# *Timing and Synchronization*

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# Overview

- Timing Systems
  - Motivation for timing and synchronization
  - Architecture of timing system

- Phase Reference System
  - Signal Generation
  - Coaxial Distribution
  - Optical Distribution
  - Demonstrated Performance

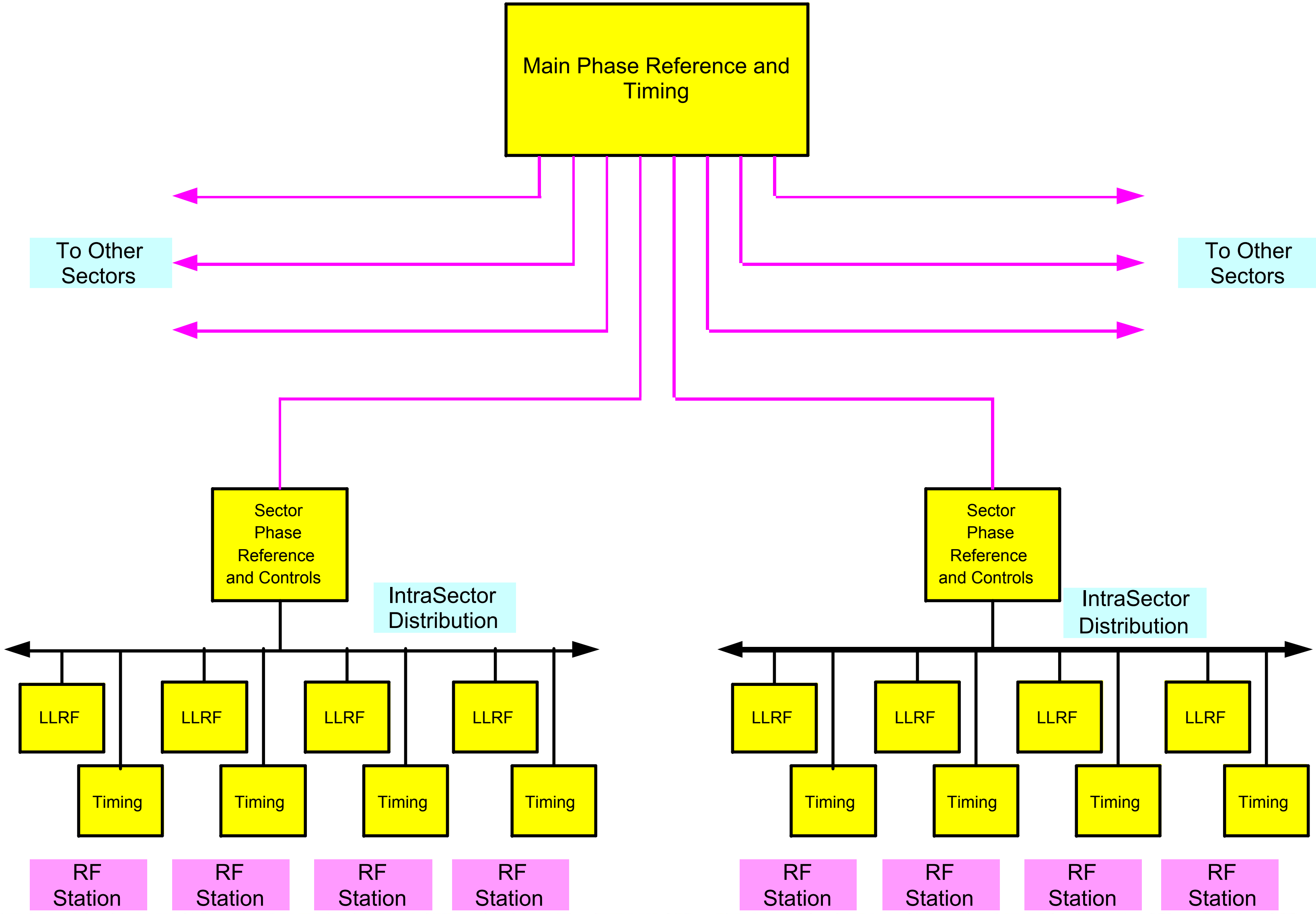
# Motivation

- Timing System
  - **Generation and distribution of event triggers to subsystems**
    … Includes time stamps, pulse IDs and data
  - **Generation and distribution of stable clocks signals**
  - **Subsystems include lasers, rf systems, beam diagnostics, and experiments**
  - **Typical stability of the order of ps (clocks) to ns (trigger)**
- Synchronization
  - **Generation and distribution of frequency references**
  - **Generation and distribution of ultrastable phase references**
    … as zero crossings of sine wave or as short pulses
  - **Subsystems include lasers, rf systems, beam diagnostics, and experiments**
  - **Typical stability of the order of fs (phase) to ps (frequency)**

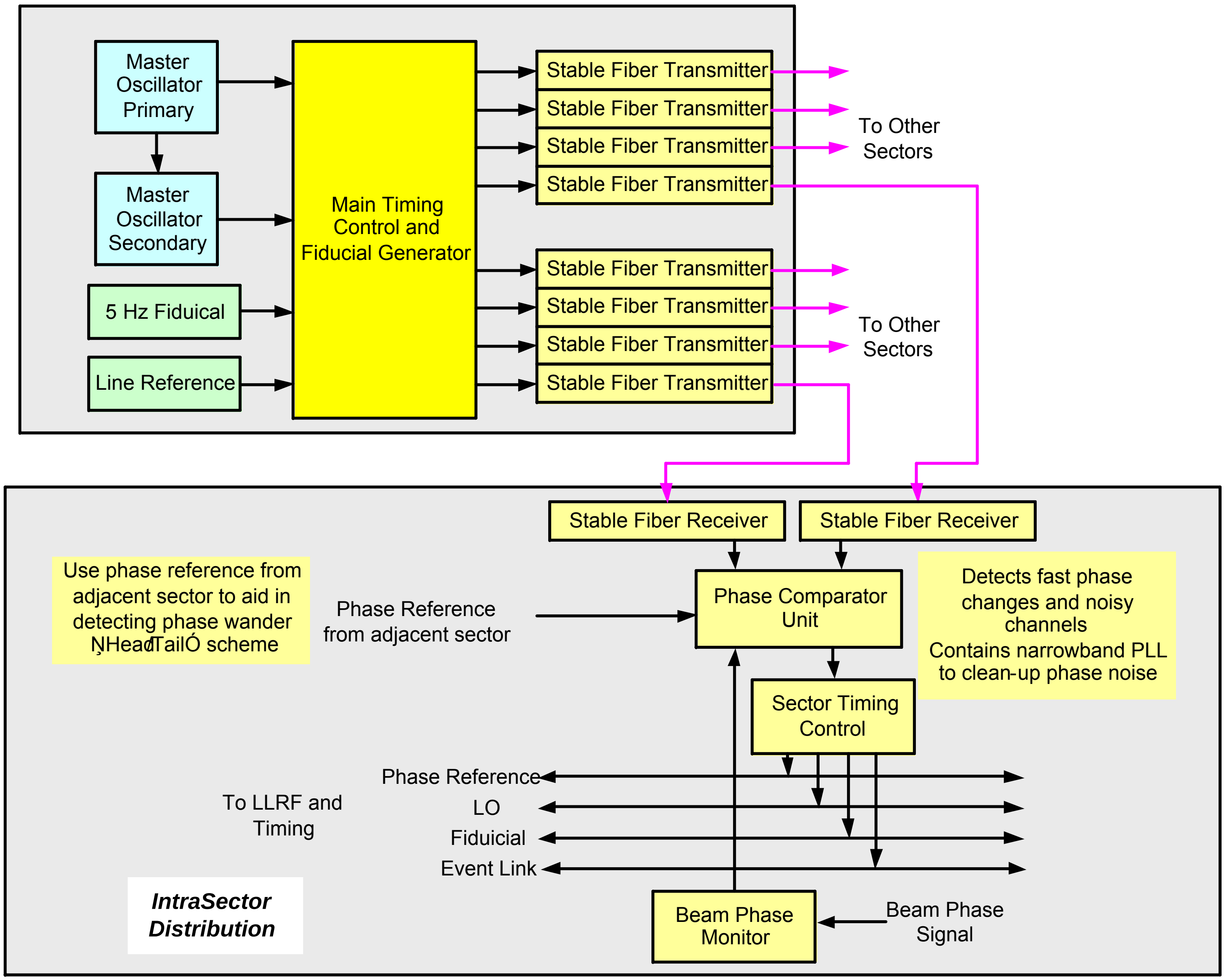
# Timing and Synchronization Needs

| | | accelerator sub-systems | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | LL RF | mag. & PS | undul. | diags. | timing | lasers | ctrl |
| accelerator sections | inj | x | x | | x | x | x | x |
| | low en linac | x | x | | x | x | | x |
| | bunch compr. | | x | | x | x | | x |
| | linac | x | x | | x | x | | x |
| | spread | | x | | x | | | x |
| | hν gen | | x | x | x | x | x | x |
| | beam lines | | | | x | x | x | x |

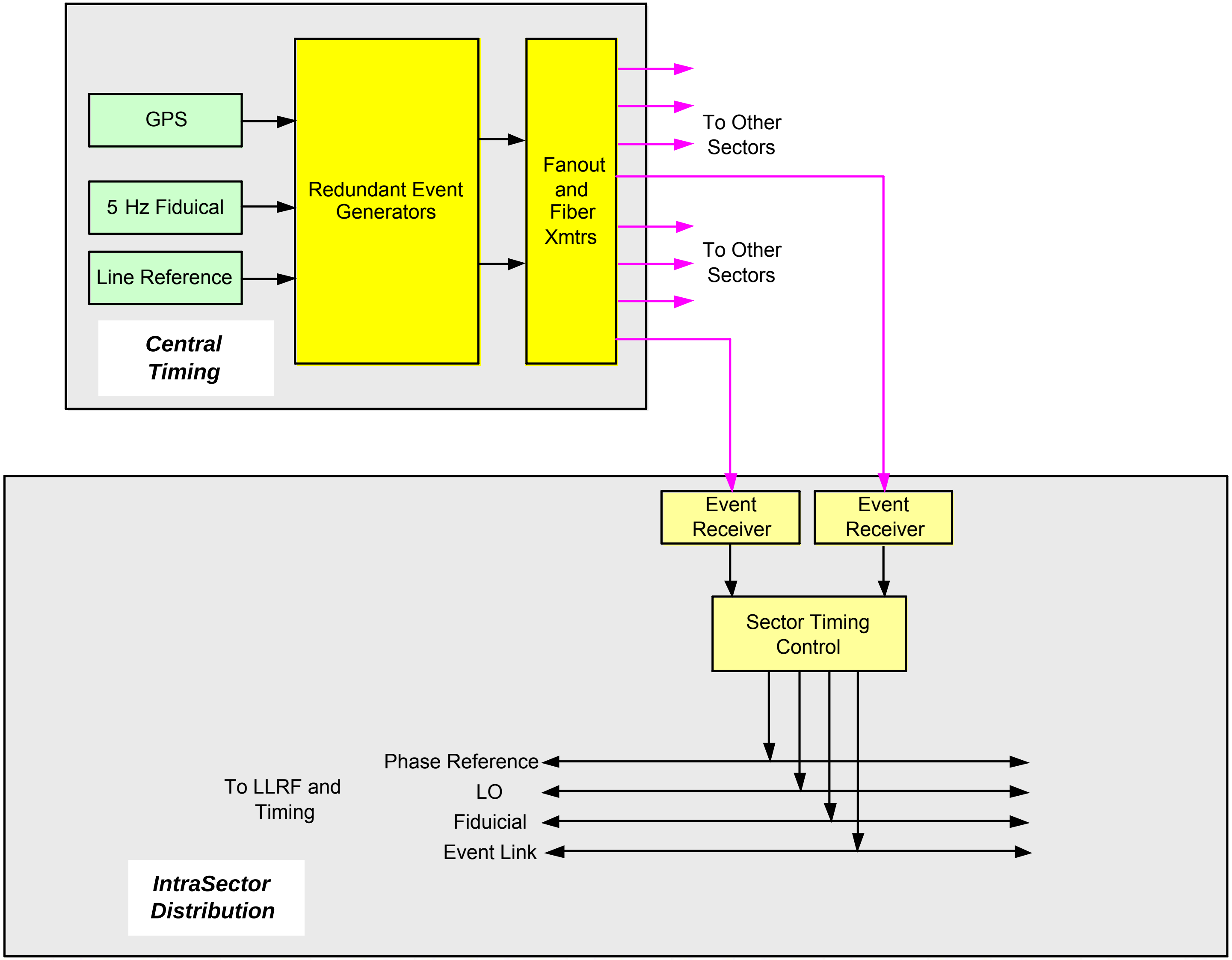
# Timing system overview



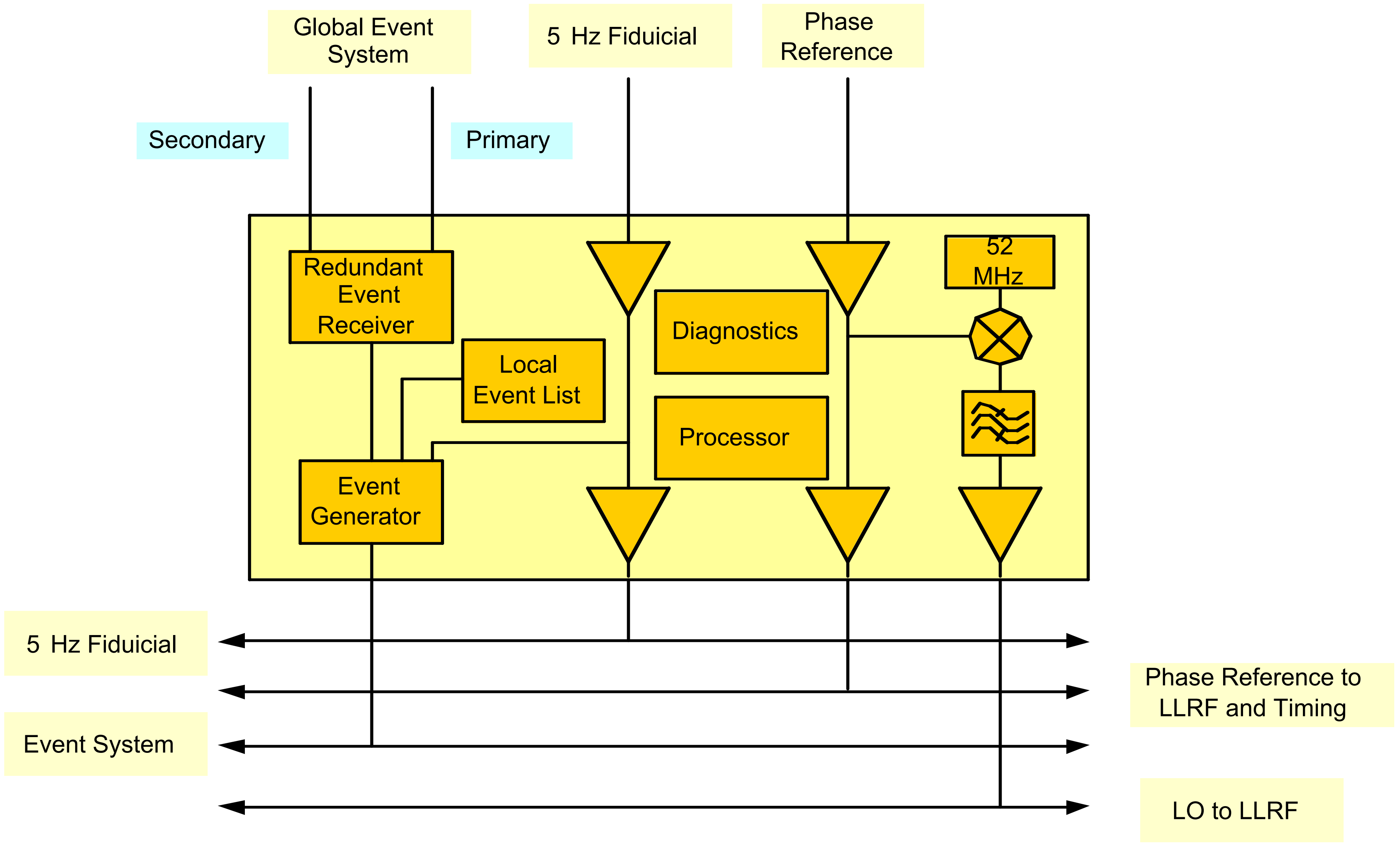
# Redundant reference transmission with failover



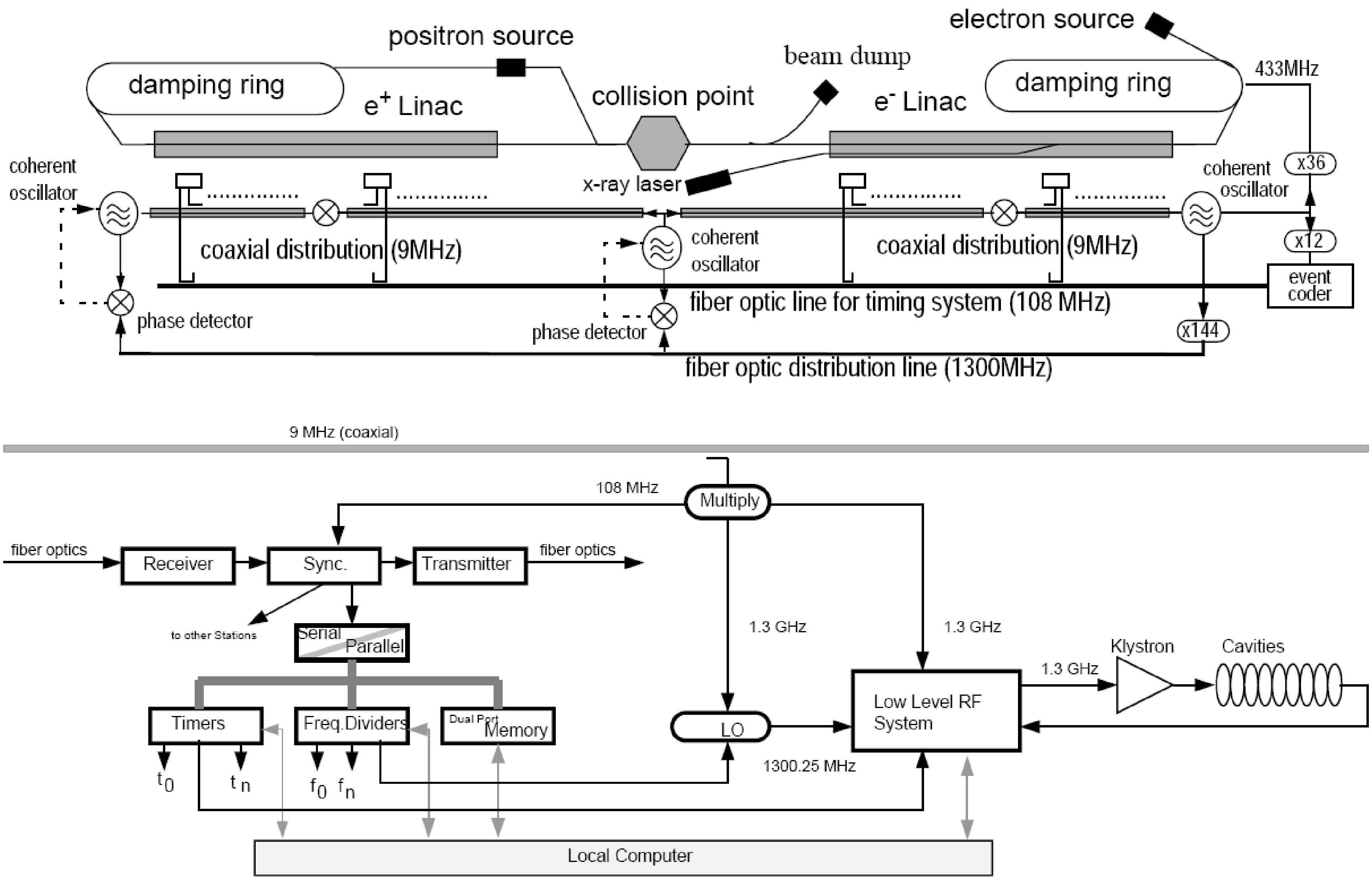
# Redundant event system distribution



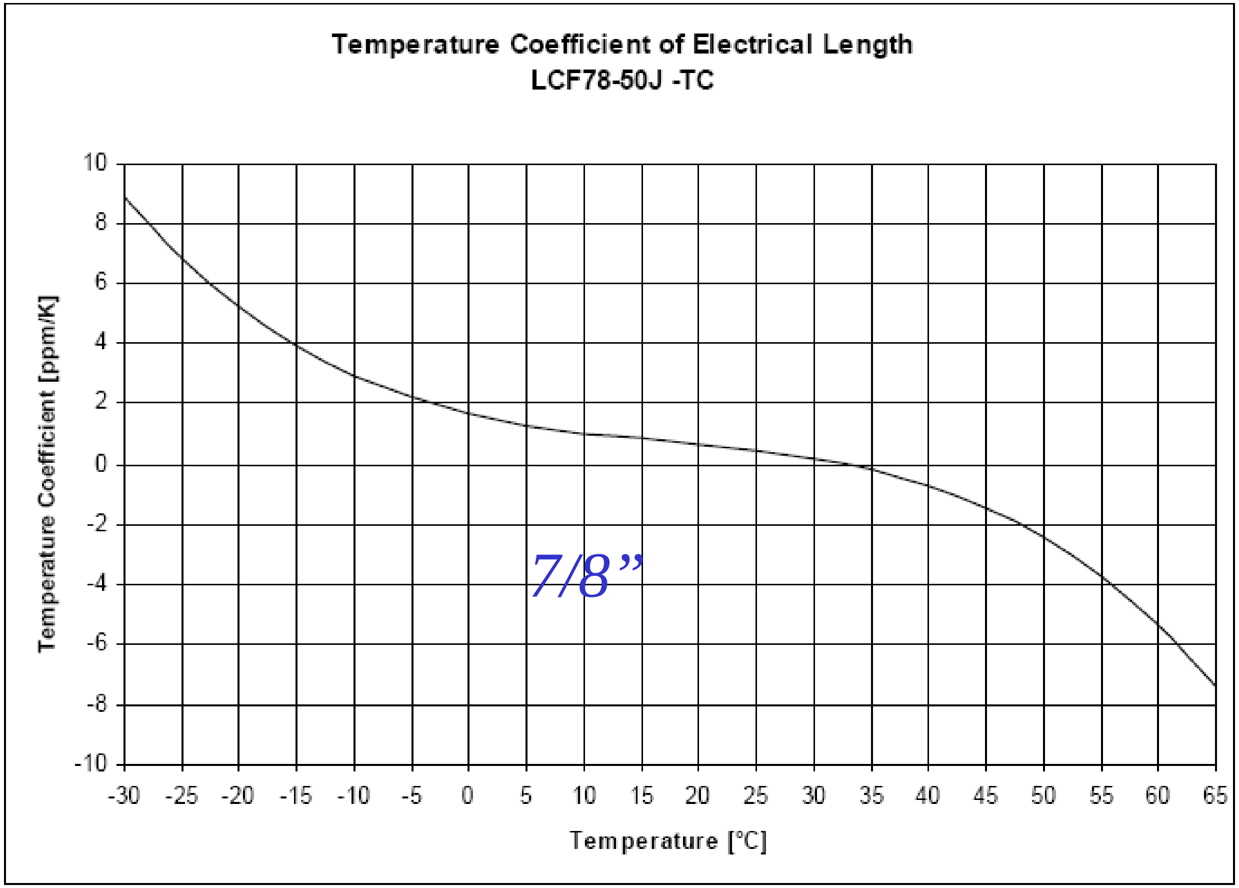
# Sector timing controller

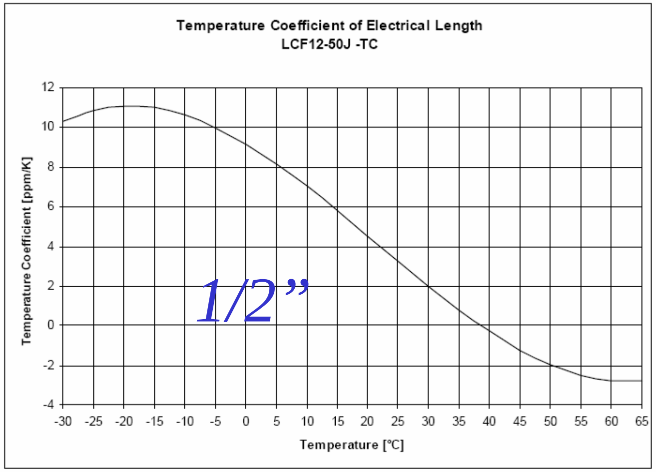


# Synchronization Concept TESLA (1996)

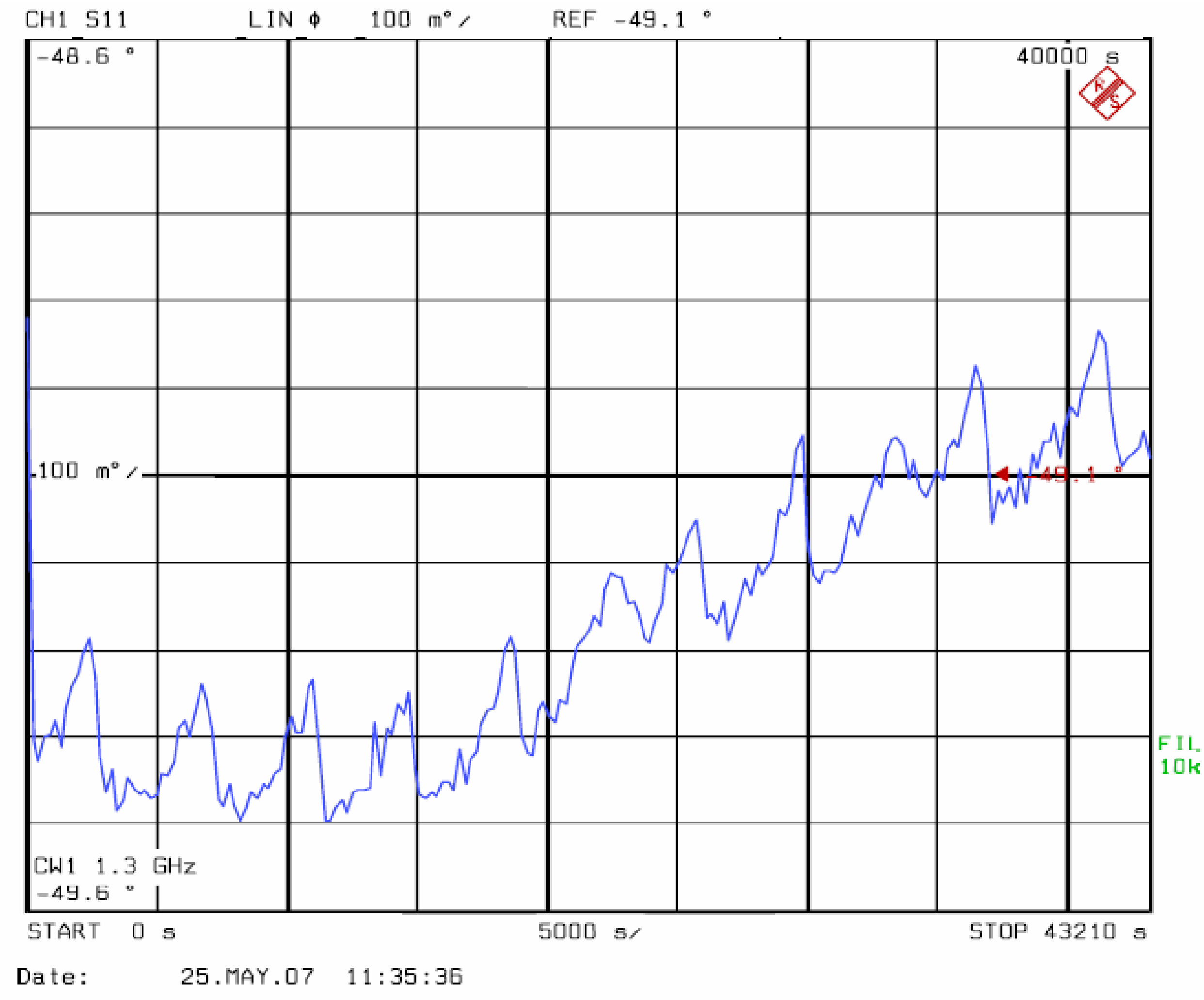


# Phase drift 7/8” and 1/2” Cellflex

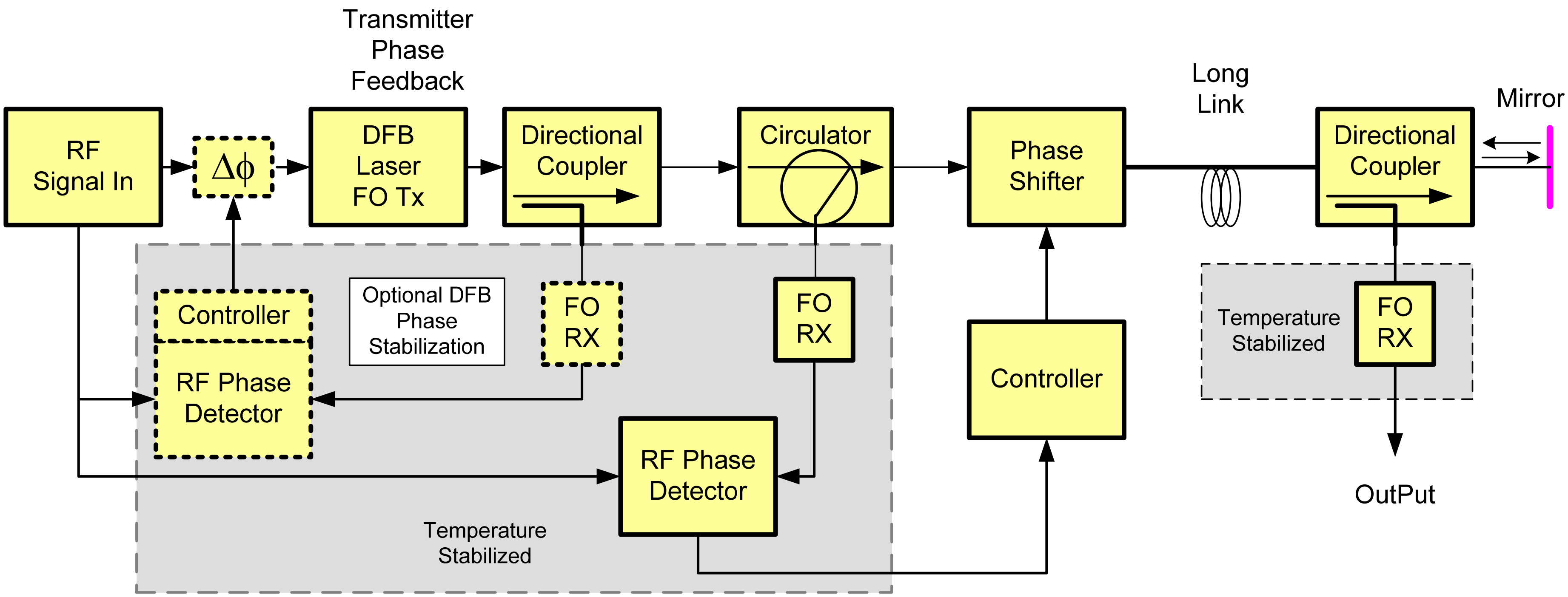


# Phase drift of 80 m 7/8" Cellflex cable



# Concept NLC 1999

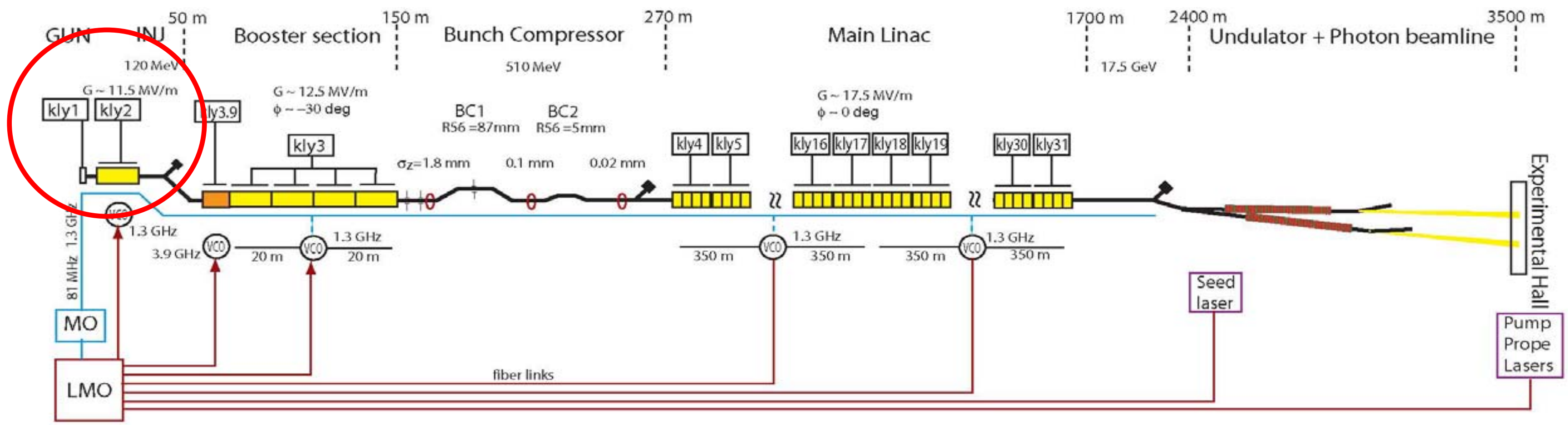


# *Why optical ?*

- **Advantages:**
  - **Optical generation and transmission with better jitter and drift performance.**
  - **Not susceptible to EMI**
  - **Ground loop avoidance**
  - **Free benefit: Some diagnostics are only possible with optical references**

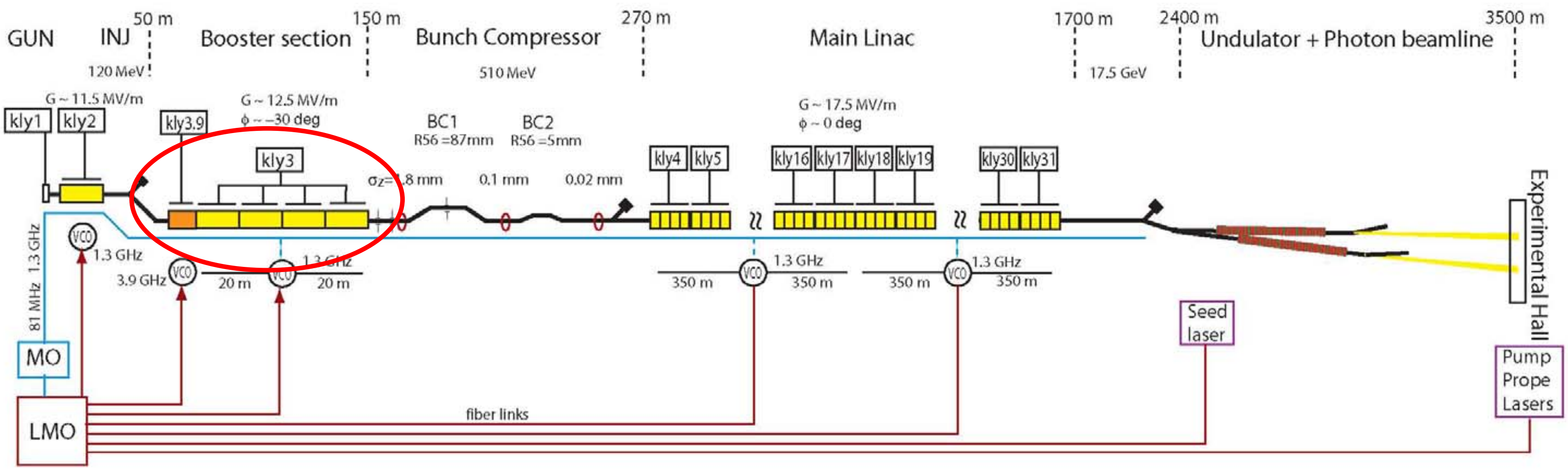
- **Disadvantages:**
  - **Only point to point links**
  - **More complex**
  - **Conversion to rf required**

# Concept of optical synchronization (XFEL)



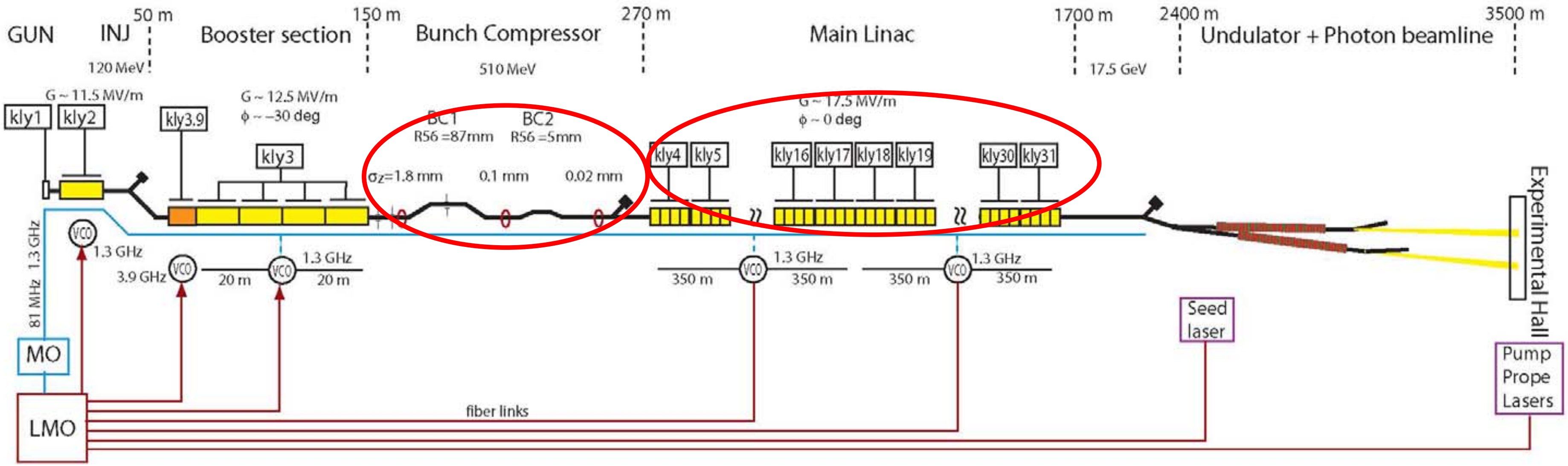

- Injector
  - Timing jitter of gun compressed by bunch compression ratio (~1/50)
  - Gun laser system can be locked optically to master laser
  - Amplitude/Phase stability critical in injector cavities (off-crest acceleration)

# Concept of optical synchronization (XFEL)




- Amplitude and phase stability crucial for final timing jitter of X-ray pulse
- Jitter of RF in cavities responsible for centroid energy jitter
- Direct transfer into timing jitter at bunch compressor
- Amplitude/Phase stability critical in booster cavities (off-crest acceleration)

# *Concept of optical synchronization (XFEL)*




- Main Linac
  - Amplitude stability: $10^{-3}$
  - Phase stability: 0.1 deg
- On-crest acceleration relaxes stability condition
- Coaxial distribution system for reference possible

# Timing jitter at exit of bunch compressor

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

Timing jitter behind BC — Gradient — Phase — Incoming Timing jitter

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

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

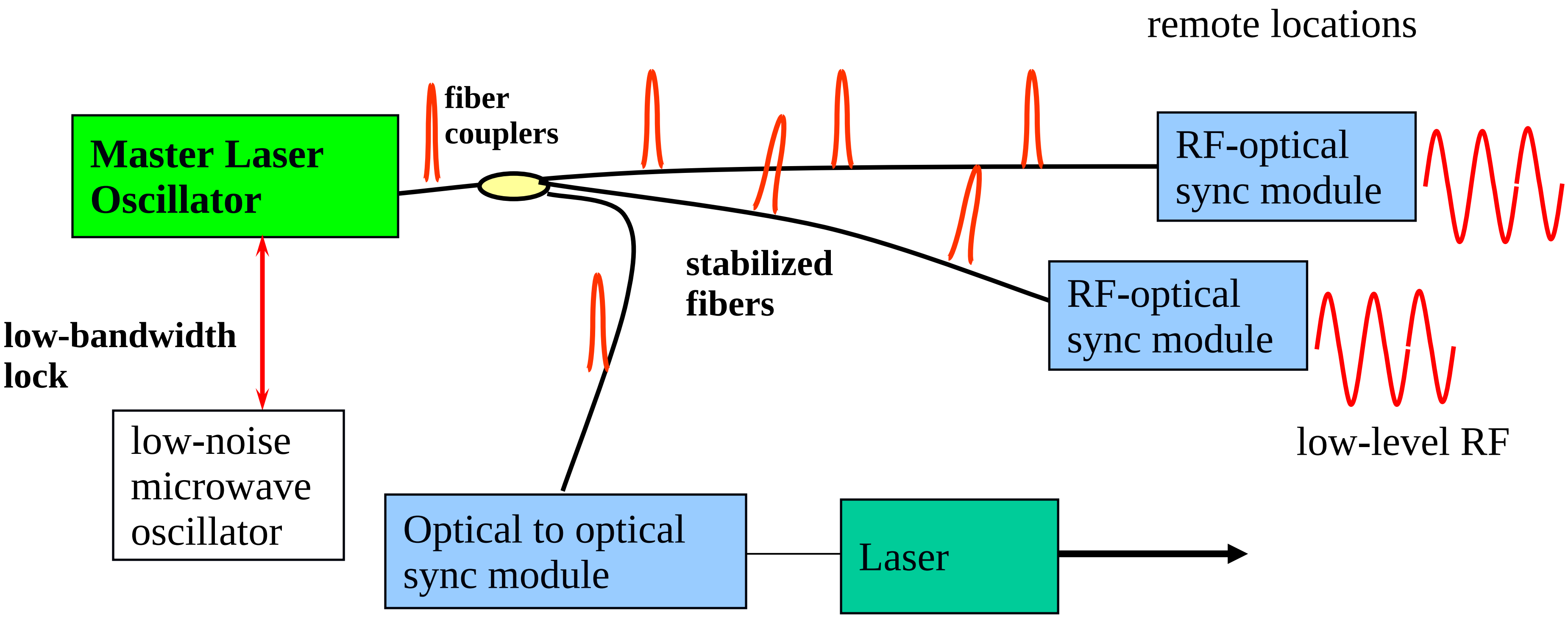
2 ps/deg

0.05 ps/ps

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

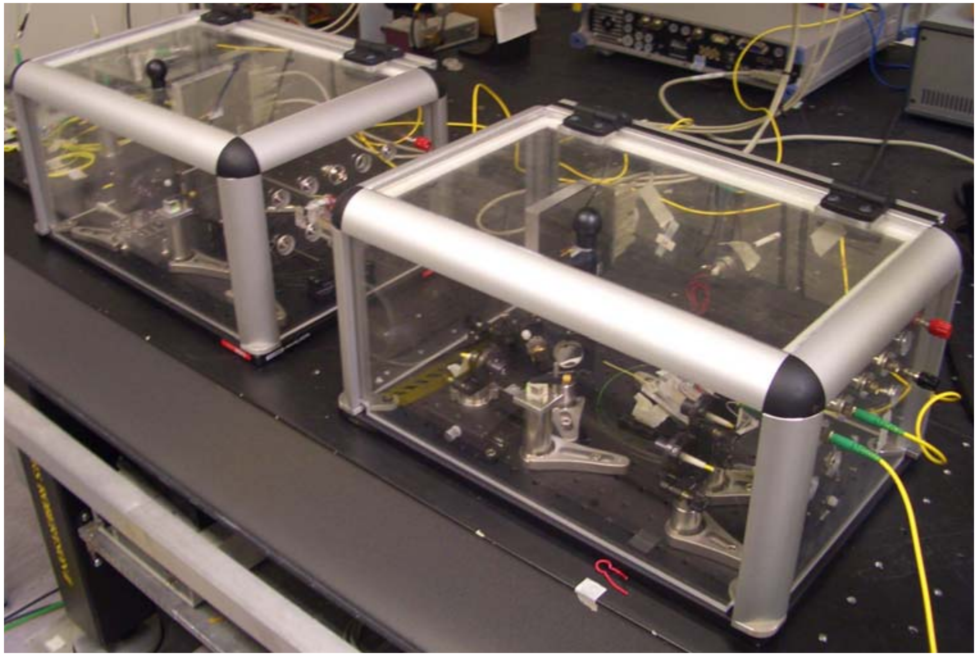
Vector sum regulation => 1 deg == 1.8% (statistic 32/8 cav. helps)
But! Phase changes can be correlated due to local oscillator changes

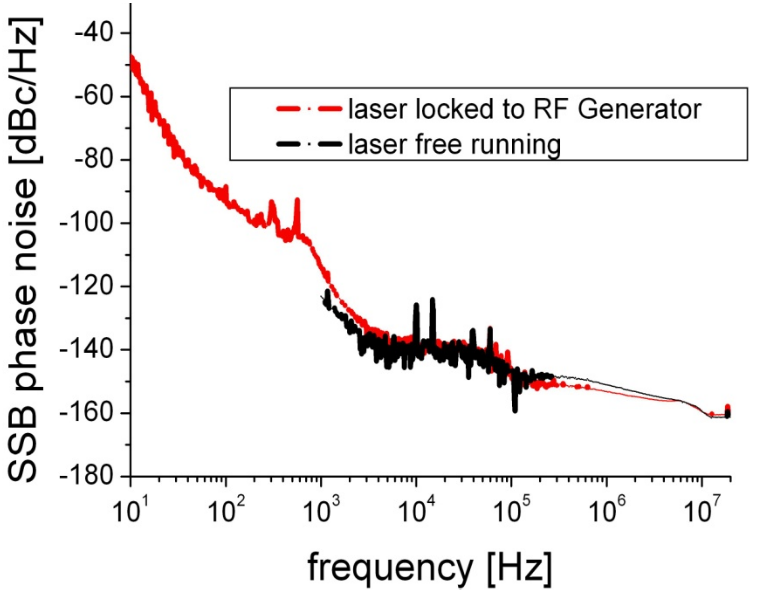
# Synchronization System Layout

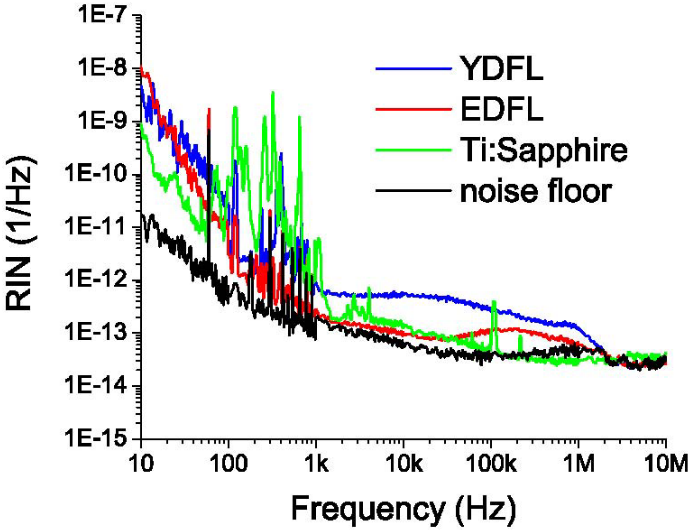



- A master mode-locked laser producing a very stable pulse train
- The master laser is locked to a microwave oscillator for long-term stability
- length stabilized fiber links transport the pulses to remote locations
- other lasers can be linked or RF can be generated locally

# *Laser Oscillator synchronized to MO*

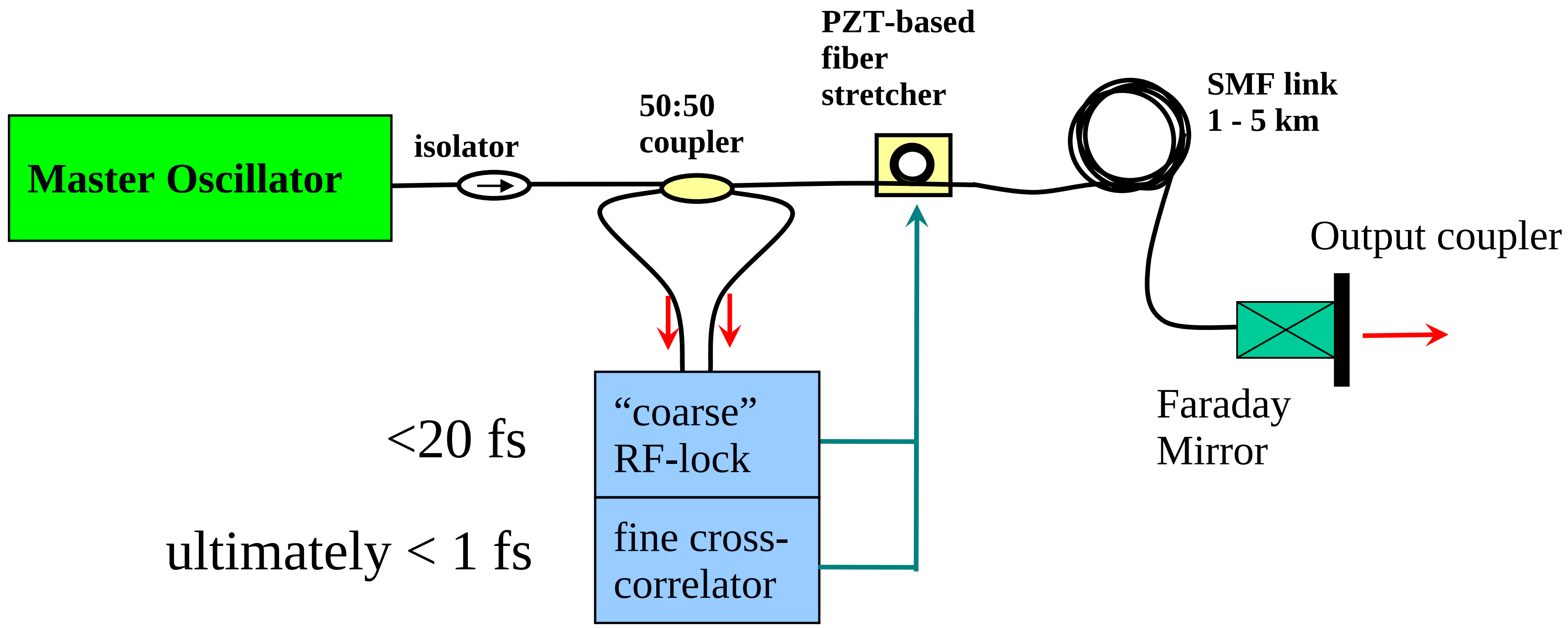




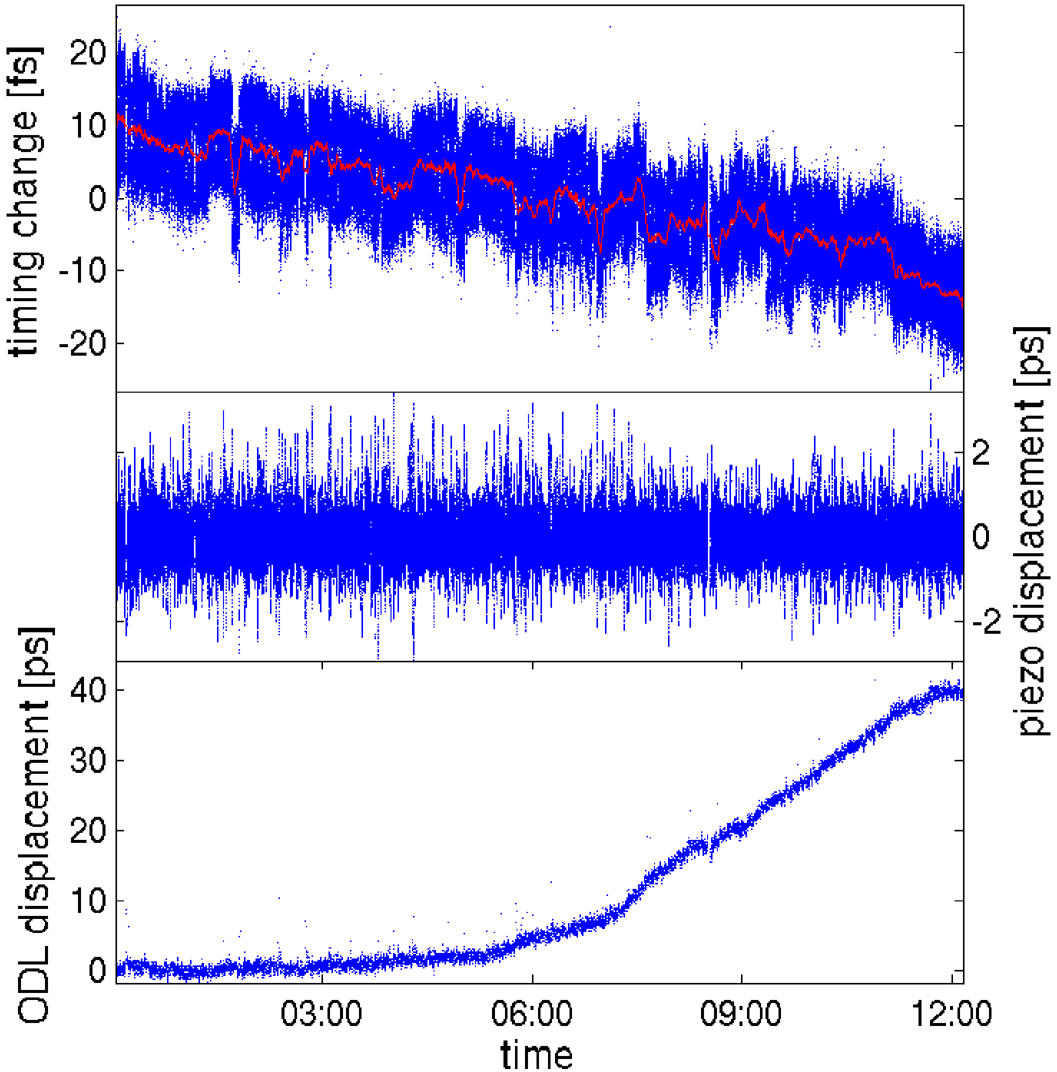

- Mode locked laser emits femtosecond laser pulses
- High pulse energy (~ 1 nJ)
- Pulse duration: ~ 100 fs FWHM
- Repetition rate: 30 -100 MHz
- Integrated timing jitter (1 kHz – 20 MHz) ~ 10 fs
- Integrated amplitude noise (10 Hz – 1 MHz): 0.03 %

# *Timing stabilized fiber links*




- Transmit pulses in dispersion compensated fiber links
- No fluctuations faster than T=2nL/c (causality!)
- L = 1 km, n = 1.5 => T=10 µs, $f_{max}$ = 100 kHz
- Fiber temperature coefficient: ~5x$10^{-6}$ /m     Lee et al. Opt. Lett. **14**, 1225-27 (1989)

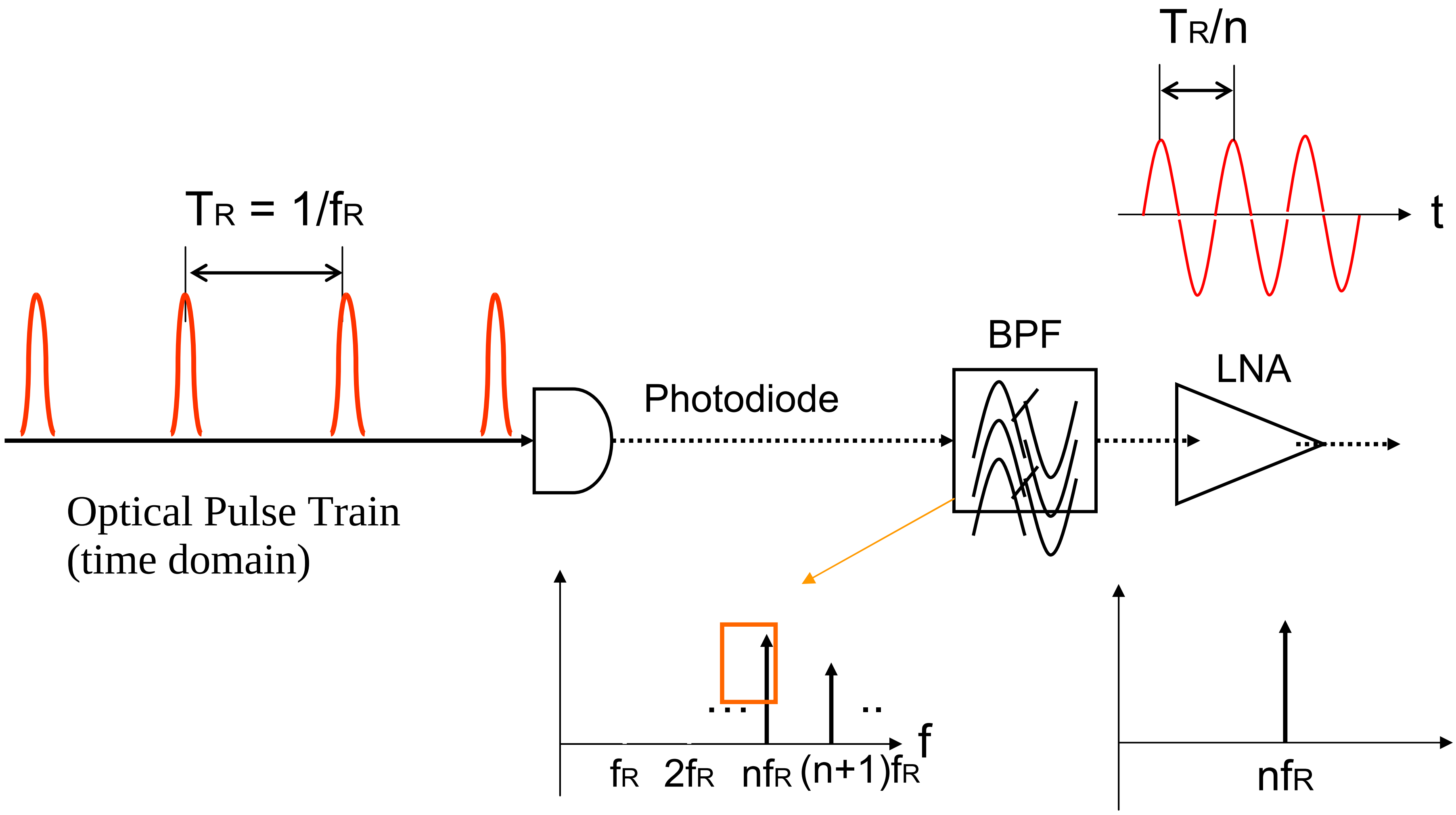
# *Fiber link stabilization*



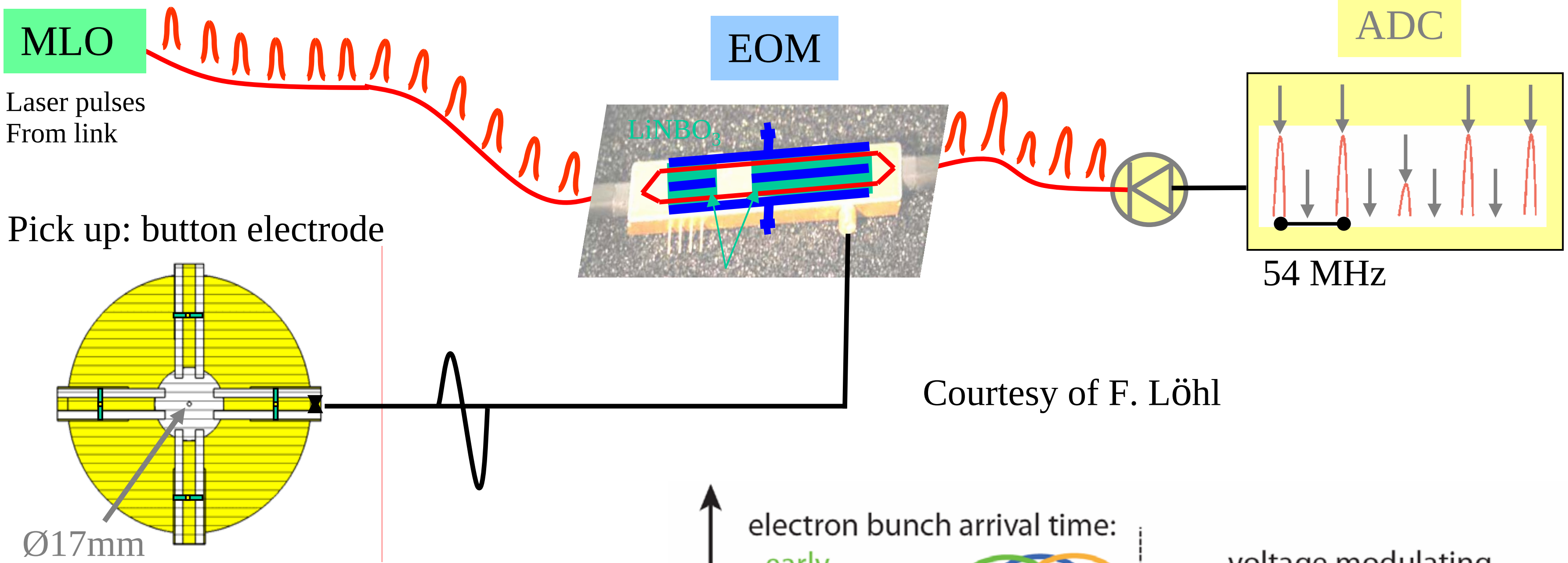

- 400 meter stabilized test link in Hall 1 at DESY
- Jitter 7.5 fs rms during 12 hours
- Additional 25 fs rms drift during that time

Courtesy F. Loehl, DESY

# Photodetection to extract RF from pulse train

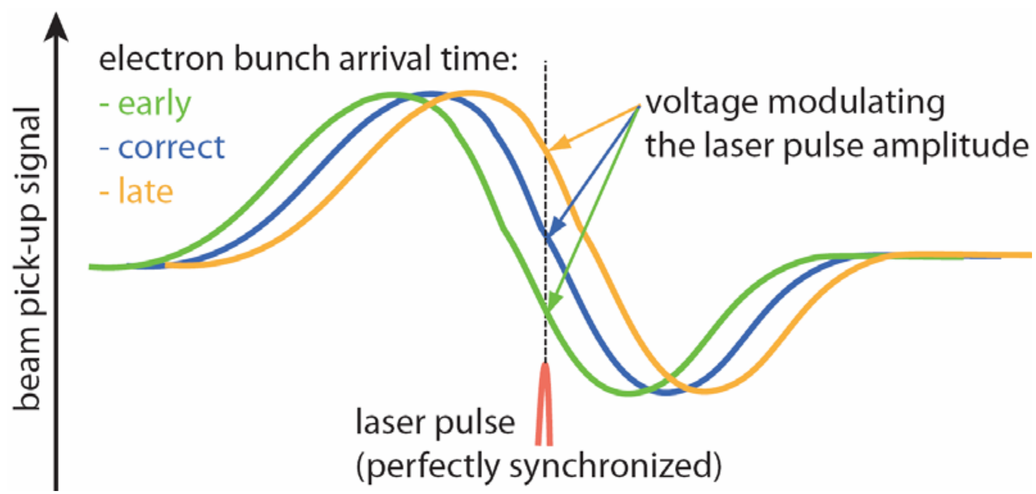


# Bunch Arrival Time Monitor (BAM)




Courtesy of F. Löhl

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.



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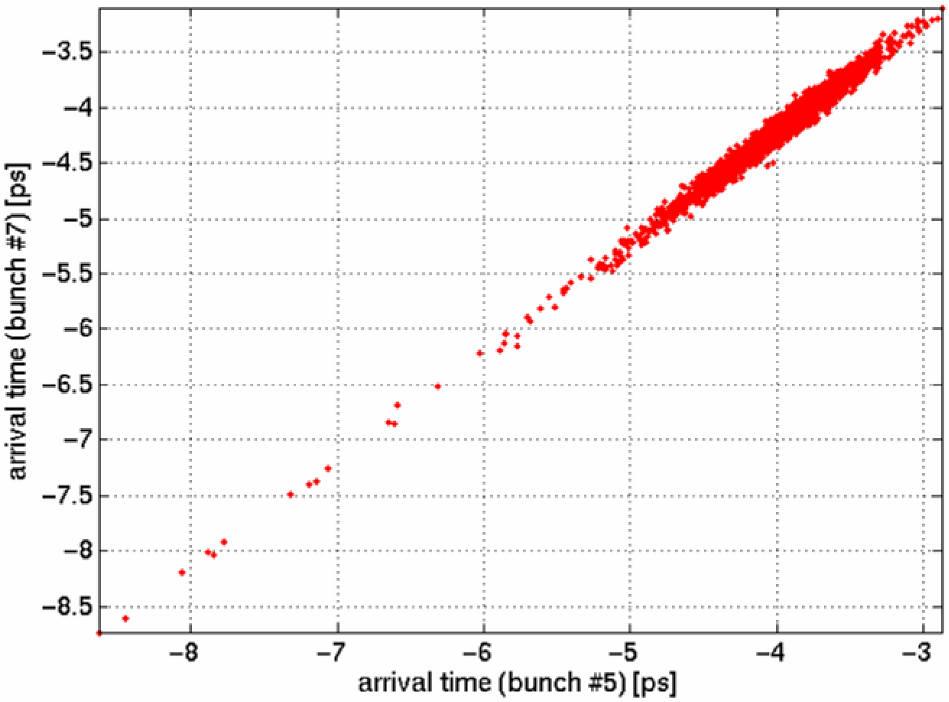


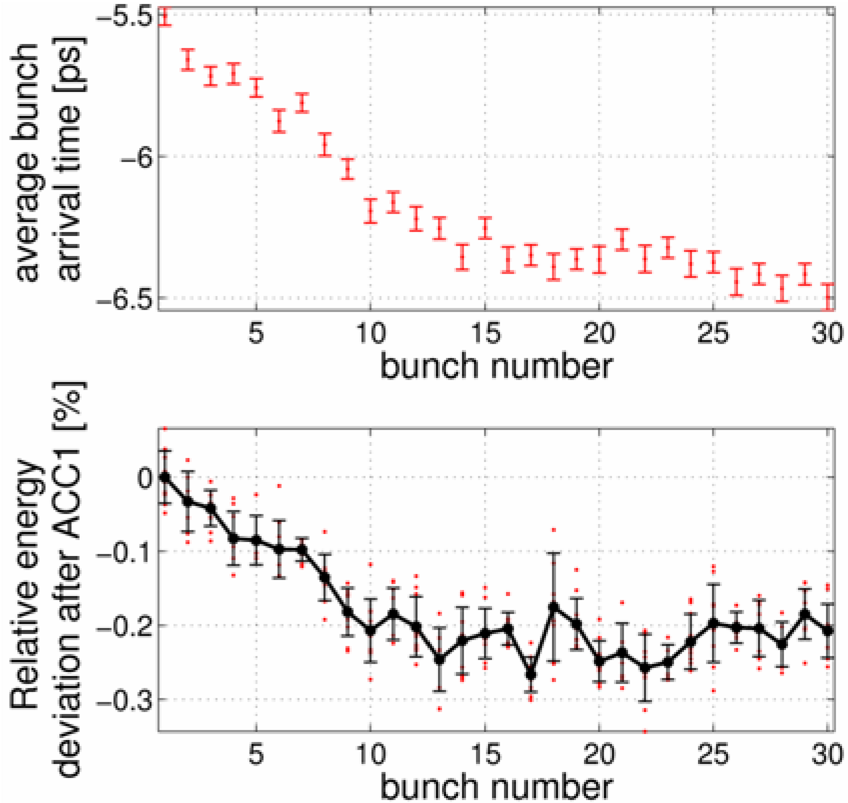


Jitter between two adjacent bunches: ~ 40-50 fs
Timing resolution with respect to reference laser: < 30 fs

- Arrival time measurement for all bunches in the bunch train possible!
- Prime candidate for implementation into feedback system

# Demonstrated timing stability

| item | dev. at | value [$fs_{RMS}$] | bandwidth | notes |
|---|---|---|---|---|
| **μ-wave ref. osc.** | off-the-shelf | <10 | 100-10MHz | $f_C$=10GHz |
| **Optical Master Clock** | MIT/<br>DESY | 10<br><20 | 1kHz-Nyq.<br>1kHz-Nyq. | Er Fiber laser<br>Er/Yb glass laser |
| **Fiber Optic stabilized link** | MIT field test at MIT-BATES | 12 | 0.1Hz-10kHz | group delay stabilization |
| | LBNL | <2/°C<br>0.1/h | L=200m<br>long term drift | phase delay stabilization |
| **RF over FO trans-mission** | MIT | 8.8±2.6 | 1Hz-1MHz | Optical to RF conversion |
| | LBNL | 15 | 1kHz-40MHz | 11fs noise of the RF source |