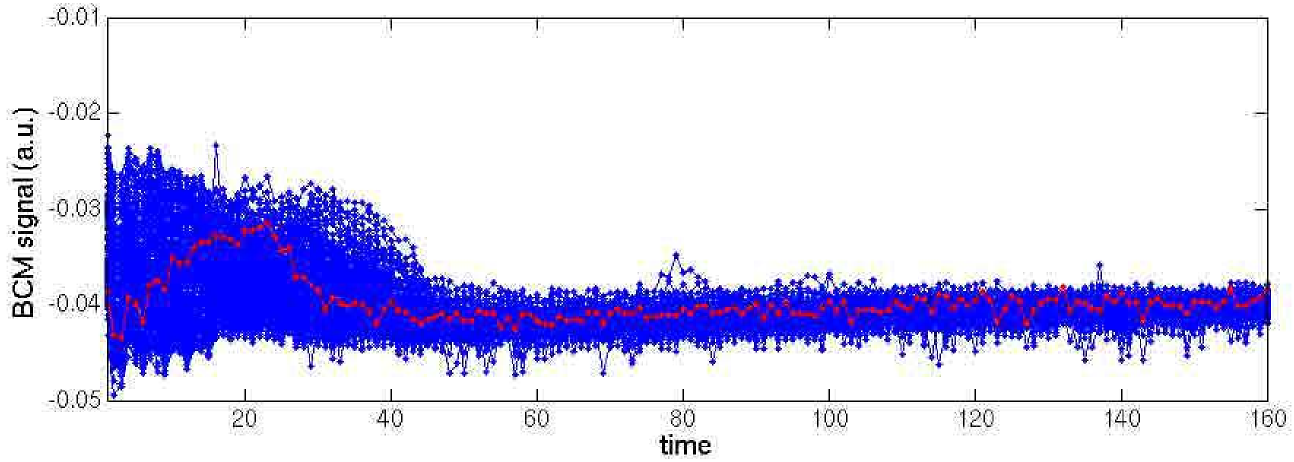
Bunch compression feedback

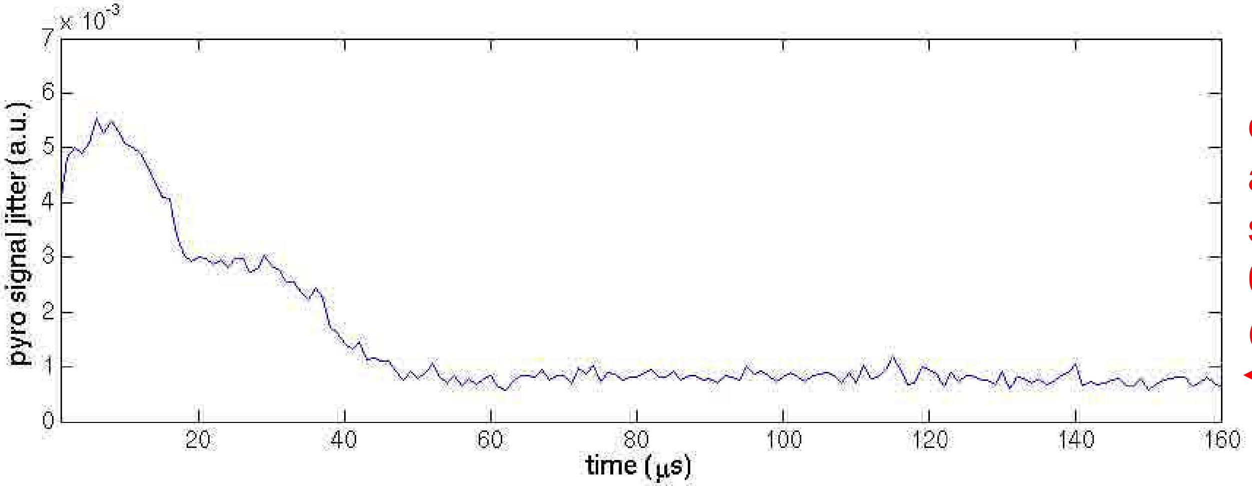
compression feedback off



Bunch compression feedback

compression feedback on

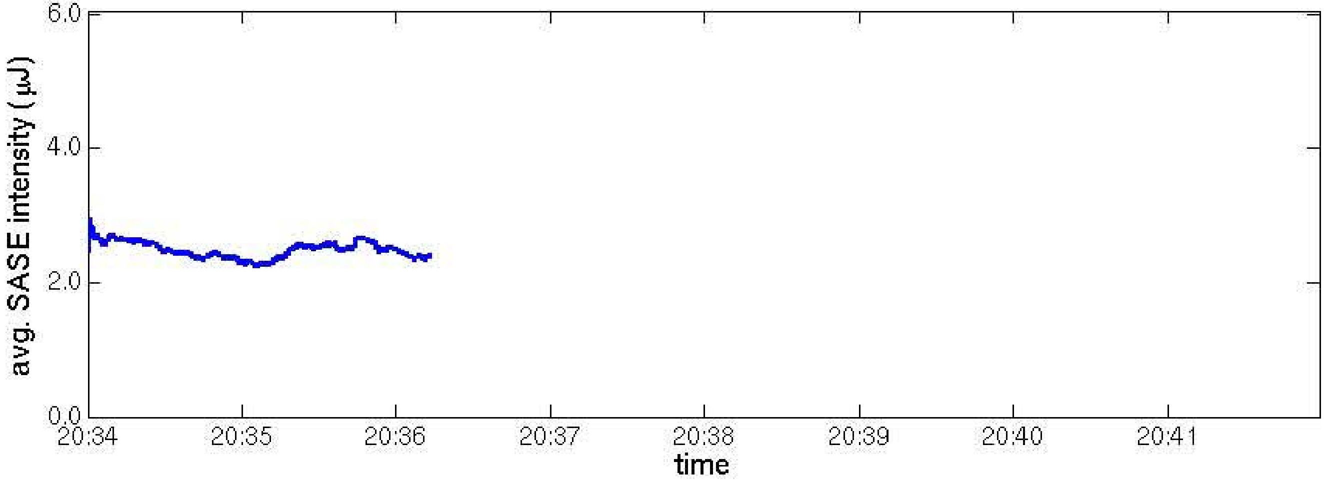


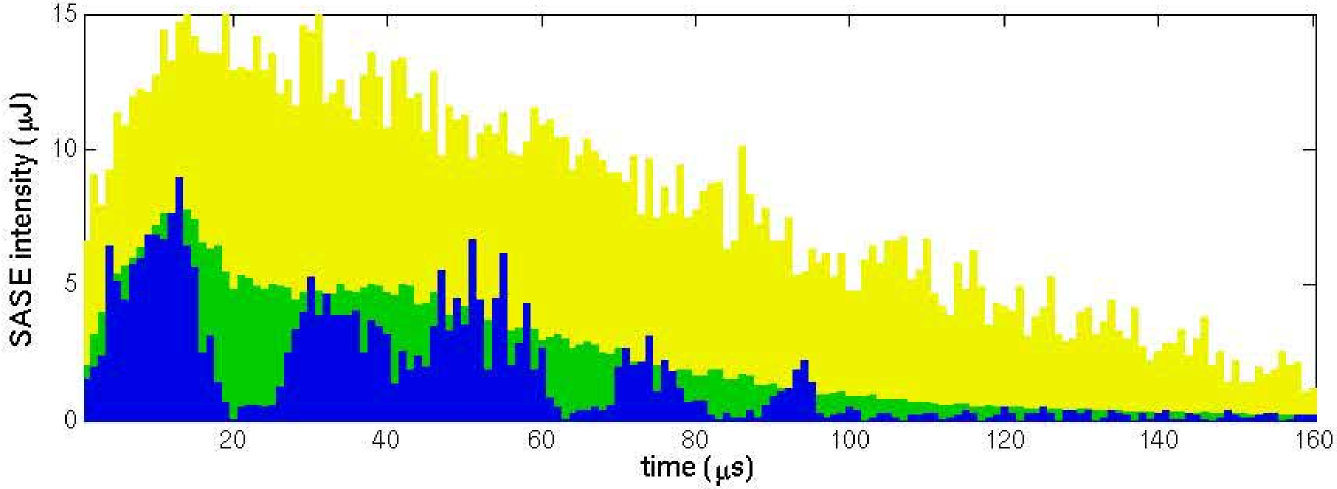


corresponds to an ACC1 phase stability of **0.025 deg** @ 1.3 GHz

Effect of feedbacks on the SASE distribution over the pulse train

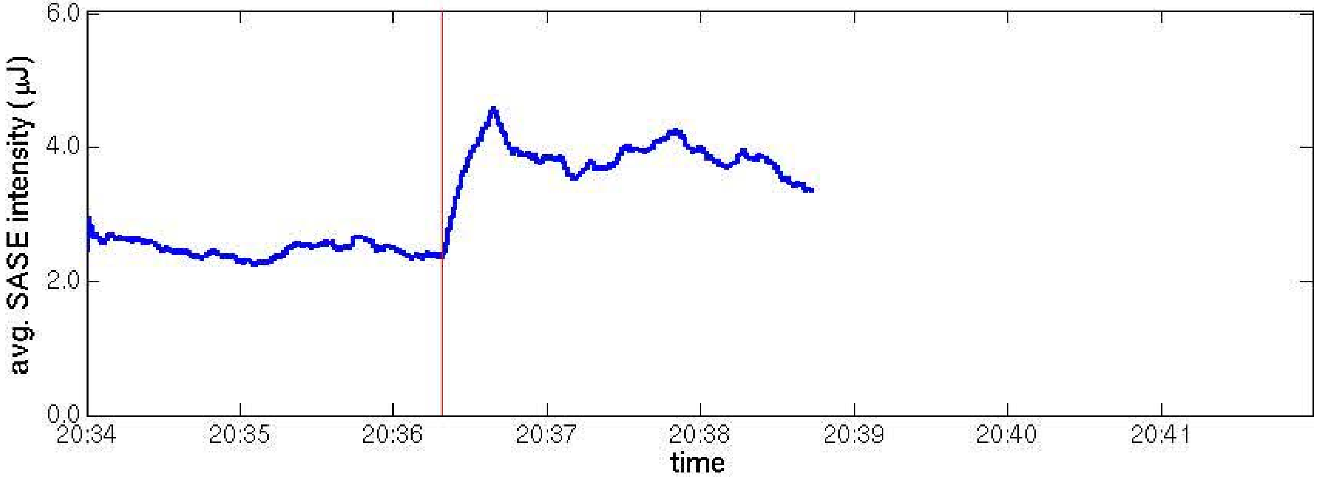
compression feedback off, arrival time feedback off

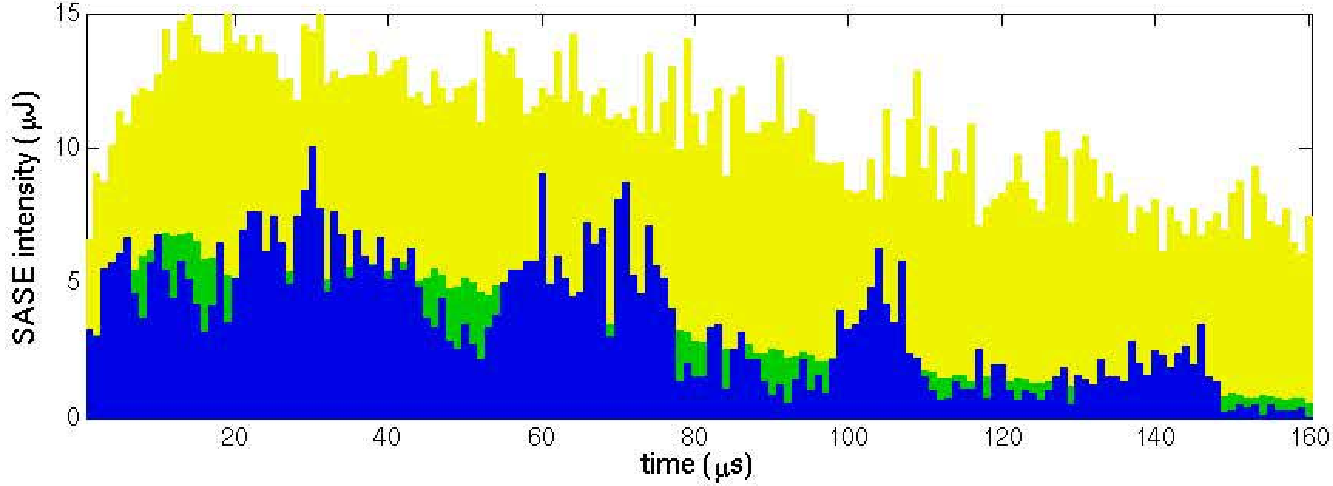




Effect of feedbacks on the SASE distribution over the pulse train

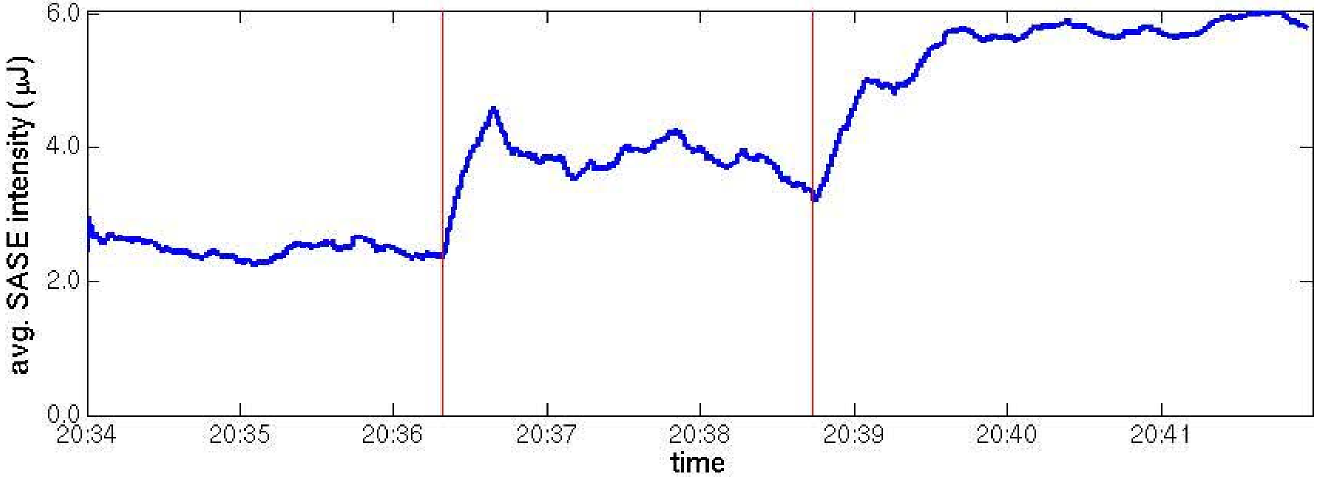
compression feedback on, arrival time feedback off

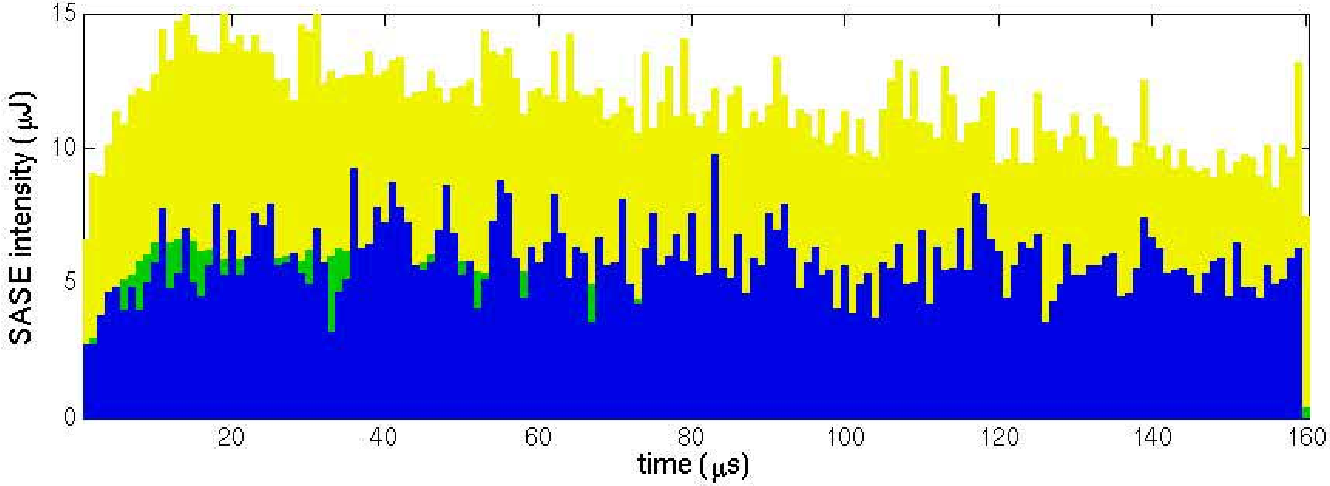




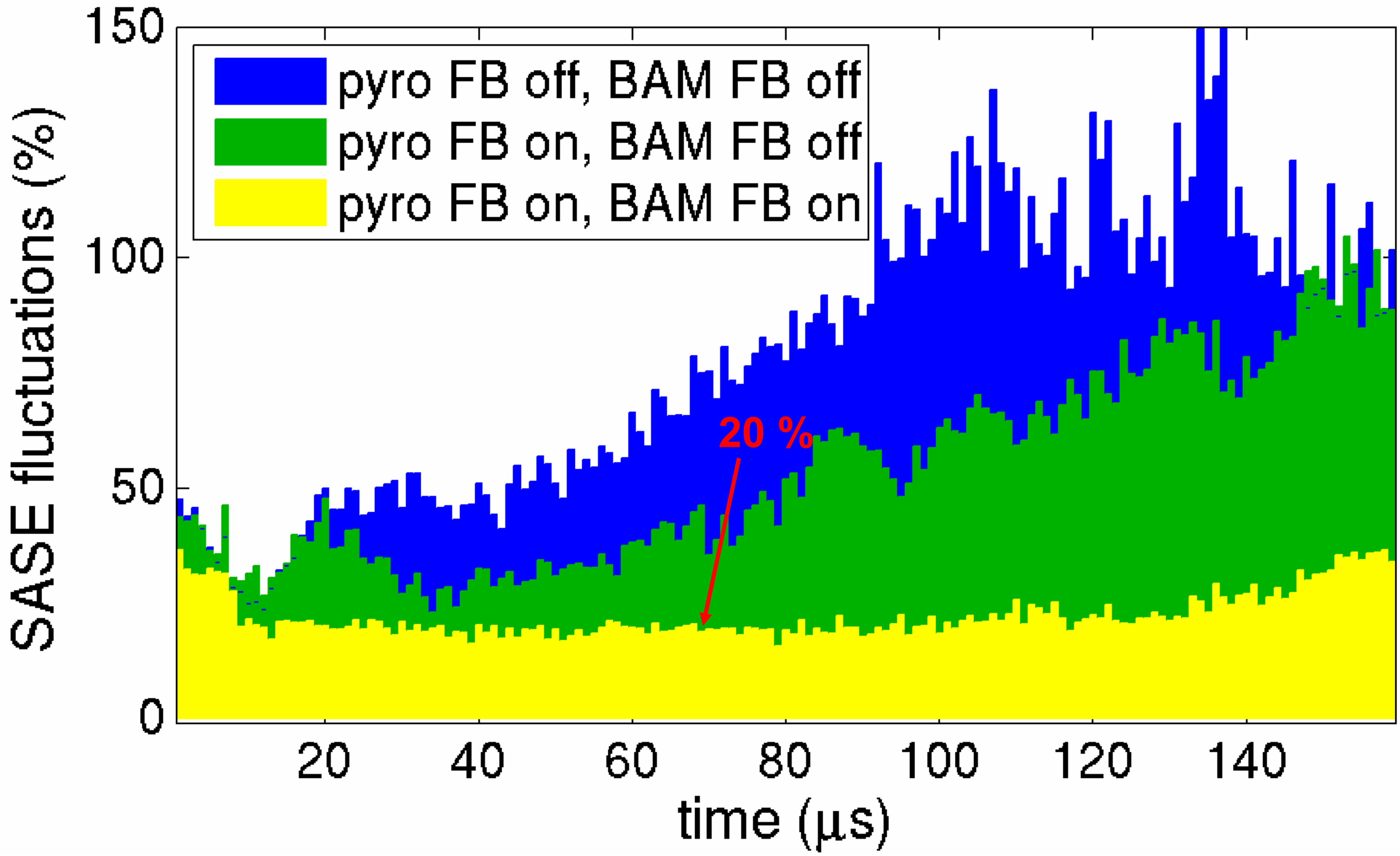
Effect of feedbacks on the SASE distribution over the pulse train

compression feedback on, arrival time feedback on

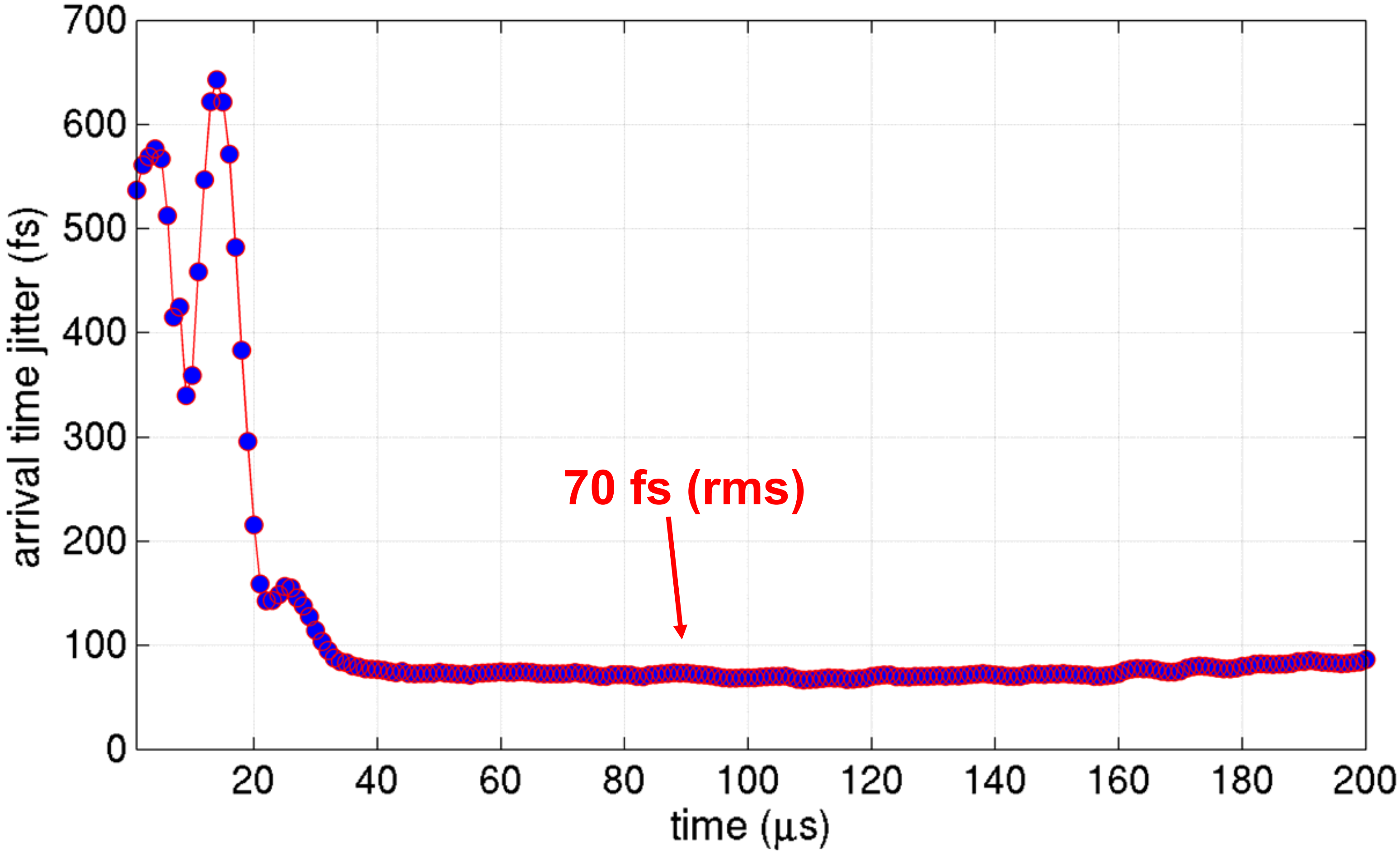




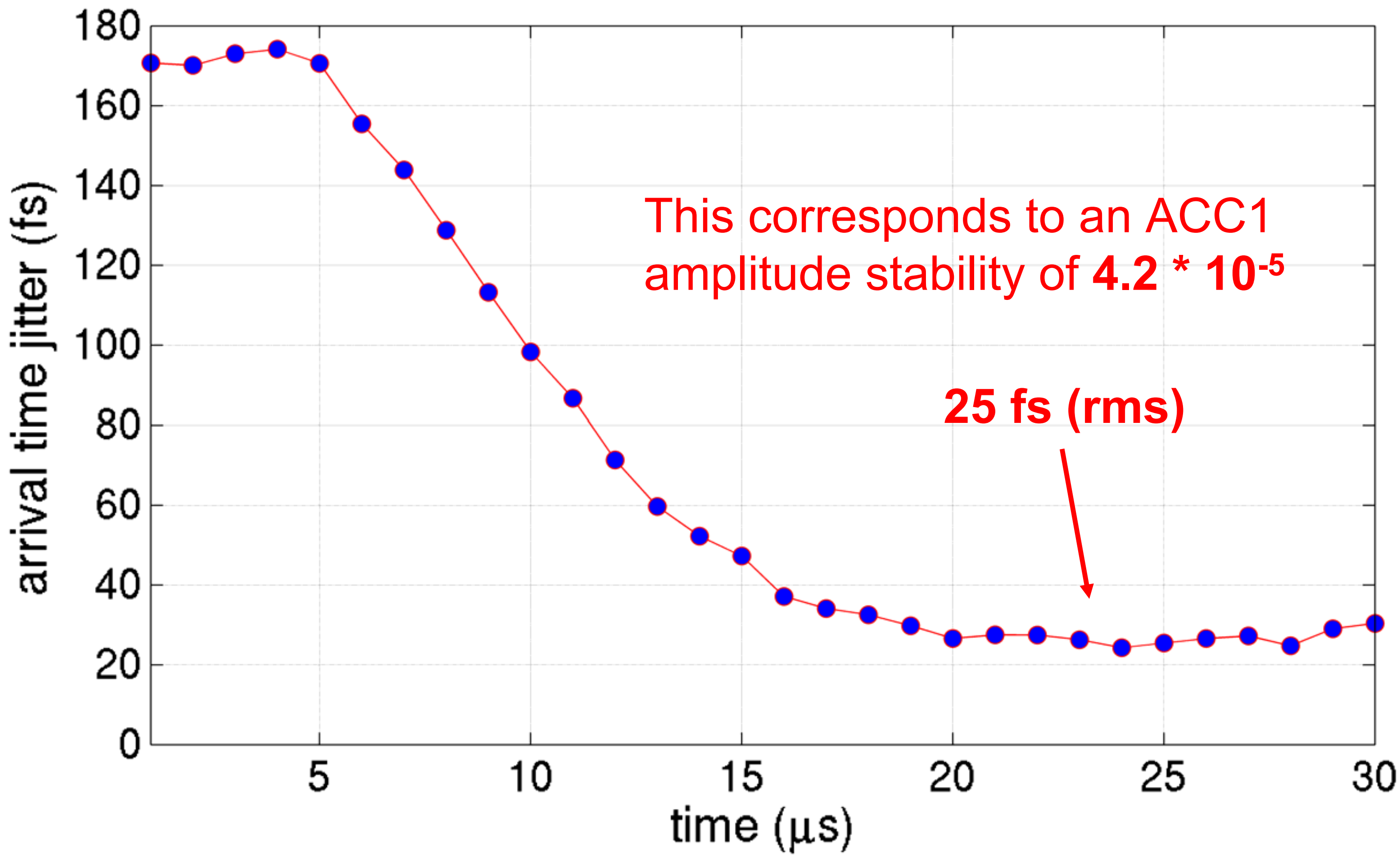
Effect of the two feedbacks on the SASE stability

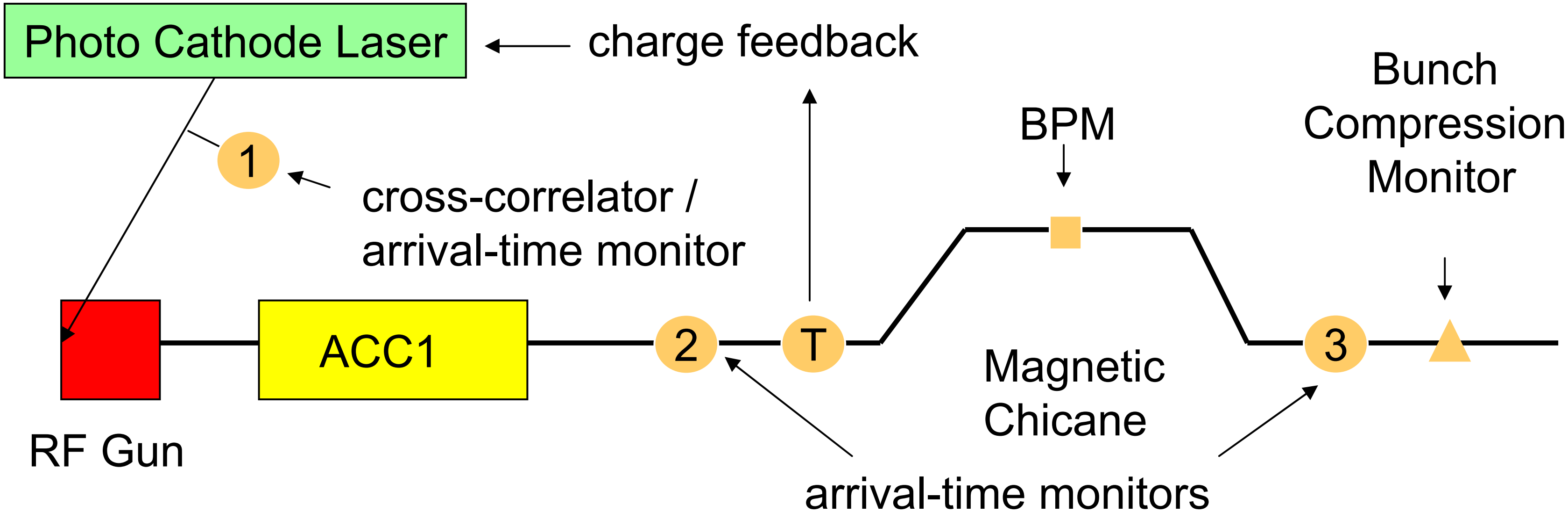


Arrival time stability during SASE run



Best arrival time stability achieved until now



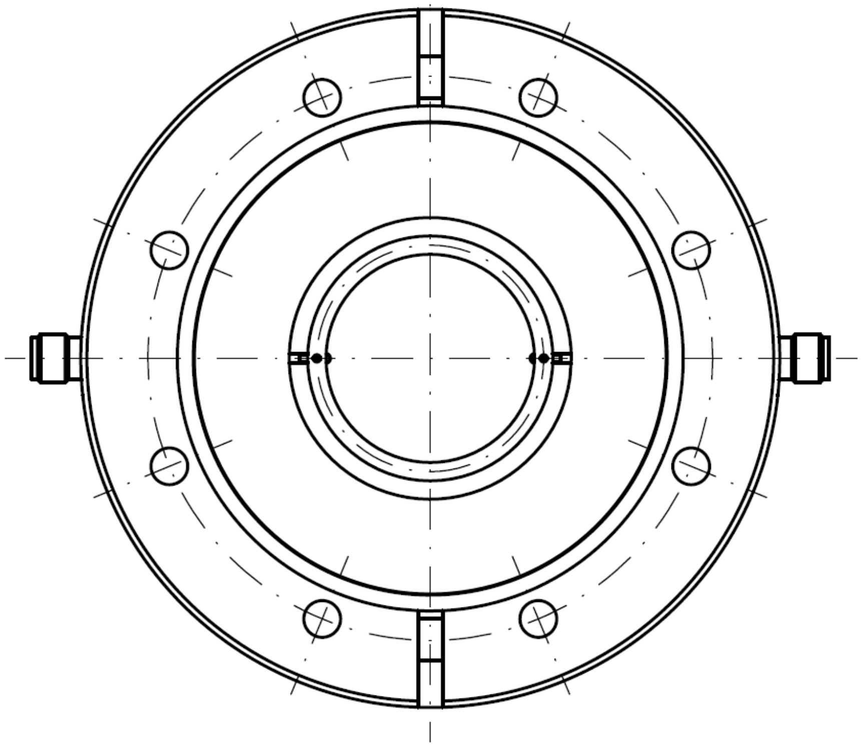


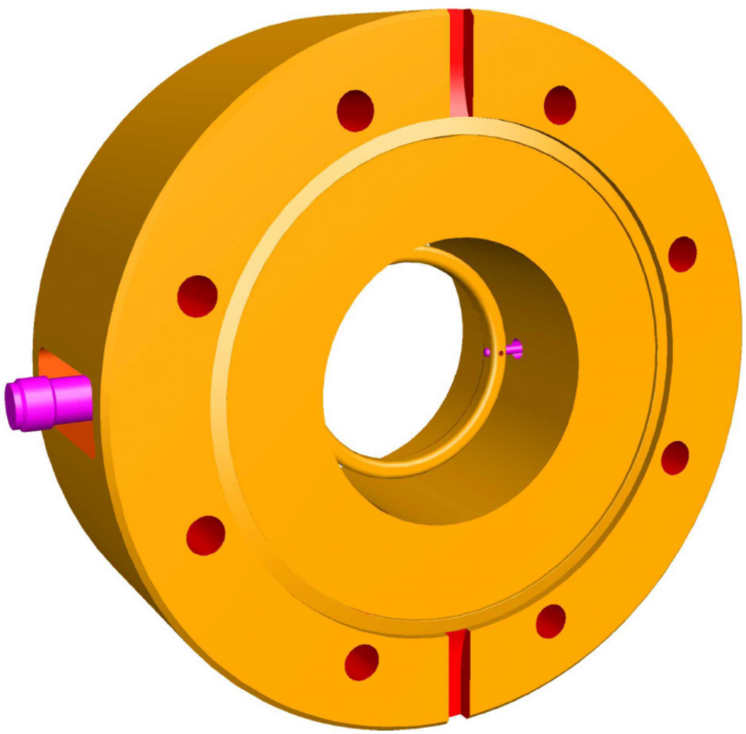
expected energy resolution (FLASH): 1.5e-5

Detection of main arrival-time jitter sources

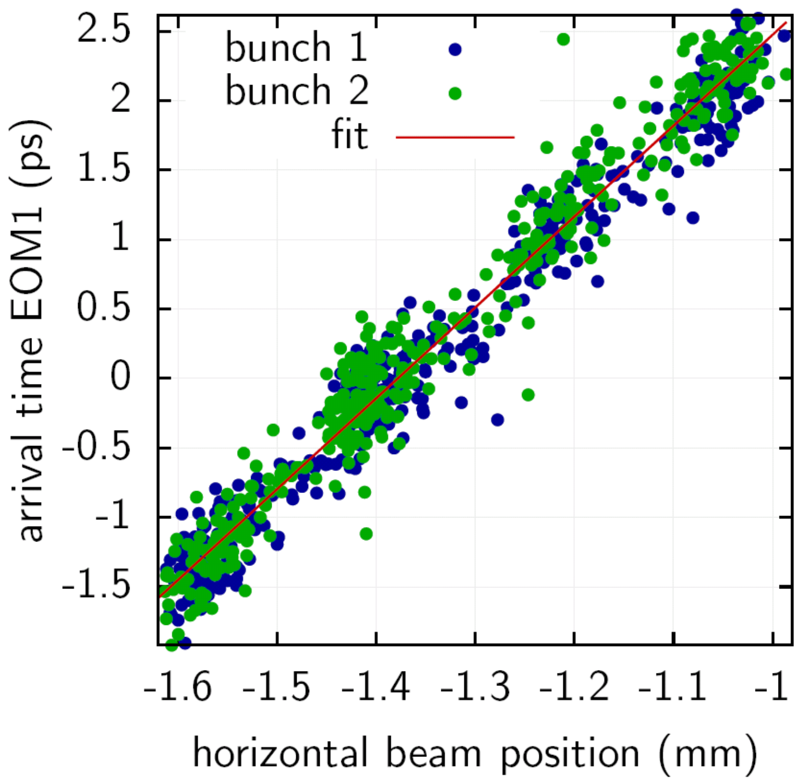
- Arrival time of photo cathode laser pulses **(CC / 1st arrival time monitor)**
- Phase of RF gun **(difference between 1st and 2nd arrival time monitor)**
- Amplitude of ACC1 **(BAM3 – BAM 2 / BPM in magnetic chicane)**
- Phase of ACC1 **(Bunch Compression Monitor)**
- Arrival time of pump-probe lasers **(cross-correlation with timing system)**

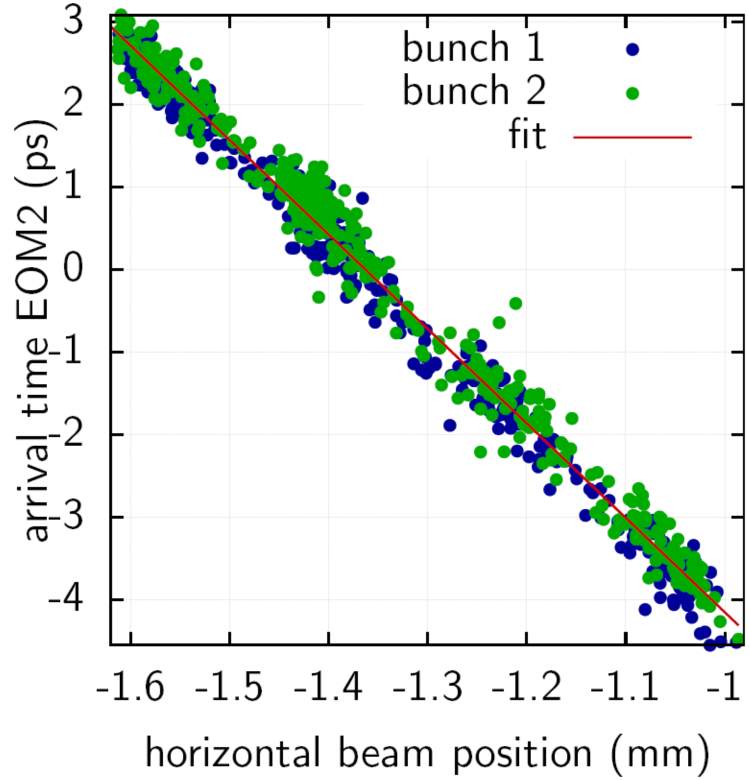
First version of the BAM beam pick-up:





Optical beam position measurement using a BAM





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

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

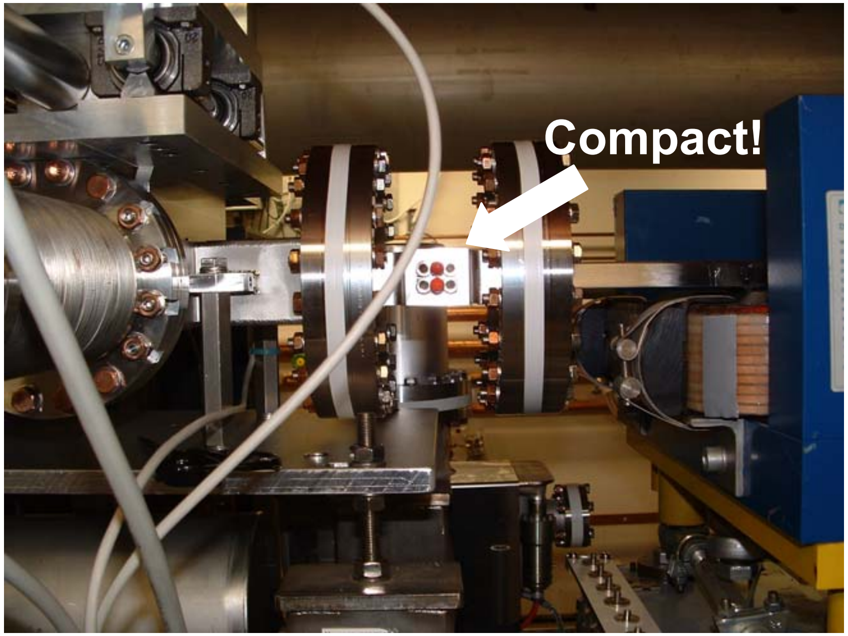
$$a_{x,1} = (-6.94 \pm 0.05)\frac{\text{fs}}{\mu\text{m}} \qquad a_{x,2} = (10.7 \pm 0.02)\frac{\text{fs}}{\mu\text{m}}$$

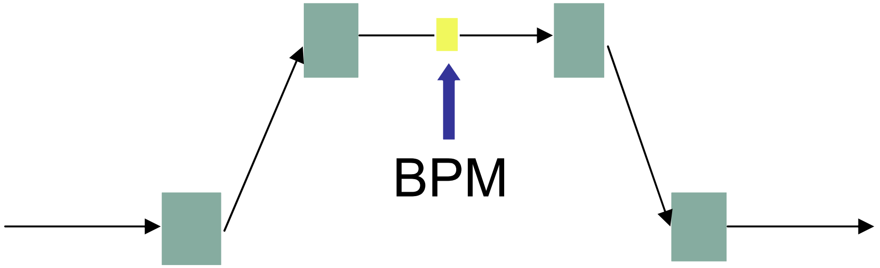
$$a_{y,1} = (-0.16 \pm 0.07)\frac{\text{fs}}{\mu\text{m}} \qquad a_{y,2} = (0.29 \pm 0.02)\frac{\text{fs}}{\mu\text{m}}$$

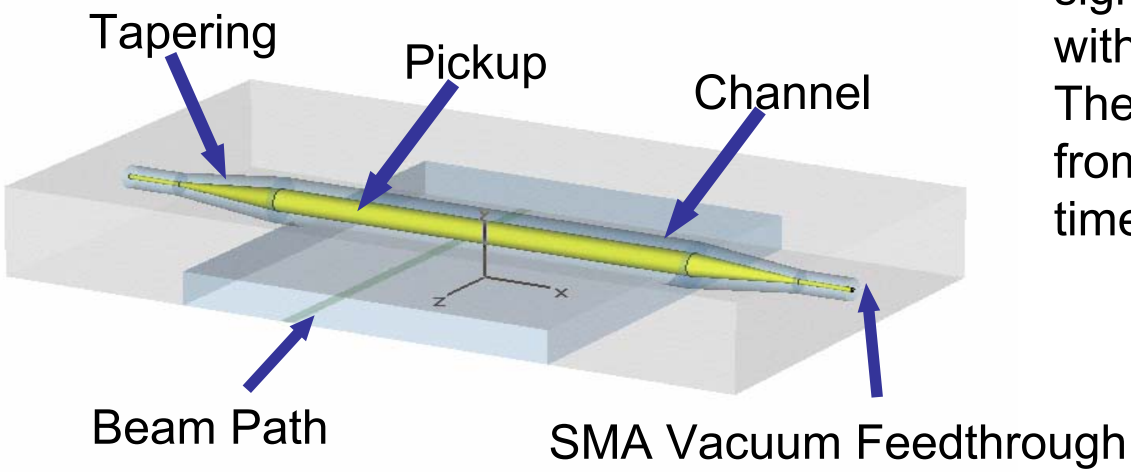
The setup had 30 fs resolution

→ 3 µm resolution

Beam position monitors in the bunch compressors



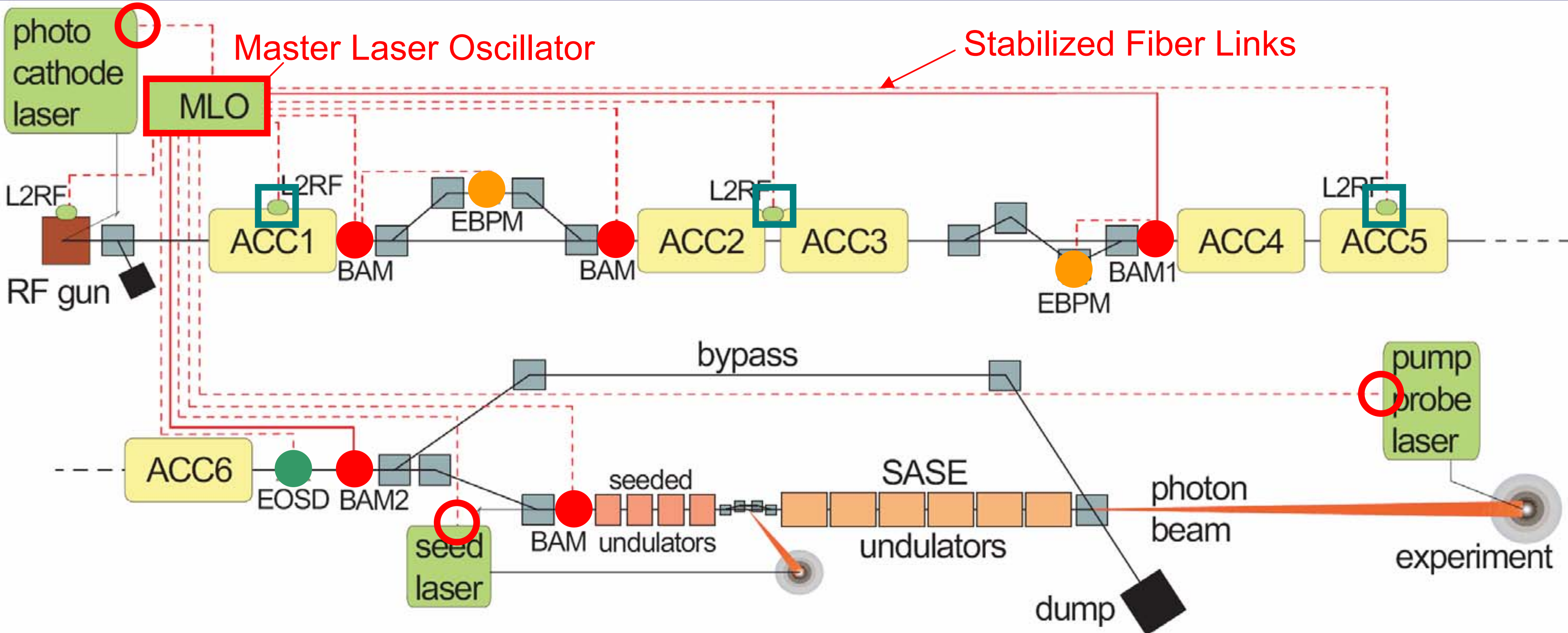




The arrival time of the pickup signals is measured at both ends with a BAM.
The beam position is determined from the difference of both arrival times.

Courtesy of K. Hacker

Outlook: The optical synchronization system at FLASH



- Bunch Arrival Time Monitor (BAM)
- Energy Beam Position Monitor (EBPM)
- Electro Optic Longitudinal Beam Profile Monitor
- Optical Cross-Correlator to Lock Lasers
- Laser to Microwave Signal Conversion

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