Femto-second synchronization system for FLASH

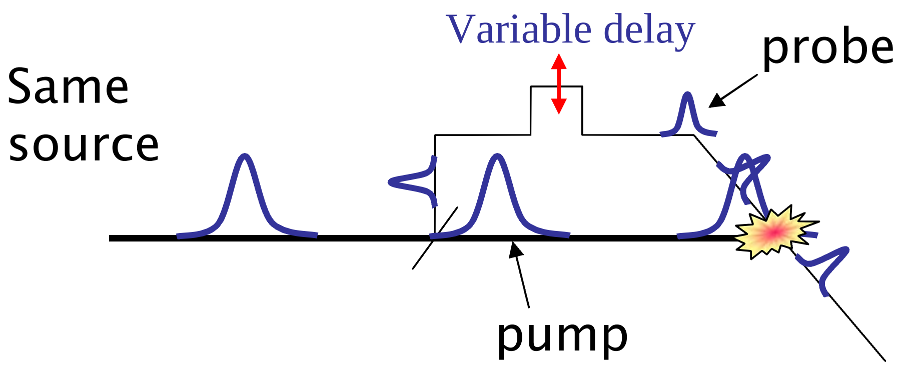
- Prototype for XFEL -

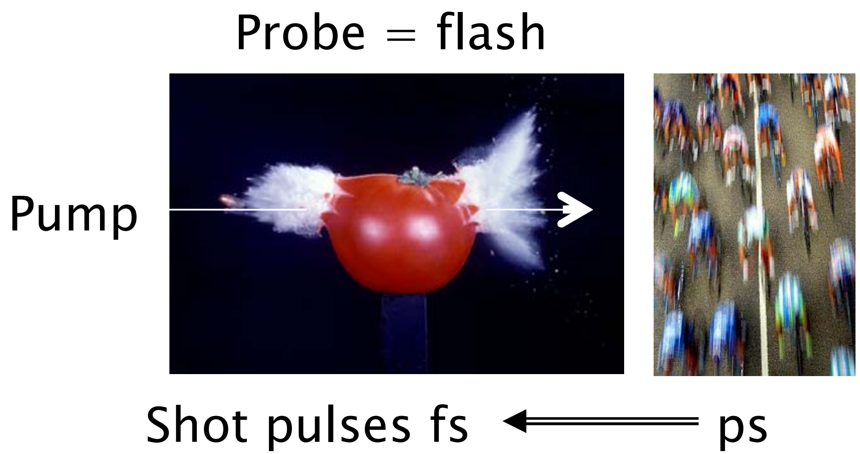
Holger Schlarb, in collab. with MIT

March 27th 2007

Pump-probe experiments

Classical setup:





Knowledge of time delay between pump and probe is crucial!

Spatial resolution 800nm → 0.1 nm

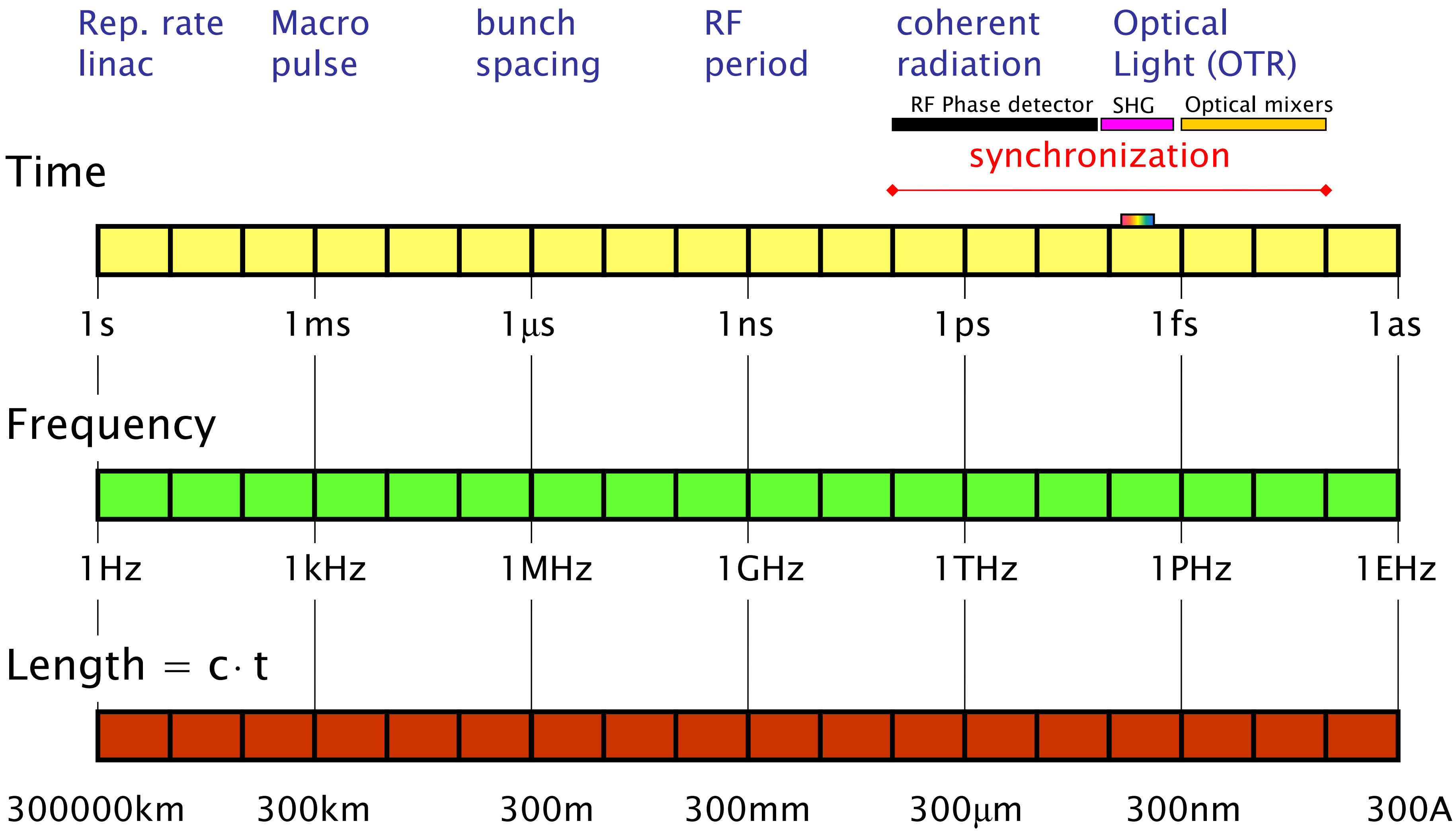
- Atomic / Molecular Physics

  (e.g. dynamics (2 photon/meta-stable states) /nonlin. processes in VUV/XUV/X-ray)
- Solid state dynamics

  (e.g. magnetization dynamics, non-thermal melting)
- Plasma physics

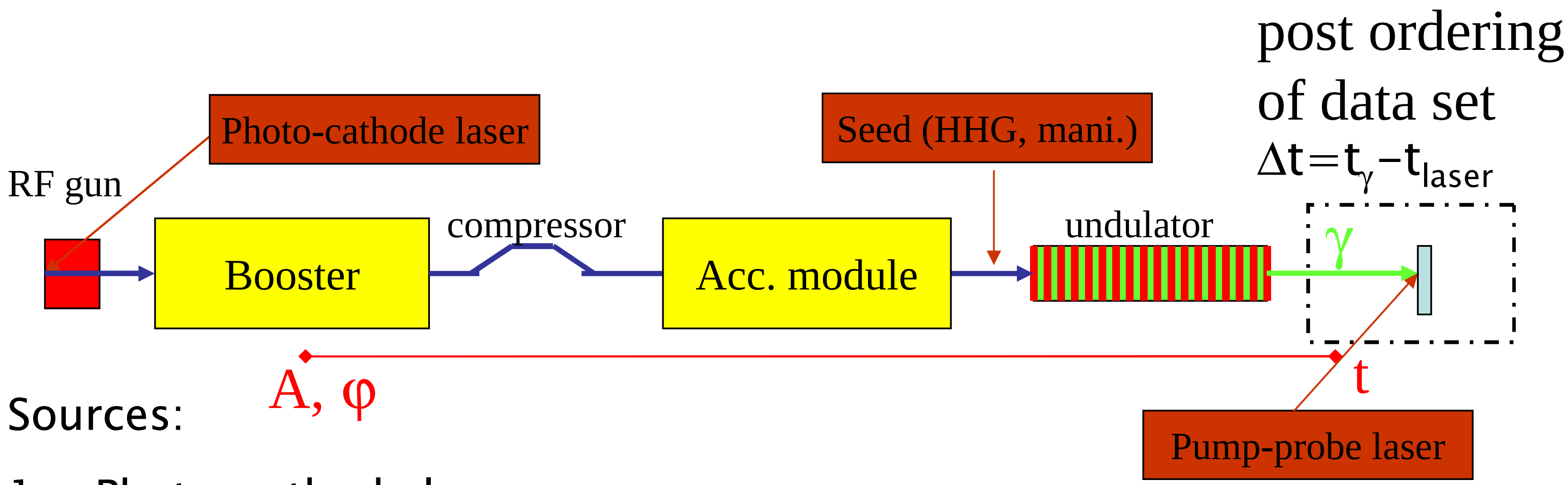
  (probing high electron densities / producing “warm dense matter”)

Synchronization range



Source of timing jitter

1. longitudinal and transverse electron beam quality
2. arrival time for high resolution pump-probe experiment



Sources:

1. Photo-cathode laser
2. RF gun (non-relativistic electrons)
3. Pump-probe laser/ Seed laser (post ordering not possible)
4. RF phase and amplitude stability of acceleration upstream of BC

- Point to point timing jitter is relevant (100m-3km)

Source of timing jitter - Caused by RF acceleration prior BC -

Timing jitter Behind BC → Σ_t^2

Gradient → $\left(\frac{R_{56}}{c_0}\frac{\sigma_A}{A}\right)^2$

Phase → $\left(\frac{\sigma_\phi}{c_0 k_{rf}}\right)^2$

Incoming Timing jitter → $\Sigma_{i,t}^2$

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

XFEL: 3.3 ps/%
FLASH: 5.5ps/%

2 ps/deg

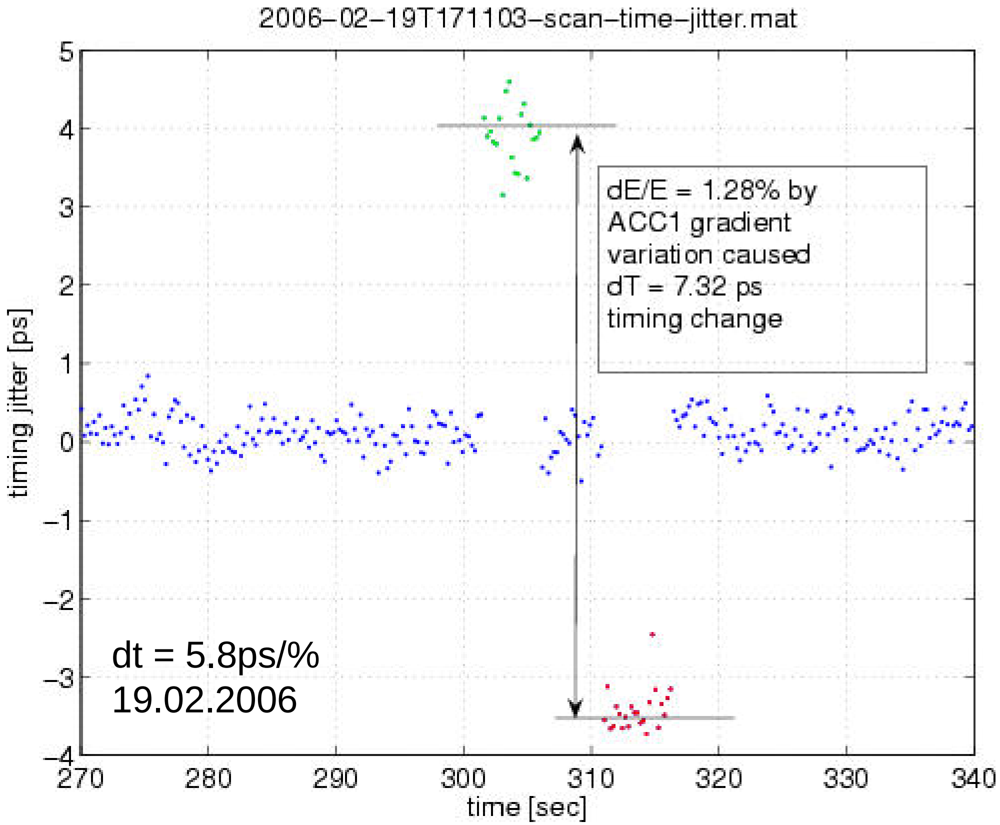
0.05 ps/ps

C compression factor (20)
R_{56} ~ 100 mm/180 mm
k_{rf}: wavenumber RF acceleration (27.2/m)

Vector sum regulation of 32 cavities => 1 deg == 1.8% (statistic 32 cav. helps)
But! Phase changes can be correlated due to local oscillator changes

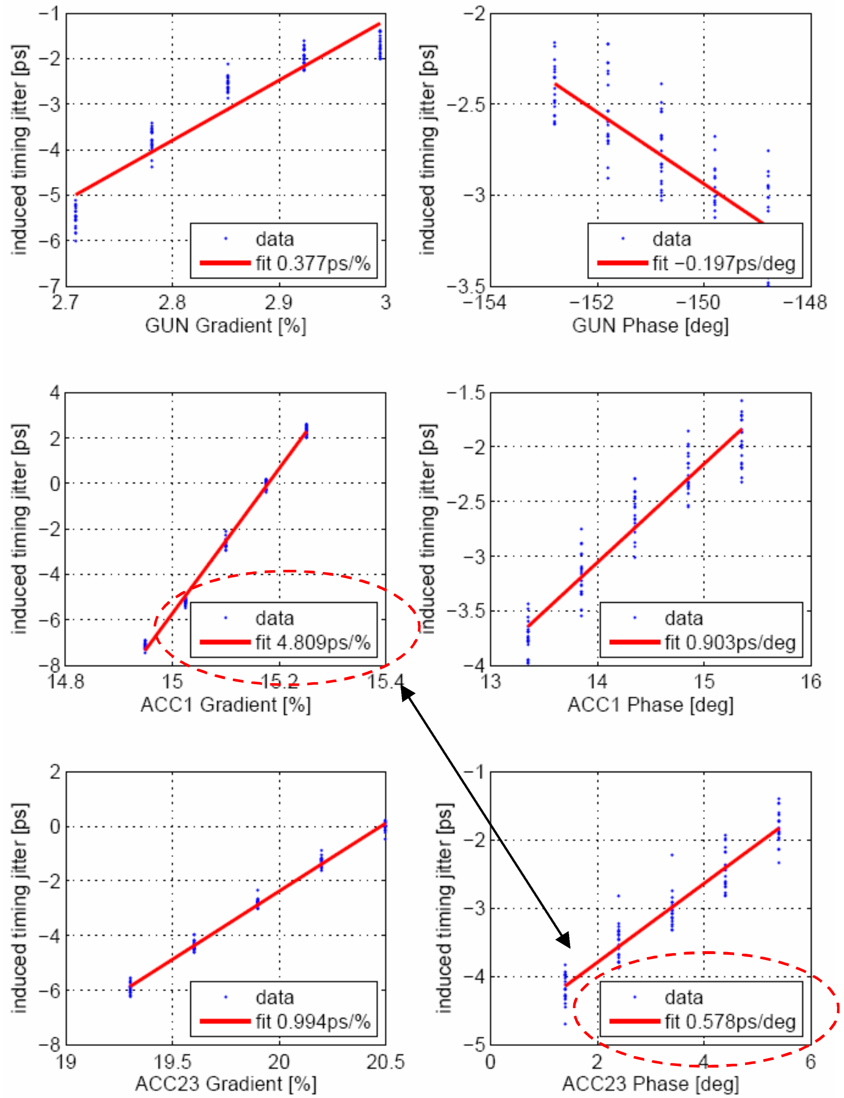
Source of timing jitter
- characterization at FLASH -

Measurement of arrival time with LOLA

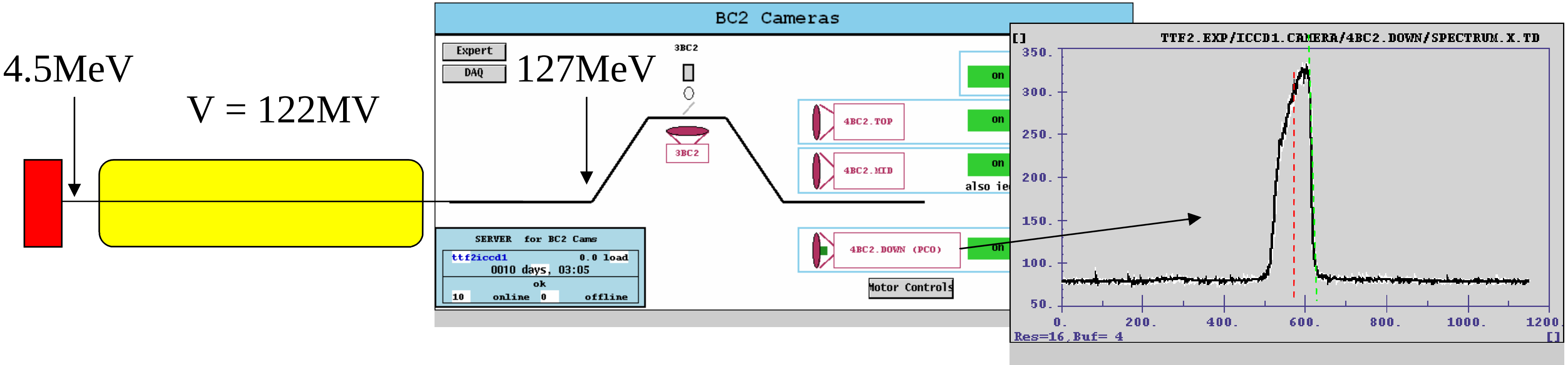


- is reduced choosing smaller R_{56}
- or if ACC23 is operated off-crest

RF ampl. & phase sensitivity scan



dE/E measurements ACC1



Contribution of gun:

⇒ dE/E (4.5MeV) gun < 5e-4 ≅ 2.2keV or
⇒ dE/E (127MeV) < 2e-5

Using ultra low energy spread of beam!

⇒ σ_E ~ 1-2 keV from gun
⇒ If beam would be ideally focused on screen using high energy edge about $\sigma_E/10$ could be resolved dE/E ~ 1e-6
⇒ But finite beam size and camera resolution: σ_x ~ 30 um, point spread camera ~ 10um dE/E ~ 1e-5 (for R_{16} ~ 300mm)

Incoming orbit jitter $\sigma_{x,jitter}$ ~ 30-50um

no correction: dE/E ~ 1e-4
when corrected dE/E ~ 3e-5 (10um)

Old meas. TTF1

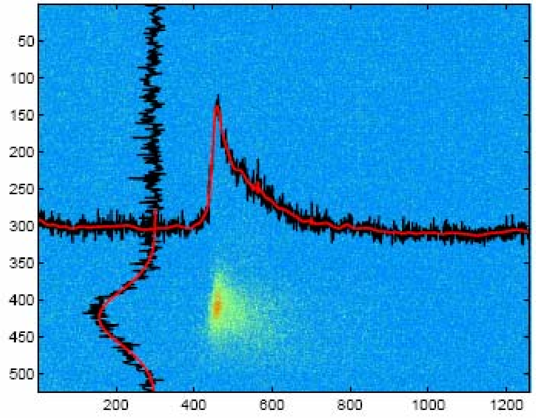
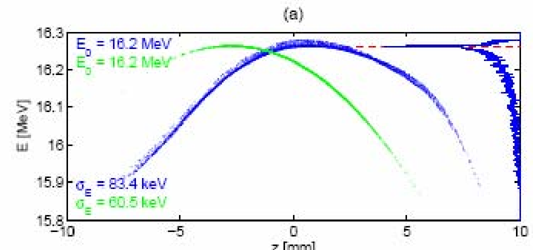
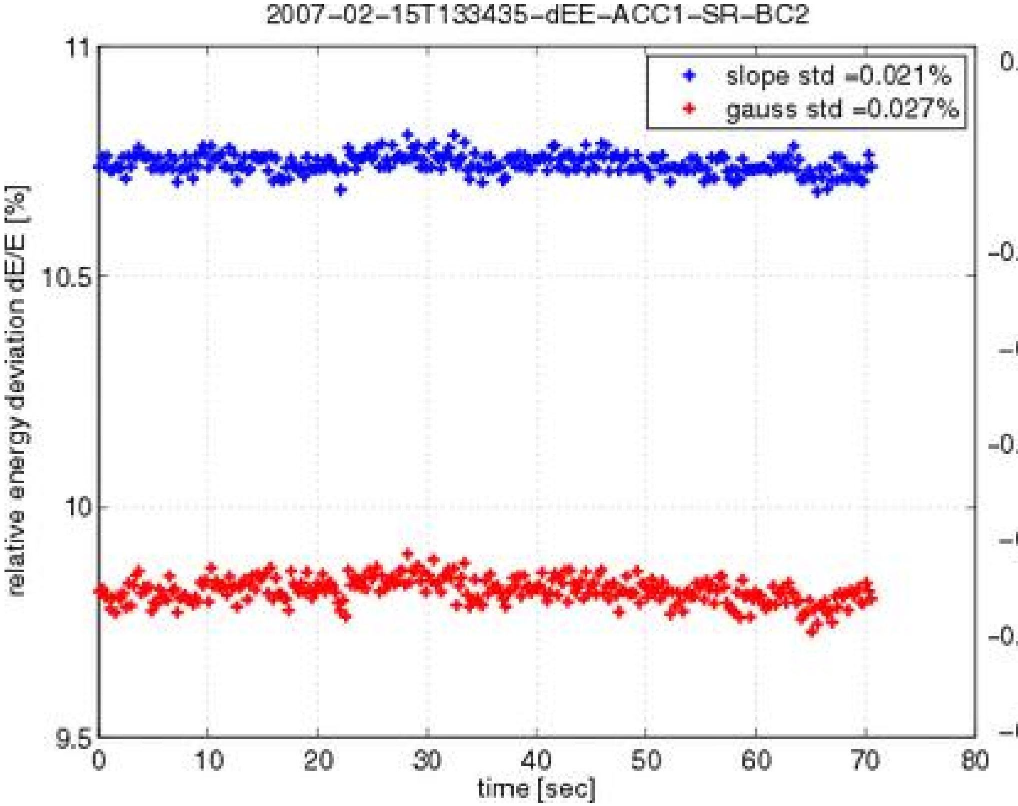


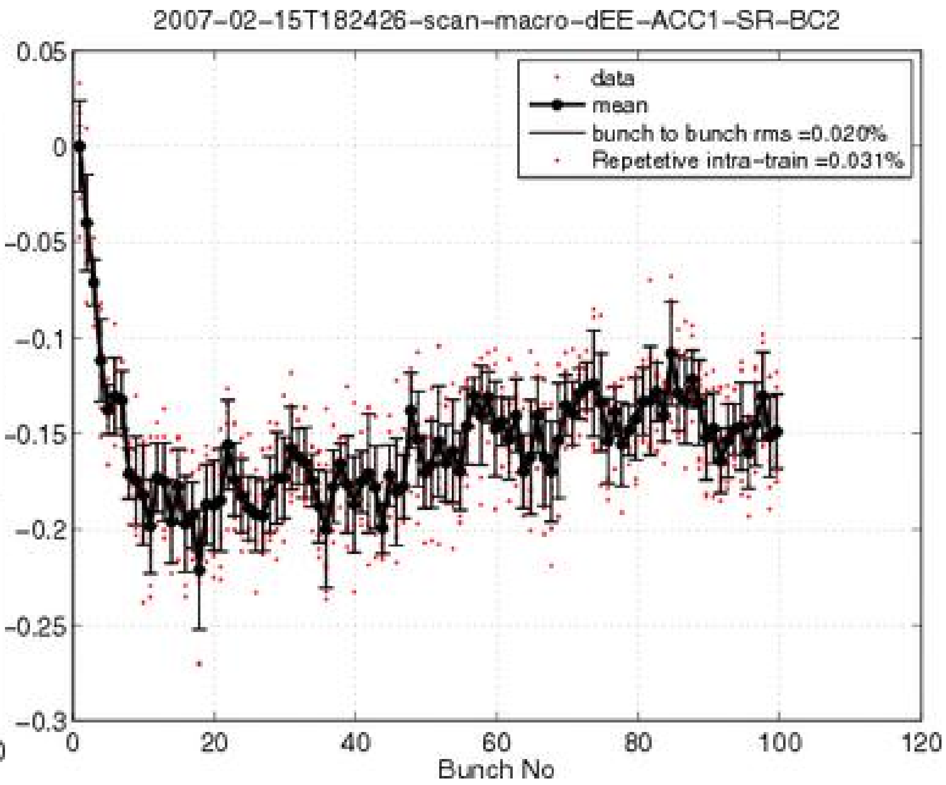
Figure 2: Image of bunch at OTR6.



Found faulty pickup signal cavity 6 in ACC1!
Has been removed from vector sum regulation

rf control parameters: GUN: AFF gain: -0.4, FB gain: 4, Pfwd SP: 3.02 MW
ACC1: FB gain: 15, Beam Comp: ON, Ampl=12.7, Ph=-10, acc1 phase SP -146 (== 8 deg off crest)





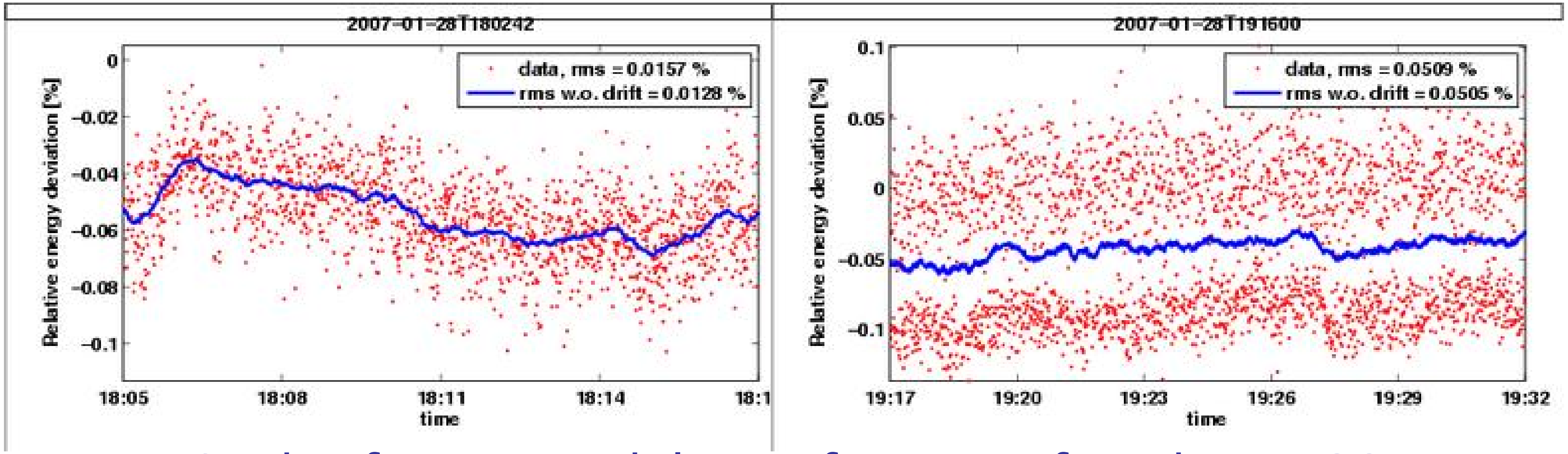
100us, 0.7nC, 1MHz, SASE cond.

XFEL
X-Ray Free-Electron Laser

Best results so far
- but not permanent -

DESY

dE/E (ACC1) stability versus gradient OTR screen 3BC2:



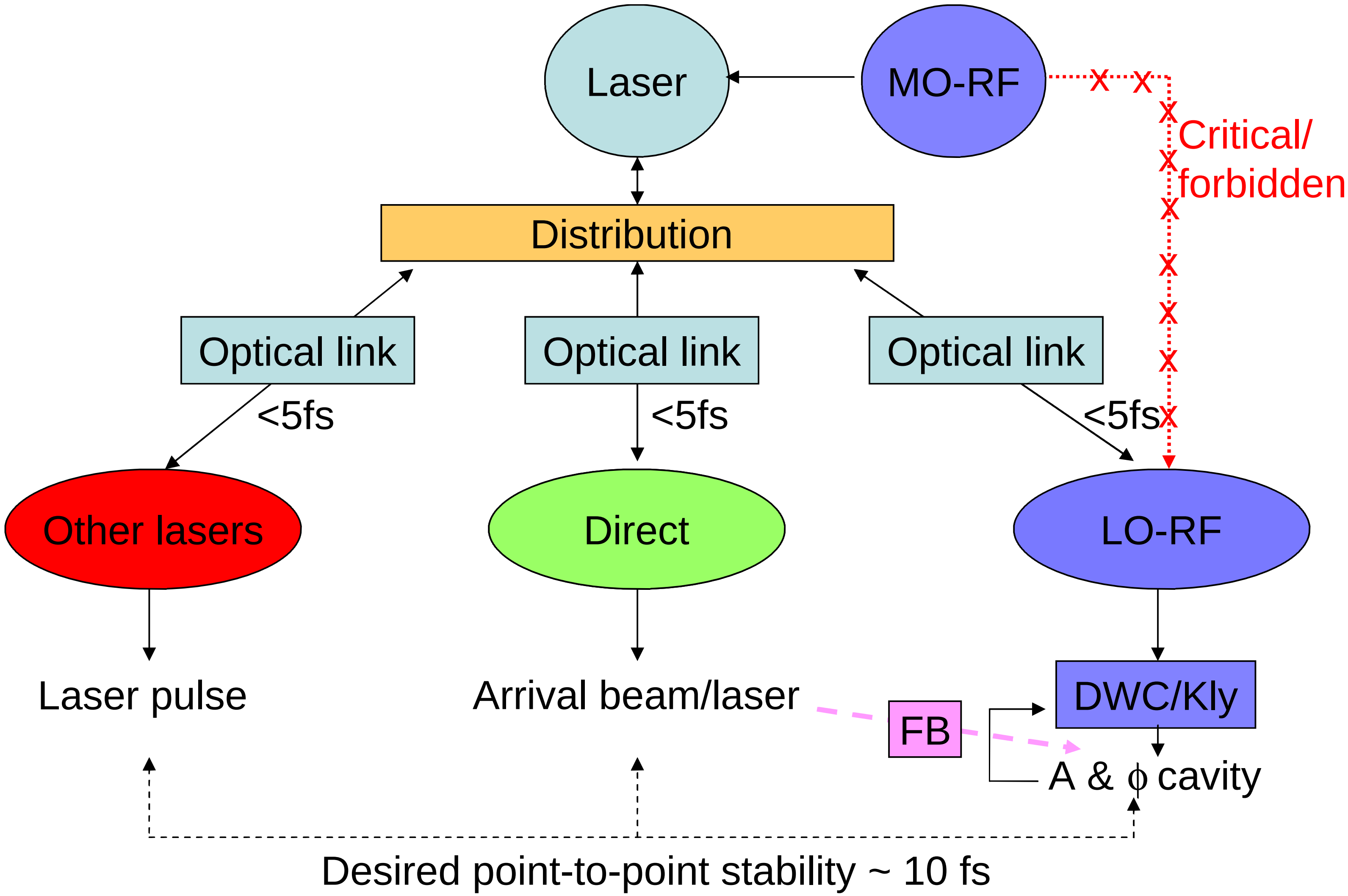
Study of energy stability as function of gradient ACC1

Gradient MV/m	F_{rep}/MHz	dE/E [%]	dE/E [%] w/o drift	
14.8	1.0	0.0188	0.0178	
15.0	1.0	0.0184	0.0177	
15.2	1.0	0.0168	0.0163	
15.2	0.04	0.0157	0.0128	
15.4	0.04	0.0237	0.0179	
15.6	0.04	0.0509	0.0505	

XFEL specs.
σ_t = 70fs rms

3000 bunches, 3 bunches for measurement, on-crest measurement

Generic layout of laser based synchronization

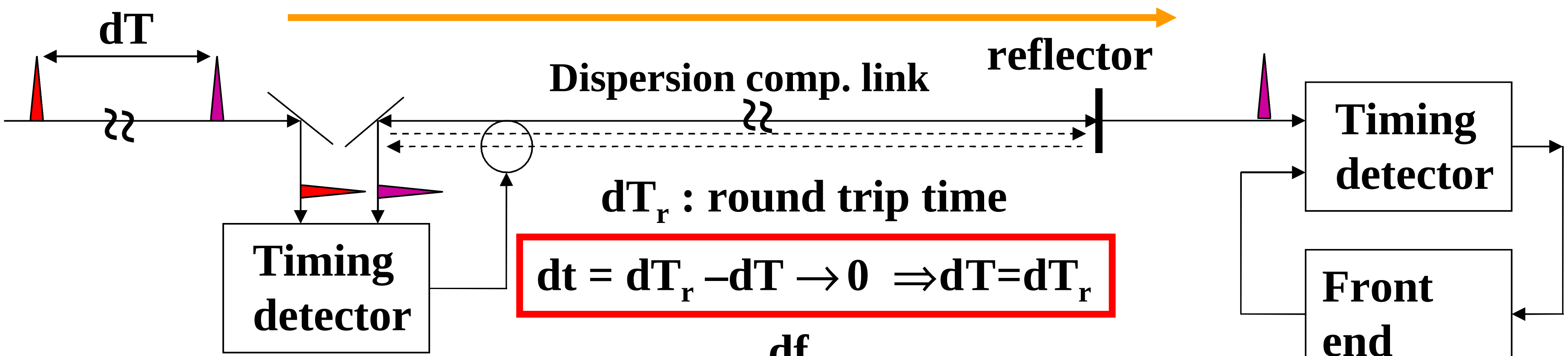


Principle

- **timing information is carried by ultra-short optical pulse**

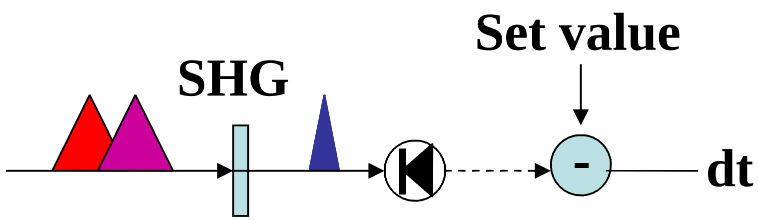
~ 200fs (FWHM) ⇔ ~ 5 THz (FWHM) bandwidth

- **fiber length stabilization based on same principle as timing detection**



$$dt_{error} = dT \frac{df_{rep}}{f} \quad 3fs \Rightarrow df/f\sim 1e\text{-}10$$

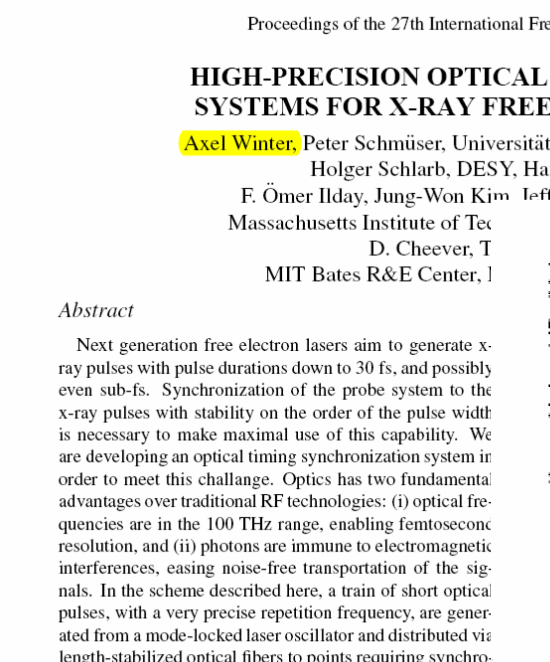
- **timing detection to optical cross-correlation basically drift free ($<<\sigma_t$)!**



For stabilisation balanced setup is used!

Where are we now!

– Fiber oscillator – first link stab. with RF 05 – CEO stabilization to 50as –

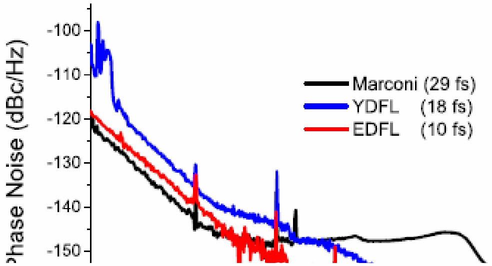

Proceedings of the 27th International Free Electron Laser Conference

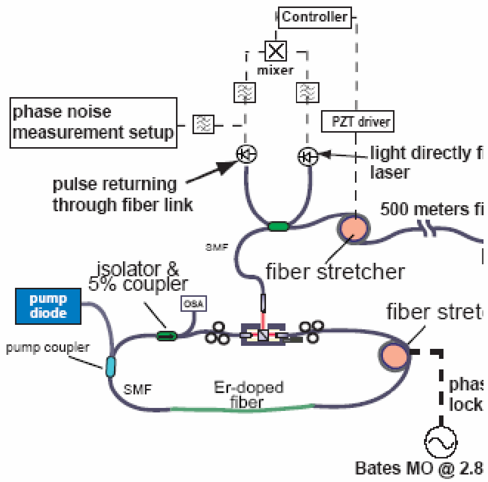
HIGH-PRECISION OPTICAL SYNCHRONIZATION SYSTEMS FOR X-RAY FREE ELECTRON LASERS

Axel Winter, Peter Schmüser, Universität Hamburg, Hamburg, Germany,
Holger Schlarb, DESY, Hamburg, Germany,
F. Ömer Ilday, Jung-Won Kim, Jeff Chen, Franz X. Kärtner
Massachusetts Institute of Tec
D. Cheever, T
MIT Bates R&E Center, I

Abstract

Next generation free electron lasers aim to generate x-ray pulses with pulse durations down to 30 fs, and possibly even sub-fs. Synchronization of the probe system to the x-ray pulses with stability on the order of the pulse width is necessary to make maximal use of this capability. We are developing an optical timing synchronization system in order to meet this challange. Optics has two fundamental advantages over traditional RF technologies: (i) optical frequencies are in the 100 THz range, enabling femtosecond resolution, and (ii) photons are immune to electromagnetic interferences, easing noise-free transportation of the signals. In the scheme described here, a train of short optical pulses, with a very precise repetition frequency, are generated from a mode-locked laser oscillator and distributed via length-stabilized optical fibers to points requiring synchro-





50 as CEO stabilization

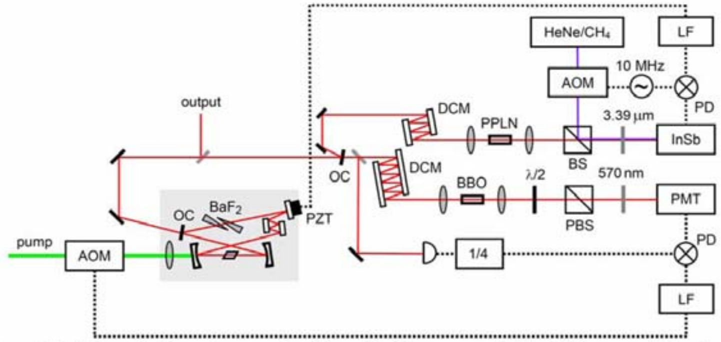
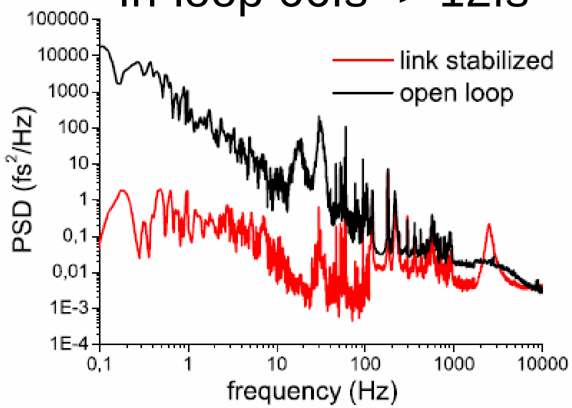


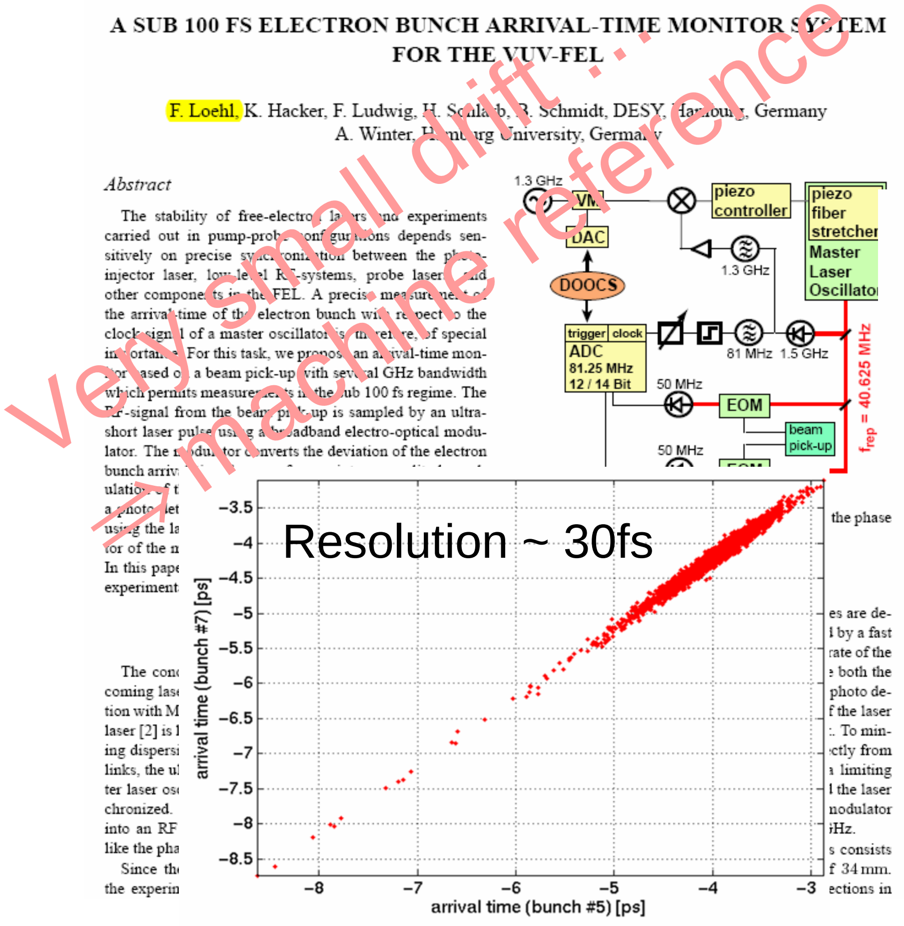
Figure IV.1: Schematic of an octave-spanning Ti:sapphire frequency comb. The CE frequency f_{CE} is phase-locked to $f_{rep}/4$ using f-to-$2f$ self-referencing, the repetition frequency f_{rep} is phase coherently derived from an optical transition in methane using a difference-frequency generation scheme.

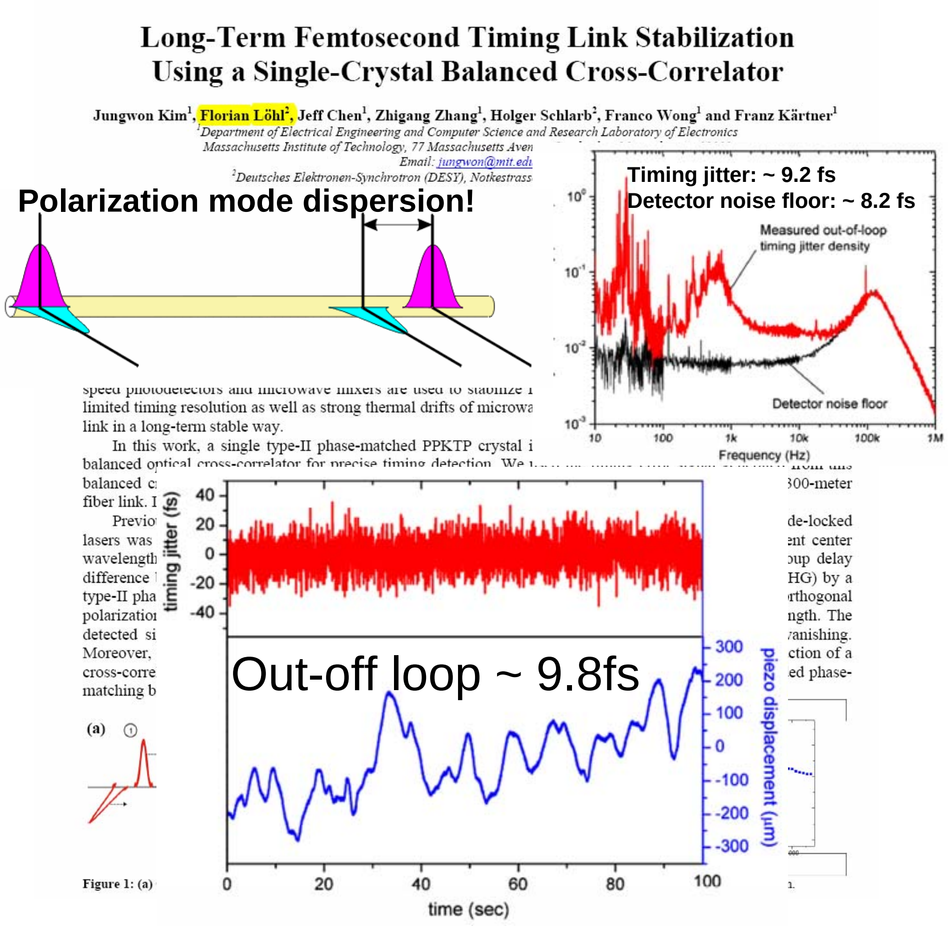
In-loop 66fs -> 12fs



Where are we now!

– Beam arrival monitor – fiber link with optical cross-correlation –





Where are we now!

- RF generation - drift free phase detection - high precision down-converter -

Long-Term Stable Microwave Signal Extraction from Mode-Locked Lasers

Jungwon Kim[1], Frank Ludwig[2], Matthias Felber[2], Holger Schlarb[2] and Franz X. Kärtner[1]
[1]*Department of Electrical Engineering and Computer Science and Research Laboratory of Electronics Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, Massachusetts 02139*
Email: junwon@mit.edu
[2]*Deutsches Elektronen-Synchrotron (DESY), Notkestrasse 85, 22607 Hamburg, Germany*

Abstract: Long-term synchronization [13-fs (10 Hz-10 MHz), <50 fs (for one hour)] between two 10.225-GHz microwave signals at +10 dBm referenced to a 44-MHz repetition rate mode-locked fiber laser is demonstrated using balanced optical-microwave phase detectors.

OCIS codes: (120.3940) Metrology; (320.7160) Ultrafast technology

Mode-locked lasers have a great potential to generate ultralow-jitter microwave signals encoded in its pulse repetition frequency. However, it is a highly nontrivial task to transfer the low noise properties in the optical domain to the electronic domain, and extract a drift-free, ultralow-jitter microwave signal from an optical pulse train. For high-precision optical-to-RF synchronization [1] as well as microwave signal readout from atomic optical clocks [2], it is crucial to convert the optical pulse train into a drift-free, low-jitter microwave signal with a satisfactory power level in a long-term stable way. One of the major limitations in direct photodetection for the microwave signal extraction is amplitude-to-phase conversion in the photodetectors [3]. The intensity noise and fluctuation can be converted into a significant amount of excess timing jitter and drift.

To circumvent the amplitude-to-phase conversion and also to ensure long-term stable operation, a balanced optical-microwave phase detector is proposed and demonstrated [4]. It is based on the precise phase detection in the optical domain using a differentially-biased Sagnac fiber loop and synchronous detection. Because the phase error between the optical pulse train and the microwave signal is detected in the optical domain before the photodetection is involved, it is robust against drifts and photodetector nonlinearities. More detailed information on the balanced optical-microwave phase detector can be found in Ref. 4.

In this paper, we measured the out-of-loop performance between two optoelectronic phase-locked loops (PLLs) using balanced optical-microwave phase detectors. The measurement result shows 12.8 fs relative jitter between two 10.225-GHz microwave signals integrated from 10 Hz to 10 MHz. In addition, the long-term drift measurement shows that the drift in microwave signal extraction is within 50 fs over one hour time scale. Note that the long-term measurement is mainly limited by the drift of the mixer and amplifier used in the out-of-loop characterization setup, which drifts up to 50 fs even when the temperature of the characterization setup is actively stabilized.

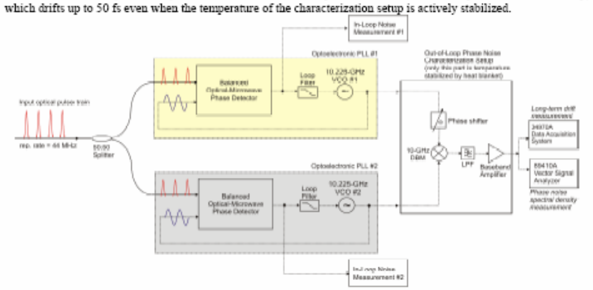
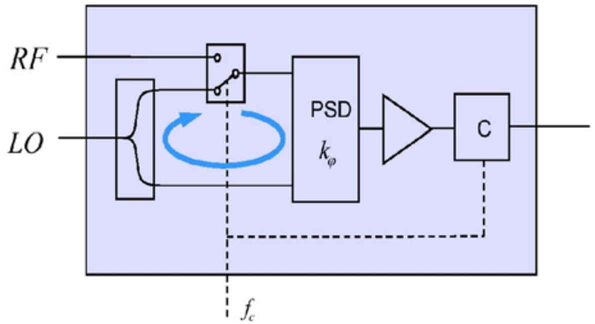


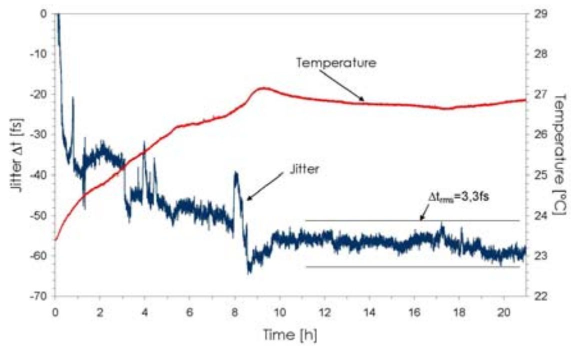
Figure 1: Experimental setup for long-term out-of-loop relative timing jitter measurement between two microwave signals referenced to a mode-locked laser. DBM: double-balanced mixer, LPF: low-pass filter, PLL: phase-locked loop, VCO: voltage-controlled oscillator.

DRO lock ~ 12fs
Good drift performance
Phase detector resolution ~ 0.8fs
(10Hz- 10MHz)

Drift free RF mixer Cortesy

F. Ludwig, J. Mueller





Timing stab. 3.3fs

Delivery Report 2006

Task No.: DS3 Synchronization	RF Amplitude and Phase Detector
Participant/Participant No.:	DESY / Holger Schlarb, Frank Ludwig
Email address of Reporting Person:	Frank.Ludwig@desy.de
Reporting Period:	01.01.06 - 31.12.06

RF Multichannel downconverter Prototype and Characterization

(Delivery report for the EUROFEL DS3 Task, Jan. 16, 2007)

F.Ludwig, M.Hoffmann, M.Felber, P.Strzalkowski, H.Schlarb
Deutsches Elektronen-Synchrotron (DESY), Notkestrasse 85, 22607 Hamburg, Germany

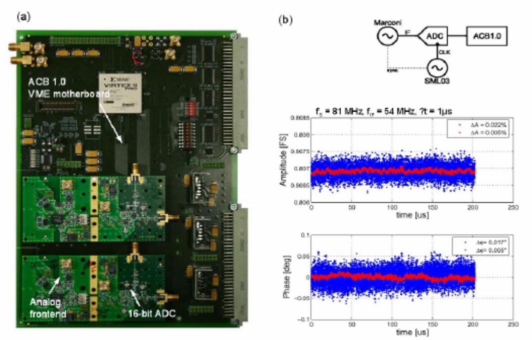


Figure 1: (a) Multi-channel DWC digital motherboard ACB1.0 (Advanced-Carrier-Board) and the rf-shielded analog frontend including analog attenuators, mixer frontend and ADC readout. (b) Setup for averaging the ADC noise using two rf-generators. The blue, respectively red curves shows the direct sampled, respectively averaged amplitude and phase values for an intermediate frequency of 54MHz, sampling frequency of 81MHz by averaging over 1μs.

Figure 2 shows the latest version of the ACB2.0 (Advanced-Carrier-Board) board. It has a faster

Capable to resolve < 10fs
and dA/A < 1e-4

Fiber link installation

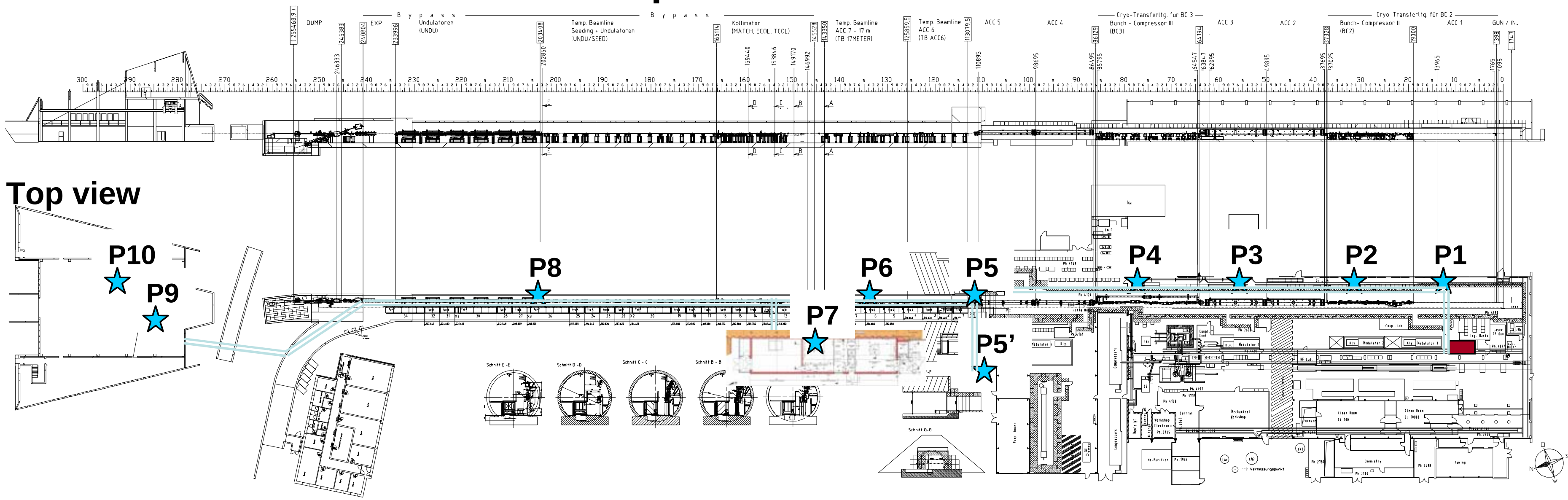
Optical fiber test section will be installed in Hall 1

- test of specialty fibers
- development of fiber link stabilization

Installation status:

Installation of pipes is already done or will be done this week
Installation of first optical fibers to be done first week of January
Splicing planned for January / February

Installation of optical fibers in the TTF linac



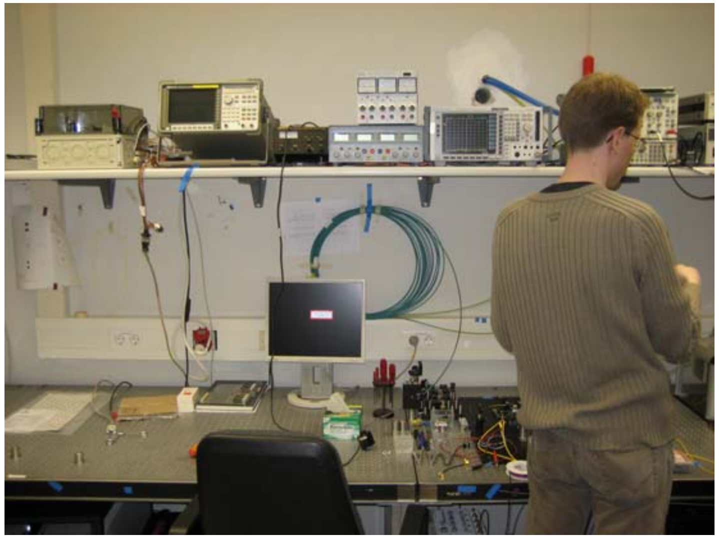
P1-10 fiber patch panel

Synchronization hutch (start point of all links)

Installation in new synchronization lab.

Installation in development laboratory

Fiber link test bench



Drift measurements

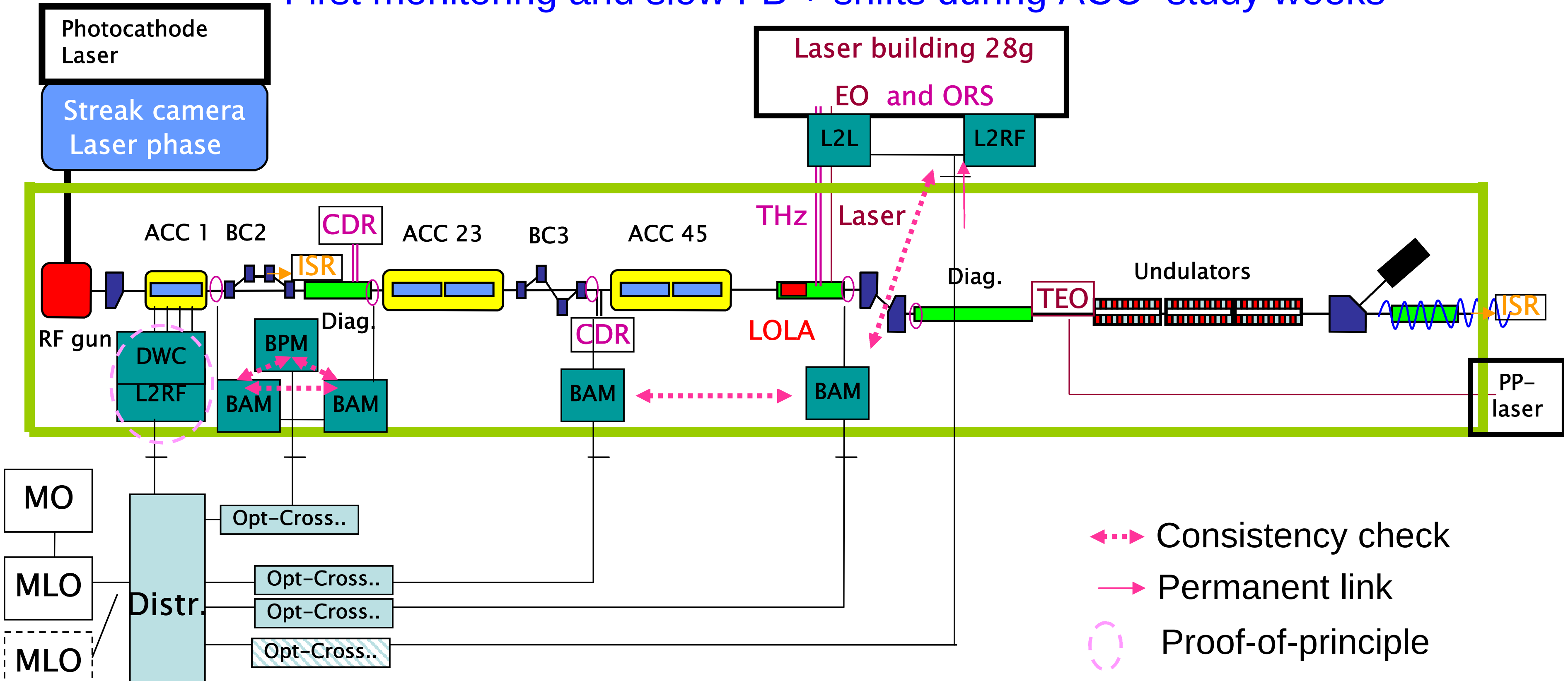
EDFA development

Current projects (Coordinator: H. Schlarb)

Master laser system (MLO)	(A. Winter, MIT)
Fiber link stabilization	(F. Loehl, MIT)
Laser to RF conversion	(F. Ludwig, B. Lorbeer, M. Felber, MIT)
Bunch arrival time monitor	(F. Loehl)
BPMs in magnetic chicanes	(K. Hacker)
New down-converter for cavity regulation	(F. Ludwig, M. Hoffmann, LLRF-Group)
Laser oscillator for CPA system (ORS)	(N. Javahiraly, A. Winter)
Fast motor control and position encoder readout	(J. Thomas, …)
DOOCS compatible laser diode driver	(A. Winter, FEB, MVP)
Digital regulation of master laser system	(W. Jalmuzna, LLRF-Group)
Digital regulation of fiber links	(G. Petrosyan, …)
Drift characterization of photo diodes, RF comp. etc	(B. Lorbeer, F. Ludwig, …)
Drift reduced RF mixer	(J. Mueller, F. Ludwig)
DOOCS compatible polarization controller	(M. Felber, K. Hacker)
Fast regulation of cavities with beam based measurements	(LLRF-Group)
Development of precise photo diode read out	(K.H. Matthiesen, …)
Cross-correlation of pump-probe laser and timing system	(V. Arsov, …)
Development of analog PI controller / piezo driver	(N. Ignachine, …)
Design of 130 MHz ADC board (DWC, BAM, BPM)	(P.Strzalkowski, M. Hoffmann, …)
Characterization of EDFAs	(J. Mueller)
Simulation of optical pulse propagation	(H. Schlarb, F.Loehl...)

Goals for 2007
- system design test using redundant measurements -

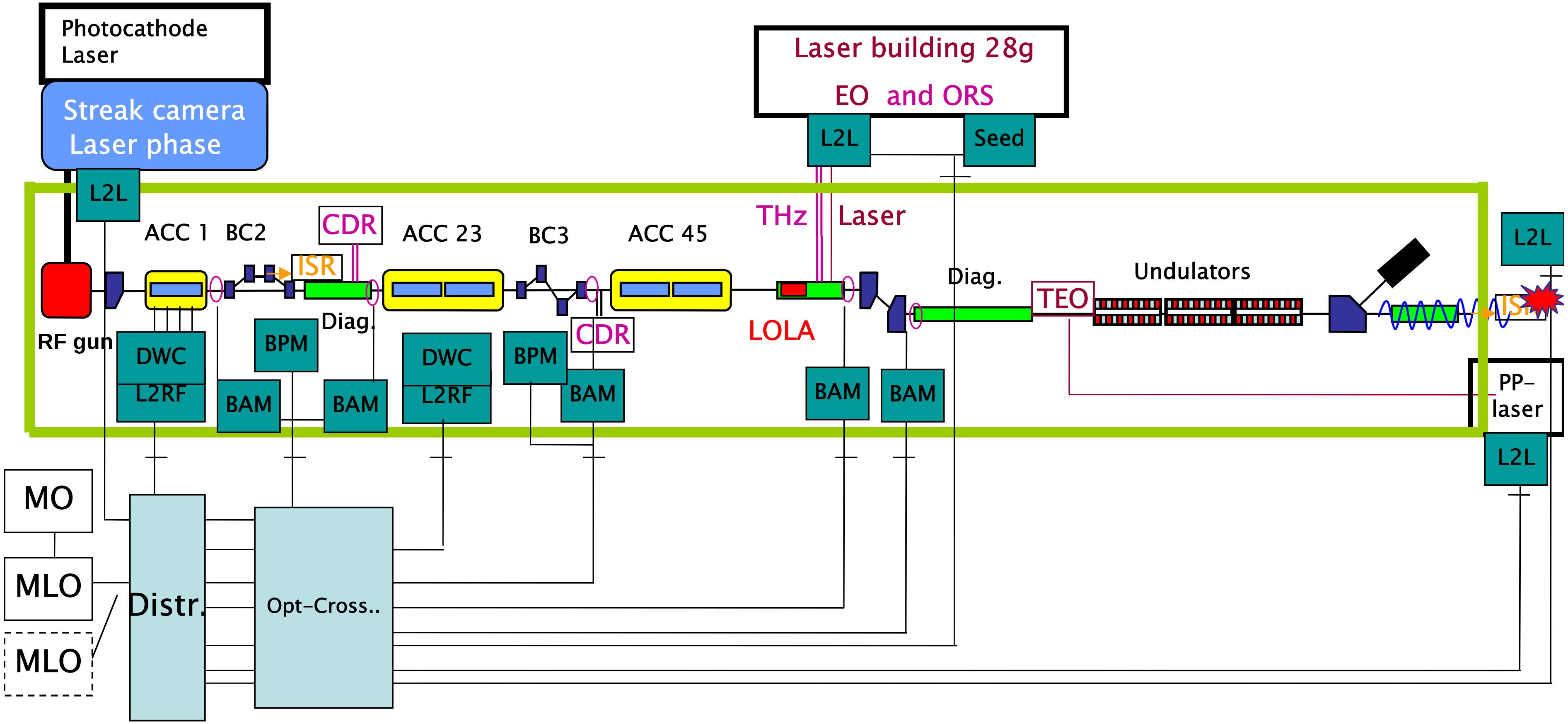
First monitoring and slow FB + shifts during ACC- study weeks



- 2 links + BAM at ACC3&ACC7 < 30fs rms
- next generation of DWC + L2RF conversion unit
- Beam feedback around ACC1 dA/A < 0.01%,
- Ti:Sa system locked via opt. cross + BAM/EO timing meas.

Goal: check first prototype design, start packaging, optimization and industrialization

Goals for 2008
- complete syn. for long term stability and availability test -



- Synchronization of all timing critical devices (<100fs, ~ 10 points)
- Permanent operation and long term stability investigation
- Point-to-point synchronization ~ 10fs rms

Summary

- Most proof-of-principle for synchronization is done
  - redesign Sagnac loop at 1.3GHz
  - PMD and its limitation
- Development of accelerator compatible system is on the way

- MLO installation and RF-MO connection	May 2007
- Splicing and patch panels	June 2007
- Link for ORS, BAM, EBPM	July-Sep 2007

- First prototype are available in 2007
  - for consistency checks
  - finalize prototype design
  - start industrialization
  - cost optimize system
- 2008: extension to entire FLASH facility
  - long term reliability check
  - accepted as Prototype facility for the IRUVX consortium