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Timing and Synchronization (Tutorial/Overview)

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Tutorial Objective

- Give an overview of techniques used for synchronization systems
- Create some order in basic concepts of synchronization (practice shows that they are often confused even by LLRF team people)
- Indicate the most important issues of synchronization subsystems (without going into details)

Definition of Synchronization

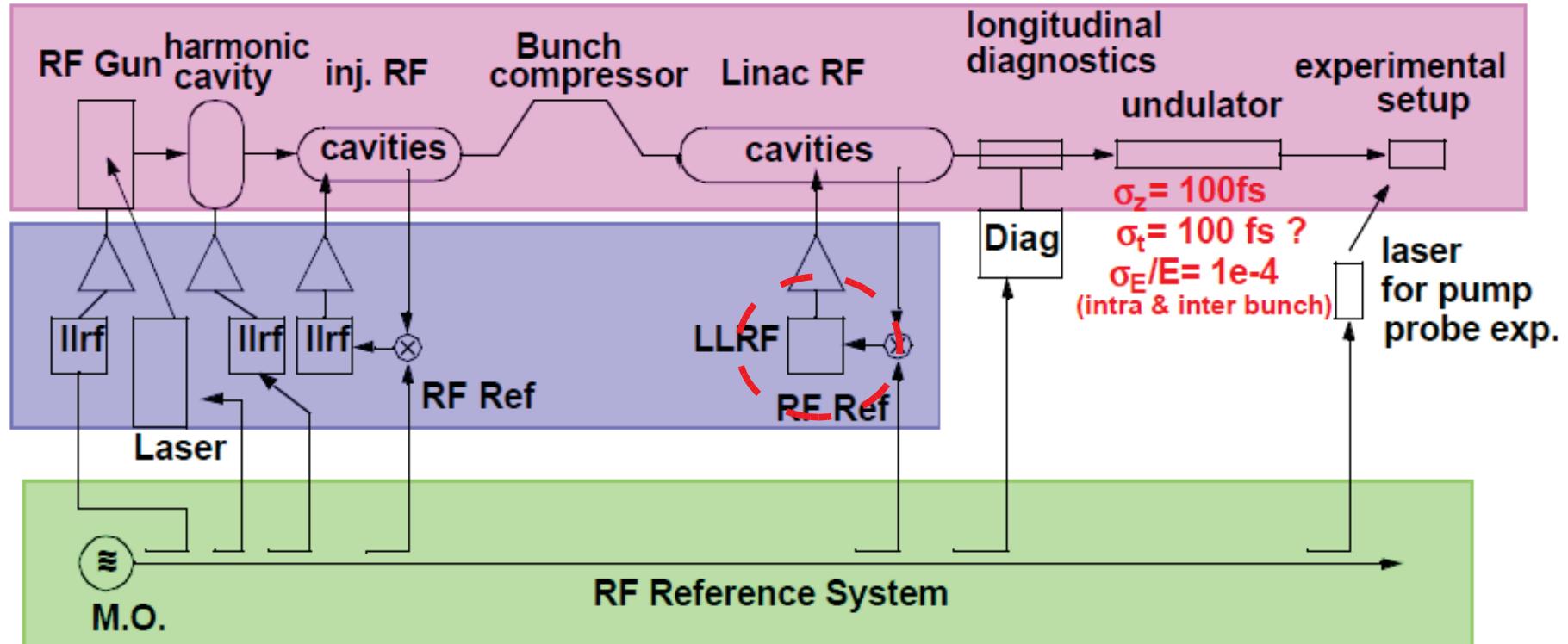
- 1. Synchronization is timekeeping which requires the coordination of events to operate a system in unison**
- 2. The relation that exists when things occur at the same time**

The synchronization is performed with use of signals readable by components of the system



Accelerator Synchronization - Overall

Generic layout of a FEL facility



Accelerator subsystem must “play” together at the same time on order to achieve desirable acceleration of particle beam (beam energy and time parameters) and SASE

Local Synchronization (LLRF)

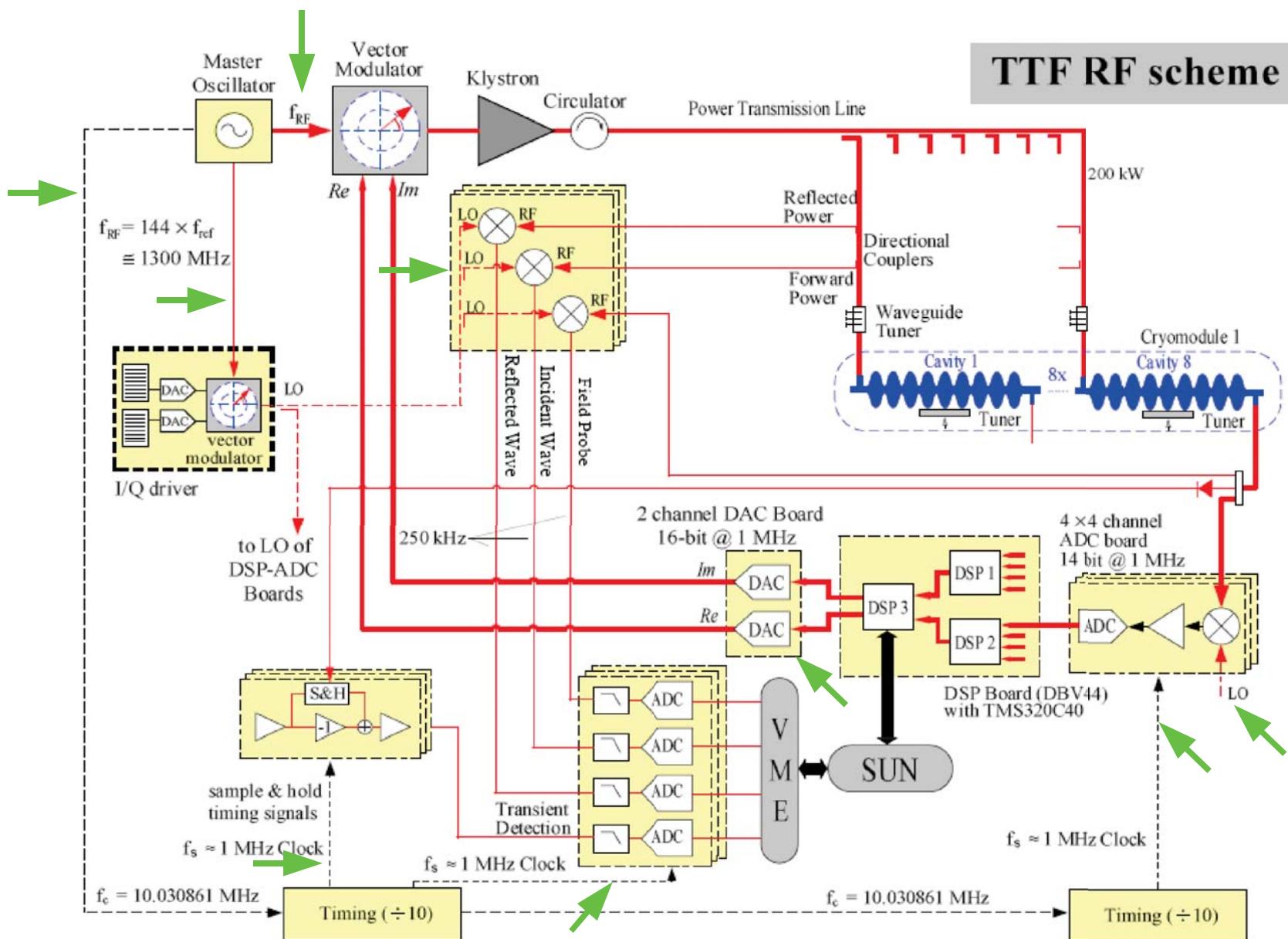


Figure source: Thomas Schilcher, "Vector sum control of pulsed accelerating fields in Lorenz force detuned superconducting cavities"

Synchronization Signals

- Analog (RF phase reference, VM, LO)
- Clocks (digital subsystems, ADC, DAC, CPU)
- Trigger signals (digital subsystems, CPU)
- Optical signals (lasers, diagnostics, experiments)

Phase Reference vs Clock

People often confuse:

- **Phase Reference Signal:** RF (MO) harmonic signal
- **Clock:** “digital” signal in common standard like CMOS, LVDS,...

Synchronization System

Consists of:

- Master Oscillator
- Phase Reference Distribution (for harmonic RF signals)
- Timing System (for clocks and triggers)

RF vs Optical Synchronization

The MO and phase reference distribution can be realized either in RF technology or in optical (laser oscillators and synchronization)

- RF:
 - mature technology
 - well known subsystems
 - limited performance (but sufficient for many applications)
 - sensitive to EMI
- Optical:
 - low loss, easier installation (fiber as media)
 - promising performance (sub-fs accuracy estimated)
 - still under development - reliability not proven
 - future projects

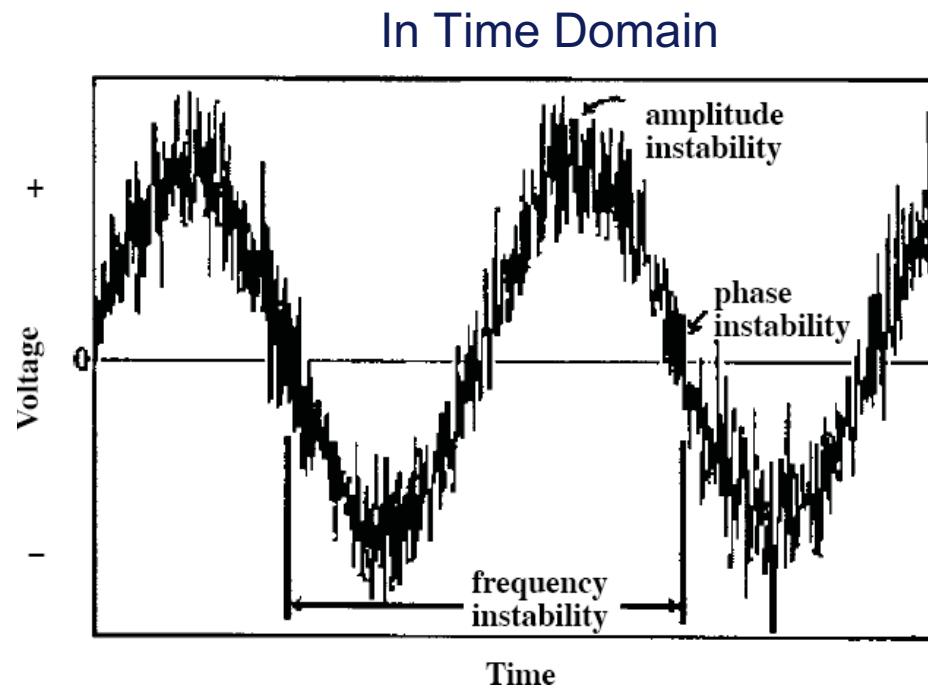
Harmonic Signal With Noise Components

Ideal Signal

$$v(t) = V_0 \sin (2\pi \nu_0 t)$$

Noisy Signal

$$v(t) = [V_0 + \varepsilon(t)] \sin [2\pi \nu_0 t + \phi(t)]$$



V_0 - the nominal peak voltage amplitude

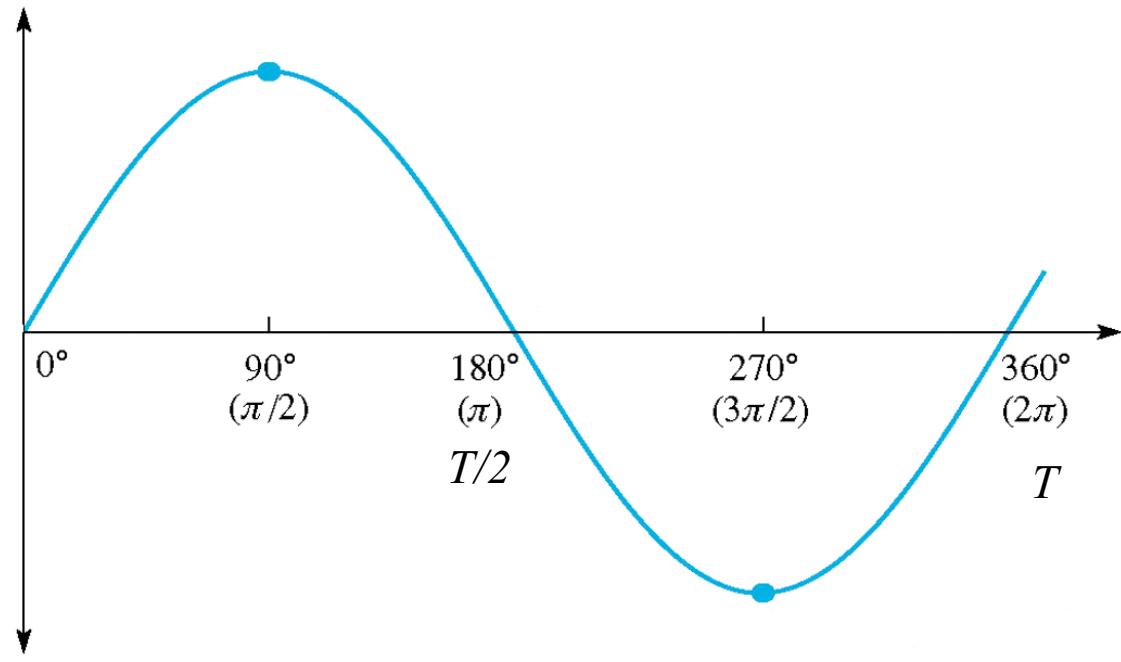
ν_0 - nominal frequency, called also instantaneous

$\varepsilon(t)$ - deviation of amplitude from nominal value

$\phi(t)$ - deviation of phase from nominal value - **noise component**

Frequency, Time and Angle – Basic Relationships

Why do you use “ps” when you talk about phase??



$$T = \frac{1}{\nu_0} \quad \text{Time domain measure}$$

$T \rightarrow 360^\circ$ in the angular domain

$$t = \frac{\phi T}{360^\circ} \quad \text{Phase to time conversion}$$

Example: $\nu_0 = 1.3\text{GHz} \rightarrow T = \sim 769\text{ps}$, $1^\circ \rightarrow 2,13\text{ ps}$

Time domain measure is convenient for phase changes in distribution media (by means of propagation delay change) because it does not depend on the signal frequency.

Frequency and Phase Instability

The instantaneous frequency of a signal with phase noise component

$$\nu(t) = \nu_0 + \frac{1}{2\pi} \frac{d\phi(t)}{dt}$$

Definition of the frequency instability

$$y(t) = \frac{\nu(t) - \nu_0}{\nu_0} = \frac{1}{2\pi\nu_0} \frac{d\phi(t)}{dt}$$

This quantity characterizes the instantaneous frequency deviation from the nominal frequency

The phase instability expressed in units of time

$$x(t) = \frac{\phi(t)}{2\pi\nu_0}$$

Short and Long Term Instabilities

The short-term instability refers to all phase/frequency changes about the nominal of less than a few second duration.

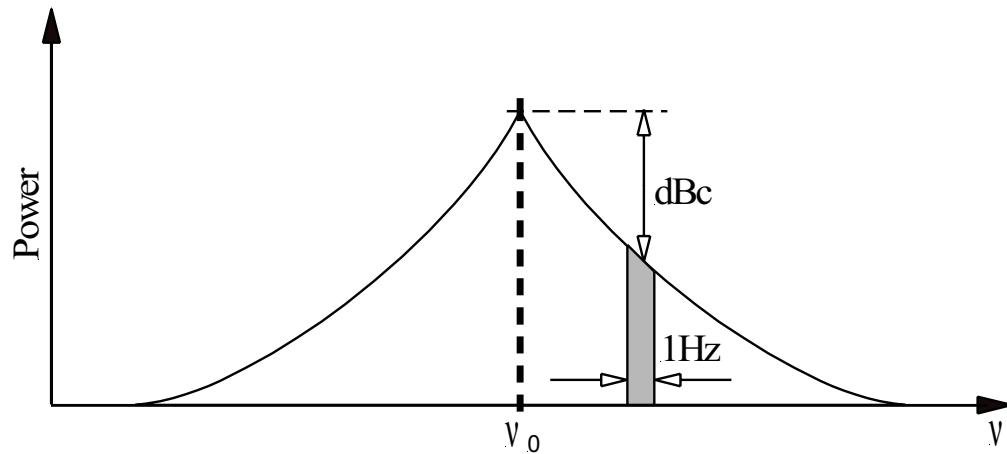
- derives from a “fast” phase noise components ($f > 1$ Hz)
- expressed in units of spectral densities or timing jitter

The long-term instability refers to the phase/frequency variations that occur over time periods longer than a few seconds

- derives from slow processes like long term frequency drifts, aging and susceptibility to environmental parameters like temperature
- expressed in units of degree, second or ppm per time period (minute, hour, day ...)

Phase Noise

It is a **frequency domain measure** of signal phase instabilities $\phi(t)$



Power Spectral Density
measured in dBc/Hz

*power density in one
phase noise modulation*

$$\mathcal{L}(f) = \frac{\text{sideband, per Hz}}{\text{total signal power}} = \frac{1}{2} S_\phi(f)$$

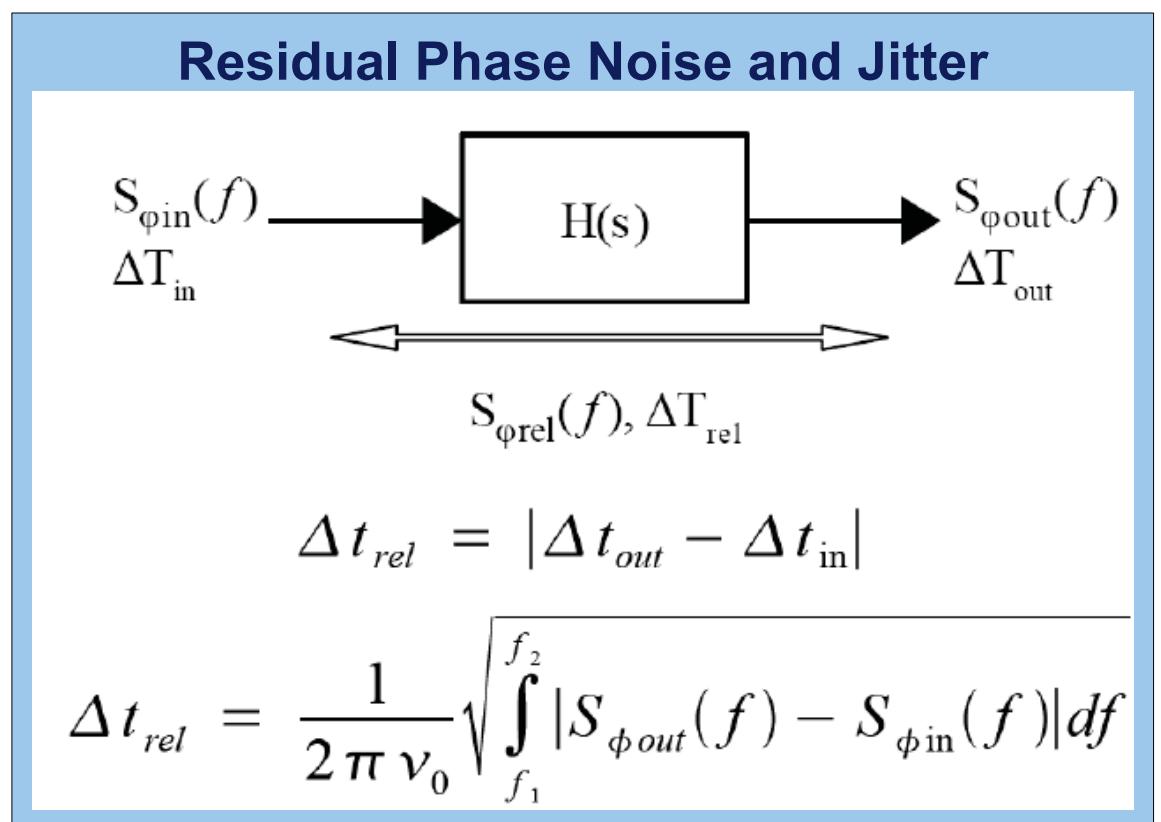
$f = \nu - \nu_0$ offset from the carrier frequency

Absolute and Residual Instabilities / Noise

The absolute instability refers to the total phase noise present at the output of the signal source or a system.

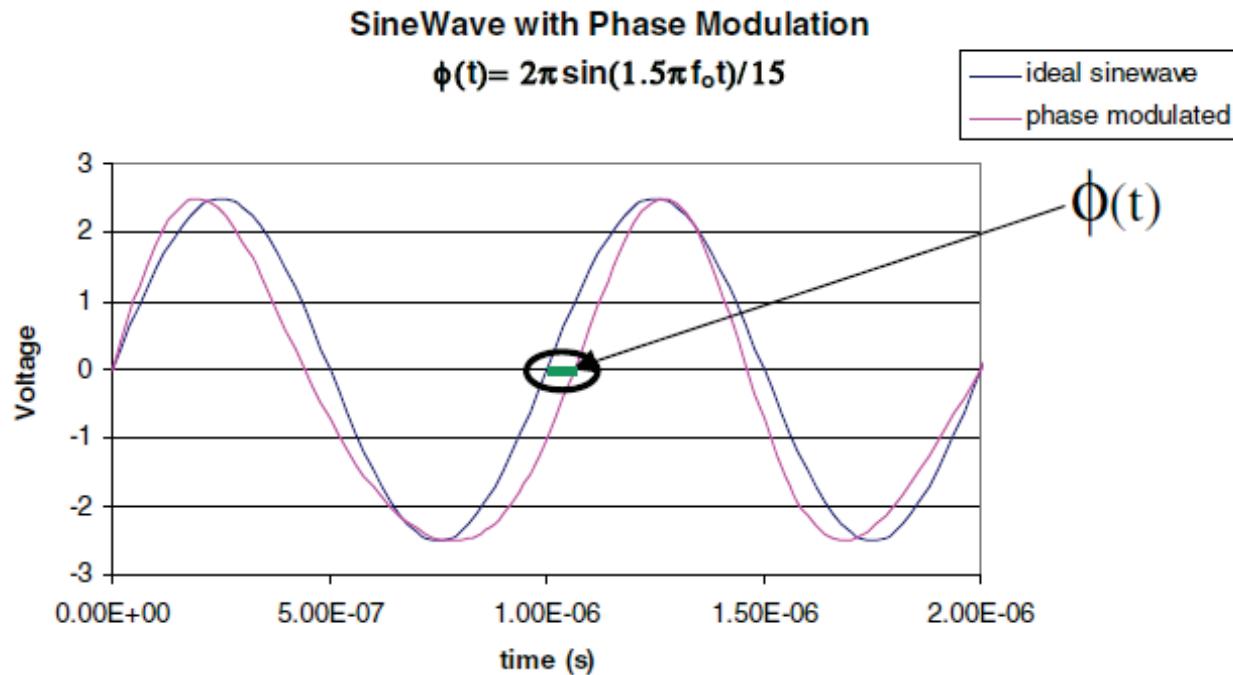
The relative instability refers to a measure between different points of a system. It is mostly caused by residual noise and phase drifts of a distribution media.

Relative stability type is of high importance for the synchronization systems



Phase / Timing Jitter

It is a **time domain measure** of signal phase instabilities $\phi(t)$



Phase jitter ϕ_{jitter}^2 is calculated in units of radian

Timing jitter Δt_{RMS} is calculated in units of seconds RMS. Used frequently with digital signals

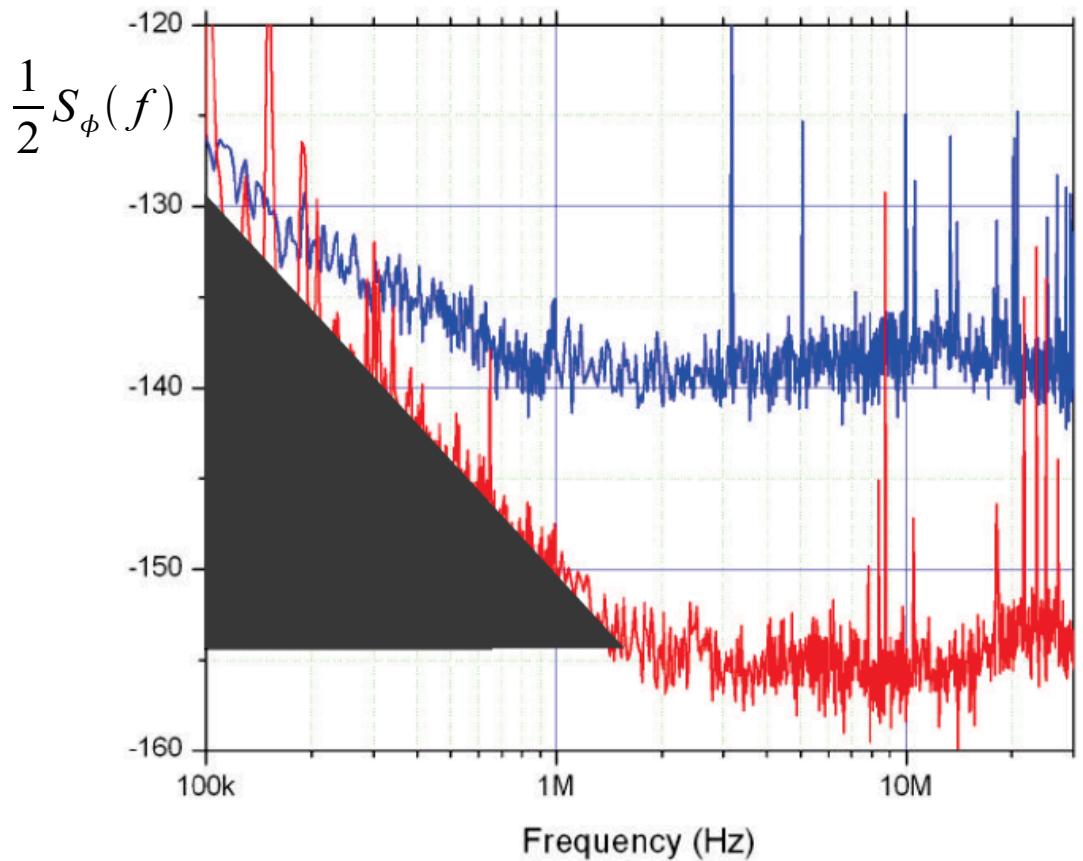
Figure source: Corning Frequency Control

Phase Noise and Jitter Relationship

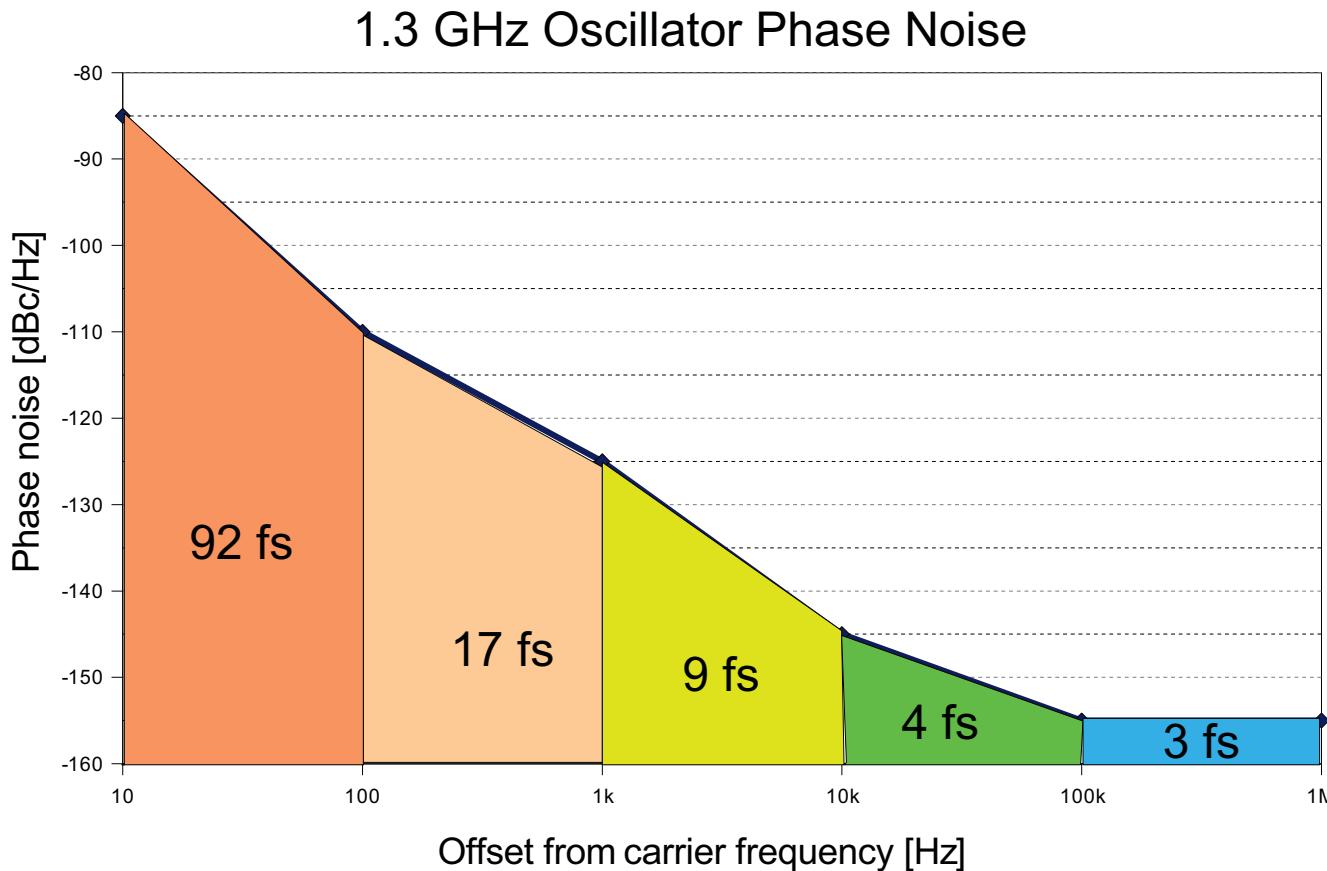
Jitter is the integral of $S_\phi(f)$ over the Fourier frequencies of application

$$\phi_{jitter}^2 = \int_{f_1}^{f_2} S_\phi(f) df$$

$$\Delta t_{rms} = \left(\frac{1}{2\pi\nu_0} \right) \sqrt{\int_{f_1}^{f_2} S_\phi(f) df}$$

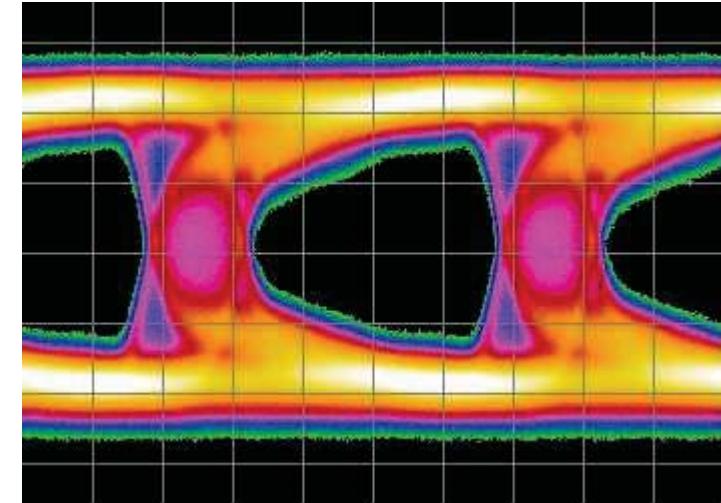
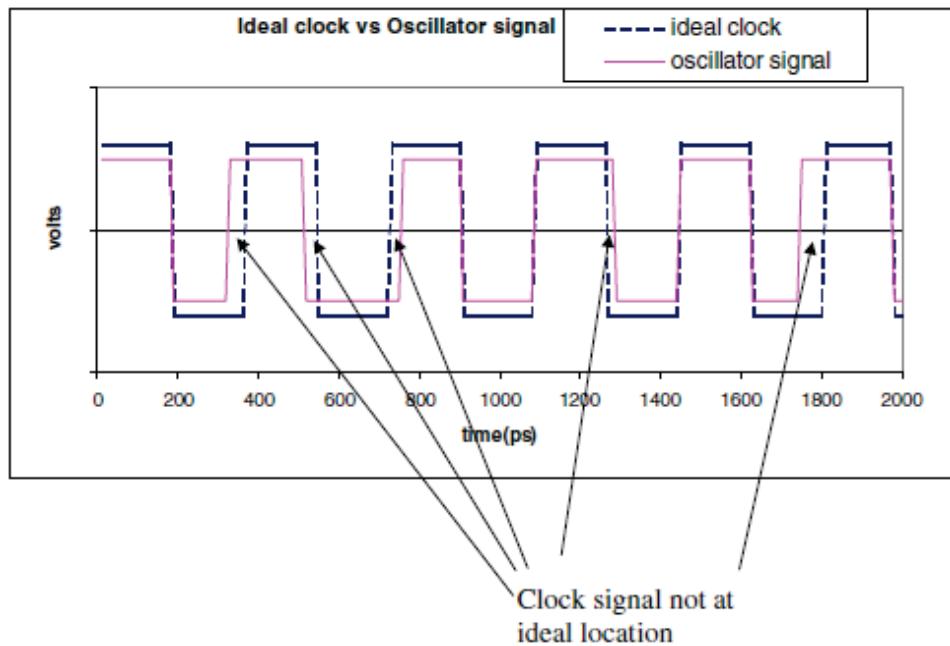


Phase Noise Contributions to Jitter



Time Domain Timing Jitter Measurement

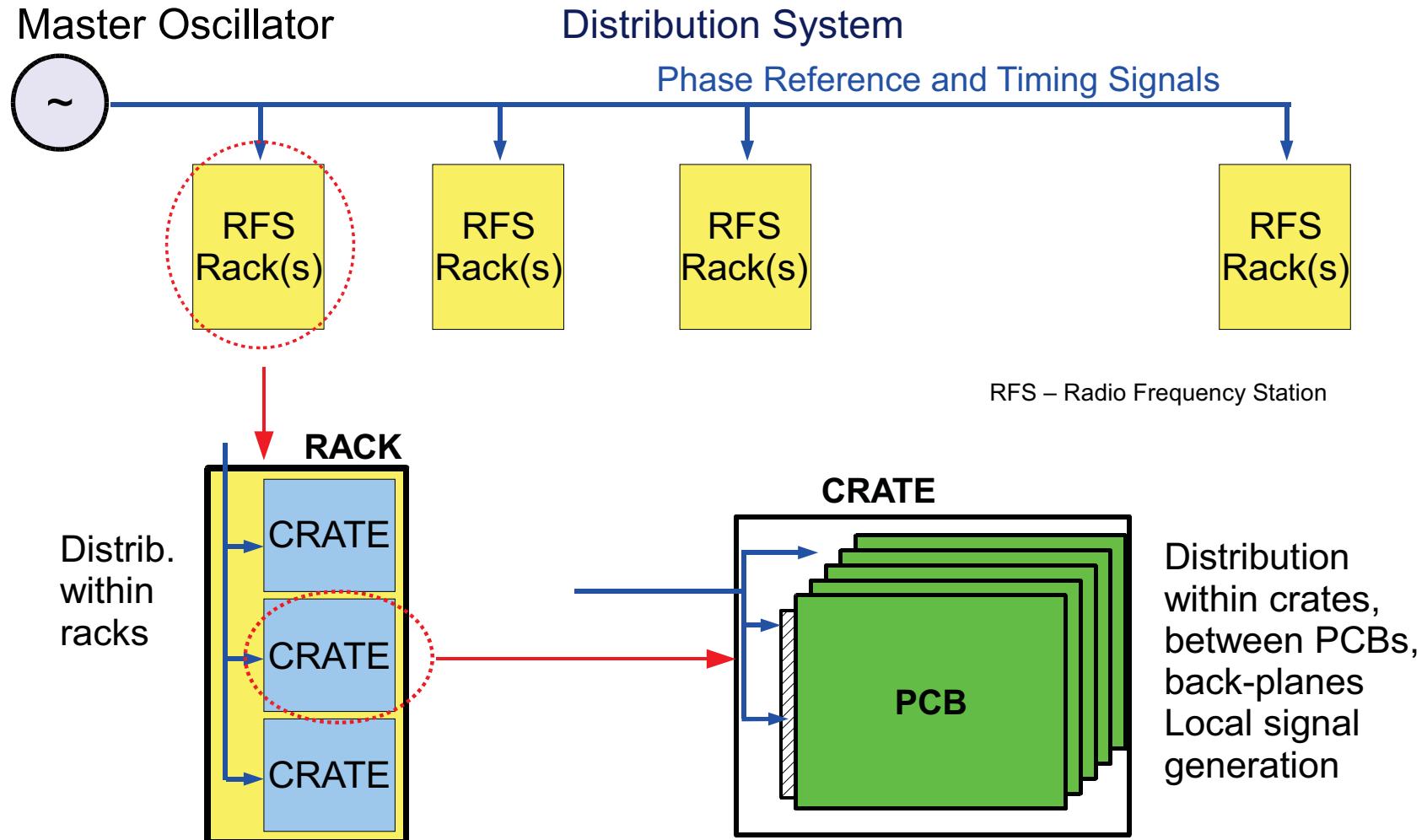
Eye Diagram



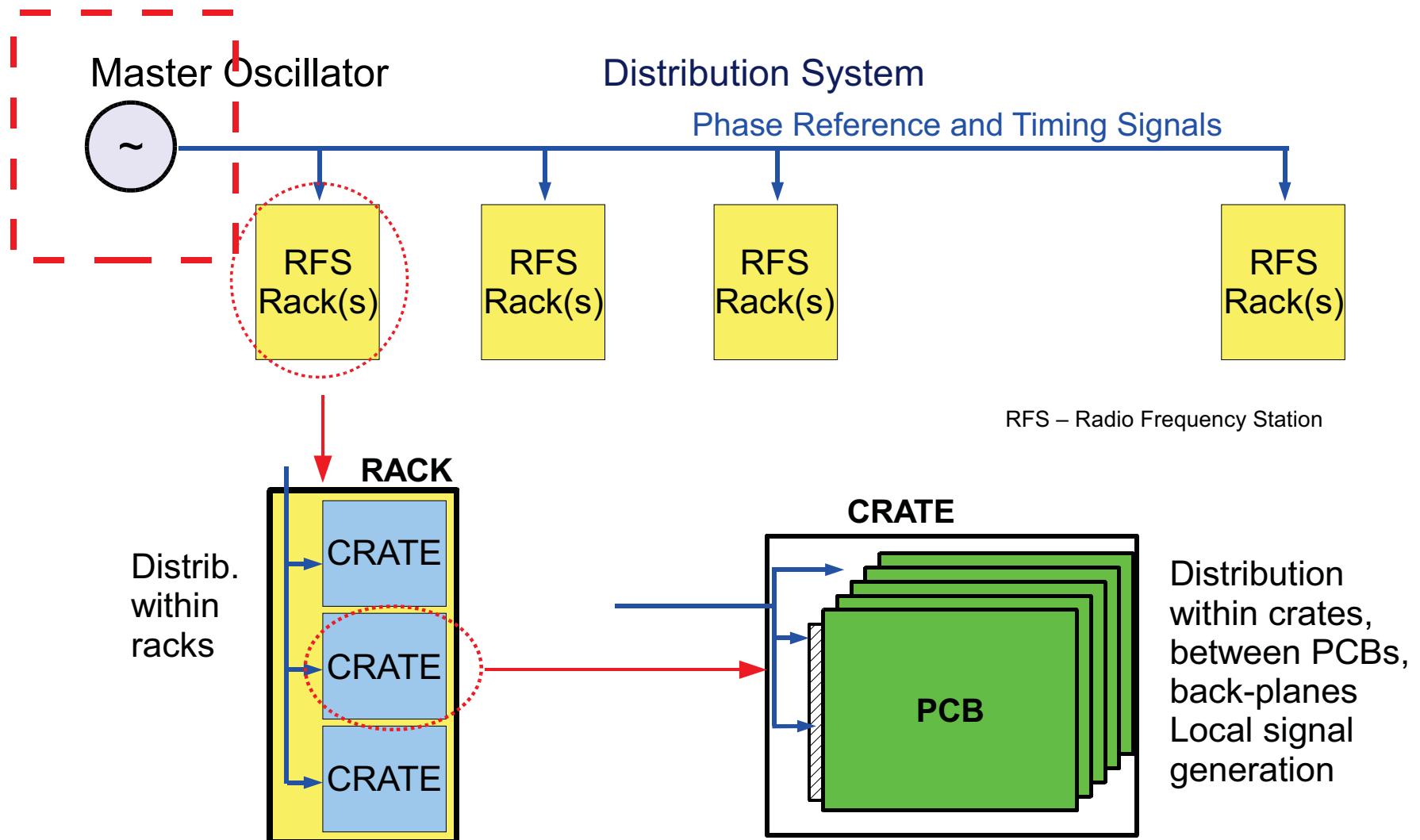
In the time domain the timing jitter is measured with a digital scope

Figure source: Corning Frequency Control

Generic Synchronization System



Generic Synchronization System



Master Oscillator

This device is providing the reference signal for the entire synchronization system

Single signal source

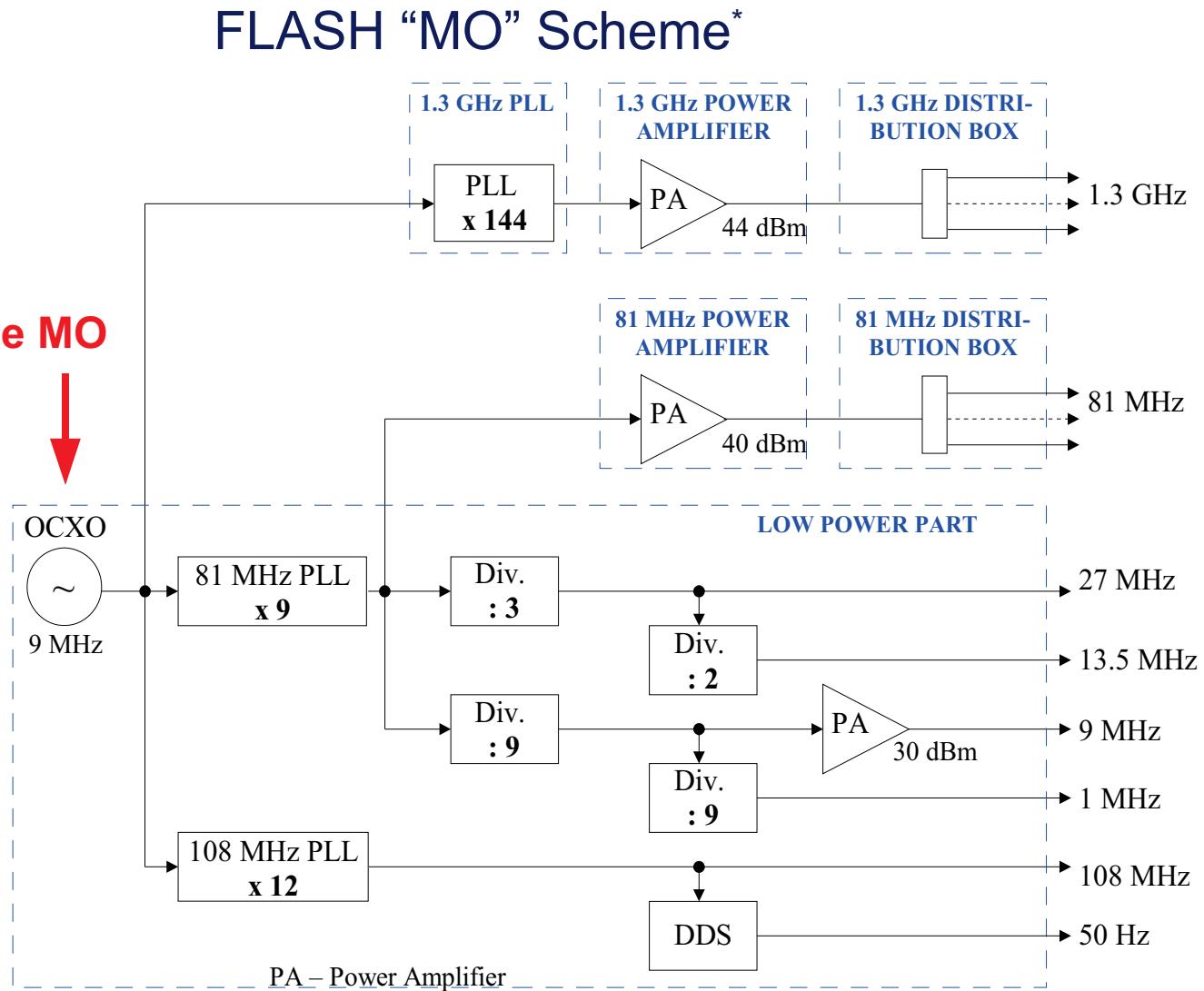
But in practice ...

Master Oscillator System Example

The MO System

But for convenience
people call it MO

The MO



* will be presented in more detail by Henning Weddig

- MO
- Frequency generation scheme
- Signal level adjustment (power amplifiers)
- Splitters and interface to distribution links
- Power supply (very important issue!), sometimes must be unbreakable
- Diagnostics

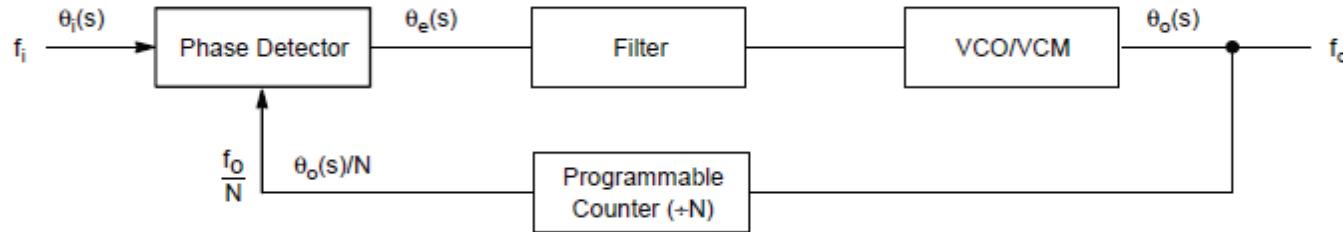
Stable Signal Sources

- Crystal Quartz Oscillators (OCXO) (from 5 MHz to 100 MHz)
 - custom, non-decimal frequencies available
 - relatively low price and size
- Atomic Standards
 - excellent long term stability
 - short term stability worse than for OCXO
 - typically 10 MHz output (problem with custom frequencies)
 - Relatively expensive
- GPS receiver
 - synchronized to 10 MHz atomic standard
 - good solution for large machine (several devices may provide good timing)
 - sensitive to atmospheric conditions

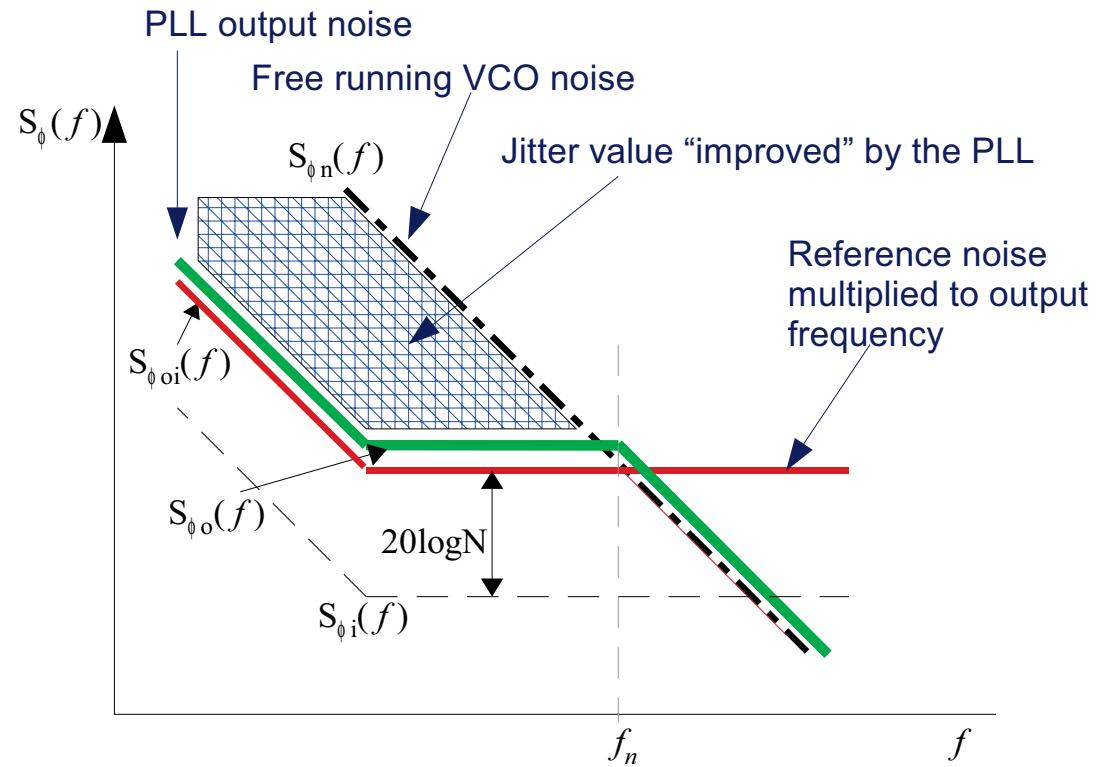
Frequency Multiplication and Division

- Frequency multipliers
 - Fixed multiplication value (x2, x4)
 - Rather small multiplication factors
- PLL multipliers (synthesizers)
 - Phase locking of a VCO to the reference signal
 - Flexible choice of multiplication factors
 - Proper design allow for minimizing system phase noise
- Frequency dividers
 - Usually based on digital counters
 - Modern devices offer very low residual jitter values, even as low as 100 fs
- Direct Digital Synthesizers (DDS)
- Combinations of units listed above

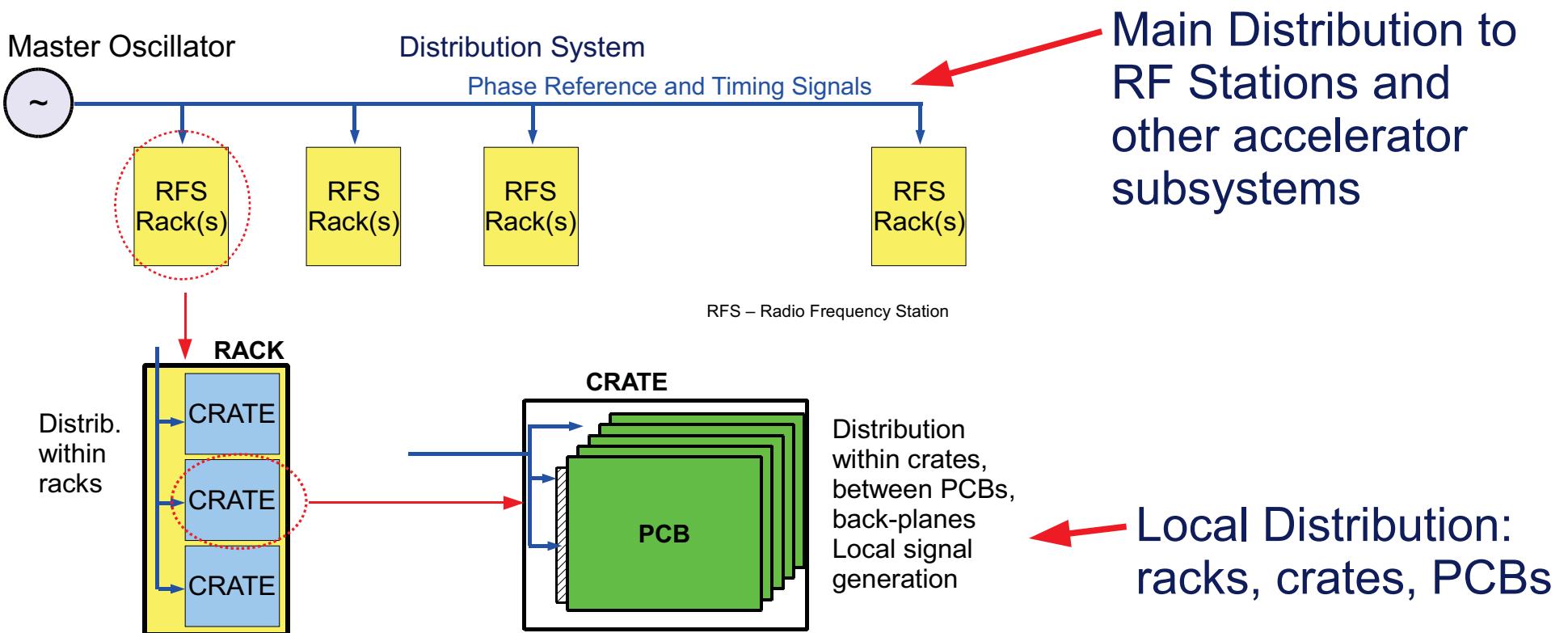
PLL Synthesizer



- Phase – locking of a VCO to a reference signal
- Flexibility in selecting output frequency
- Proper selection of PLL components allow for phase noise (jitter) reduction comparing to a standard multiplier



Stable Signal Distribution



The importance of a local distribution is frequently underestimated
Last 2 meters of a poor quality cable exposed to vibrations or a “wrong” track on a PCB can destroy the signal performance achieved over hundreds of meters of distribution!

Distribution System Issues

1. System topology:

- Star
- Line with tap points

2. Distribution media type:

- Coaxial cable or waveguide
- Optical fiber
- Air (radio synchronization)

3. Distributed signal type:

- Continuous sine wave
- Pulses used for local oscillator synchronization
- Digital signals (triggers, clocks)

4. Influence on the signal:

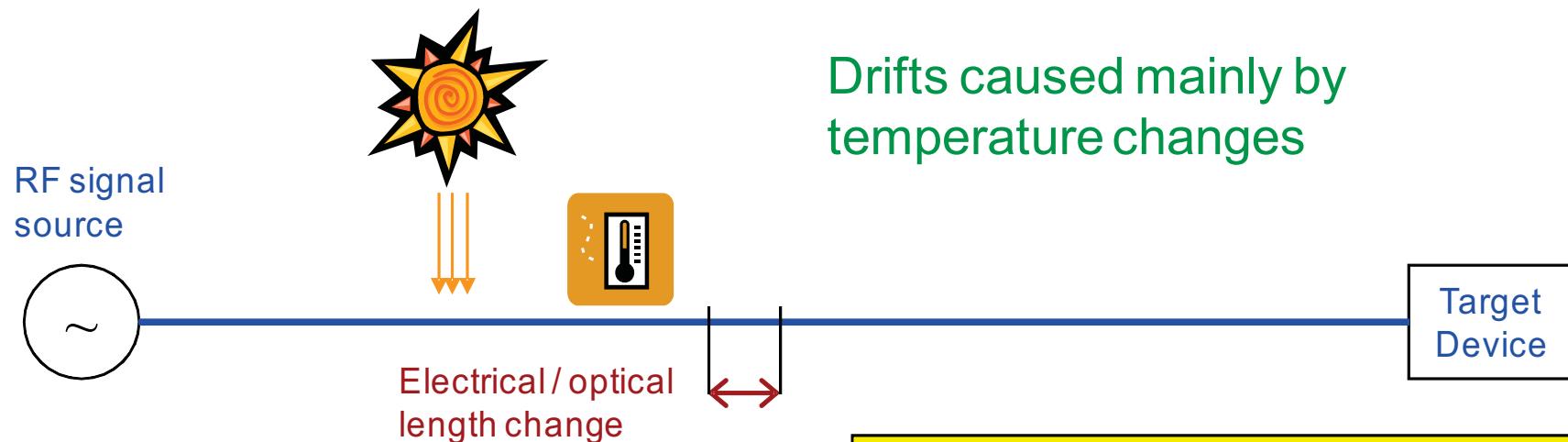
- Passive
- Stabilized: e.g. temperature stabilized cable link
- Active: with feedback circuits actively controlling signal phase

Distribution Media: Cable vs. Optical Fiber

Parameter	Coaxial	Fiber
Attenuation	High	Low at any RF frequency
Distribution distance	short	long
Temperature coefficient of phase length	$\sim 10^{-5}/^\circ\text{C}$	$\sim 10^{-5}/^\circ\text{C}$
Need of feedback controlling phase drifts	YES	YES
Price	Relatively high	Fiber – low but Tx and Rx high

The decision not obvious and usually some compromise is needed

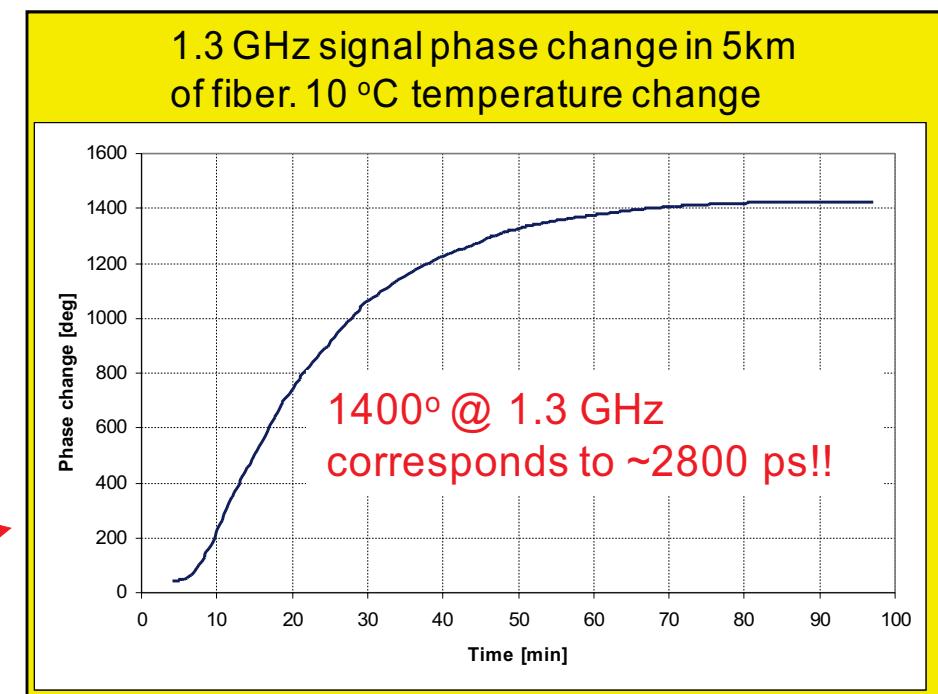
Phase Drifts in Distribution Media



Reason of drifts:

- In fiber: n_{eff} change
- In cable: physical dimension and dielectric properties change

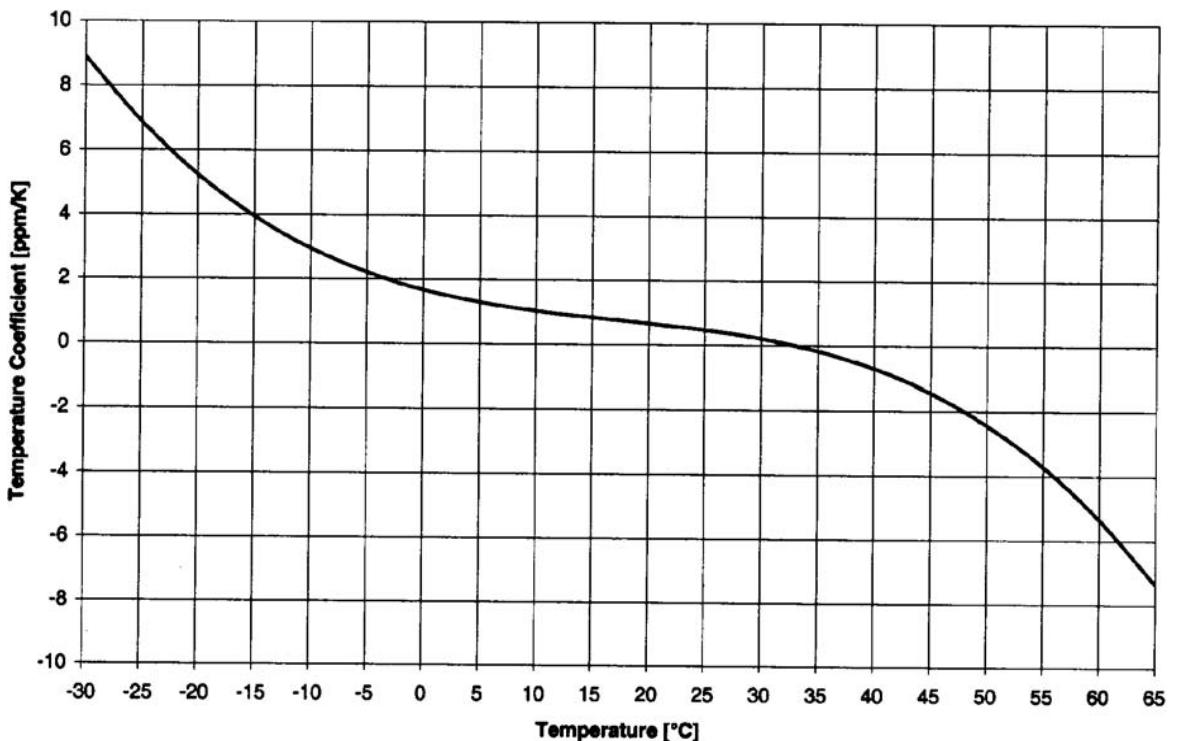
Drifts caused mainly by temperature changes



Feedback on phase required!!

Phase Drifts in Distribution Media (2)

- There are cables with low temperature coefficient available (0 to 10 ppm/ $^{\circ}\text{C}$) in given temperature range
- Unfortunately, the accelerator temperature does not always fit our needs – temperature stabilization or drift compensation may be required



- Good laboratory cables achieve tens to few hundreds of ppm/ $^{\circ}\text{C}$
- Temperature coefficients of poor quality cables reach thousands of ppm/ $^{\circ}\text{C}$
→ **1 meter of such cable inside of a rack can be worse than hundreds of meters of a thick distribution cable!**

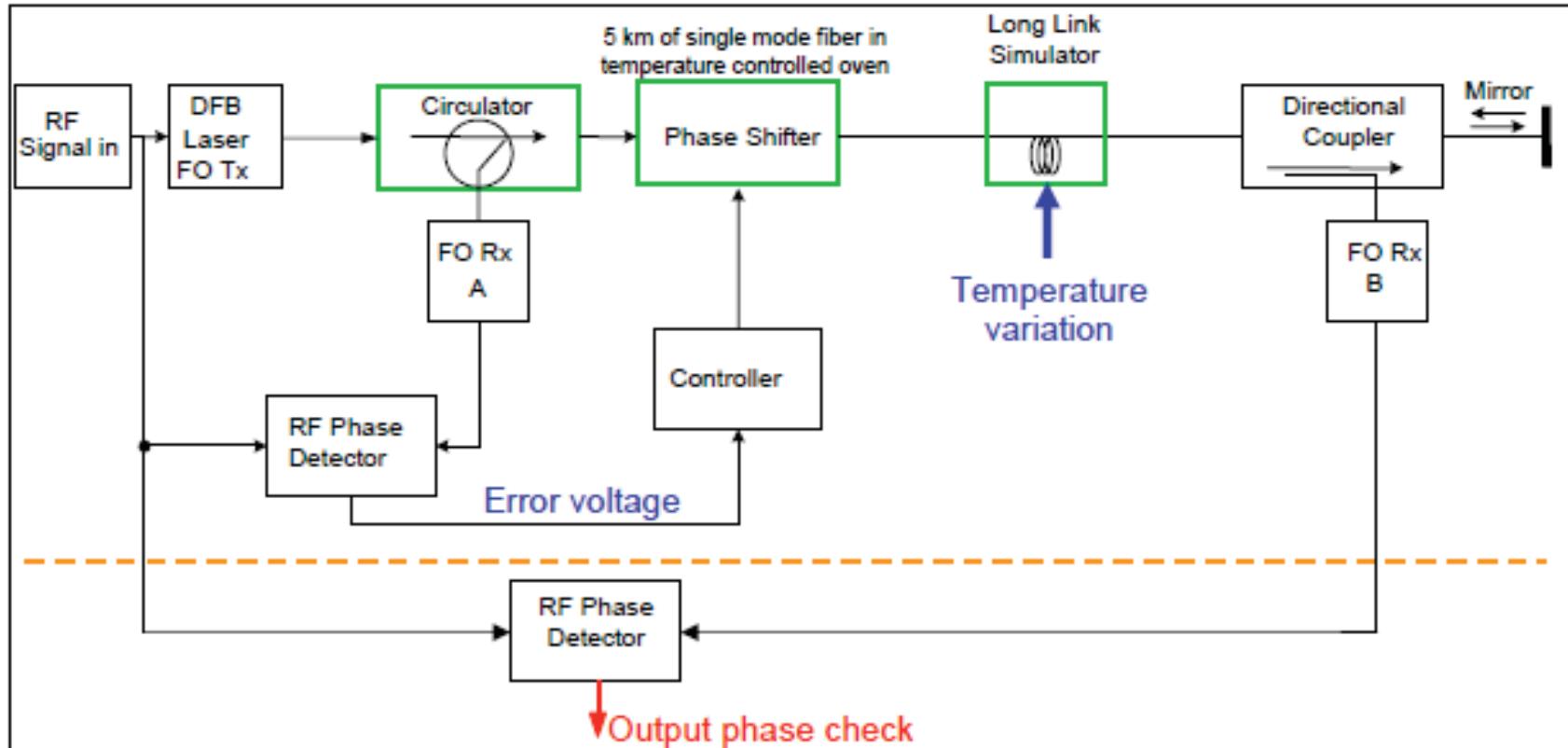
Drift Compensation by Temperature Stabilization

- Possible but difficult
- No direct influence on the distributed signal
- Usually realized by a heating tape wrapped around the cable and thermal insulation around
- Space consuming and difficult installation
- Rather for short distances (cost issue) – max. few hundred meters
- Temperature controller parameters must be adjusted very carefully! Even 0.5 °C temperature variation can cause phase modulation in the cable...

Active Drift Compensation

- So called reflectometric method used in many variations for both, fiber and coax cable
- The basic principle: correct for phase drift by measurements of a round-trip time delay changed
- Achieving 100 fs peak stability over several hundred meters is relatively easy
- Optical labs claim the ability to reach single fs!

Active Drift Compensation Example



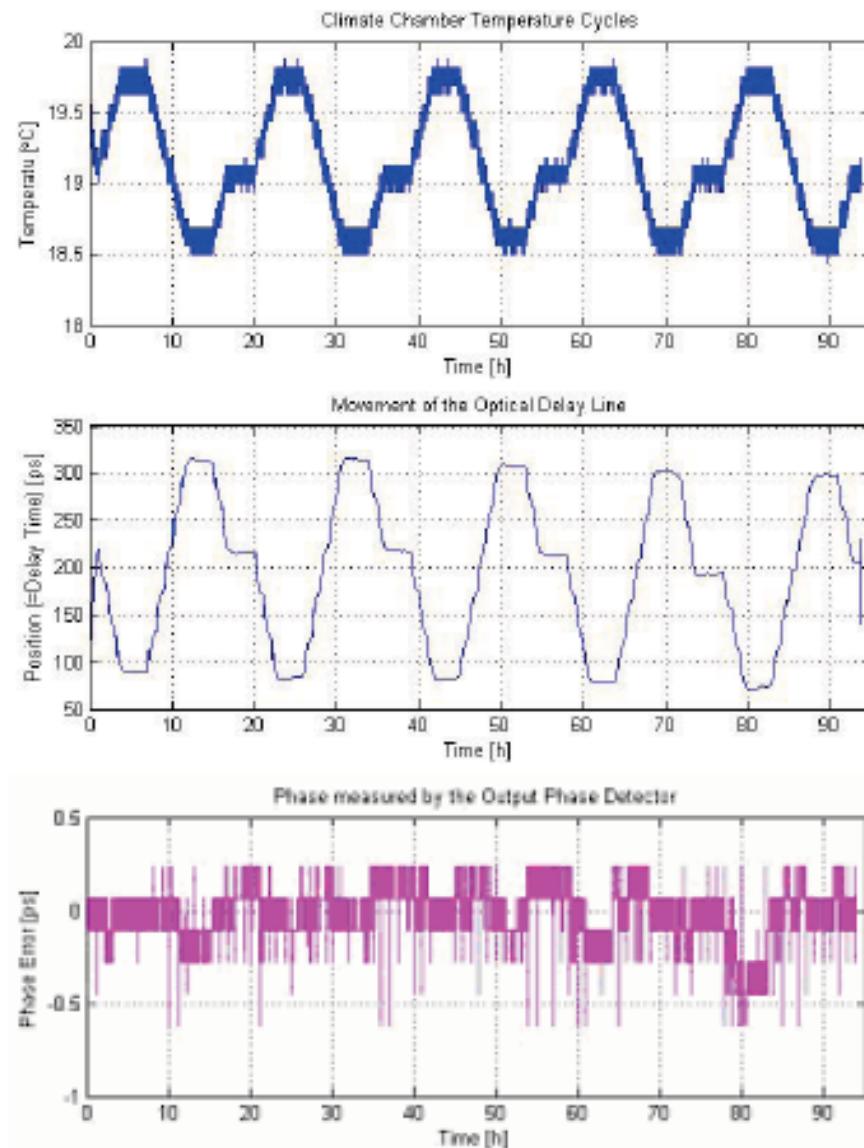
Active Drift Compensation Results

Measurement performed inside of the climate chamber
5 km of fiber used as long link
100 h measurement duration

ODL position followed temperature induced phase drifts

RESULTS

Phase Shifter	Short term stability [ps]	Long term stability [ps]
5 km fiber on spool	0.8	5
ODL	0.3	0.8



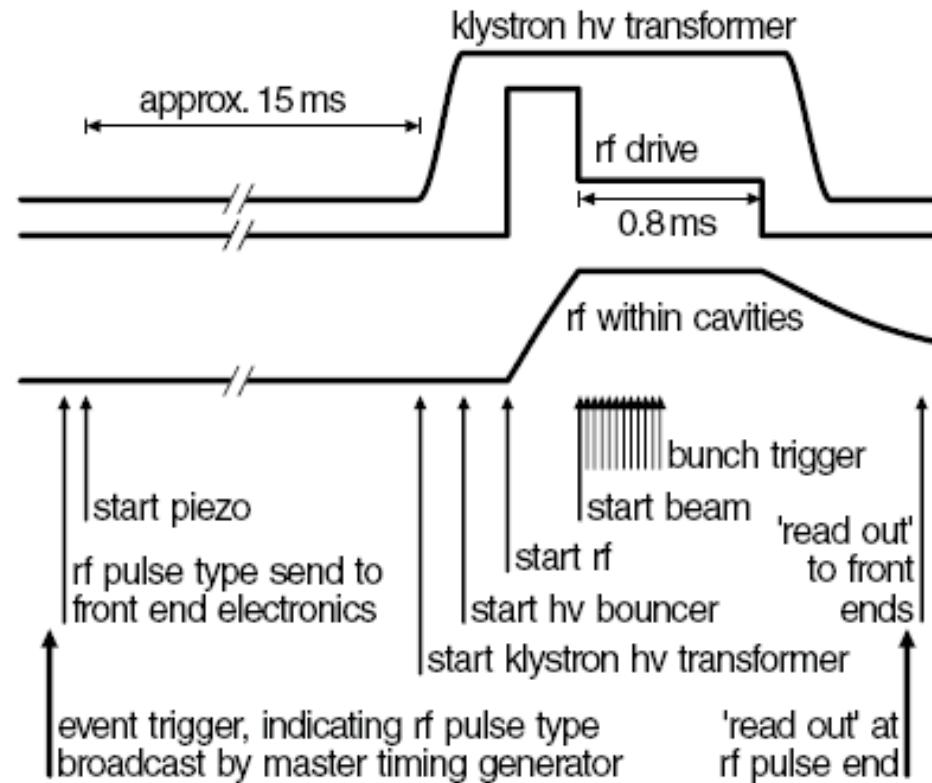
Synchronization System

Consists of:

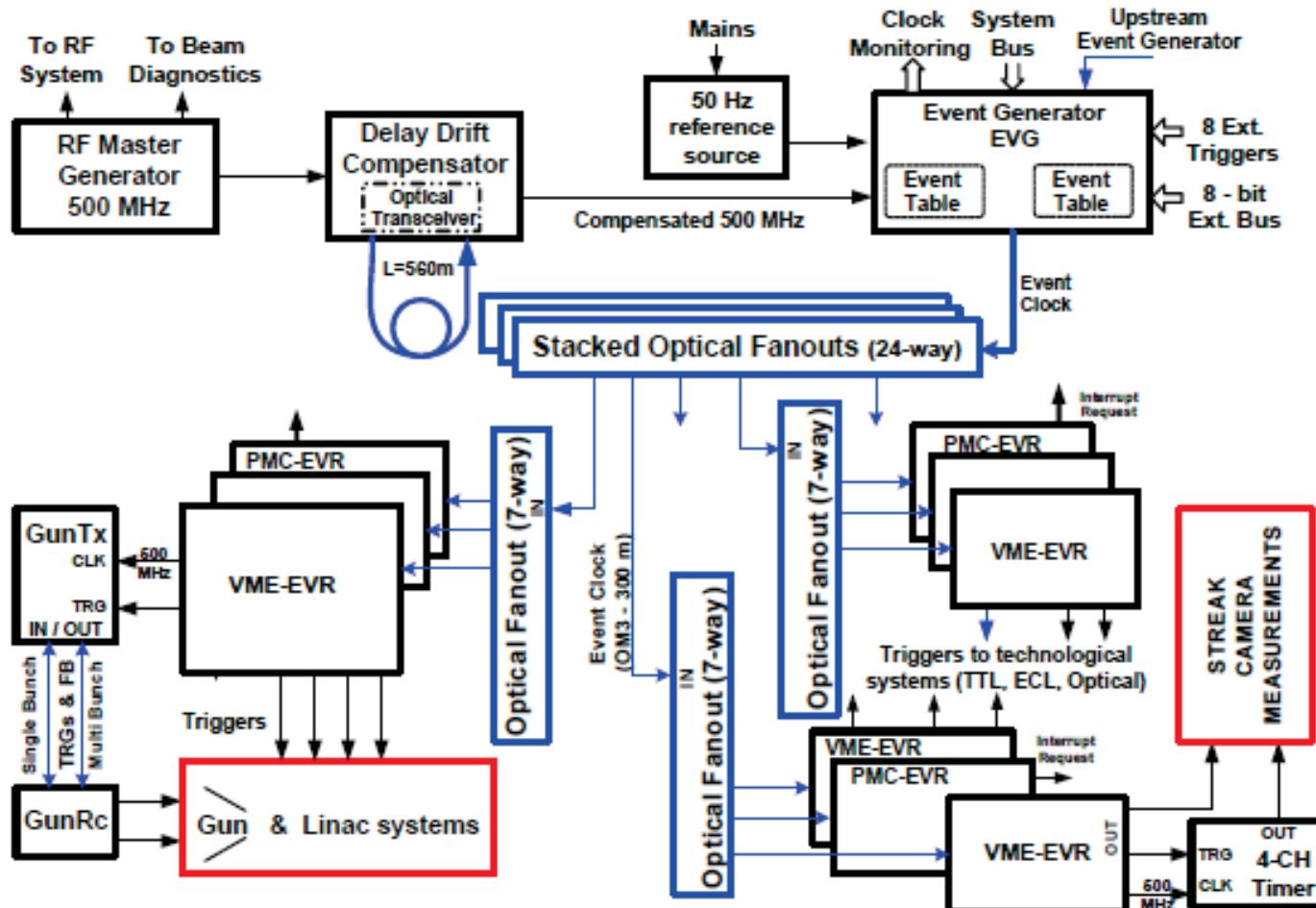
- Master Oscillator
- Phase Reference Distribution (for harmonic RF signals)
- **Timing System (for clocks and triggers)**

Timing System

- Mainly devoted to assure synchronization of accelerator subsystems for executing events necessary for accelerator operation
- Distribute signals with coded information about events, time, pulse and bunch numbers
- Clock signals can be extracted of the timing signal. But there is an opinion that ADC clocks should be generated directly from the MO signal (smaller residual jitter between ADC and DWC signal)
- Usually optical signal distribution used. Based on low cost telecom fiber transceivers.



Timing System Example



Timing Signals in PCBs and Backplanes

Seems to be separated topic but:

- We go towards hundred of MHz differential clocks to be distributed over many boards and backplane inside a crate
- ADC clock parameters become critical for the performance of the entire LLRF system
- Understanding the limitations may help in proper specifying parameters of the synchronization system and save effort and costs

Diagnostics

- Good diagnostic system can be very helpful during commissioning and maintenance of the synchronization system
- On-line readout of PLL lock signals, power levels and supply voltage presence will help with localizing potential faults and decrease the accelerator down time
- On-line temperature readout can be used for estimating phase drifts

Observation

One of the most difficult issues of a large synchronization system design is **collecting user requirements**

Conclusions

- The design of a synchronization system is a very complex and challenging task
- A lot of expertise of various fields of engineering is required to make a successful design
- Nowadays synchronization systems go to high complexity and extreme accuracy of measured by single fs
- Many new solutions must be worked out to fulfill the newest requirements

Thank You for Your Attention!