High-precision synchronization system for the XFEL

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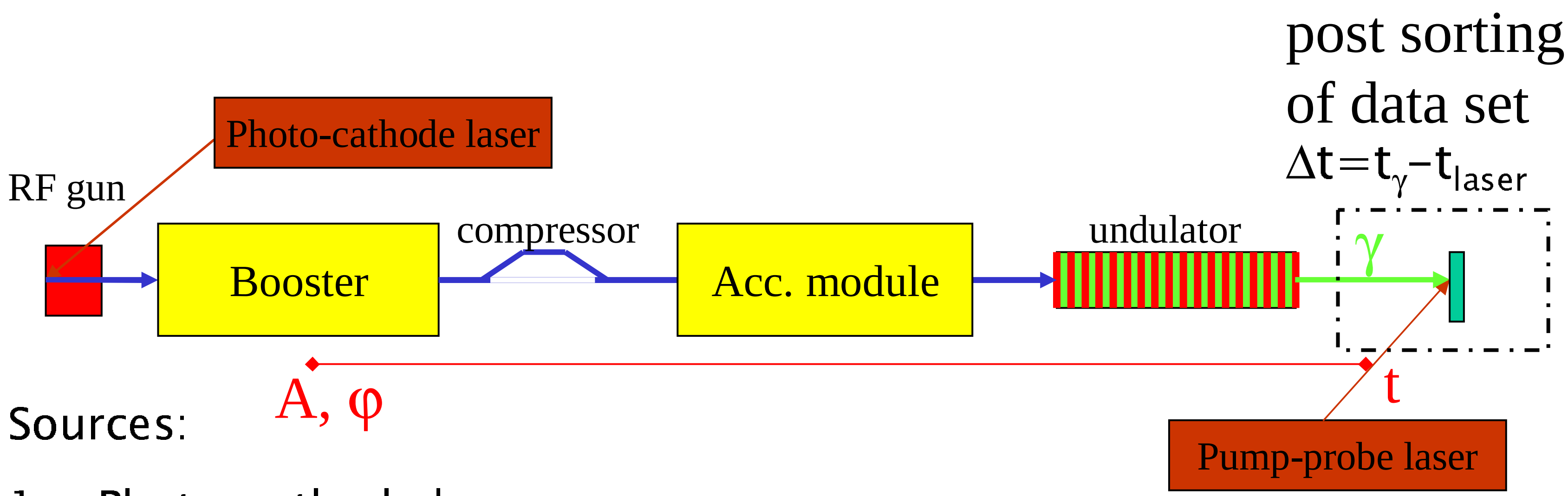
- **Motivation**
- **Principles of the system**
- **L2RF conversion**

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
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 — **Gradient** — **Phase** — **Incoming Timing jitter**

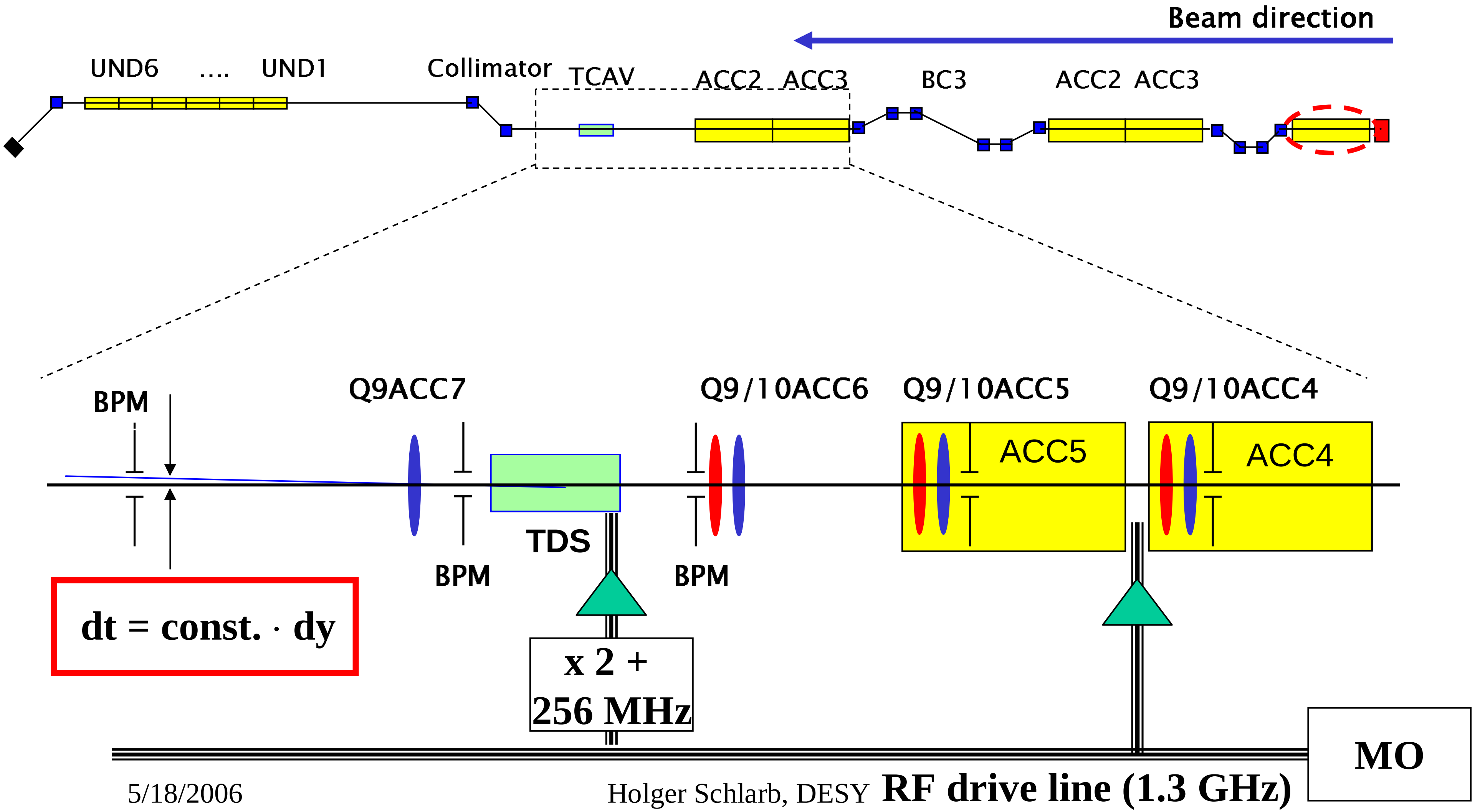
$$\Sigma_t^2 \approx \left(\frac{R_{56}}{c_0}\frac{\sigma_A}{A}\right)^2 + \left(\frac{C-1}{C}\right)^2\left(\frac{\sigma_\phi}{c_0 k_{rf}}\right)^2 + \left(\frac{1}{C}\right)^2 \Sigma_{i,t}^2$$

3.3 ps/% — 2 ps/deg — 0.05 ps/ps

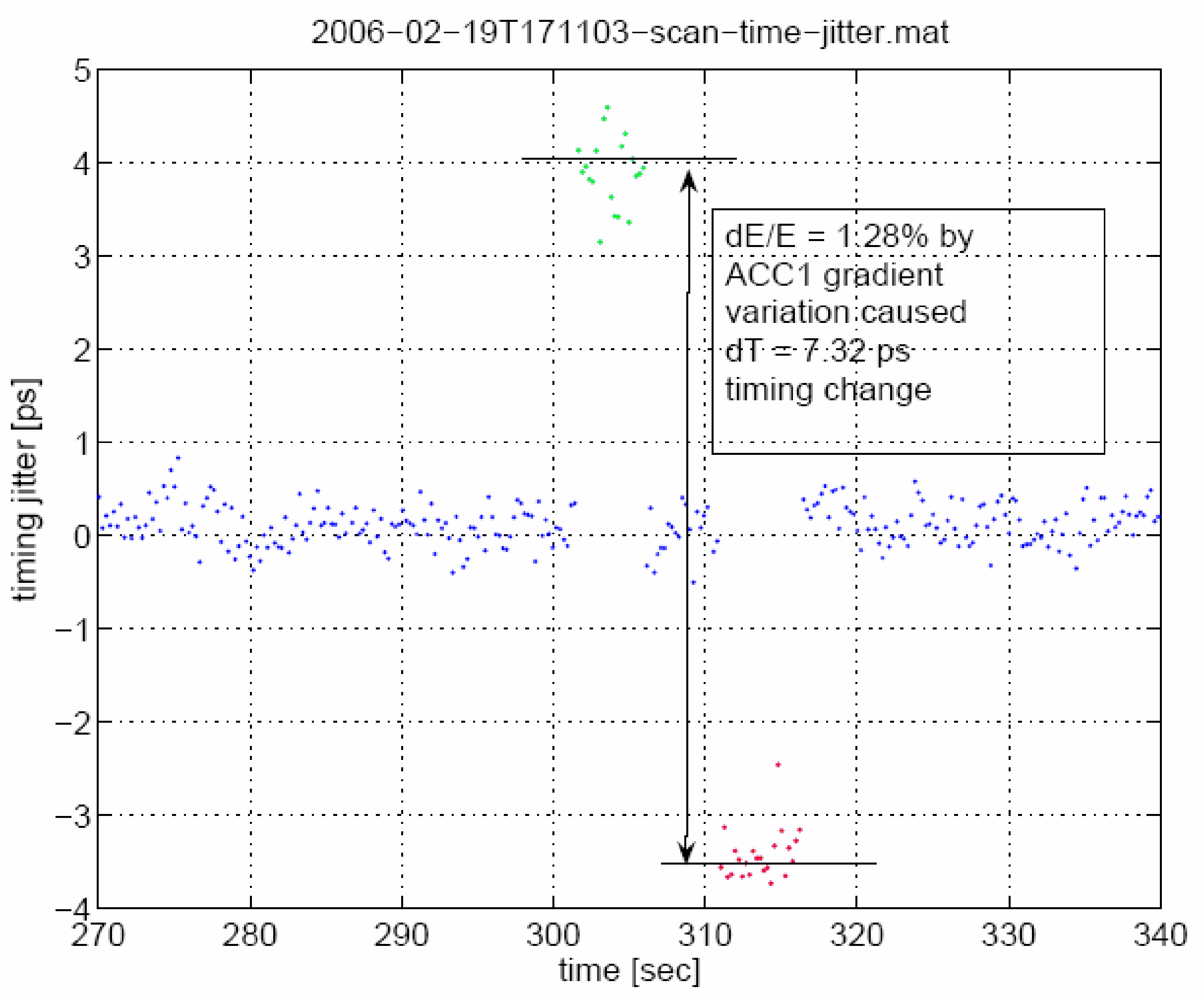
C compression factor (20)
R_{56} ~ 100 mm
k_{rf}: wavenumber RF acceleration (27.2/m)

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

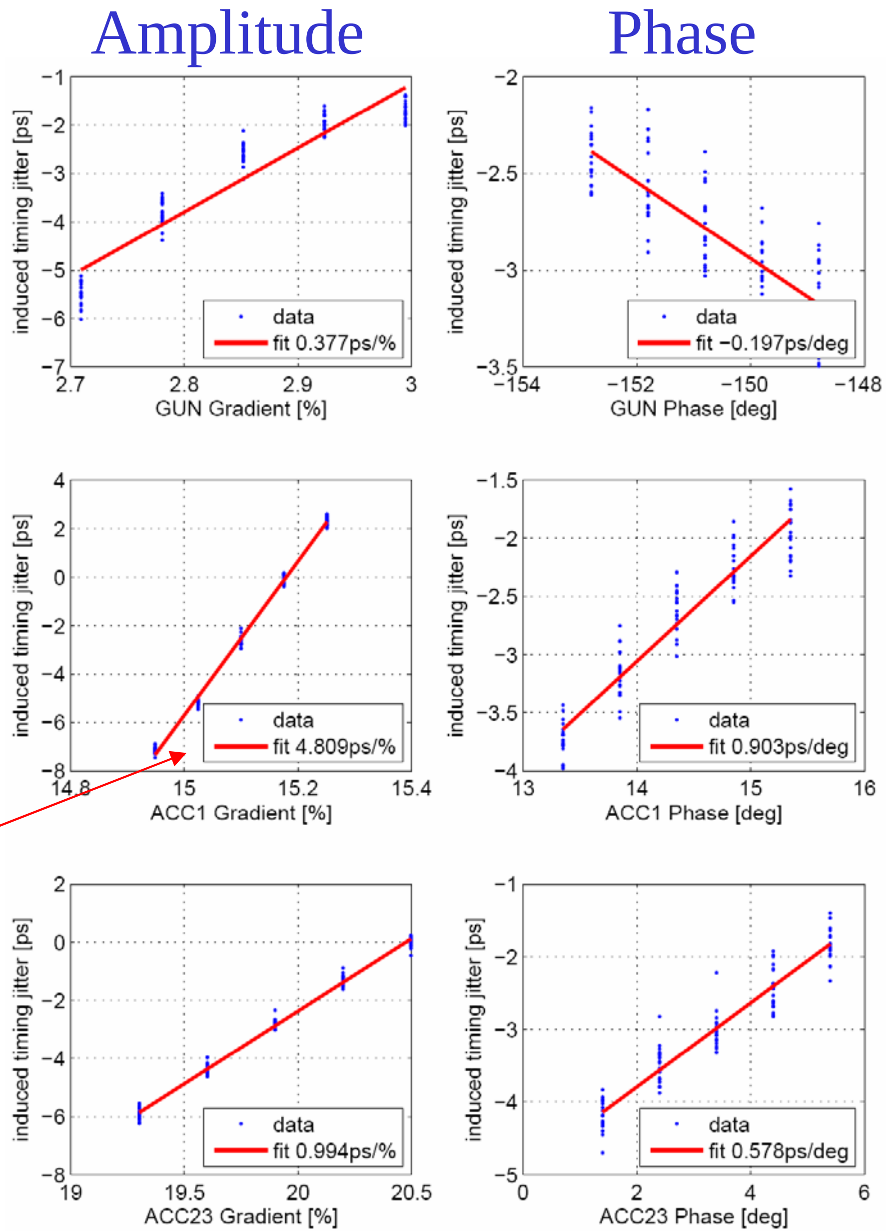
Timing jitter & sensitivity measured at FLASH with TDS (LOLA)



Arrival time sensitivity measurements



Arrival time sensitivity measurements



Gun

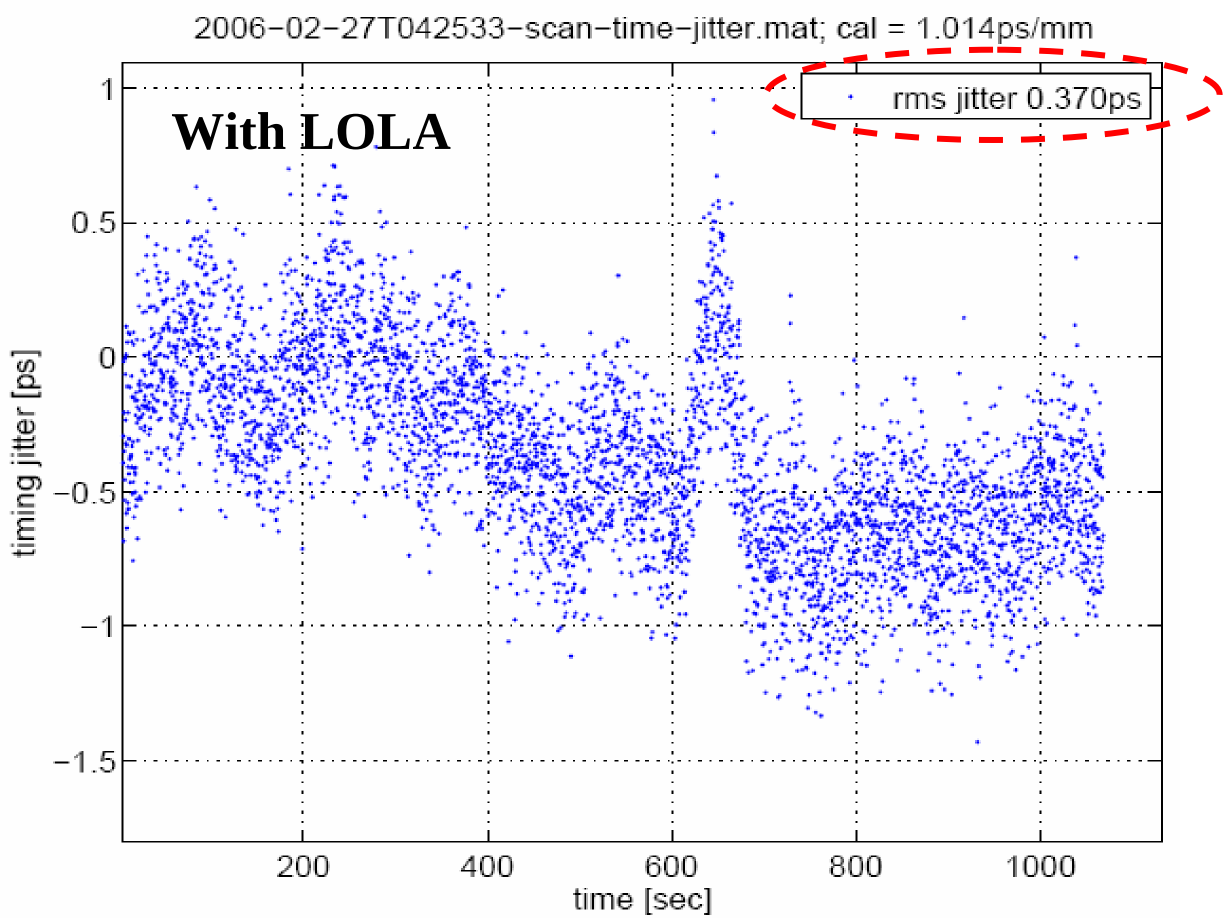
Acc1

Acc23

Acc45 no effect

Most critical at FLASH 4.8 ps/%

Arrival time measurements

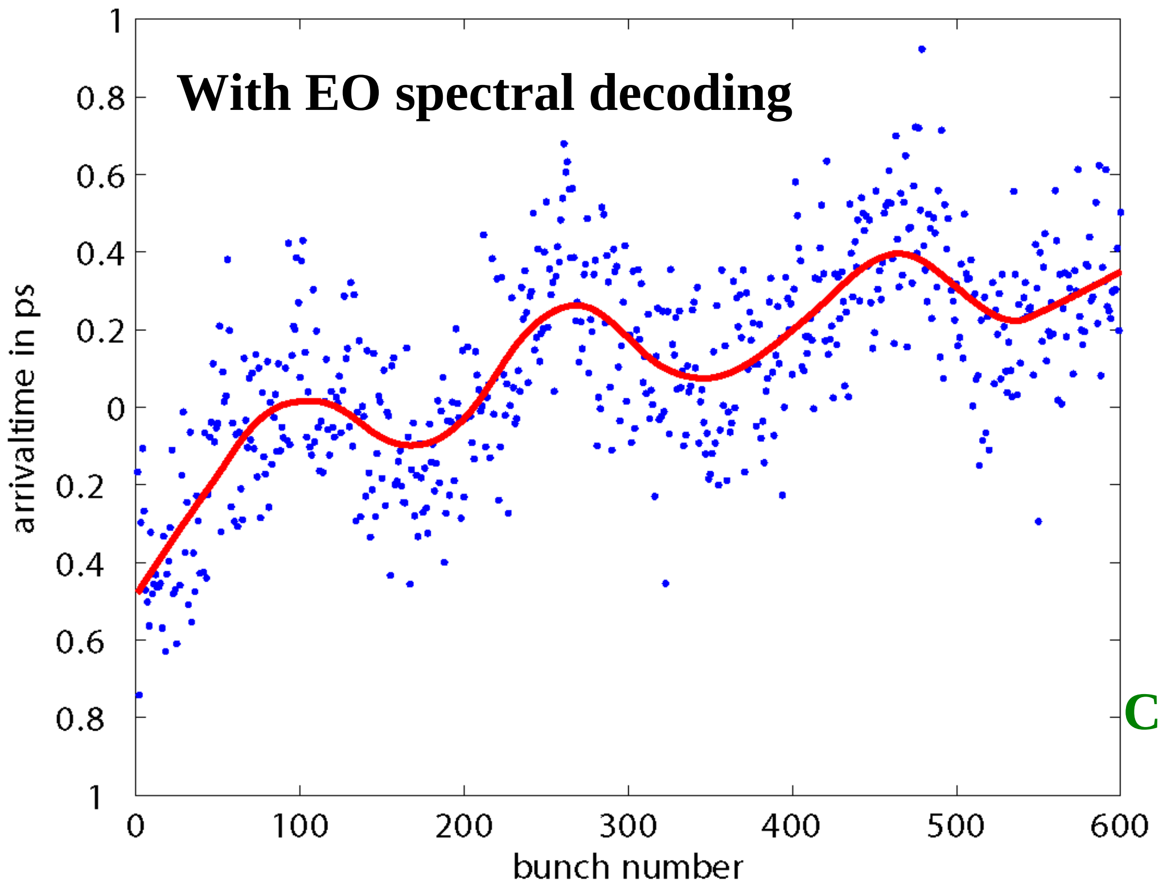


From BPM system easily sub 10fs resolution can be obtained

But! 1) RF cavity phase not known with sufficient precision

2) LO for phase measurement critical device!

Arrival time measurements



Courtesy B. Steffen

TiSa laser system is much better synchronized to reference RF (<30fs)

Timing jitter 300 sec ~ 270 fs (rms)

If correlation removed ~ 200 fs (rms)

Some conclusions:

- synchronization of the electron beam is dominated by RF stability of sections upstream of first bunch compressors (next generation LLRF controls + DCW)

- fs stability requires ~10-6 amplitude and 0.0001° phase stability

  ⇒ this is hopeless !

- laser system can be locked to reference with smaller timing jitter (< 10 fs feasible)

- remaining timing jitter need to be measured with high accuracy to timing reference system (e.g. for post-ordering, FB etc.)

How can we achieve better synchronization?

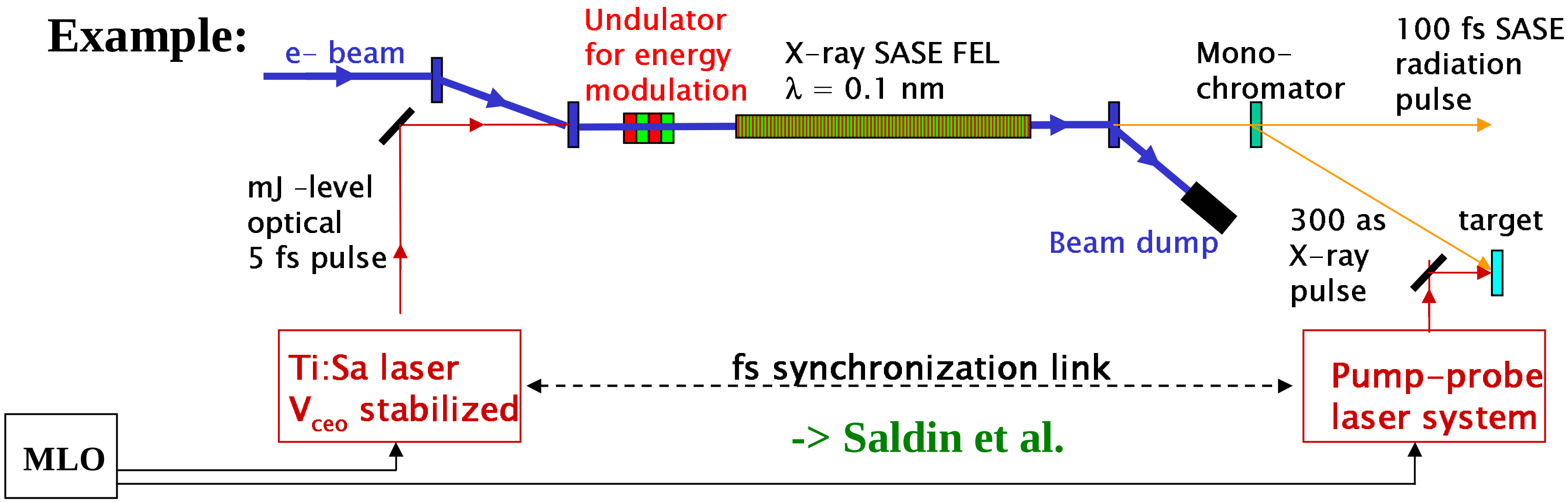
Attosecond synchronization!
- outlook & upgrade -

- always based on electron beam manipulation by lasers

Requirements:

1. Electron beam is synchronized to laser < σ_t ~ 30-60 fs
2. Manipulation laser to exp. laser on femtosecond level

Example:



Optical clocks for lasers: synchronized to 100as level within macro pulse (1ms)

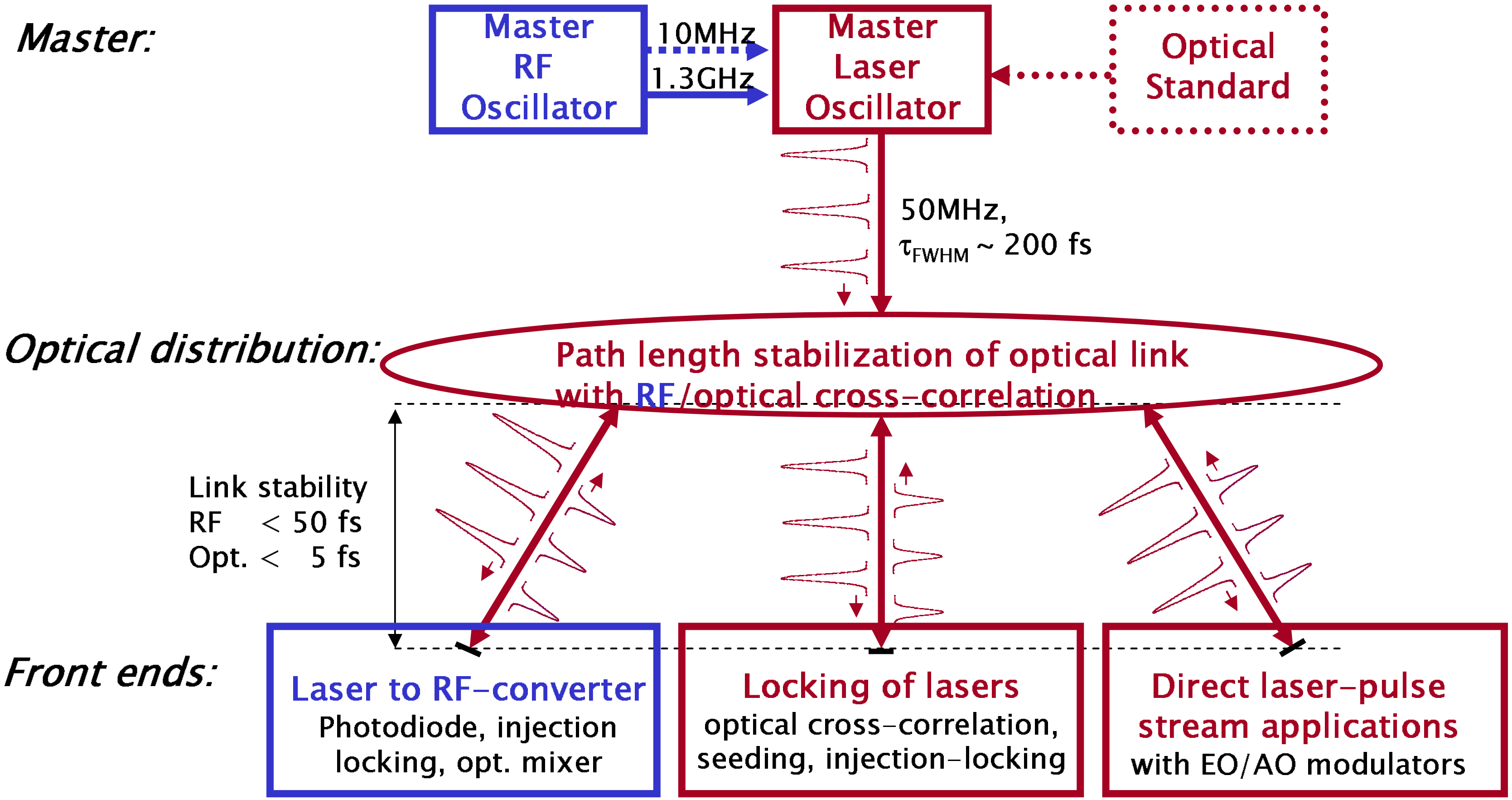
Avoids problems with vibration and diffuse ground motion (< 1kHz, 30ns=100as)

Fiber link operates at small unity gain frequency (10Hz) for resynchronization

Requirements on synchronization system

- It should serve as a timing reference to the XFEL, providing femtosecond stability between all significant points throughout the facility with small or negligible drifts over days and weeks.
- This reference system must be self-contained, without the need for re-calibrations.
- It must provide RF signals or the possibility to lock ultra-low-noise RF local oscillators to the timing reference at different frequencies,
- It must provide a mechanism to lock various laser systems, as in those used for electron beam generation, beam diagnostics, pump-probe experiments, seeding, and other applications.
- The system stability, robustness, and maintenance should not limit machine availability or delay commissioning.
- The failure modes should be transparent and allow for rapid repair and start up.
- The expenditures should be moderate and cost-effective.

Layout of laser based synchronisation



Applications:

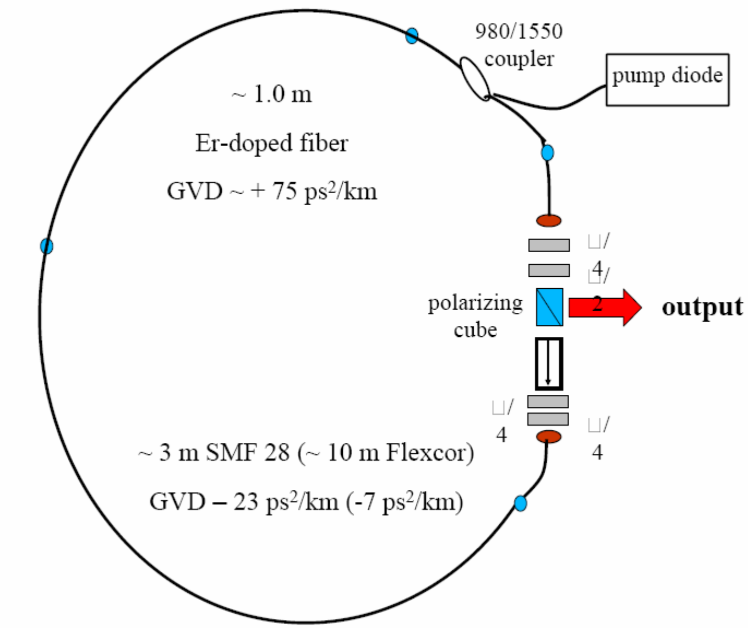
LO generation
- down converter LLRF
- PPL for synchronization
- RF signals for diagnostics

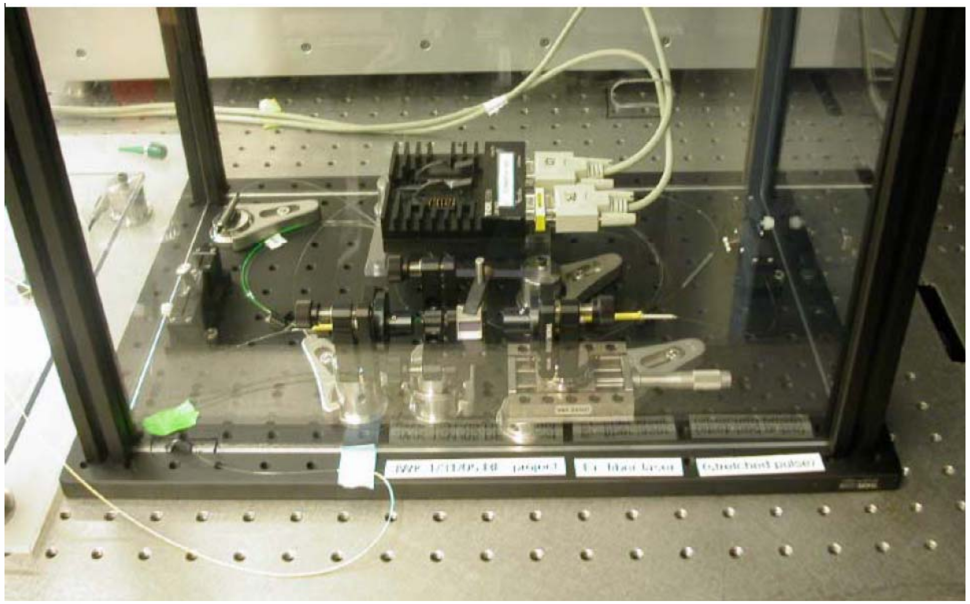
Lasers for
- photo-injector
- pump-probe experiment
- e-beam diagnostics
- e-beam manipulation

High precision appl.
- Beam phase monitor
- Laser phase monitor
- Optical down converter
- Chicane BPM

Master laser oscillator

- Dispersion managed soliton fiber-laser
- Fiber stretcher for passive mode locking to RF generator
- Gain medium Erbium, 1550 nm wavelength
- High output power up to ~ 1 nJ (50 mW average)
- Pulse duration ~ 100 fs FWHM
- Repetition rate ~ 50 MHz





www.bilkent.edu.tr/~ilday

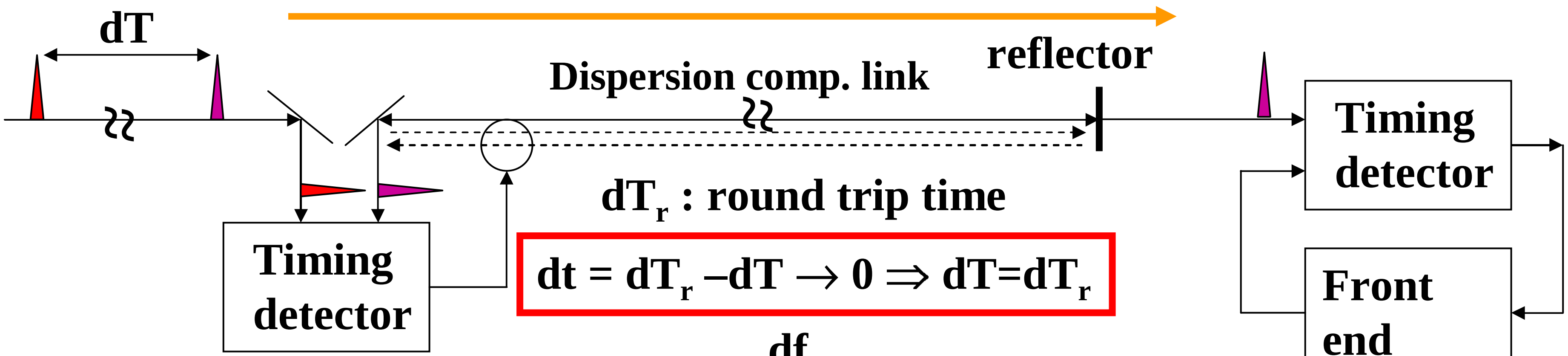
Courtesy: I. Ömer, A. Winter

Important characteristics

• 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

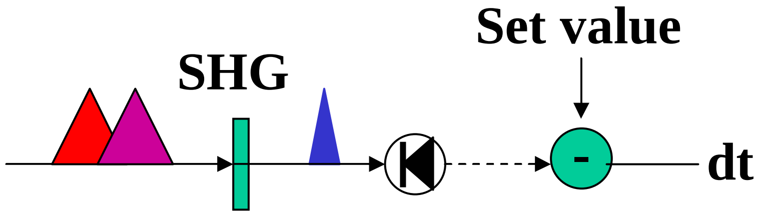


dT_r : round trip time

$$dt = dT_r - dT \rightarrow 0 \Rightarrow dT = dT_r$$

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

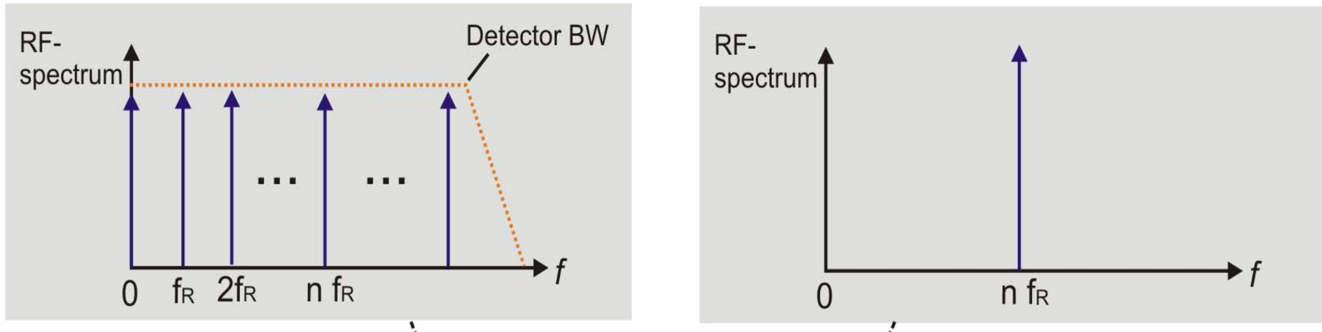
• timing detection to optical cross-correlation basically drift free ($<<\sigma_t$)!



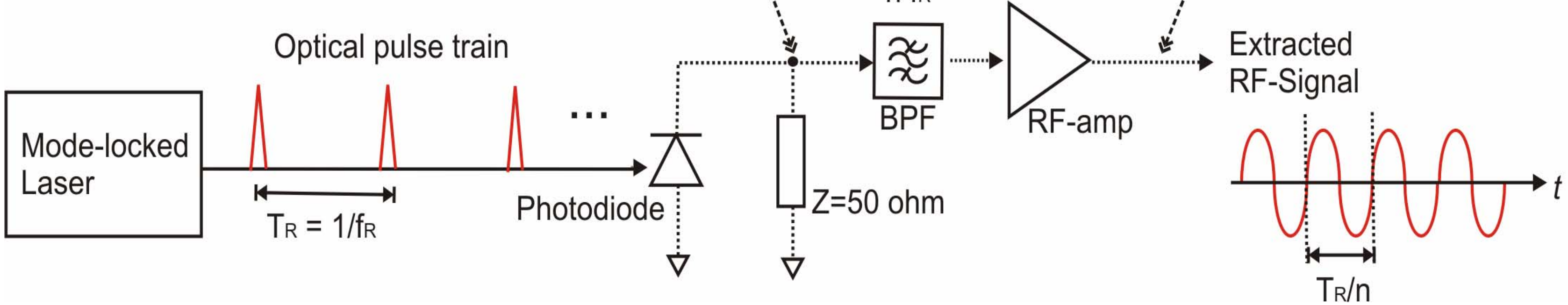
For stabilisation balanced setup is used!

Laser to RF conversion

Mode locked laser pulse train in frequency domain



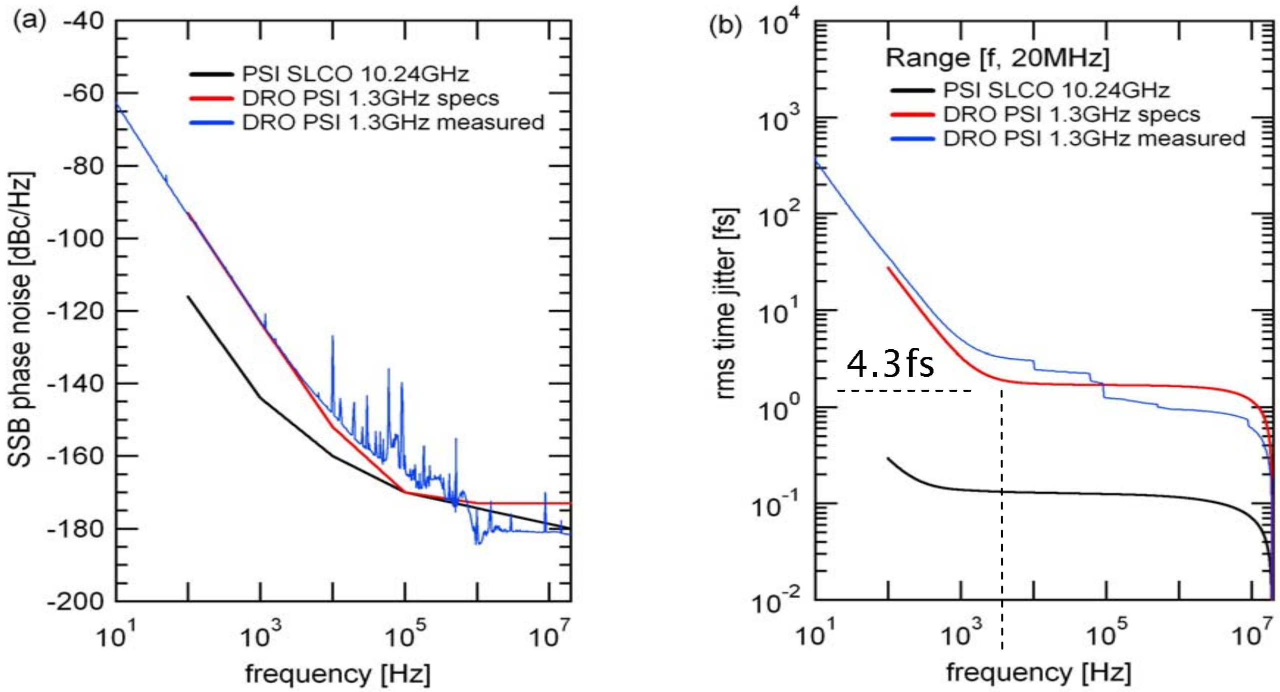
1) Direct conversion:



- **AM to PM conversion requires accurate stabilization of laser power (photo-detector 1 ps/mW @ 10mW -> dP/P < 10-3 for 1 fs)**
- **Drifts may critical to control since PD and Amplifier are out of loop**
- **Thermal noise limitation of PD due to limited output power (~10fs)**

Laser to RF conversion

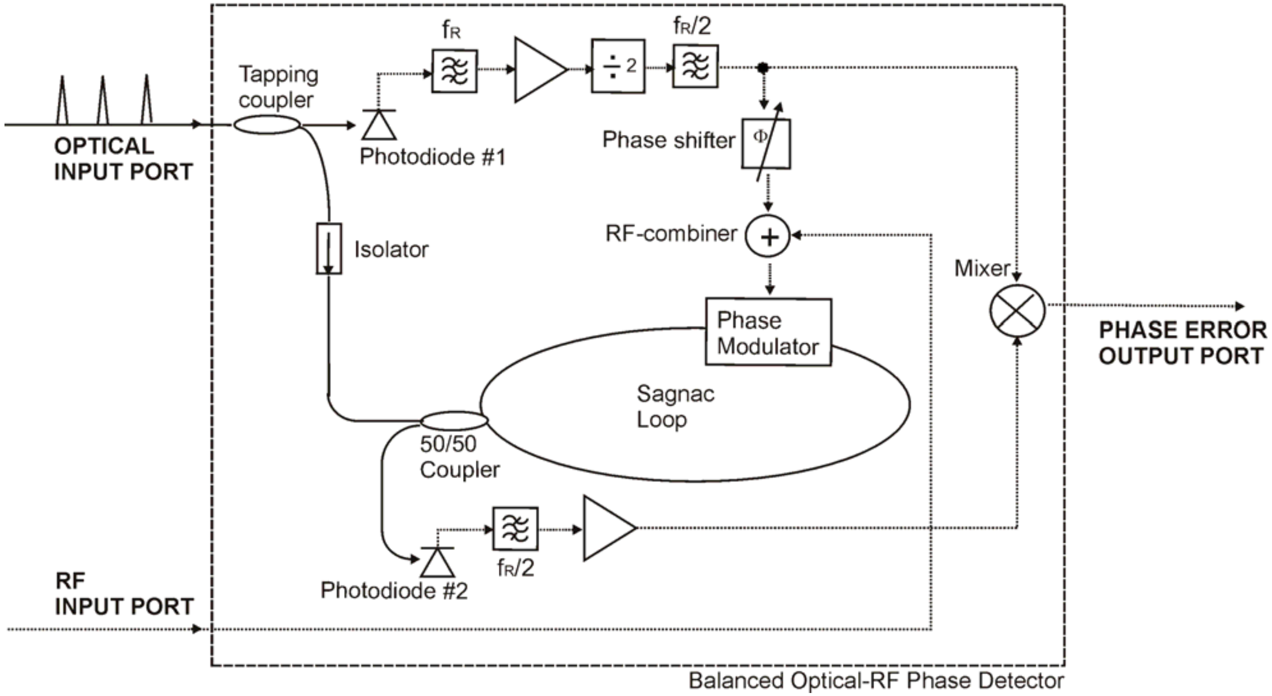
2) Injection locking



- Still rely on phase detection by photodiode (drift?, ampl. Stab. required)
+ Full PD output used
+ Thermal noise limiation at high offset frequencies given by DRO

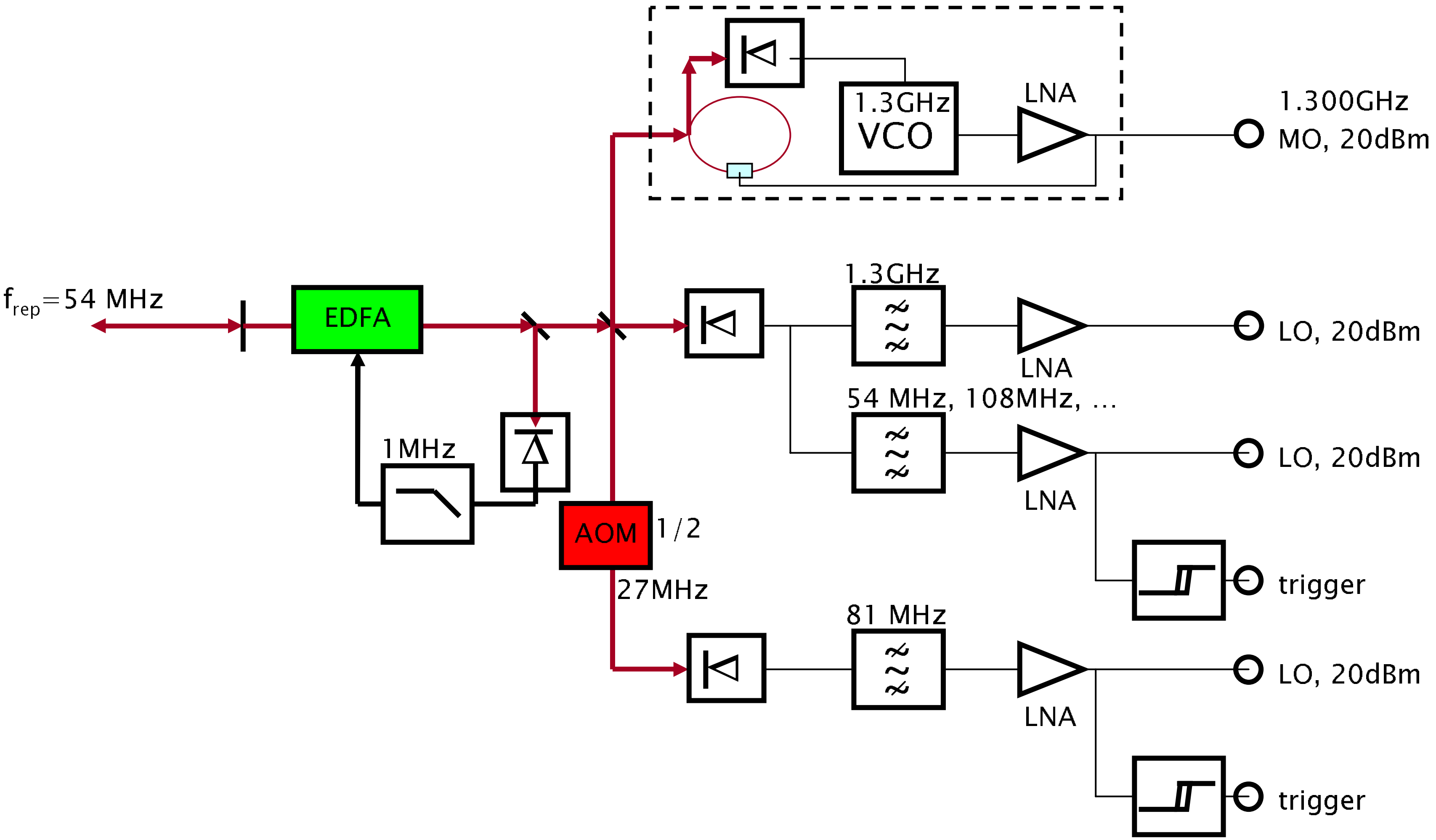
Laser to RF conversion

3) Balanced optical-RF phase detector



+ Does not rely on phase detection by photodetectors (EOM are used)
+ to first order gain and offset drifts are compensated
- More complex setup

Scheme of L2RF converters



Summary

- **laser based timing system has capability to synchronize various components in the linac to another with fs precision**

- **envision system is very flexible**

- **indivual parts have been demonstrated successfully**

- **reliability of a complete system needs to demonstrated!!!!!**

⇒ Installation of LbSynch at FLASH planned for 2007!