

# State of the art in High-Stability Timing, Phase Reference Distribution and Synchronization Systems

*Mario Ferianis - Sincrotrone Trieste S.c.p.A, Italy - WE3GRI02*

- Recent advances in **high-stability electronic** and **electro-optic timing** and **synchronization** systems are presented. These systems have been proposed for several **new FEL facilities**, and are in development at several labs.
- Several basic technical implementations are in development, some based on **pulsed mode-locked laser** technology, others using **CW systems**. There are numerous technical choices with regard to the **stability**, **synchronizability**, **capability of multi-drop operation**, **availability of inherent diagnostic information**, **complexity of transmitters vs. receivers**, use of **commercial vs. custom-designed** components, etc.
- This talk presents an **overview of the basic timing and synchronization requirements** in accelerator systems, and **reviews the state of the art**. Contrasts are made between the **CW** and **pulsed optical distribution** approaches.
- The technology in development to distribute a **38GHz phase coherent LO** at the ALMA radio telescope is highlighted as a related technical system in development.

## Timing &amp; Synchronization (T&amp;S) systems

- In 4th Generation Light Sources (4GLS) the required jitter is as low as  $<10\text{fsec}_{\text{RMS}}$  (*it is few ps in 3GLS*)
- In 4GLS T&S systems we have:
  - **Timing** generates the Bunch Clock
  - **Phase Reference** represents the Ref. at the bunch level
  - **Distribution** delivers to the end user the two above
- The **jitter** of a *periodic signal* can be defined as the measurement of *its time fluctuations*, measured over a certain observation time and wrt a phase reference
- It is relative to fast fluctuations which may occur at various frequencies
- In the frequency domain, it is referred to as: *Phase Noise*
- **Drift** is related to *slow time fluctuations* of the signal wrt the reference
- In a T&S system, drift may be caused by changes in:
  - **propagation time** (temperature dependant) in the distribution system
  - **reference frequency** (stability of the master oscillator)
- Drift is related to the *stability* of the T&S system

*recent book: Phase Noise and Frequency Stability in Oscillators*  
E. Rubiola, FEMTO-ST Institute, Université de Franche Comté, Besançon

## 2009 Joint Meeting of the European Frequency and Time Forum and the IEEE International Frequency Control Symposium

20 to 24 April 2009

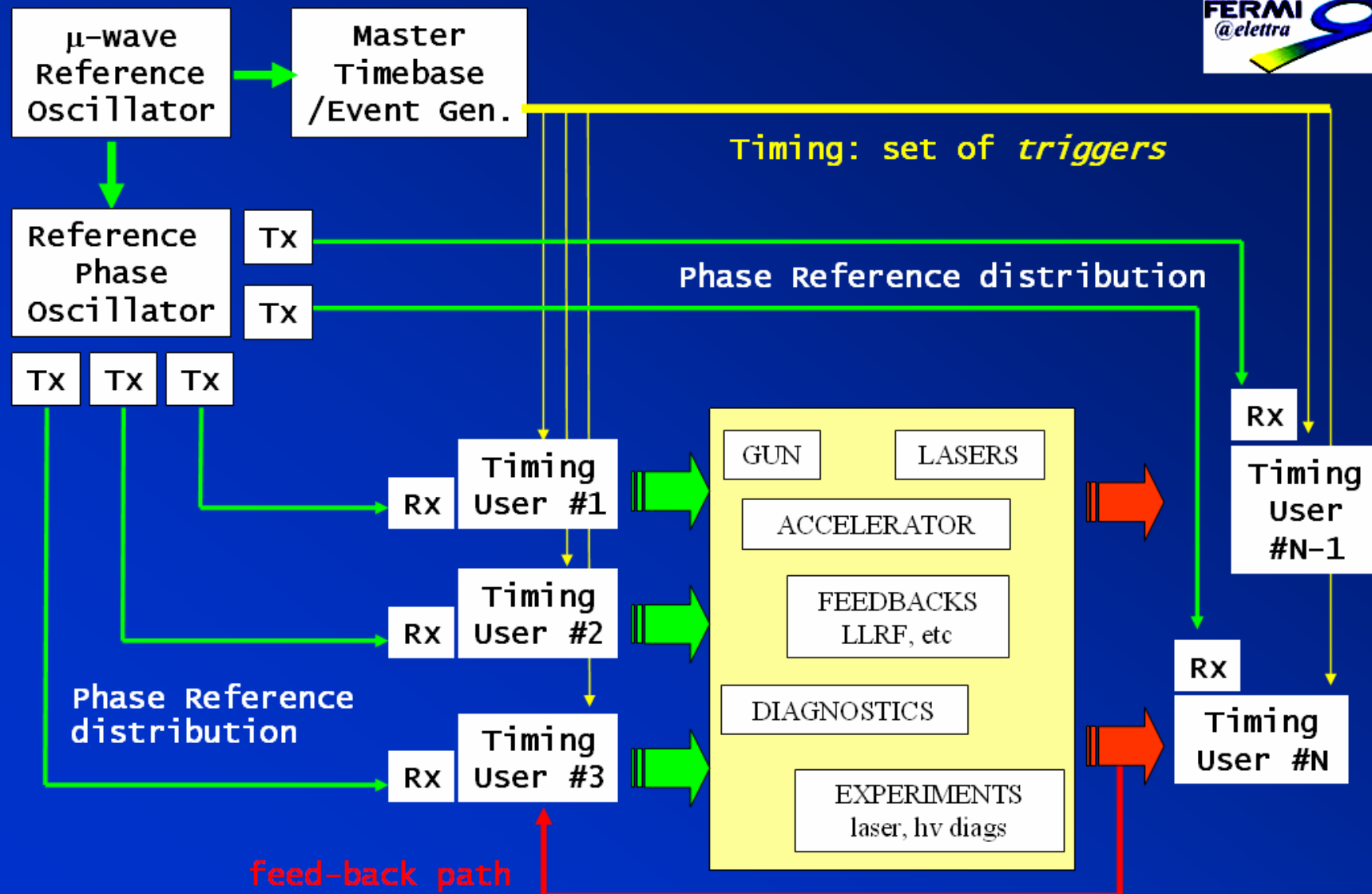


<http://www.eftf-ifcs-2009.com/index.html>



Courtesy of Jesse Searls, Poseidon S.I. ltd





To develop fsec T&S systems: moving to Optical / O/E techniques

A fsec Timing & Synchronization system has:

- to meet the **demanding specifications**:
  - **jitter**
  - **drift**
  - **T&S clients distributed over the whole facility** ( extension  $\cong$  km)
  - **to be remotely controllable** (*Control System integrated*)
  - **rad-hard** (at least for some sub-systems)
- to **reliably operate**: T&S systems are deployed in Facilities (24h-7d)  
need to use engineered sub-systems:  
(**true for Telecom components**; table-top sub-systems ?)
- **cost** could also be an issue (*Fiber Optics are cheap, fsec are not*)
- to be “easily” **upgradable** (considering here also system **maintenance**)
- to make our job easier, these systems typically operate in a protected, quiet (**vibration free**) and **temperature controlled** ( $\Delta T \leq 1^\circ\text{C}_{\text{pk-pk}}$ ) environment

# To measure & characterize a fsec T&S system

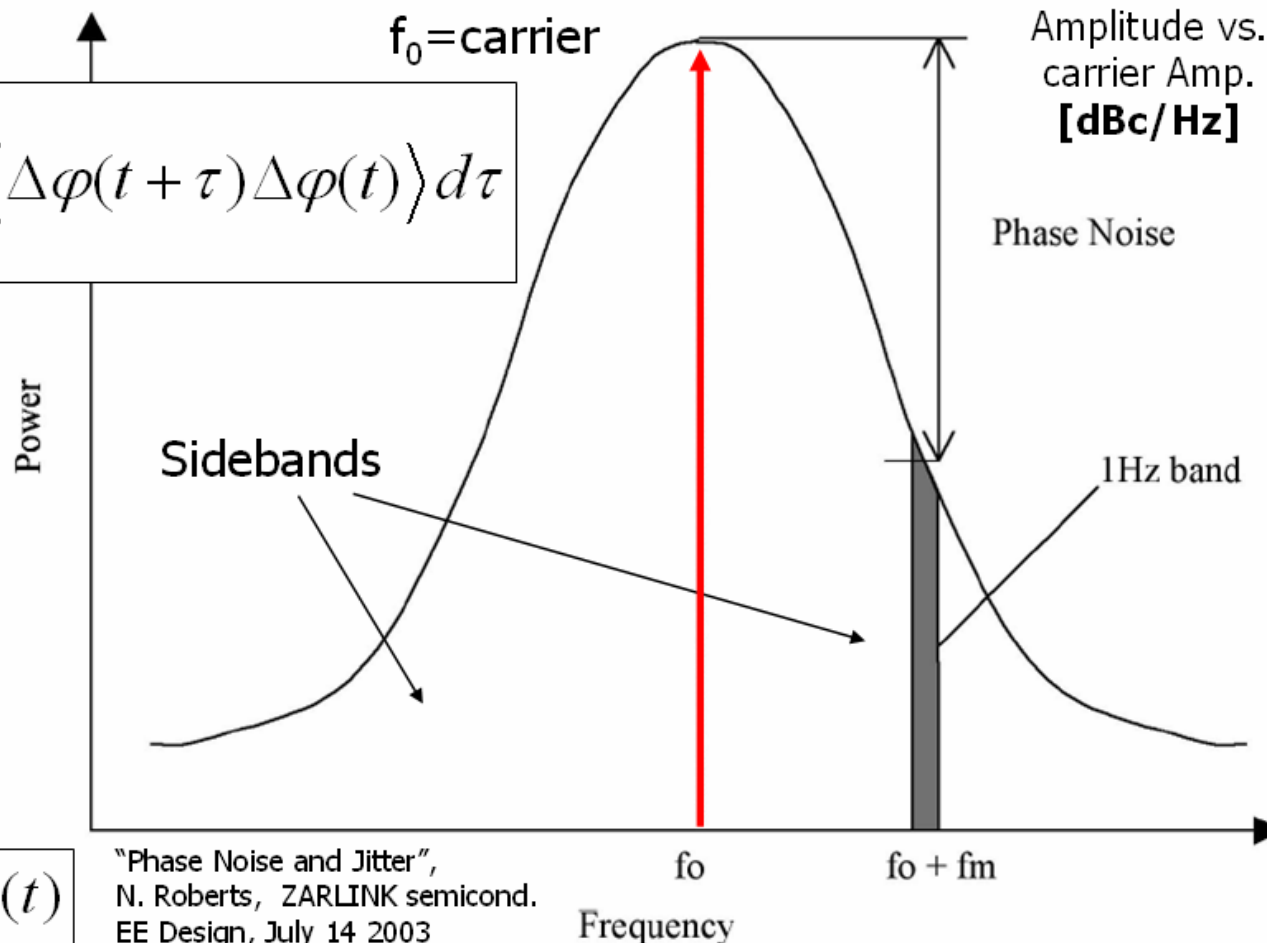
- time domain is not sufficient (...scopes only for coarse measurements)  
although current samplings (and associated photodiodes) go up to 100GHz...
- frequency domain allows higher resolution (**Phase Noise Spectrum**)  
we implicitly agree on *averaged measurements*, no Real Time SP. AN.
- take your **Reference signal (aka Carrier)**, typically  $f_c \cong \text{GHz}$
- plug it in into a Spectrum Analyzer and:
  - select a sufficiently small *Span & Resolution Bandwidth (1MHz & 10Hz)*
  - you can observe your carrier and its **Sidebands** which (from *Signal Theory*) are a clear and high sensitivity signature of your Carrier quality
  - if you see two peaks, symmetrically located around your Carrier:  
you are in troubles: *AM detected* !
  - being more clever with your Reference Oscillator you will see a central peak with symmetrical slopes on each side: where are now my fsec ?

$$V(t) = (V_0 + \Delta V(t)) \cdot \cos(\omega_o t + \Delta\varphi(t))$$

$$L(f) = \int_{-\infty}^{+\infty} e^{-j2\pi f\tau} \langle \Delta\varphi(t+\tau) \Delta\varphi(t) \rangle d\tau$$

The single-sideband phase noise is mathematically defined as the power spectral density of the phase fluctuations

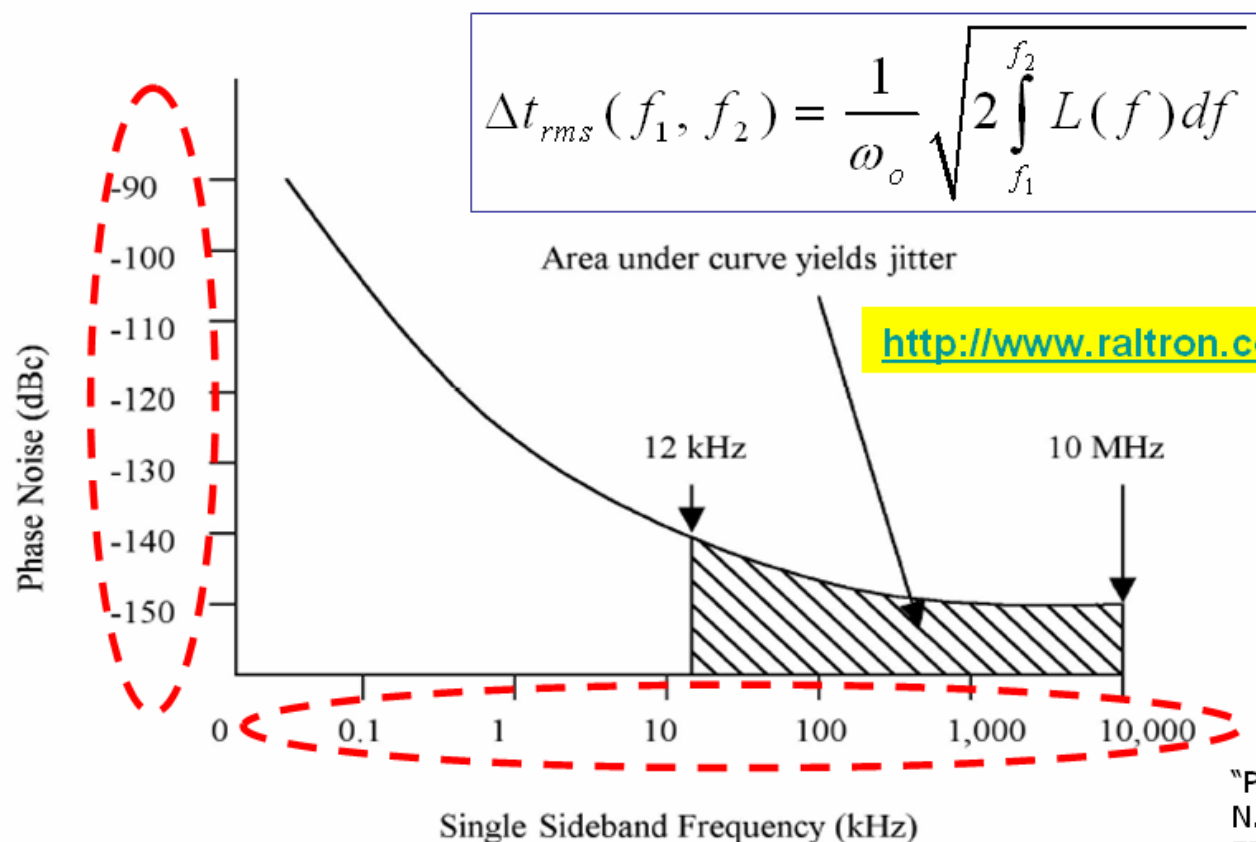
$$\Delta\varphi(t) = \omega_o \cdot \Delta t(t)$$



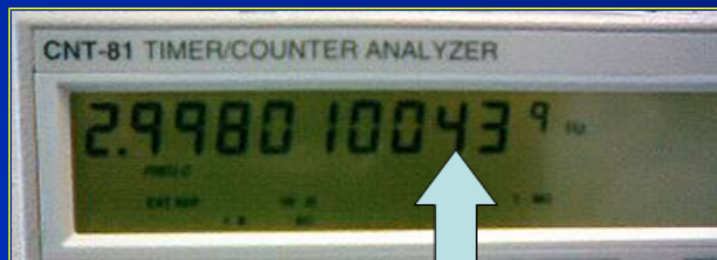


To extract the RMS timing jitter occurring in a certain frequency range from the phase noise

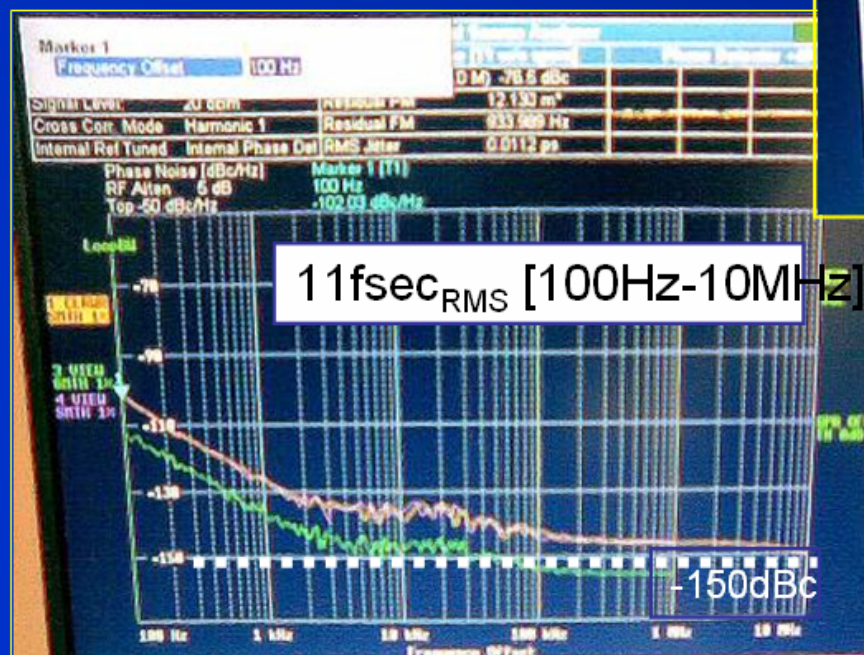
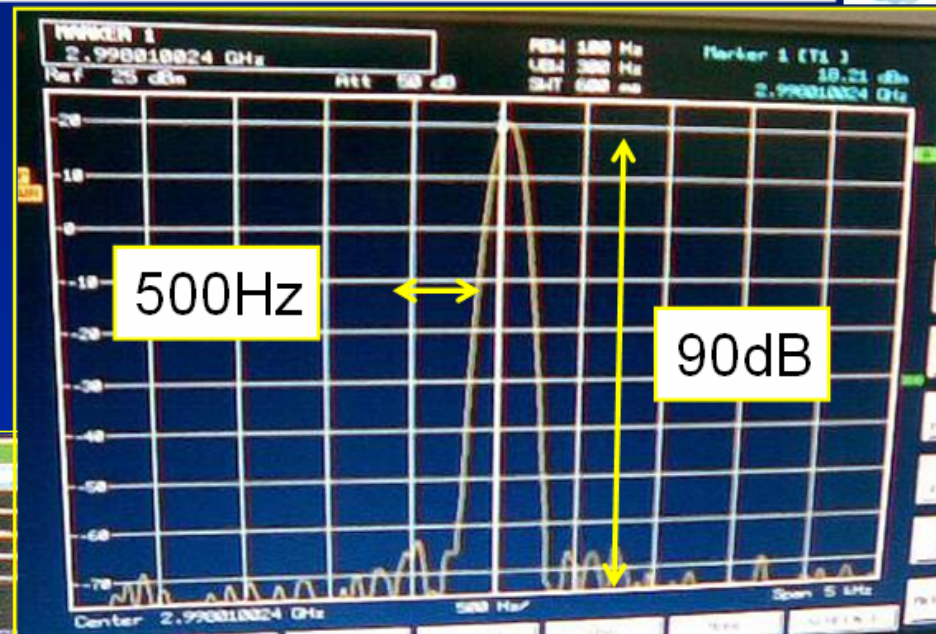
It is a complex spectrum over positive and negative frequencies, so it has to be taken twice if we integrate only over the positive frequency range



"Phase Noise and Jitter",  
N. Roberts, ZARLINK semicond.  
EE Design, July 14 2003

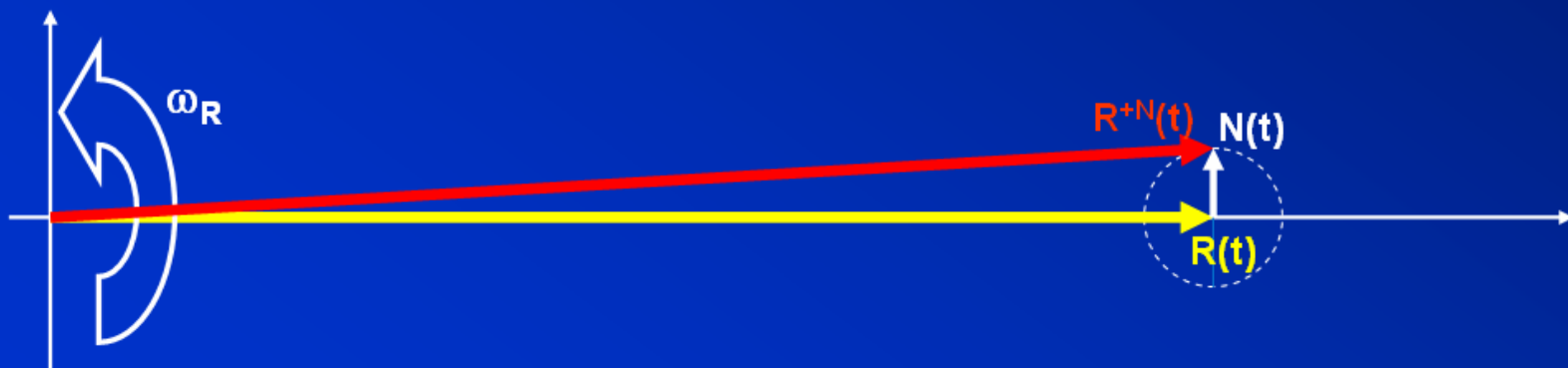


Ref. INWAVE gmbh



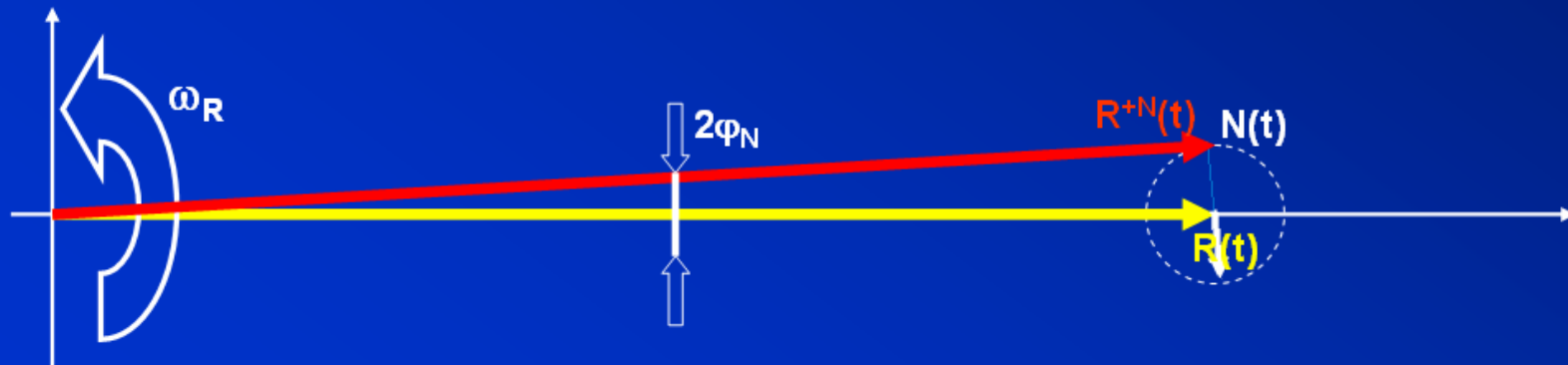
Ref. Poseidon Scientific Instruments Ltd.

- Which is the physical meaning of a phase noise component for a high frequency signal (i.e. carrier, Phase Reference)
- Let's represent it as  $R(t) = A_R \sin(2\pi f_R t + \phi_R)$  by using the vector notation
- It is a vector, rotating at  $\omega_R = 2\pi f_R$
- Let's add to it a phase noise components  $N(t) = A_N \sin(2\pi f_N t)$
- For each value of  $N(t)$  we obtain the resultant  $R^{+N}(t)$  by applying vector sum
- $R(t)$  is oscillating around its nominal angle at  $f_R$  and by  $\pm \phi_N$
- The value of  $\phi_N$  depends on the ratio  $A_N/A_R$ ; proportional pk-pk jitter of  $R(t)$
- The rate at which  $R(t)$  moves depends on  $f_N$ ; i.e. the offset frequency in the phase noise spectrum





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Artist view: amplitude changes not shown!!!



how does a 100Hz phase noise component affect a RF signal?

- let's plug in some numbers...  $f_R = 3 \text{ GHz}$ ;  $f_N = 100 \text{ Hz}$ ;
- from phase noise measurements, we get relative amplitudes:  $A_R / A_N = 80\text{dB}$  (typical)
- $\varphi_N [\text{rad}] \cong A_N / A_R = 0.0001 \text{ rad}$
- $\tau_R = 330\text{ps}$ ;  $\varphi_N = 0.0057 \text{ deg} = \mathbf{5.309\text{fsec}}$   
( $2\pi 3 \cdot 10^9 \times 5.309 \cdot 10^{-15} = 1 \cdot 10^{-4}$ )

by how much does the phase of a noisyPhase Reference signal change in few  $\mu\text{s}$ ?

(the *time of flight* of FERMI@Elettra is few  $\mu\text{s}$ )

- $\tau_N = 10\text{ms}$ ; consider  $2\mu\text{s}$  around zero crossing
- phase deviation  $\rightarrow \mathbf{0.00667\text{fsec}!!!}$
- The peak value (5.309fsec) is reached after 2.5ms



$\varphi$	$F_N$	t	f(t)
[fsec]	[Hz]	[sec]	[fsec]
5,308686	100	0,000000	0,000000
5,308686	100	0,000002	0,006671
5,308686	100	0,002000	5,048861
5,308686	100	0,002500	5,308686
5,308686	100	0,005000	0,000000
5,308686	100	0,007500	-5,308686
5,308686	100	0,010000	0,000000

## fsec T&amp;S system clients &amp; requirements



- In order to properly operate, all the relevant systems (T&S clients) have to share a common phase reference
- The client sensitivities to jitter are not all equal though

$$\text{Jitter}_{\text{total}} = \sqrt{\text{jitter}_{\text{REF}}^2 + \text{jitter}_{\text{DEV}}^2}$$

- **RF plants**

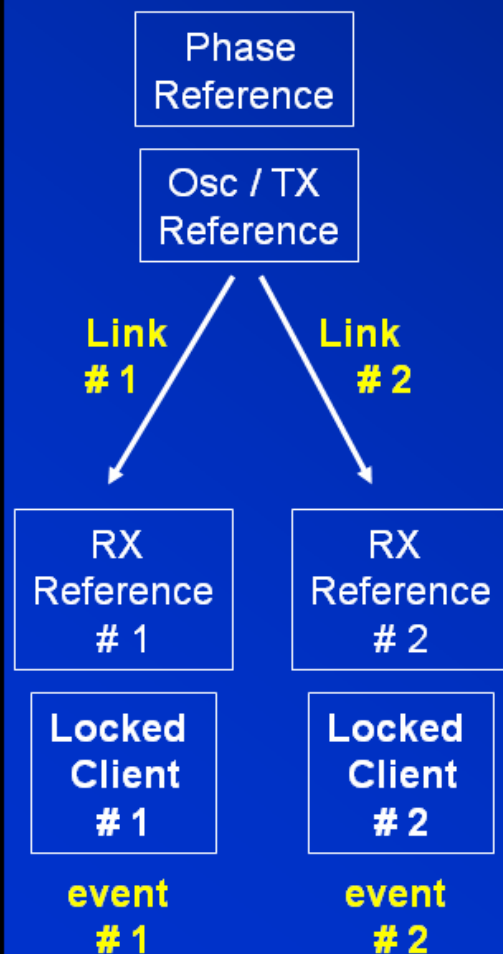
REF		total	
■ accelerating sections (S-band & L-band)	<100 fsec <sub>RMS</sub>	71	
■ harmonic linearizer (X-band)	<70 fsec <sub>RMS</sub>	50	

- **Lasers**

■ photo-injector	<100 fsec <sub>RMS</sub>	71
■ laser heater	<100 fsec <sub>RMS</sub>	71
■ seed	<15 fsec <sub>RMS</sub>	10
■ user	<15 fsec <sub>RMS</sub>	10

- **Diagnostics**

■ Bunch Arrival Monitors (BAMs)	<15 fsec <sub>RMS</sub>	10
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absolute	relative (1-2) . [fsec <sub>RMS</sub> ]
10	0
10	0
10	14.1
10	17.3
10	20.0

- To generate and to distribute the phase information
- Jitter  $<10\text{fsec}_{\text{RMS}}$ 
  - the bandwidth (BW) over which jitter is defined depends on the *time structure* of the beam:
    - [10Hz - 10MHz] for long macro-pulses
    - [100Hz - 10MHz] for pure single bunch
- Drift  $<10\text{fsec}_{\text{RMS}}$
- Frequency 100s MHz to GHz range
- State of the art solutions are based on **Optical clock**
- **RLE@MIT – Cambridge, MA** (prof. FX Kaertner group):  
PULSED OPTICAL PHASE REFERENCE SYSTEM
- **CBP @ LBNL – Berkeley, CA** (J.M. Byrd, R. Wilcox et al.)  
CW OPTICAL PHASE REFERENCE SYSTEM



- Why OPTICAL ?
- What is PULSED and what is CW ?

## ■ OPTICAL

- the key issue is not only the generation of a phase reference signal with fsec jitter, but also distributing it over the whole Facility without spoiling the **Reference Oscillator** jitter
- **Optical Oscillators** (*soliton* fiber lasers) are typically performing better than  $\mu$ -wave oscillators in the BW of interest ( $>1\text{kHz}$ )
- Optical link **stabilization techniques** have been demonstrated and implemented able to keep jitter  $\leq 10\text{fsec}_{\text{RMS}}$
- **Electro optical diagnostics** have been implemented; making full use of the **Optical Reference**, these can provide resolution  $<10\text{fsec}$  as well

## ■ how does it work?

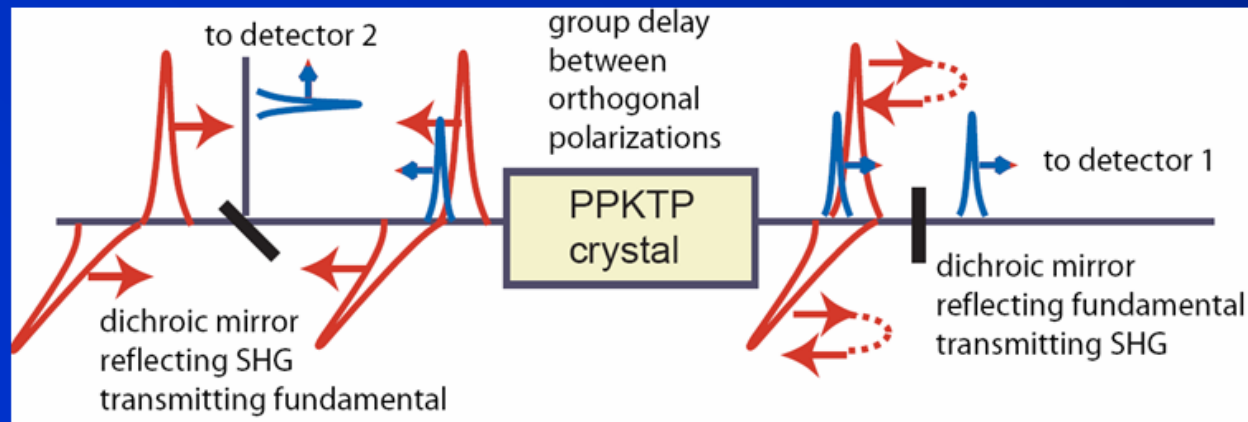
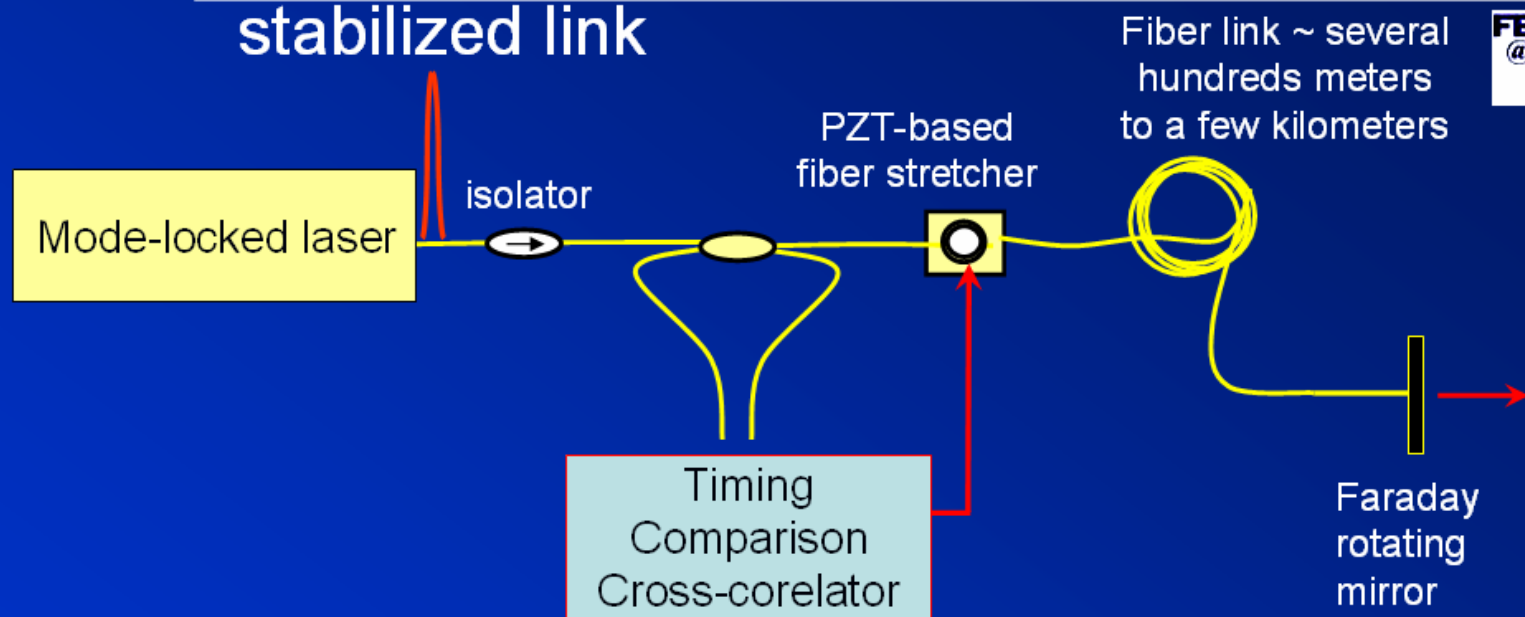
- the phase information is *encoded* into the repetition rate of a soliton fiber laser which is phase locked to a  $\mu$ -wave reference for improved jitter (low frequencies end) and drift
- a train of optical pulses is sent over single mode optical fibers (rep rate  $\approx 100$  MHz)
- the propagation over the fiber links is stabilized by means of active loops adopting a x-correlator as *phase detector*
- ideally suited for **synchronization of remote laser oscillators**
- **direct seeding of remote optical amplifiers** is under investigation
- extraction of an harmonic RF electrical signal at the remote stations has been implemented as well
- **longitudinal diagnostics** have been implemented for Bunch Arrival Time Monitor with res  $< 10 \text{ fsec}_{\text{RMS}}$
- aiming at: **single oscillator facility**

... there are also Continuous Wave (CW) T&S clients:  
the accelerating structures and the associated RF plants

## ■ CW OPTICAL PHASE REFERENCE

- the Optical Link is stabilized making use of the Optical Mixing concept, applied to the Optical carrier and its 100MHz frequency shifted replica ( $f_{CAR}=190\text{THz @}1560\text{nm}$ )
- As heterodyning preserves phase relationships:
  - 1 degree at optical = 1 degree RF
  - 1 degree at 110 MHz = 0.014 fsec at optical
  - Gain  $10^5$  leverage over RF-based systems in phase sensitivity
- RF is sent over the stabilized link
- System has been optimized through the years; it is integrated into the Low Level RF (LLRF) system used to locally (at each plant) stabilize (in amplitude and phase) the accelerating field seen by the particles

# Pulsed Optical Phase Reference: stabilized link

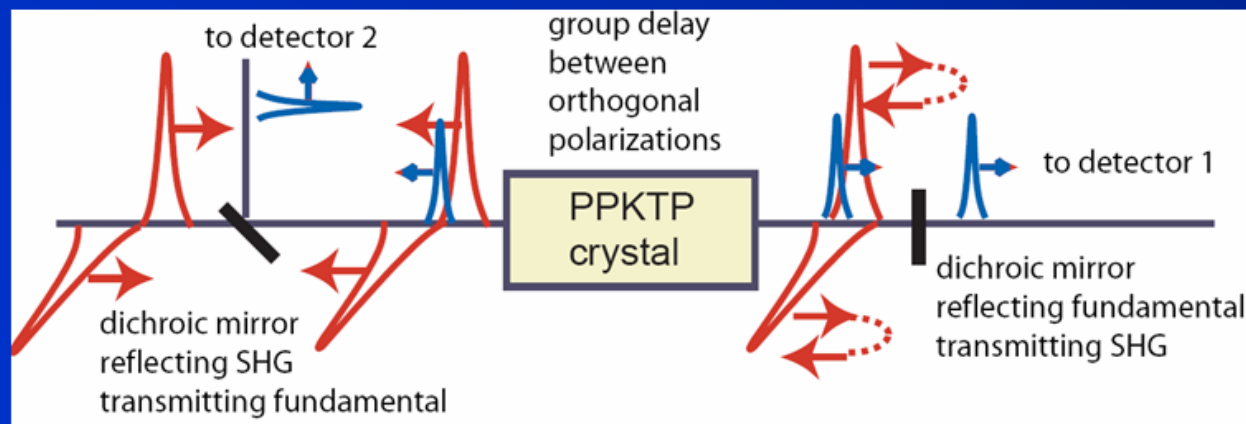
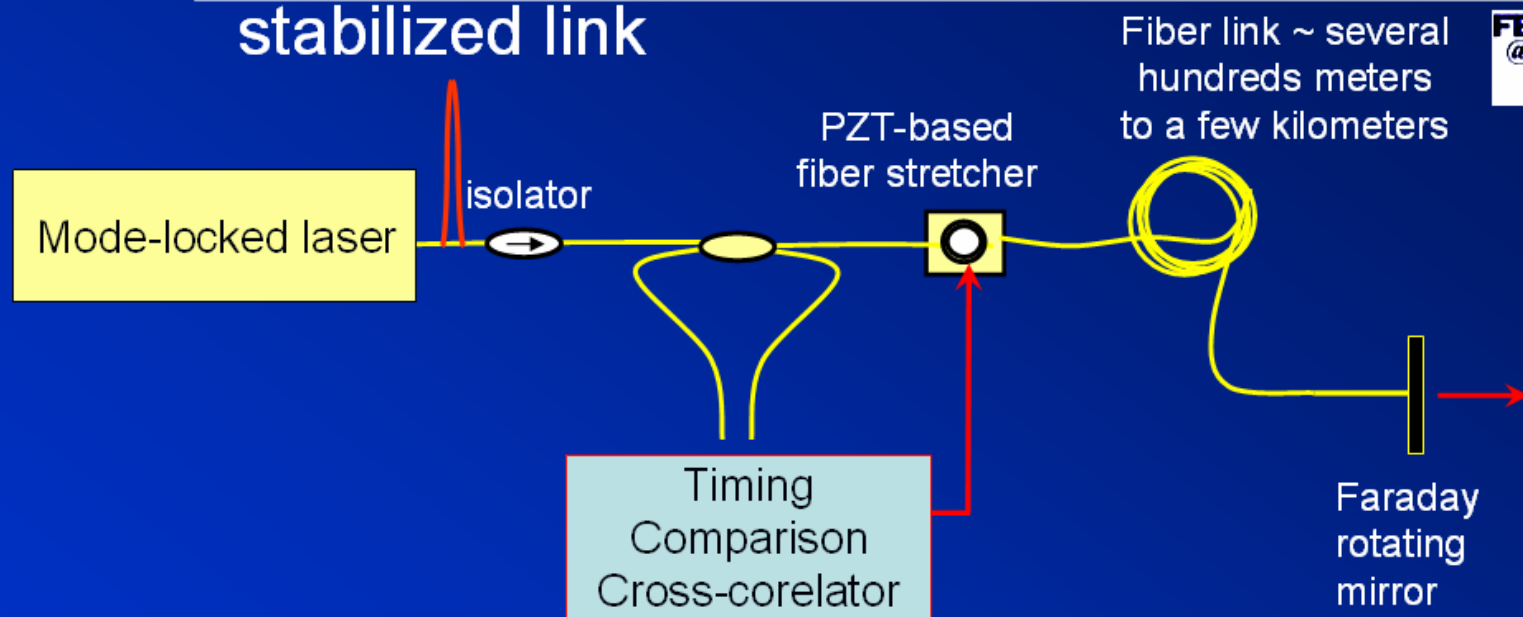


**PPKTP:** periodically poled Potassium Titanium Oxide Phosphate ( $\text{KTiOPO}_4$ )

Courtesy of: prof. F.X. Kaertner RLE/MIT; F. Loehl DESY



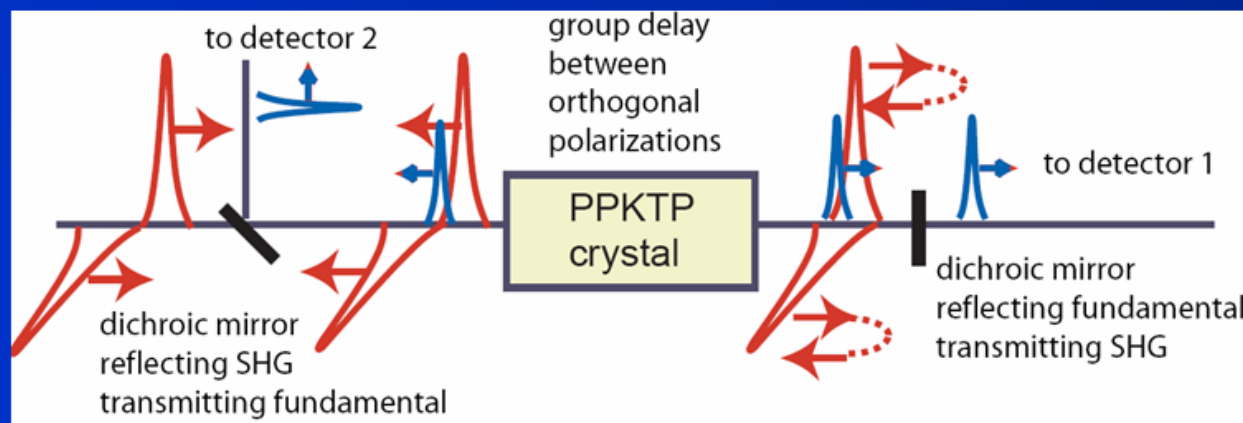
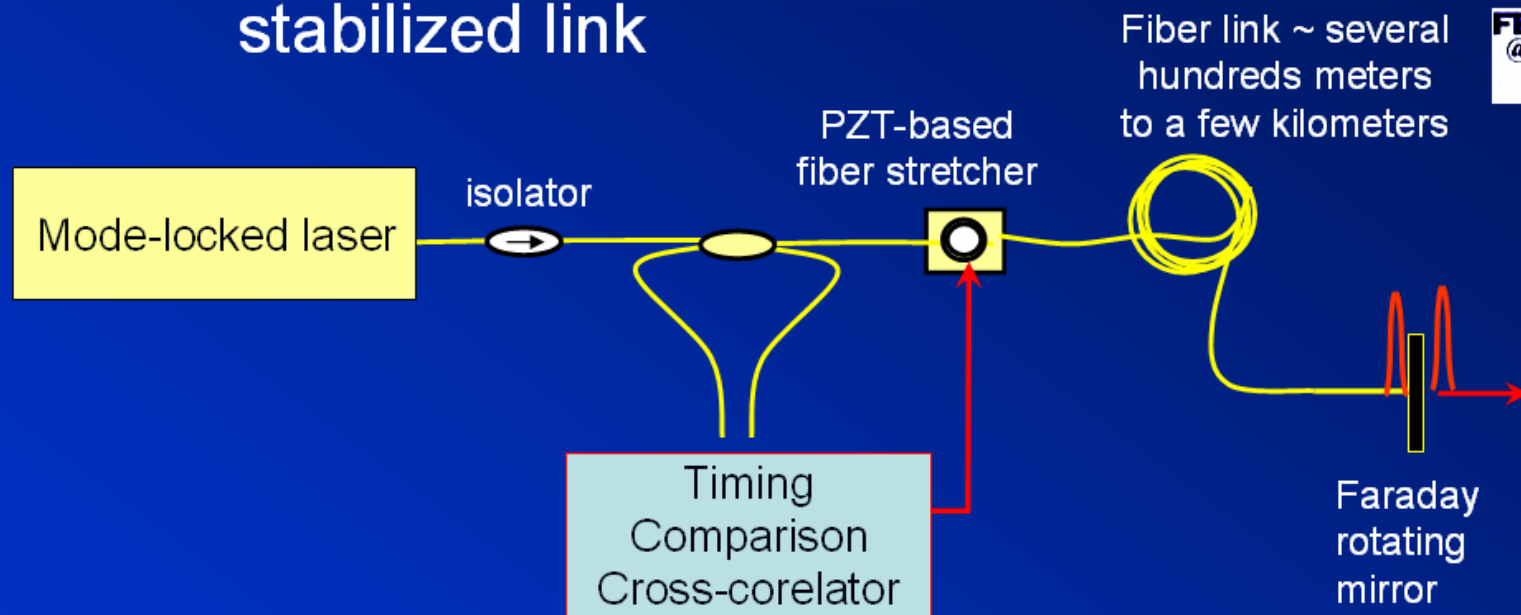
# Pulsed Optical Phase Reference: stabilized link



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Courtesy of: prof. F.X. Kaertner RLE/MIT; F. Loehl DESY

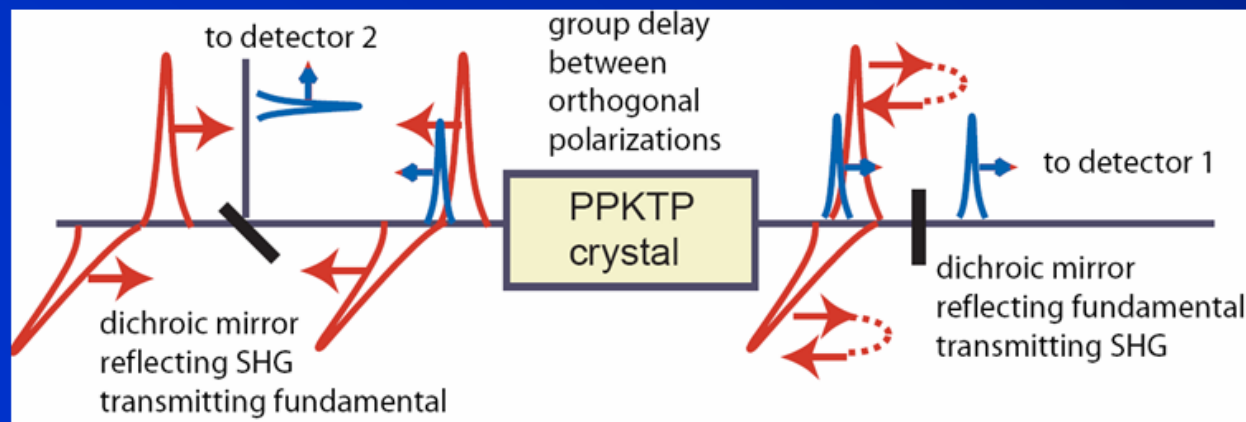
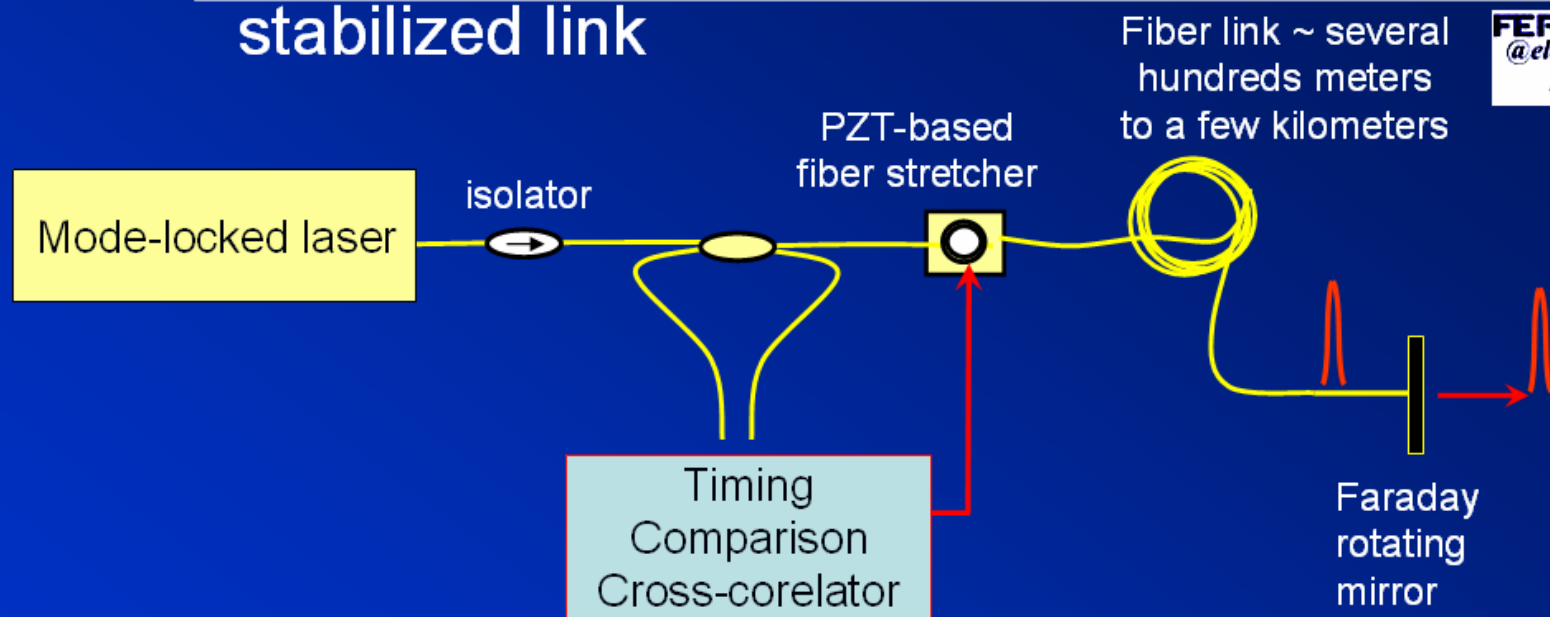
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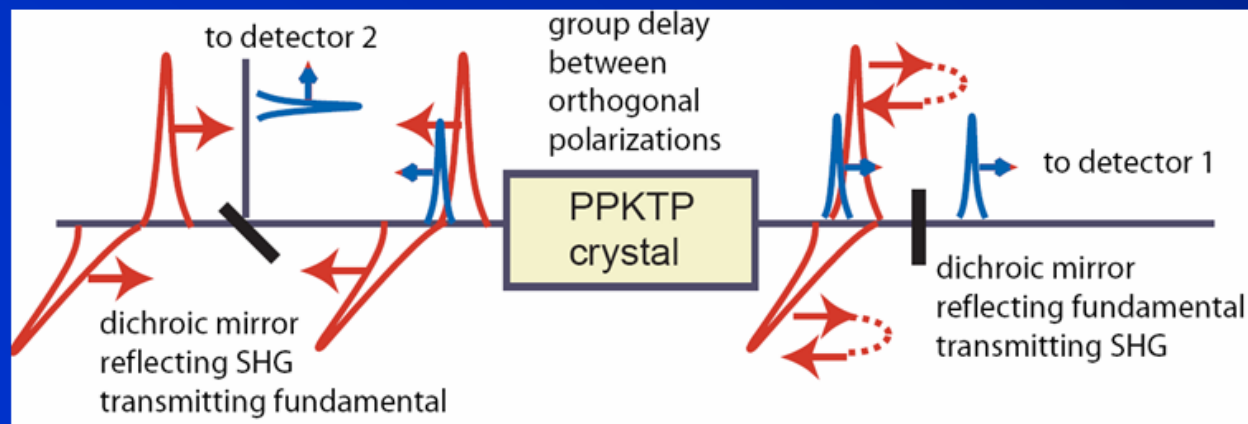
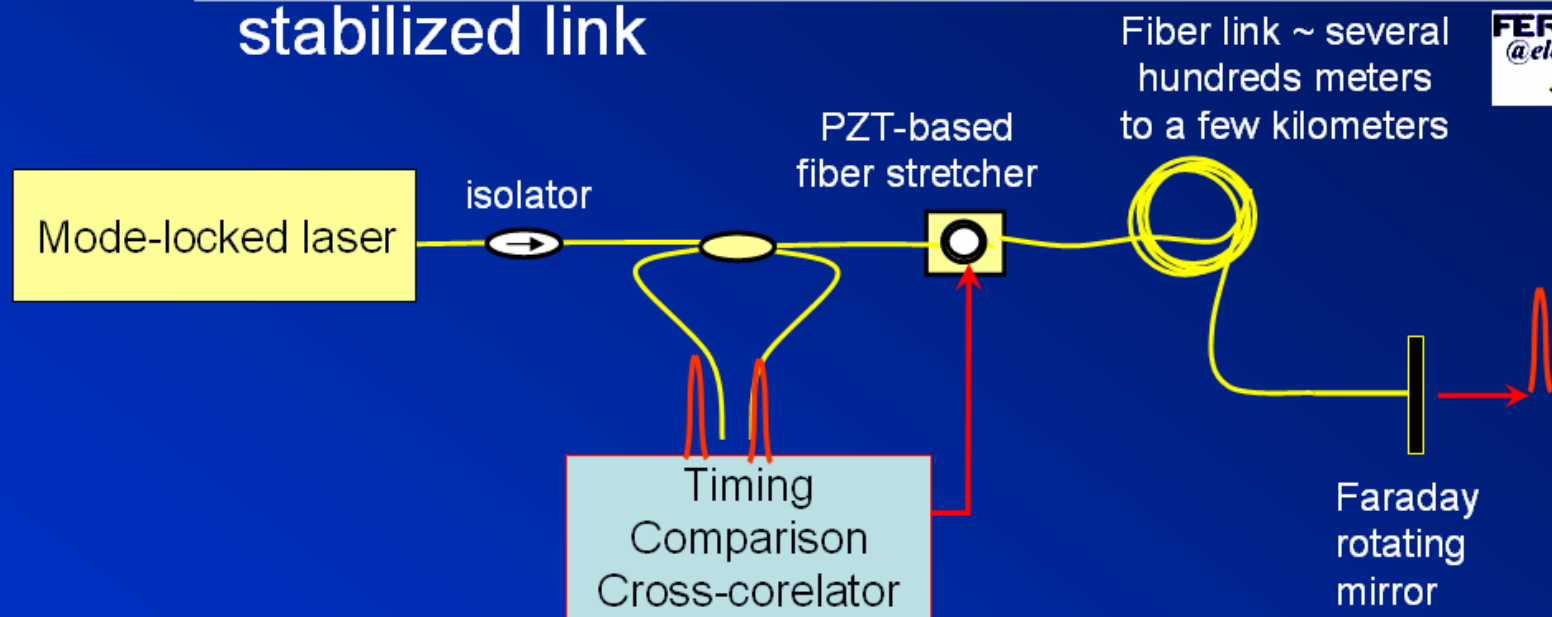
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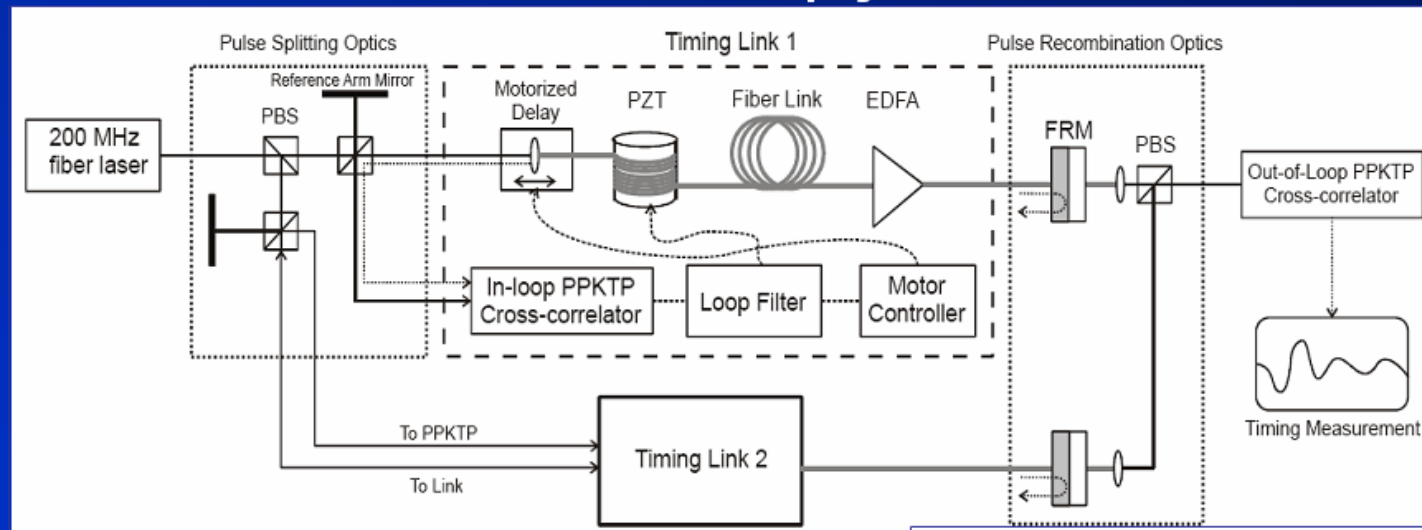
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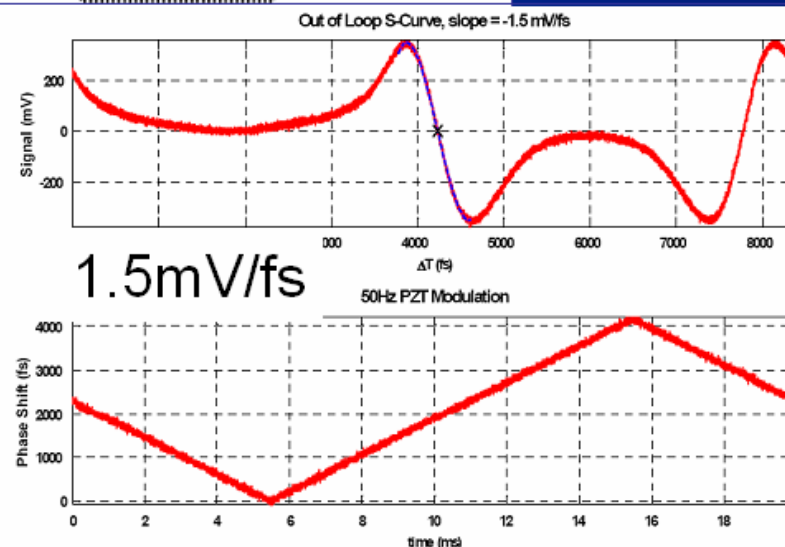
Courtesy of: prof. F.X. Kaertner RLE/MIT; F. Loehl DESY

# Pulsed Optical Phase Reference: two-links out of loop jitter measurement



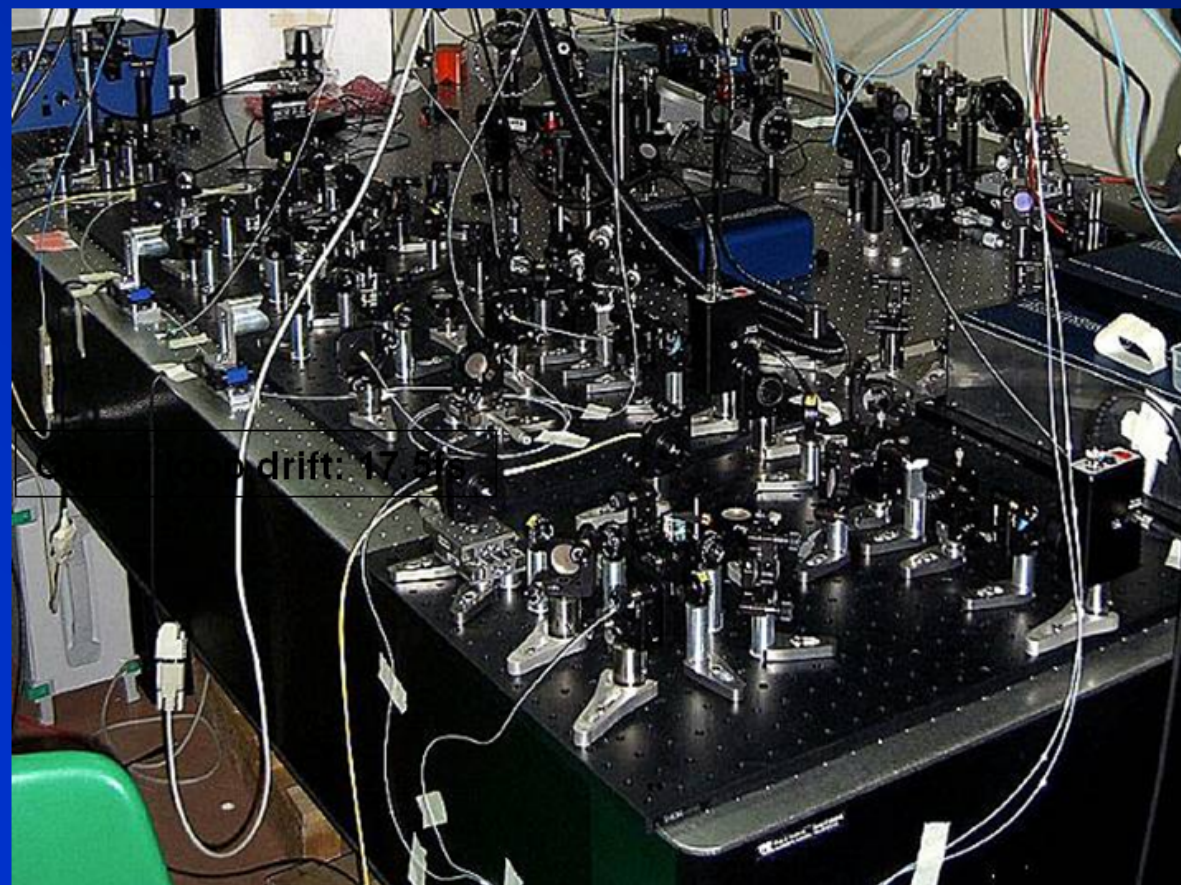
Two link stabilization system. The outputs of 2 separate stabilized links are recombined for an out-of-loop drift measurement with a third PPKTP cross-correlator.

The transfer function (s-curve), for the PPKTP cross-correlator is the calibration for the measurement sensitivity of the X-correlator. It is performed by modulating the piezo to provide a time-varying delay to one link.



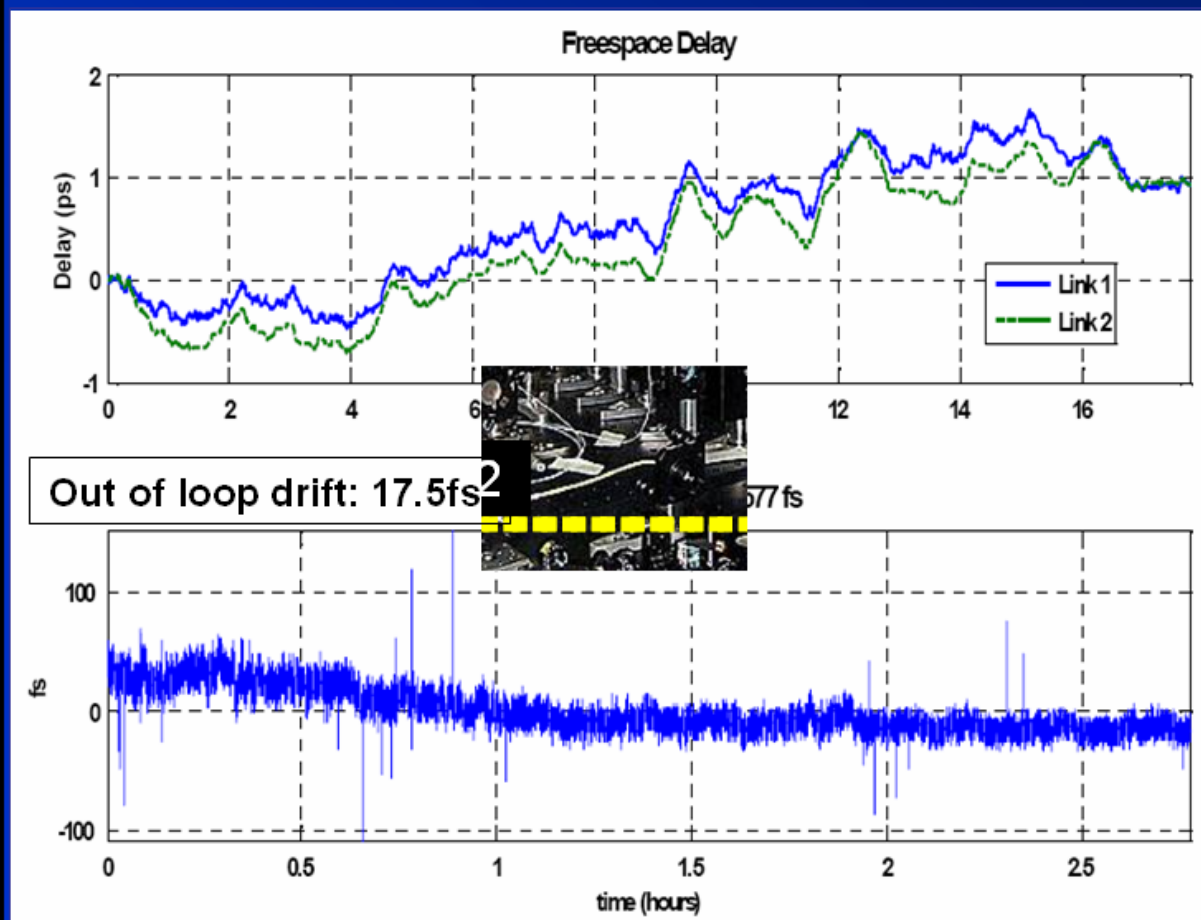


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Courtesy of: J.Cox RLE/MIT; F. Rossi ELETTRA

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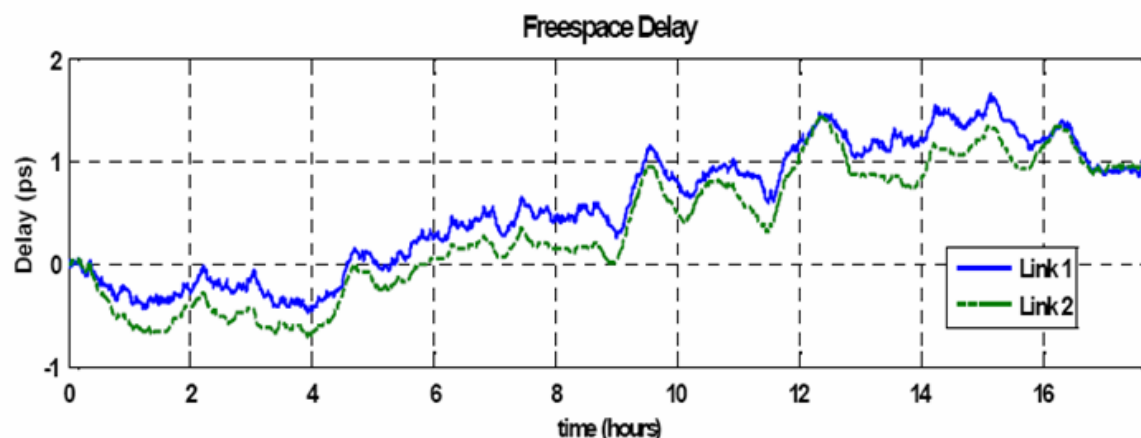


The results obtained for the 2 link measurement. The upper plot shows the drift of the fiber link which the system compensates for over 18 hours, as revealed by monitoring the position of the free-space motorized delay.

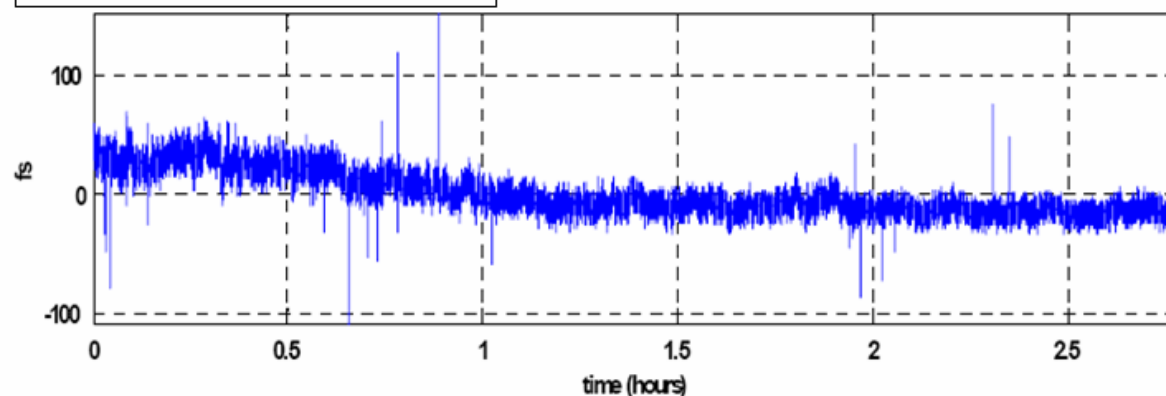
The lower plot shows the out-of-loop drift as measured by X-correlator between both links. The drift is  $18 \text{ fsec}_{\text{RMS}}$  over 3 hours.

Courtesy of: J.Cox RLE/MIT; F. Rossi ELETTRA

# Pulsed Optical Phase Reference: two-links out of loop jitter measurement



Out of loop drift: 17.5fs Timing Drift, RMS = 17.5577 fs



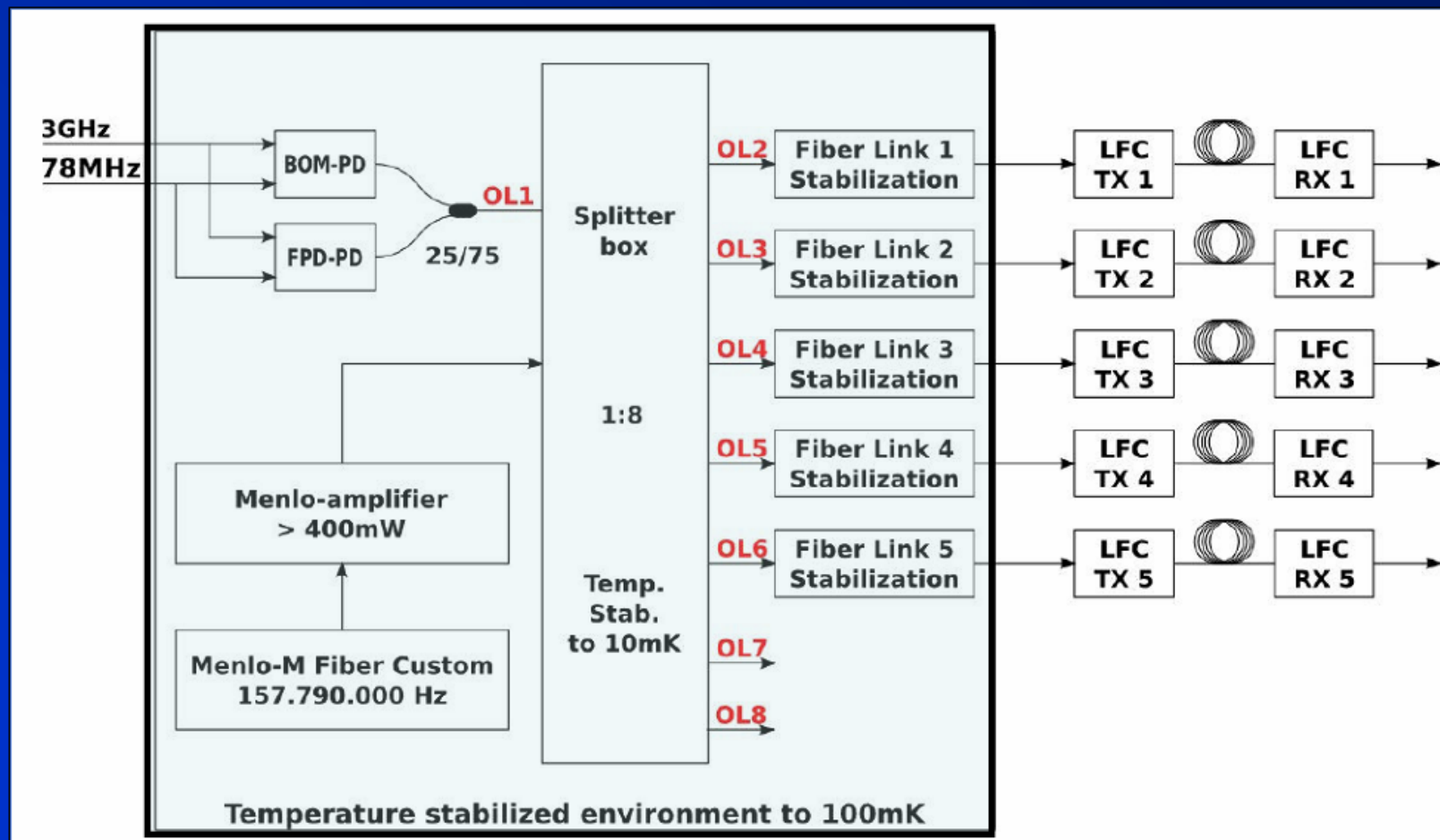
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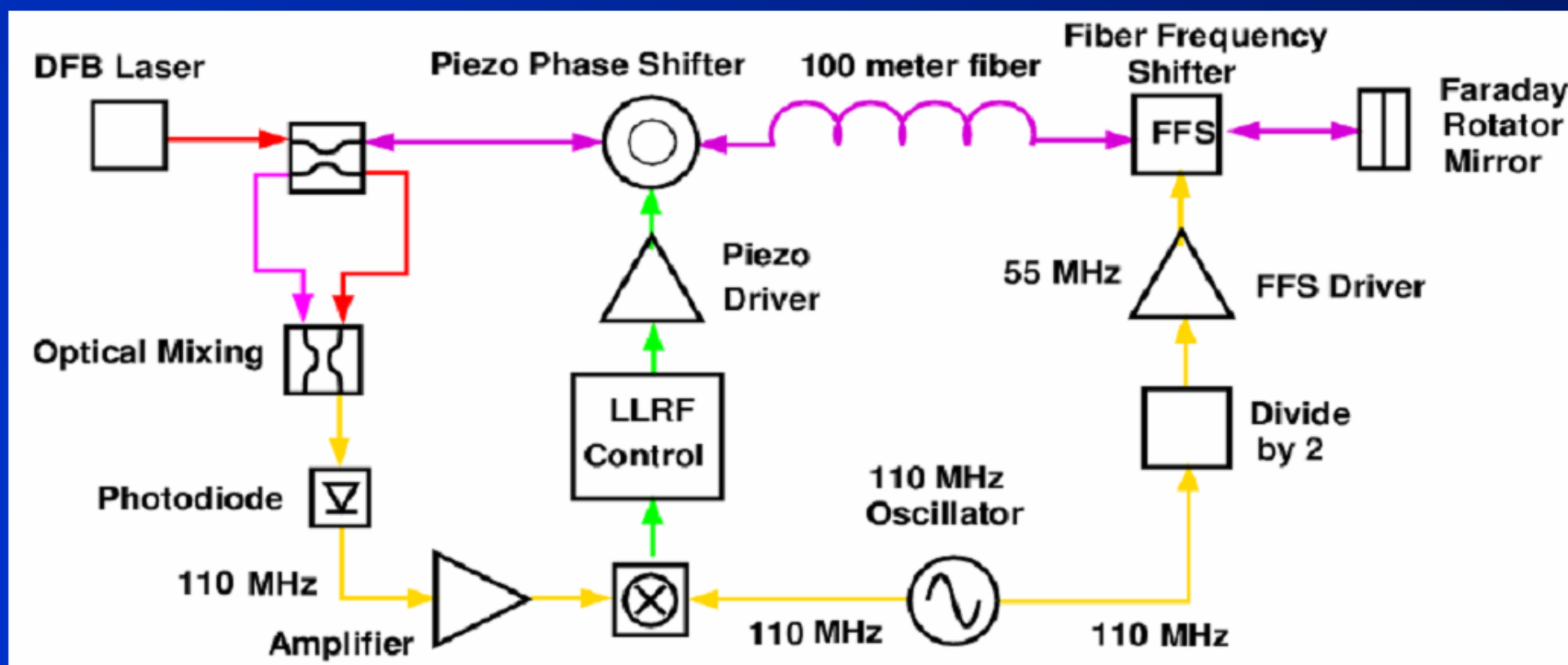
# Pulsed Optical Phase Reference: engineered system for *FERMI@elettra*



Ref. MENLOsystems

# CW Optical Phase Reference: link stabilization

- Optical carrier at 1560nm
- Frequency shifted ( $2 \times 55\text{MHz}$ ) & back reflected at the far end

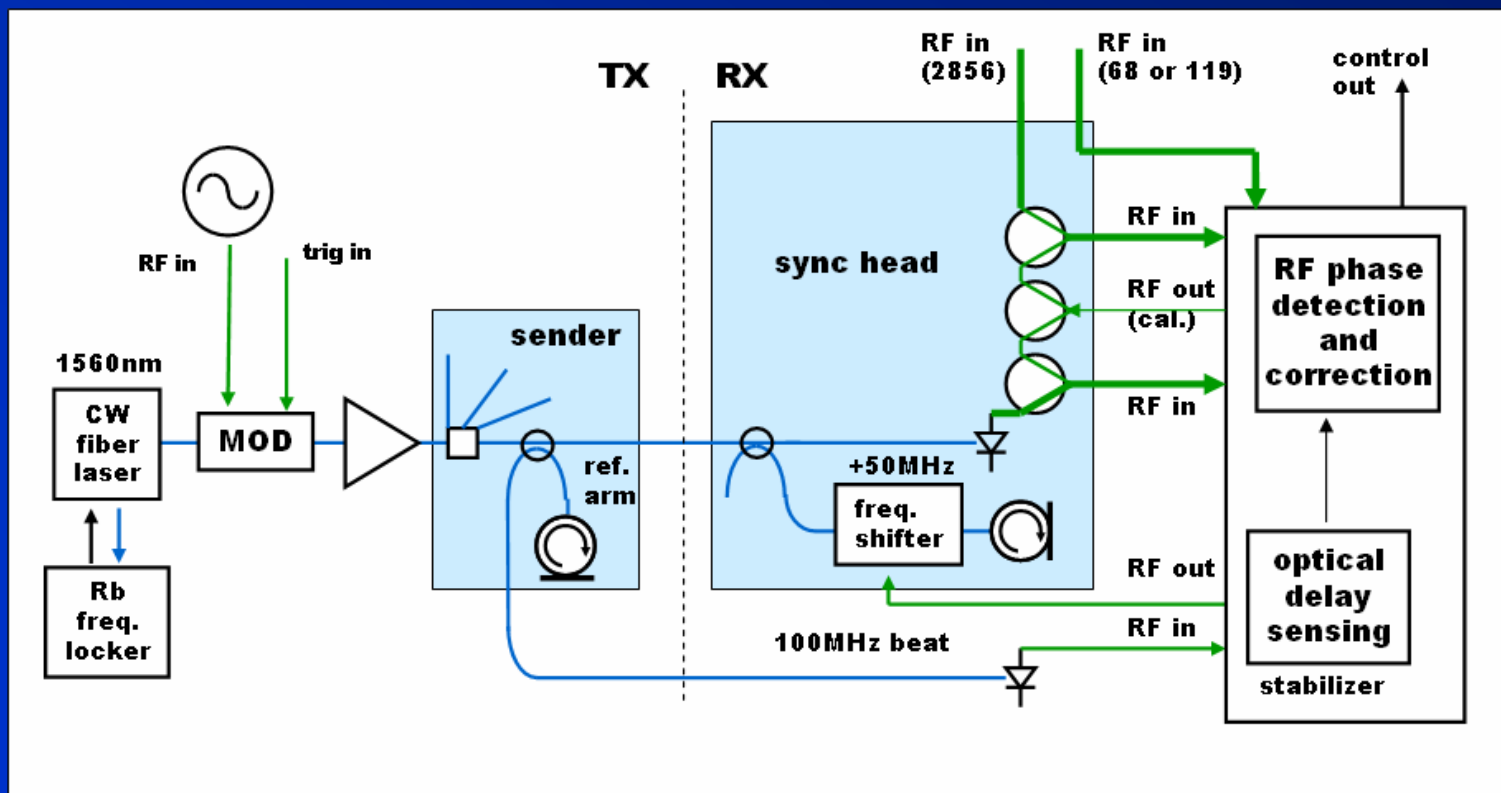


Courtesy of R. Wilcox LBNL



# CW Optical Phase Reference: link stabilization

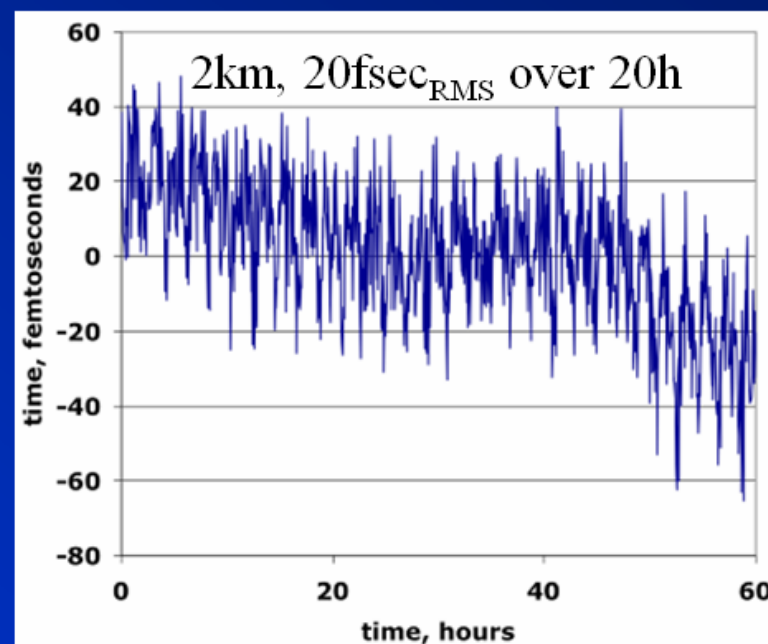
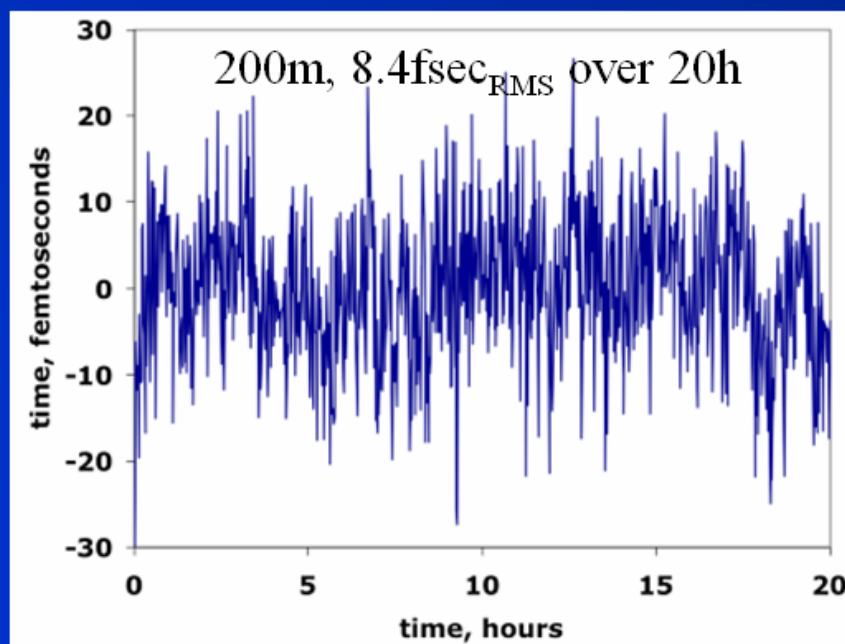
- Final version: no more piezo for length correction
- The delay is sensed and locally added at each remote station



Courtesy of J. Byrd and R. Wilcox, LBNL

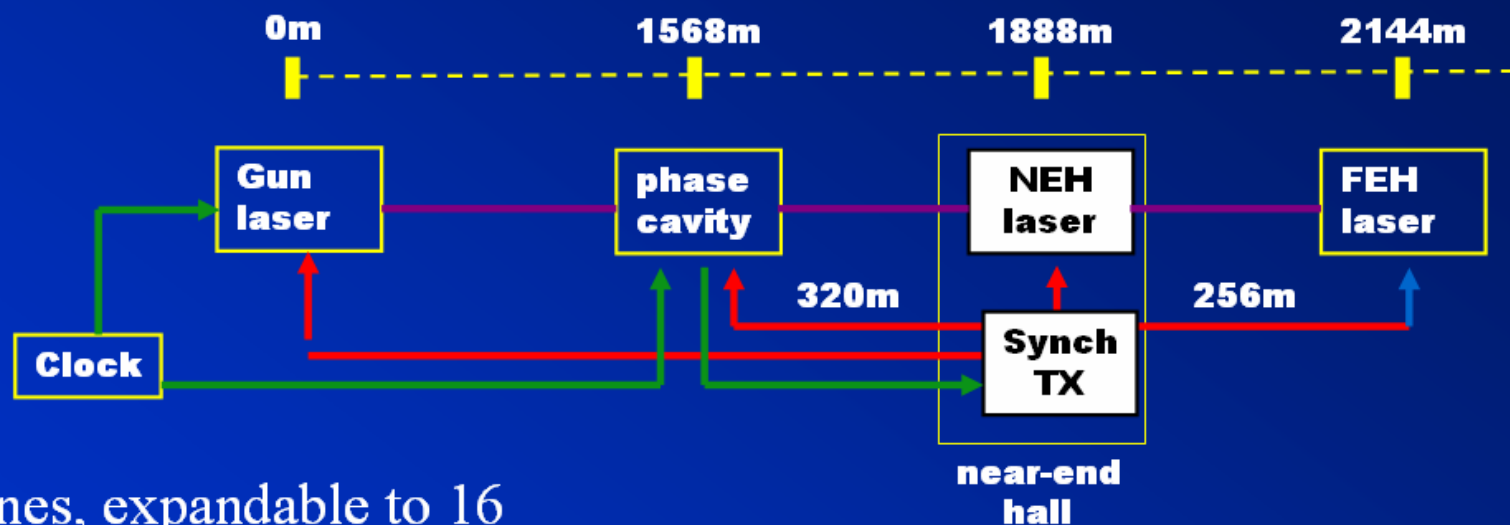
# CW Optical Phase Reference system: RF transmission at 2850MHz

- Comparison of RF phase transmission through 2m fiber and 200m or 2km
- Fiber in loose coils in lab, with  $\pm 2$  degree C air temperature stability
- Periodic error in 2km data is air conditioning cycle
- In 2km case, 15fs RMS for first 48 hours



Courtesy of J. Byrd and R. Wilcox, LBNL

# CW Optical Phase Reference system: tested on field at LCLS

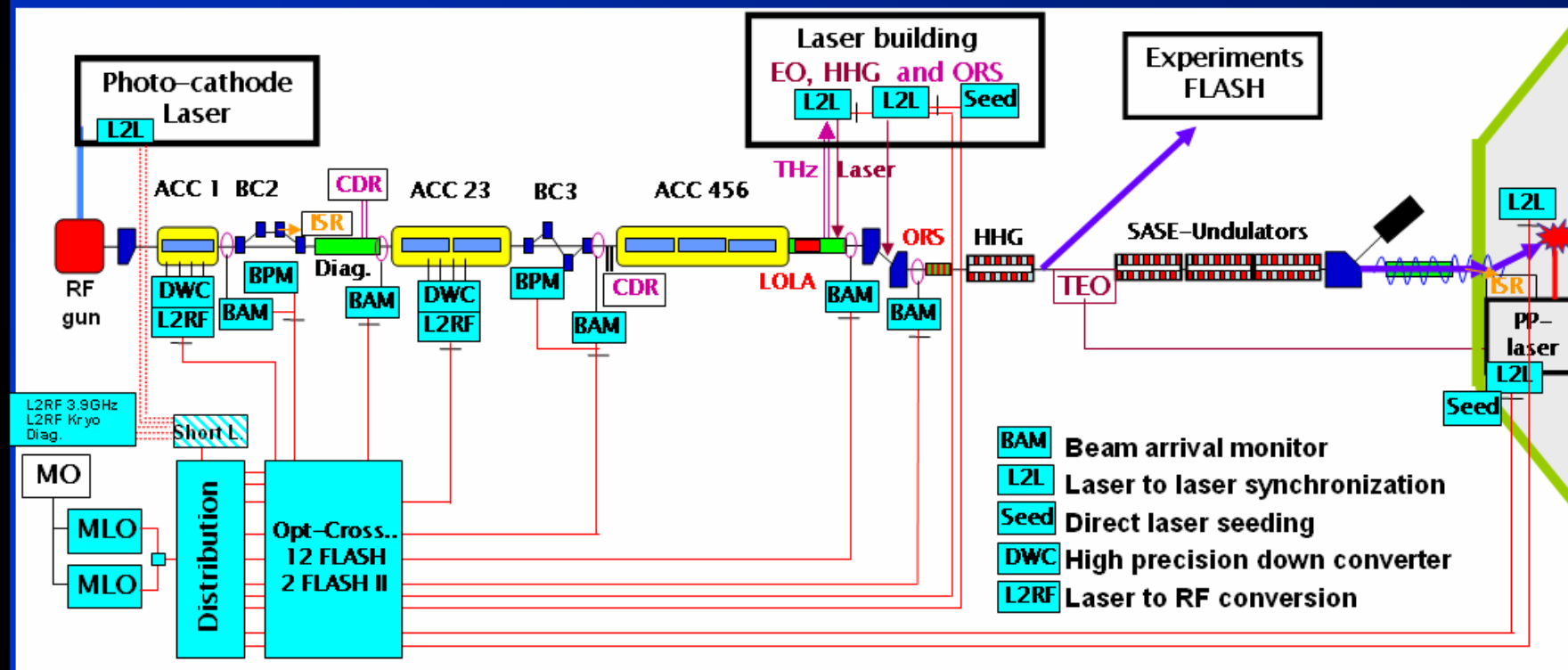


- 4 lines, expandable to 16
- $<100\text{fs}_{\text{RMS}}$  error over 24h
- Continuous operation over one week
- Deliver signals capable of synching mode locked lasers:  
0dBm, 2850 (RF), 476 and 68MHz

Courtesy of J. Byrd and R. Wilcox, LBNL

# Pulsed Optical Phase Reference: 1<sup>st</sup> deployed on field at FLASH (DESY)

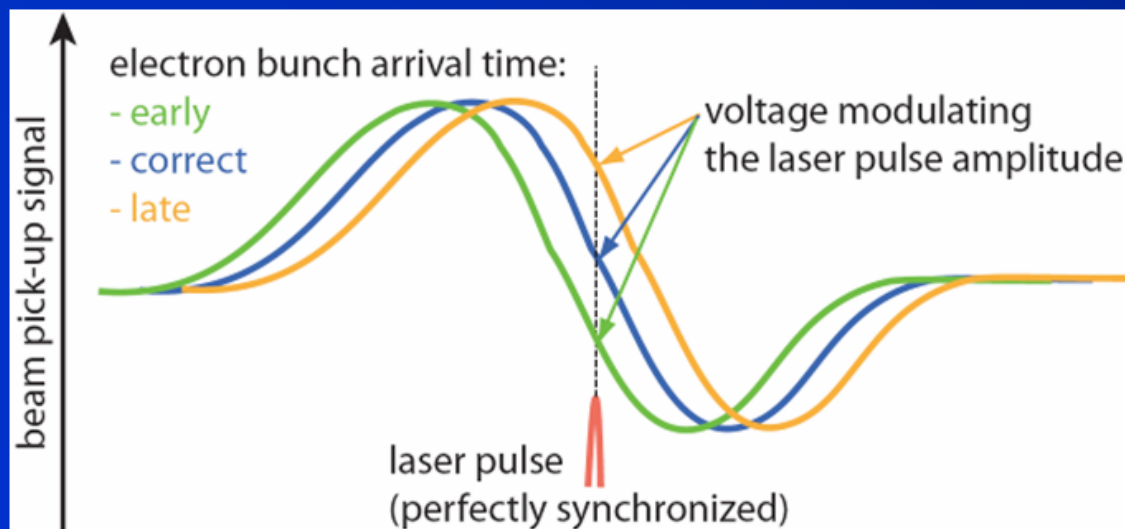
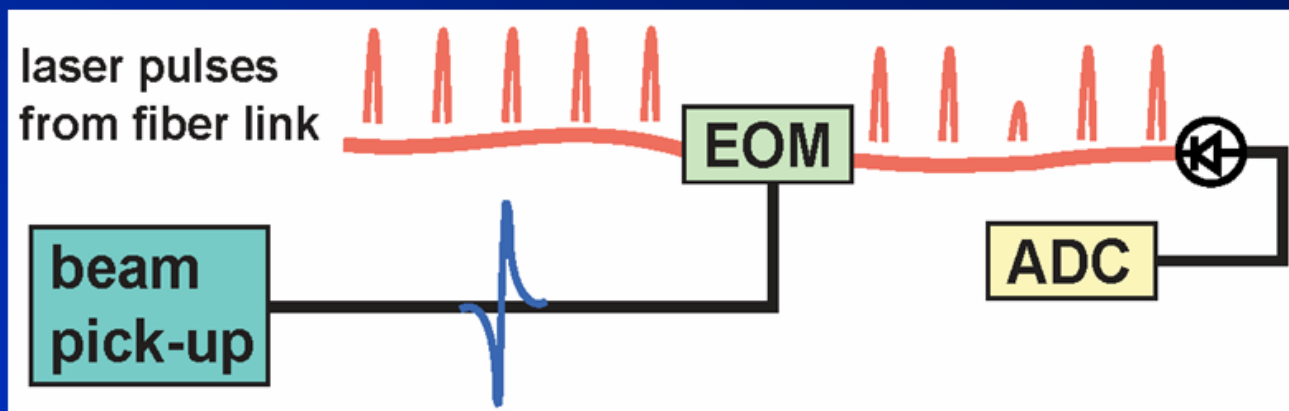
- The most complete Optical Timing system implemented so far
- Dual MLO for improved redundancy; *short link* Option
- fully integrated diagnostics: BAM, Energy BPM



Courtesy of H. Schlarb, DESY

# Pulsed Optical Phase Reference: Bunch Arrival Monitor at FLASH (DESY)

- Based on an original idea that makes full use of the Optical timing
- Amplitude of the Ref. laser pulses is modul. according to the relative timing

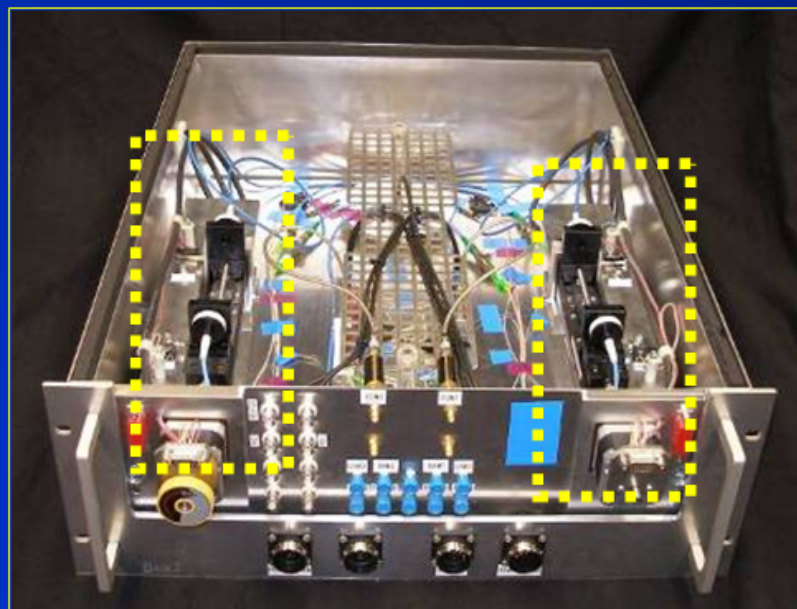


A fsec relative timing measurement is transformed in an amplitude meas. (ADC)

Courtesy of F. Loehl, DESY



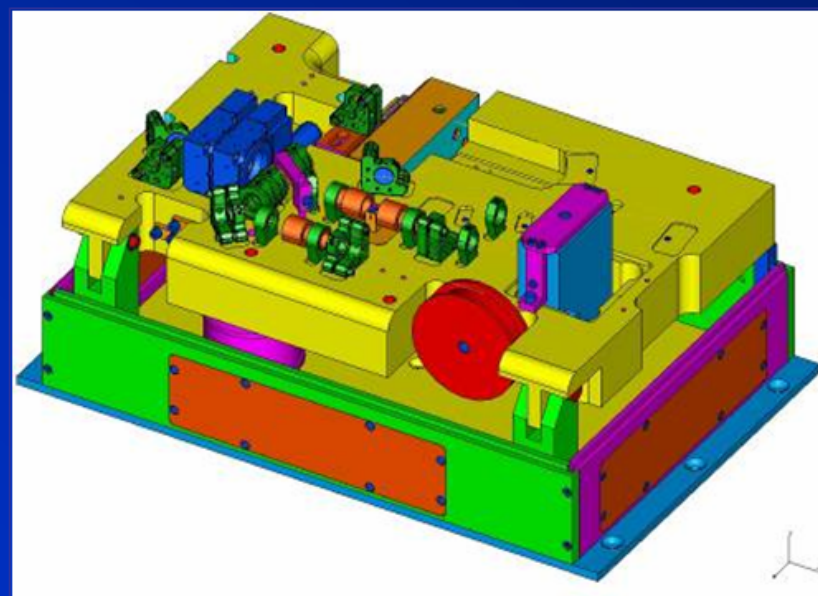
# Pulsed Optical Phase Reference: Bunch Arrival Monitor at FLASH (DESY)



- 1<sup>st</sup> Front End prototype installed in tunnel



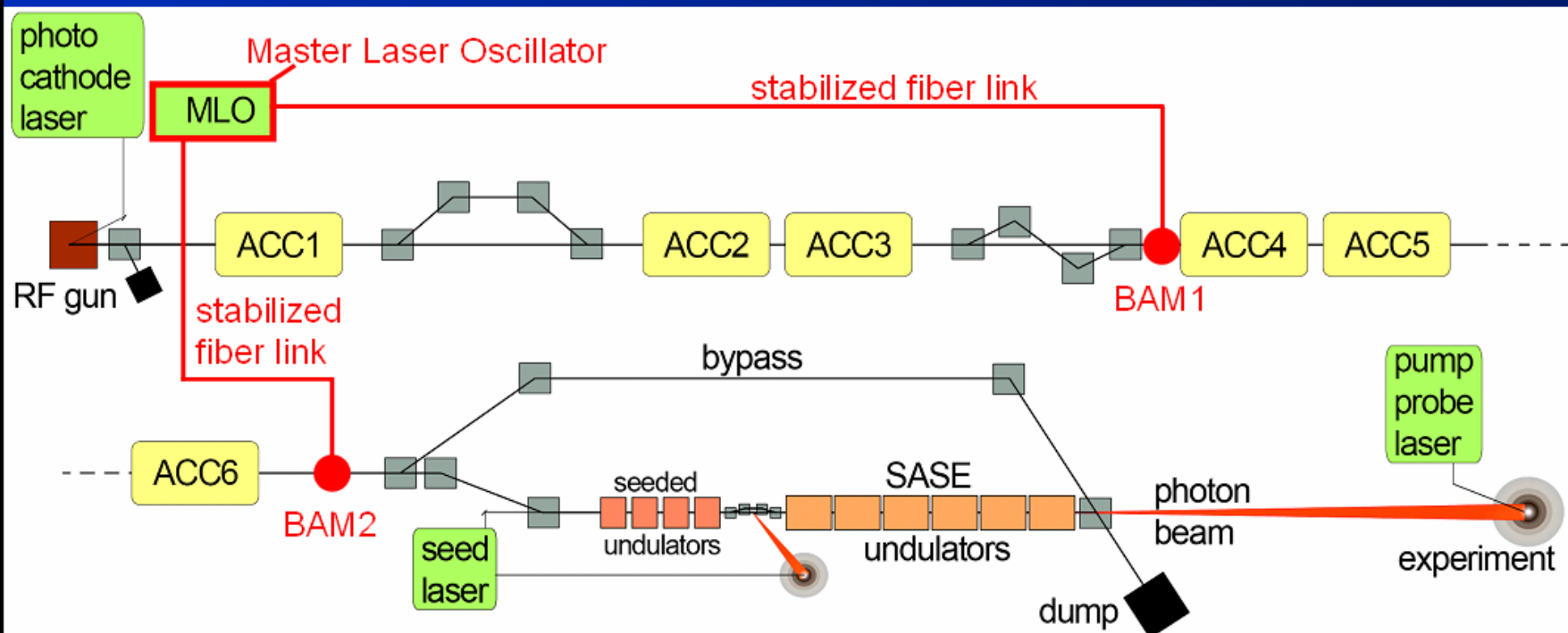
2<sup>nd</sup> prototype is underway with  
new optical delay lines with  
improved reliability



Courtesy of F. Loehl, DESY

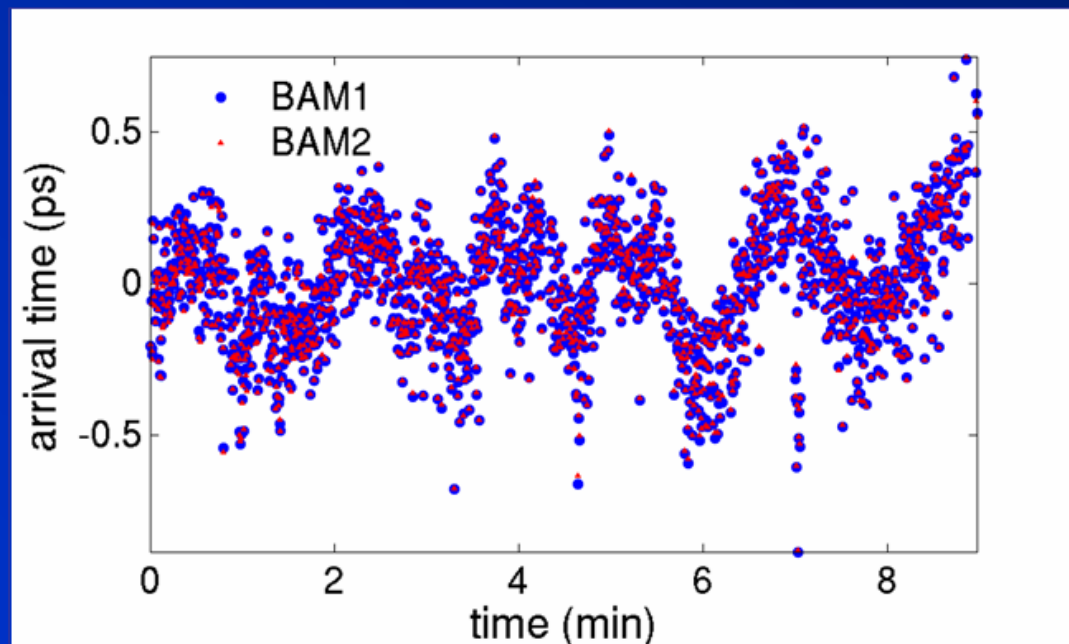
# Pulsed Optical Phase Reference: Bunch Arrival Monitor at FLASH (DESY)

- two BAMs tested at two different locations along the accelerator
- distance BAM 1 to BAM 2 = 60m



Courtesy of F. Loehl, DESY

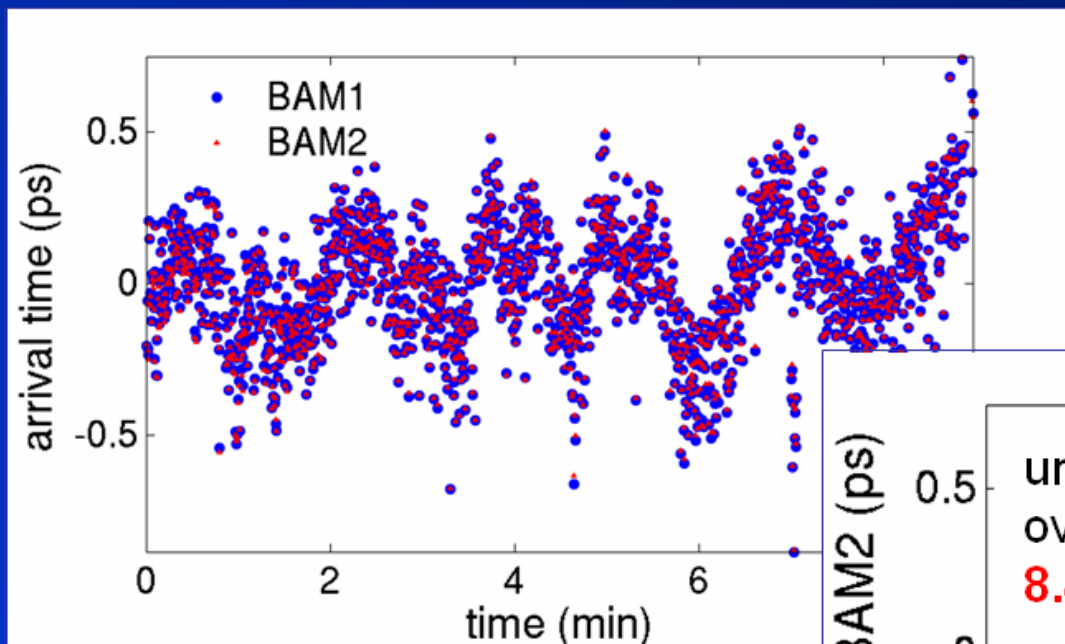
# Pulsed Optical Phase Reference: Bunch Arrival Monitor at FLASH (DESY)



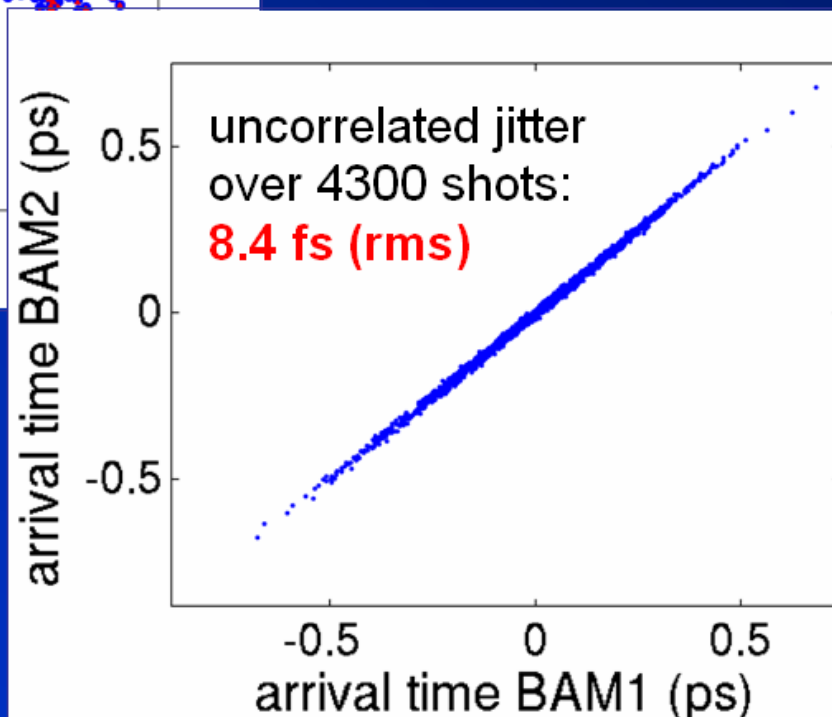
Arrival time correlation  
between two BAMs

Courtesy of F. Loehl, DESY

# Pulsed Optical Phase Reference: Bunch Arrival Monitor at FLASH (DESY)



Arrival time correlation  
between two BAMs



Single bunch resolution of entire  
measurement chain (laser, links,  
BAMs)  $< 6 \text{ fsec}_{\text{RMS}}$

Courtesy of F. Loehl, DESY



- In order to keep track of the developments and of T&S installation activities, in March '08 the 1<sup>st</sup> T&S Workshop has been held at Sincrotrone Trieste



2008

2009

- The 2<sup>nd</sup> T&S Workshop has been held in March '09 @ICTP Miramare (Italy) organized by INFN/LNF
- It is a “traditional” event where experts meet and discuss

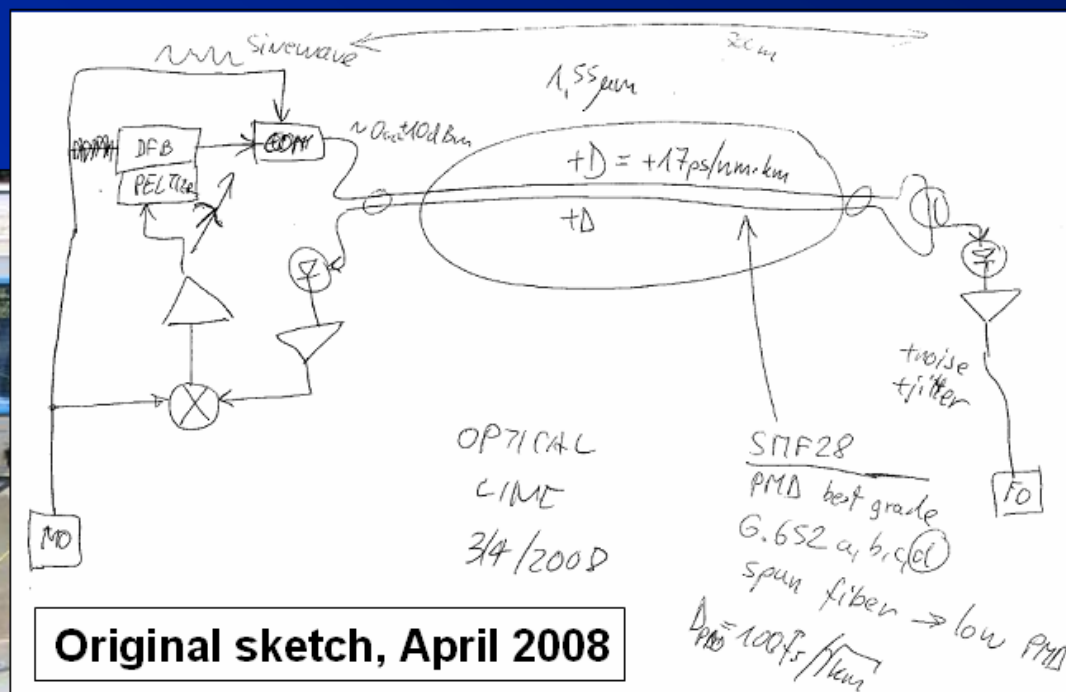
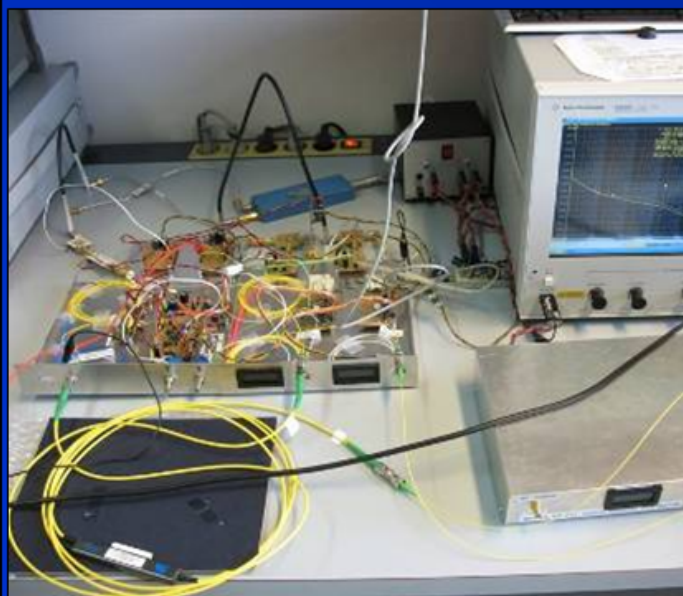


- Tutorial on Optical Synchronization held at DESY IRUV-X FP7 (OCT '08)



In the framework of an ST collaboration contract with I-tech and Ljubljana Univ. (SLO), a prototype link has been built and is currently being tested for the transmission over stabilized FO link of a Reference 3GHz signal.

*Patent Pending*



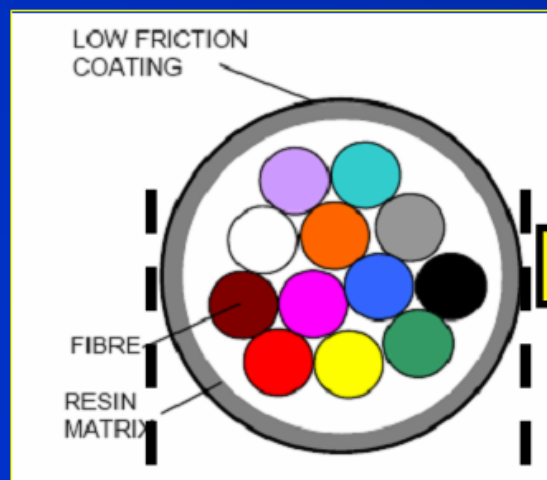
Courtesy of prof. M. Vidmar, UNI LJ (SLO)



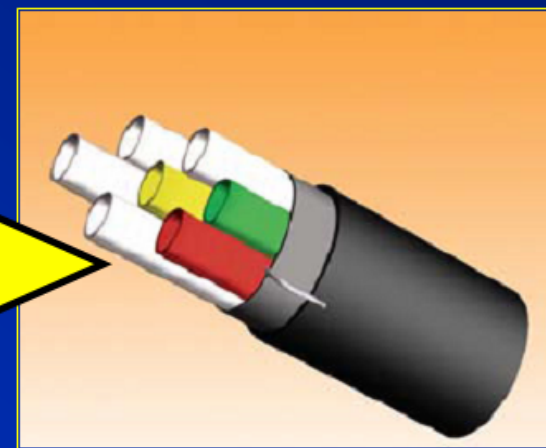
Patent Pending

Courtesy of prof. M. Vidmar, UNI LJ (SLO)

- High quality single mode fiber optics are available
- Length are limited, if compared to telecom links ( $>100\text{km}$ )
- Systems are available to simplify the installation to the facility:  
**bundles of fibers** (up to 12 / bundle) are *blown* in **thin pipes** ( $>1\text{km}$ )
- Successive upgrades / FO replacements feasible at low impact



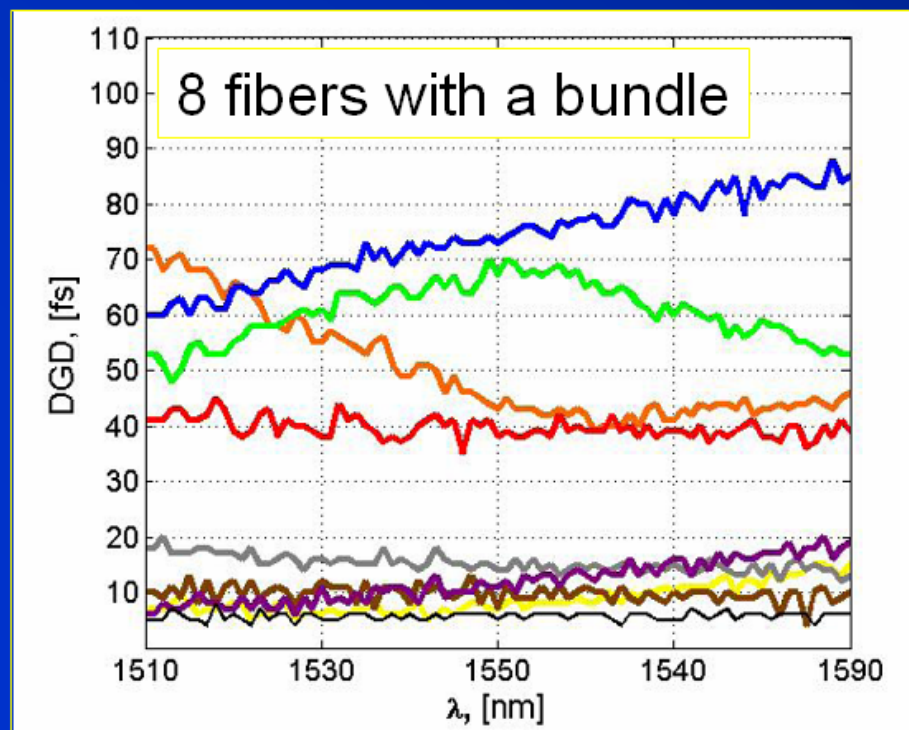
**D=3mm**



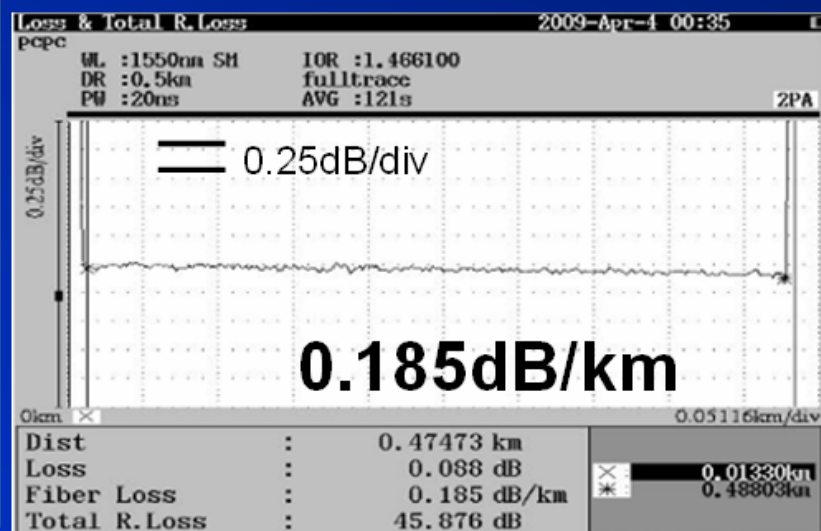
[www.prysmian.com](http://www.prysmian.com)

- Prior to installation in the accelerator, measurements have been carried out to qualify the optical fibers
- Polarization Mode Dispersion has been measured on a 8 fiber bundle (L=500m) by prof. A. Galtarossa (Lab. di Fotonica, (DEI) Uni. Padova)

Differential Group Delay (DGD)



$$PMD_C = \frac{DGD}{\sqrt{L}} \left[ ps/\sqrt{km} \right]$$



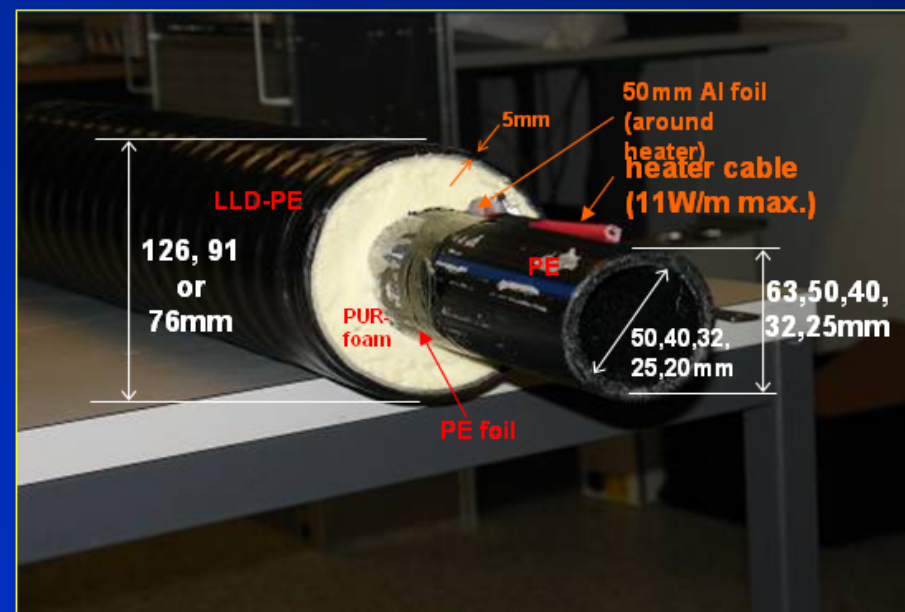


- At PSI, for the FEL/LEG test stand the program is:
  - to start with a high performance coaxial system (well known technology, fallback) using an electrical Master Oscillator
  - to start then an Optical Master Oscillator
  - to implement fiber based optical distribution to improve performance, functionality and flexibility

■ Rather than a coaxial cable, it is a coaxial assembly to provide thermal control over the cable:

- temp. sensors located in cable
- heater control loop
- 45 €/m
- long term drift <50fsec

Courtesy of S. Hunziker (PSI, CH)

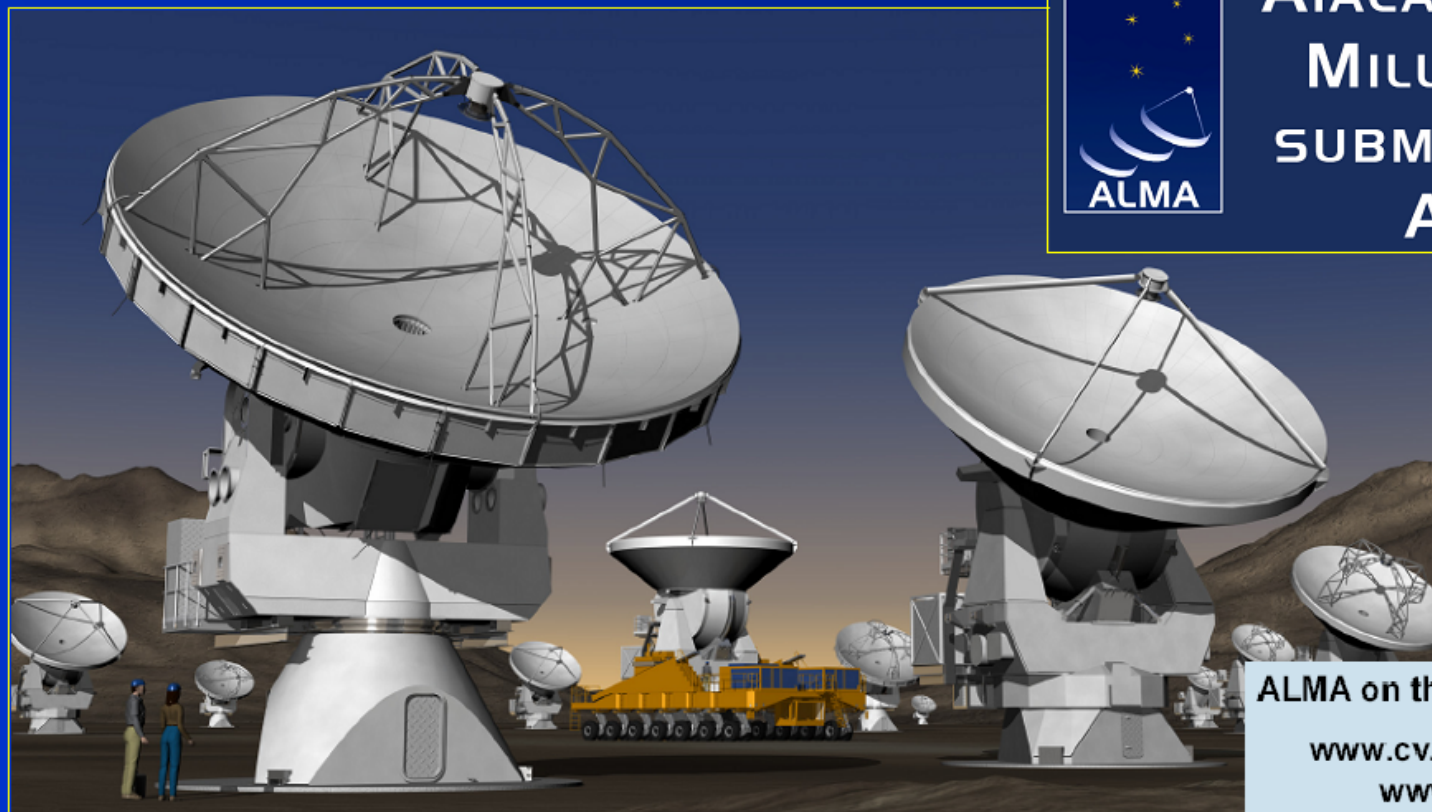




ALMA, the Atacama Large Millimeter/ submillimeter Array, will be a single research instrument composed of up to 80 high-precision antennas, located on the Chajnantor plain of the Chilean Andes in the District of San Pedro de Atacama, 5000 m above sea level.



## ATACAMA LARGE MILLIMETER / SUBMILLIMETER ARRAY

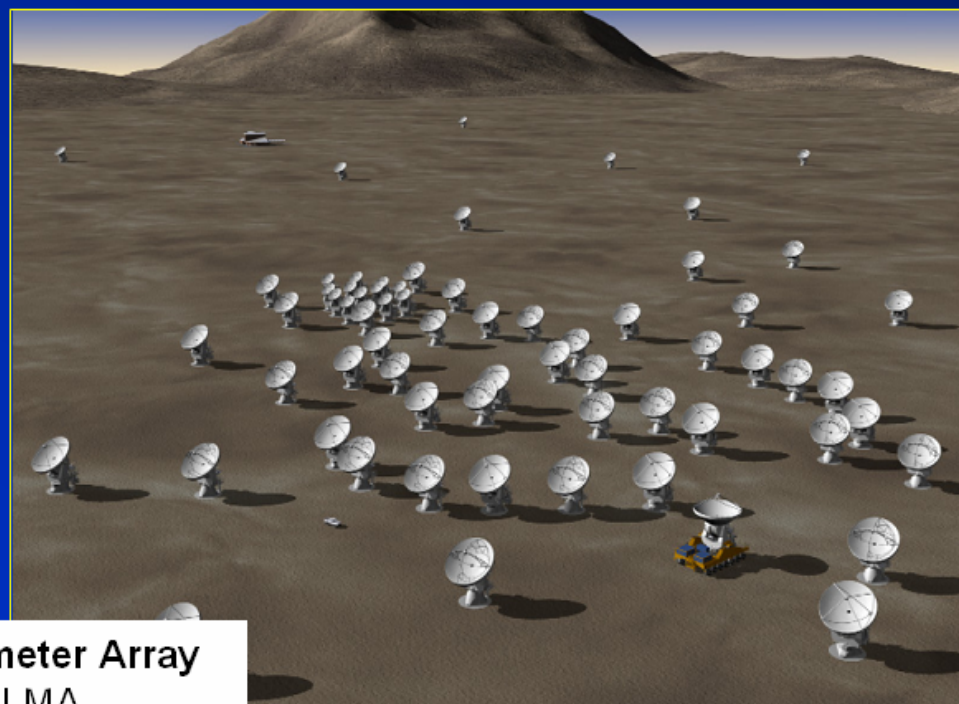


ALMA on the World Wide Web

[www.cv.nrao.edu/naasc](http://www.cv.nrao.edu/naasc)

[www.alma.info](http://www.alma.info)

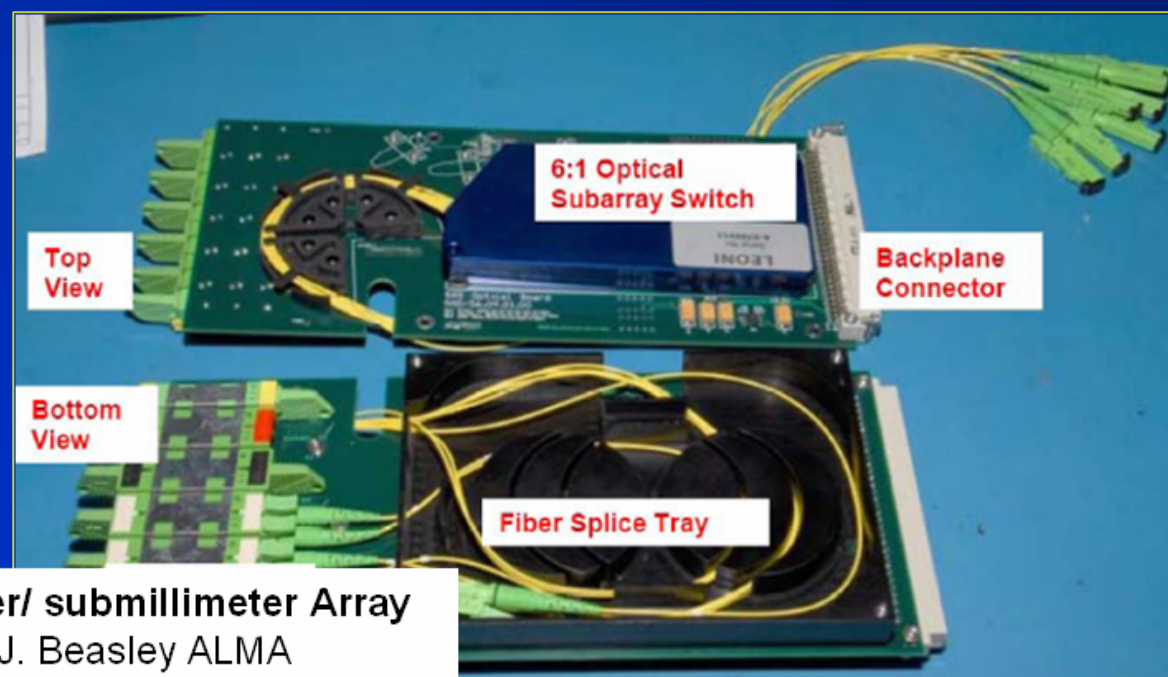
- One of the major challenges for ALMA is distributing the reference signal to the antennas, which may be as much as 16km apart, with sufficient precision to keep the local oscillators synchronized to an accuracy of much better than a radian of phase, even at the highest observing frequencies.
- The limit on noise in the timing is 38 fsec on short time scales with drifts of only 13 fsec allowed on times of 20 to 300 seconds.
- An advanced photonic system has been developed to achieve this.
- The reference signal, typically at a frequency of about 100 GHz, is distributed on optical fibers as the beat between two tunable lasers, a “slave” laser locked to an ultra-stable “master”.



**The Atacama Large Millimeter/ submillimeter Array**

Richard E. Hillsa and Anthony J. Beasley ALMA

- This beat is detected by a photo-mixer at each receiver cartridge and used to lock the local oscillator. A small sample of the laser light is taken off at the receiver, shifted in frequency by 50 MHz and returned to the central laboratory.
- The optical path in each fiber is then monitored and changes due to thermal expansion or mechanical movements can be compensated by means of a “line-stretcher” in which a coil of fiber is stretched under control of a servo loop.
- This scheme has been extensively tested and production of the various parts of the system is now underway.



**The Atacama Large Millimeter/ submillimeter Array**  
Richard E. Hillsa and Anthony J. Beasley ALMA



# PARTICLE ACCELERATOR CONFERENCE

**Vancouver  
British Columbia, Canada**

**May 4 – 8, 2009**

**Thank you for your attention**

**...time for Questions**