WARSAW UNIVERSITY OF TECHNOLOGY

RF Phase Reference Distribution Systems for Large Experiments

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Objectives

- Give an overview of techniques used for RF synchronization (RF phase reference) systems working with high accuracy

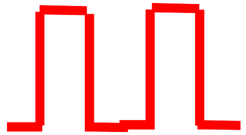
- Show the most important problems and limitations of RF synchronization subsystems

Synchronization Signals

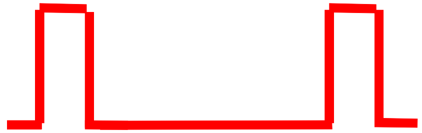
There are various types of signals (frequently confused by users):

- **Analog (RF phase reference, LO)**

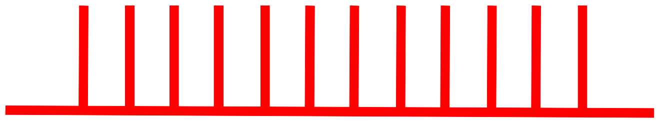
- Clocks (digital circuits, ADC, DAC, CPU)



- Trigger signals (digital subsystems, CPU)



- Optical pulse trains (lasers, diagnostics, experiments)



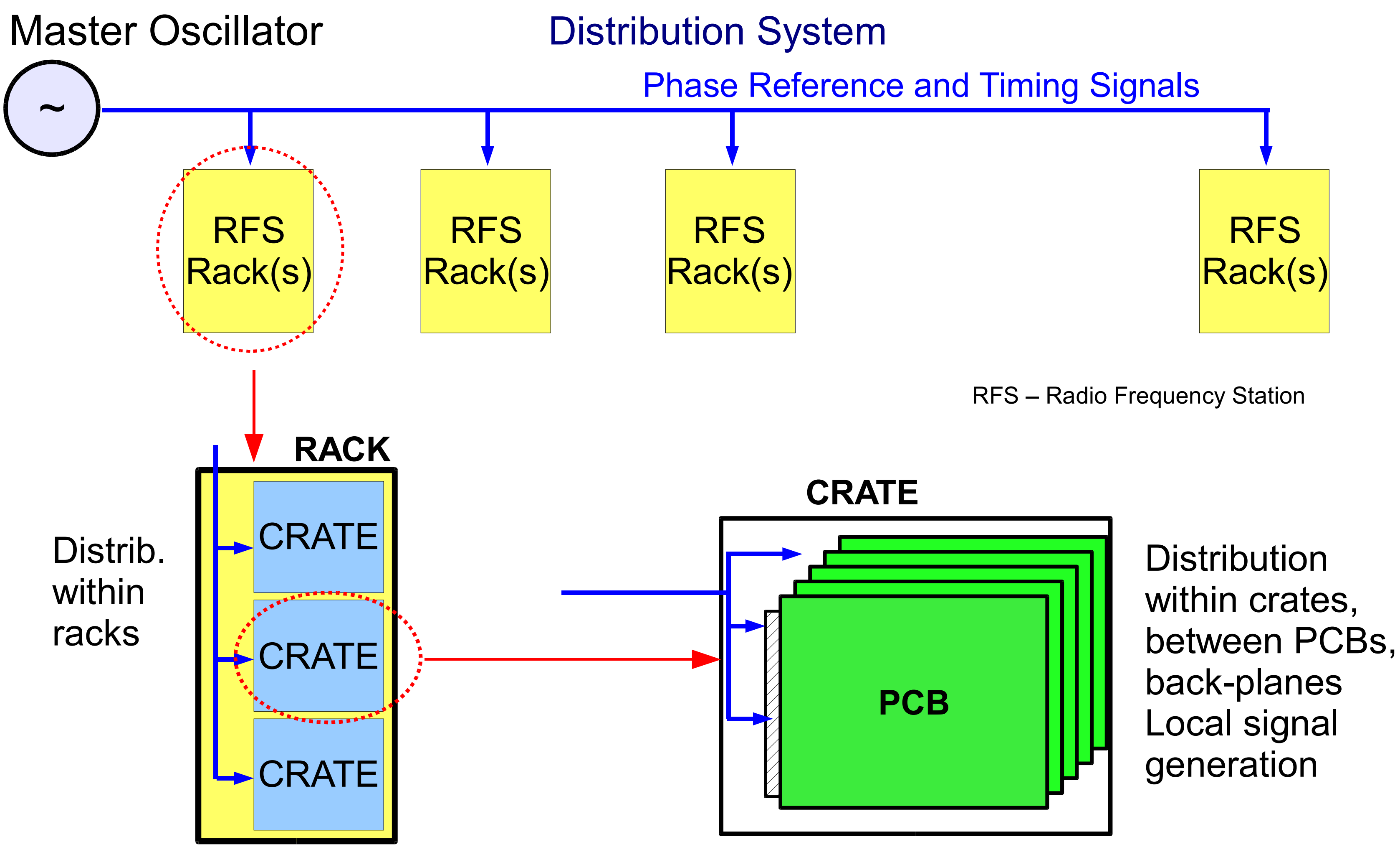
Demand for Precise RF Phase Reference Signals

- LLRF systems of accelerators (LO for downconverters, klystron drive phase reference), diagnostics (BPM, HOM, ...)
- Particularly at Free-Electron Lasers (FEL) LINACs
- Required synchronization accuracy nowadays reaches sub 10fs levels (e.g. European-XFEL)

RF Synchronization System Components

- Master Oscillator
- Phase Reference Distribution (for harmonic RF signals)
- Diagnostics
- Interfaces to other subsystems

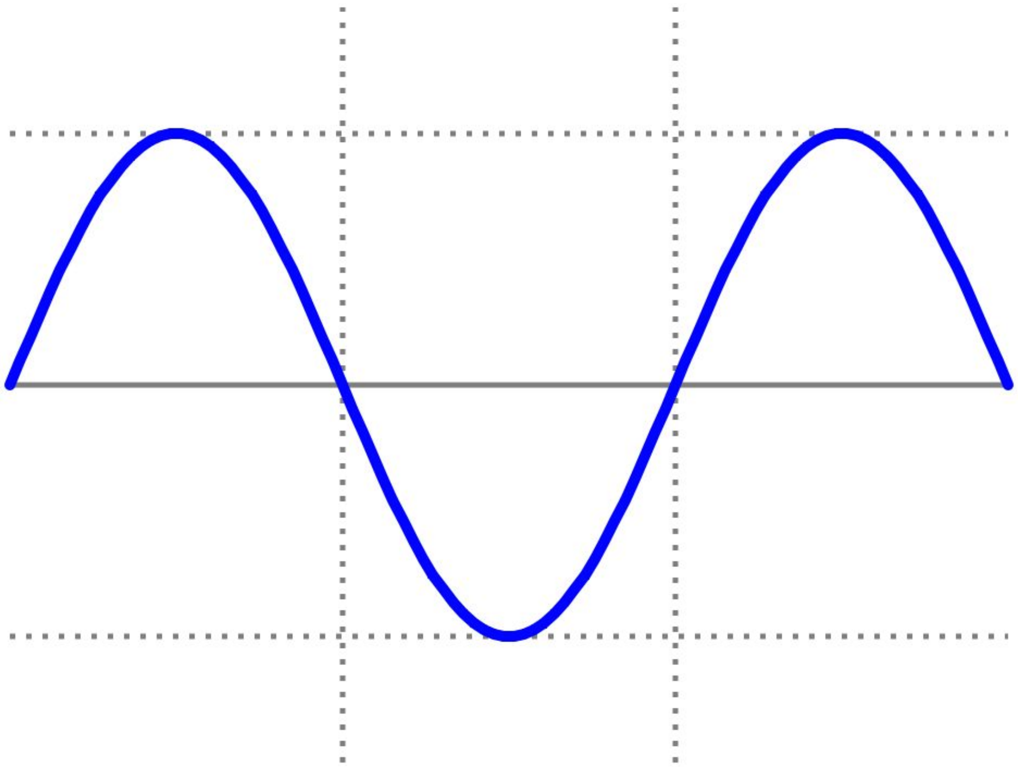
Generic RF Synchronization System



Some Basic Definitions

Before we go to RF Synch. sub-components

We Would Like to Distribute Pure Sine Wave



BUT

Harmonic Signal With Noise Components

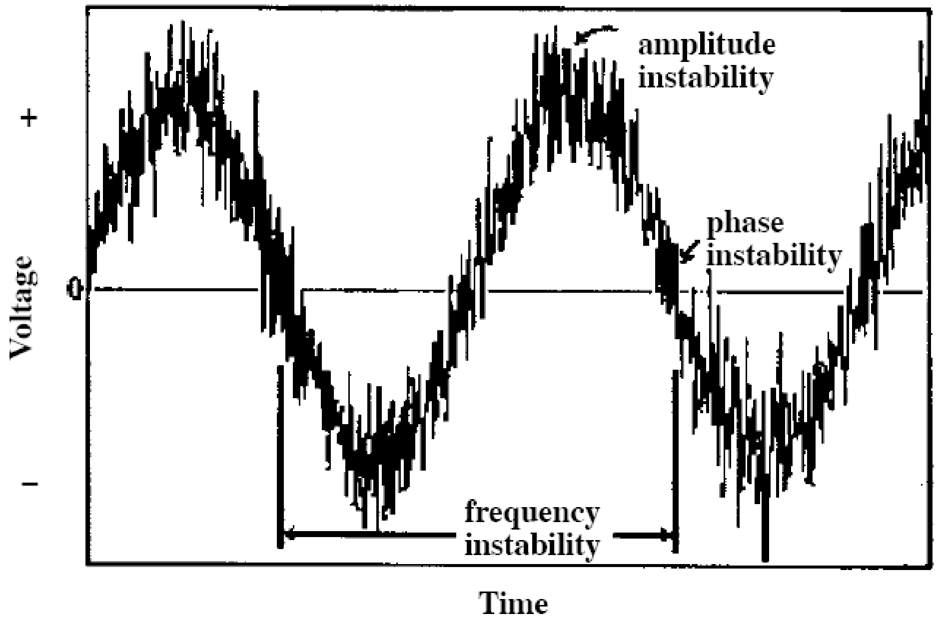
In Time Domain

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**

Short and Long Term Instabilities

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

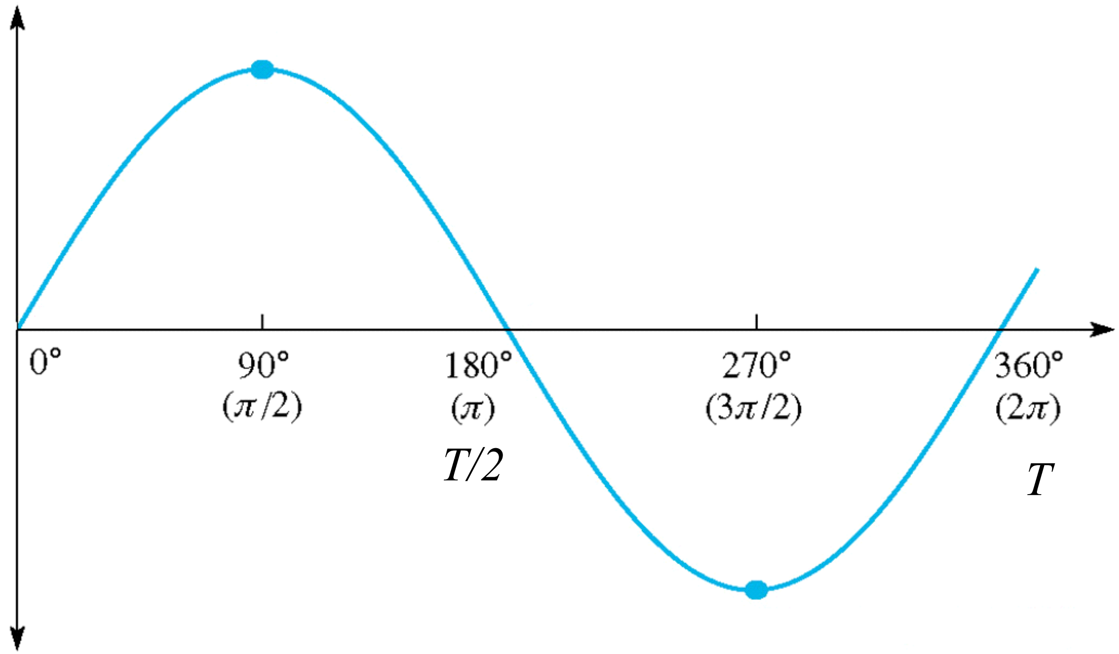
- derives from a "fast" phase noise components ($f > 1$ Hz)
- expressed in units of spectral densities or timing jitter

<u>The long-term instability</u> 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 ...)

Frequency, Time and Angle – Basic Relationships

Why do we use "ps" when you talk about phase??



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

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

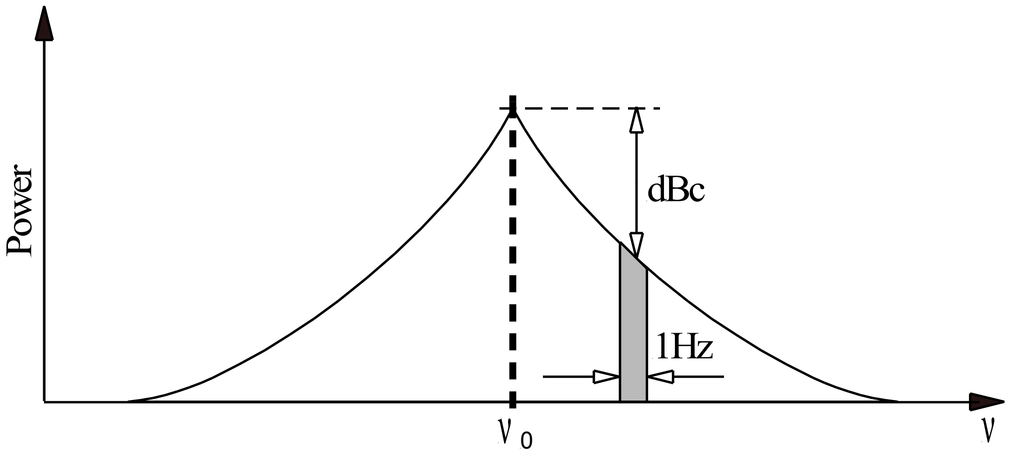
$$t = \frac{\phi T}{360^o}$$ Phase to time conversion

Example: v_0 = 1.3GHz → T = ~769ps, 1° → 2,13 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.

Phase Noise

It is a **frequency domain measure** of signal phase instabilities **ϕ(*t*)**



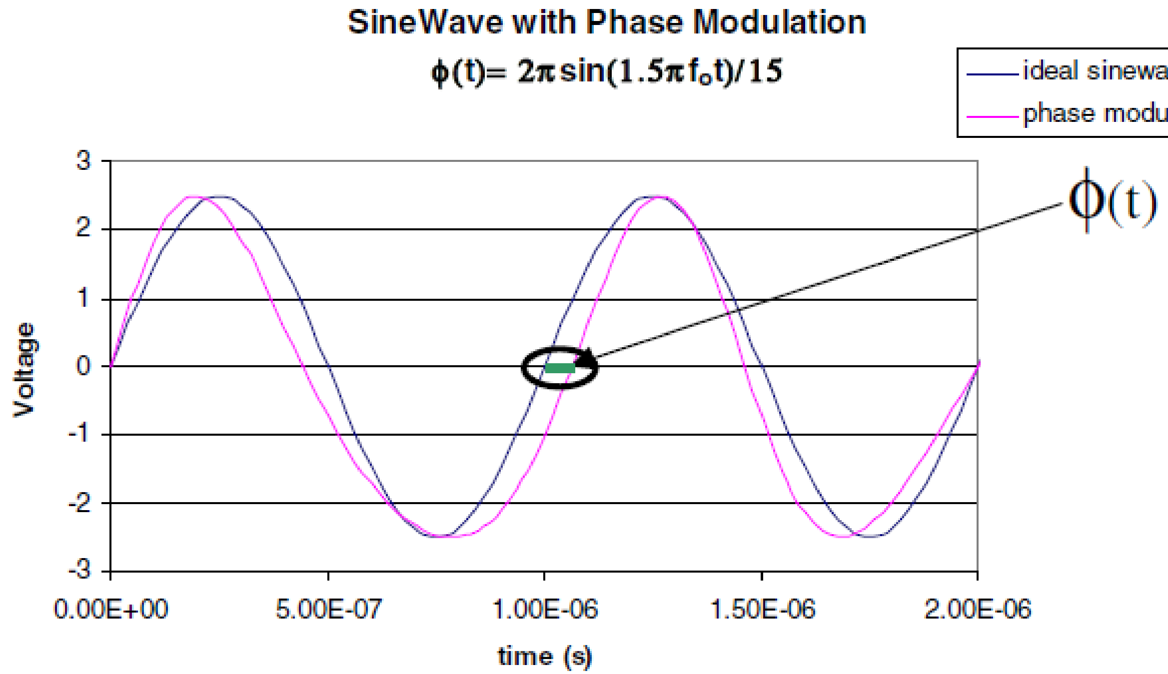
Power Spectral Density measured in dBc/Hz

$$\mathscr{L}(f) = \frac{\begin{matrix}\textit{power density in one}\\ \textit{phase noise modulation}\\ \textit{sideband , per Hz}\end{matrix}}{\textit{total signal power}} = \frac{1}{2} S_{\phi}(f)$$

$$f = \nu - \nu_0 \quad \text{offset from the carrier frequency}$$

Phase / Timing Jitter

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



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

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

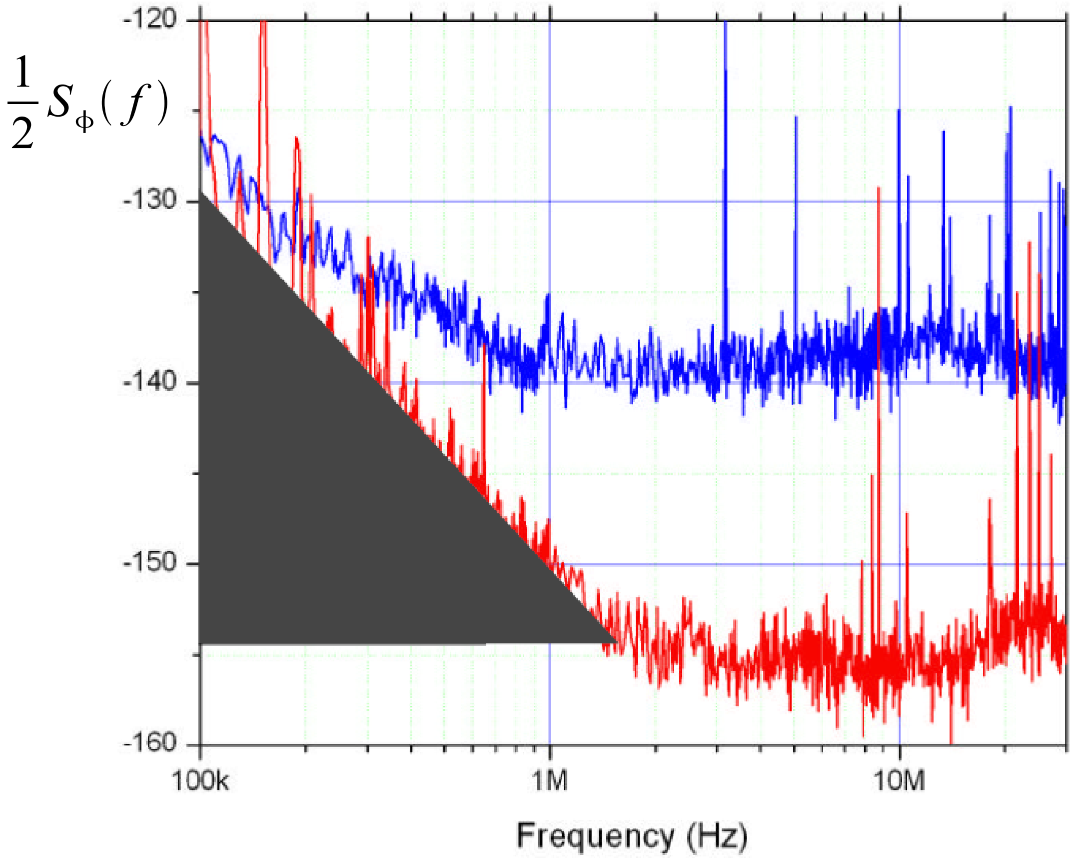
Figure source: Corning Frequency Control

Phase Noise and Jitter Relationship

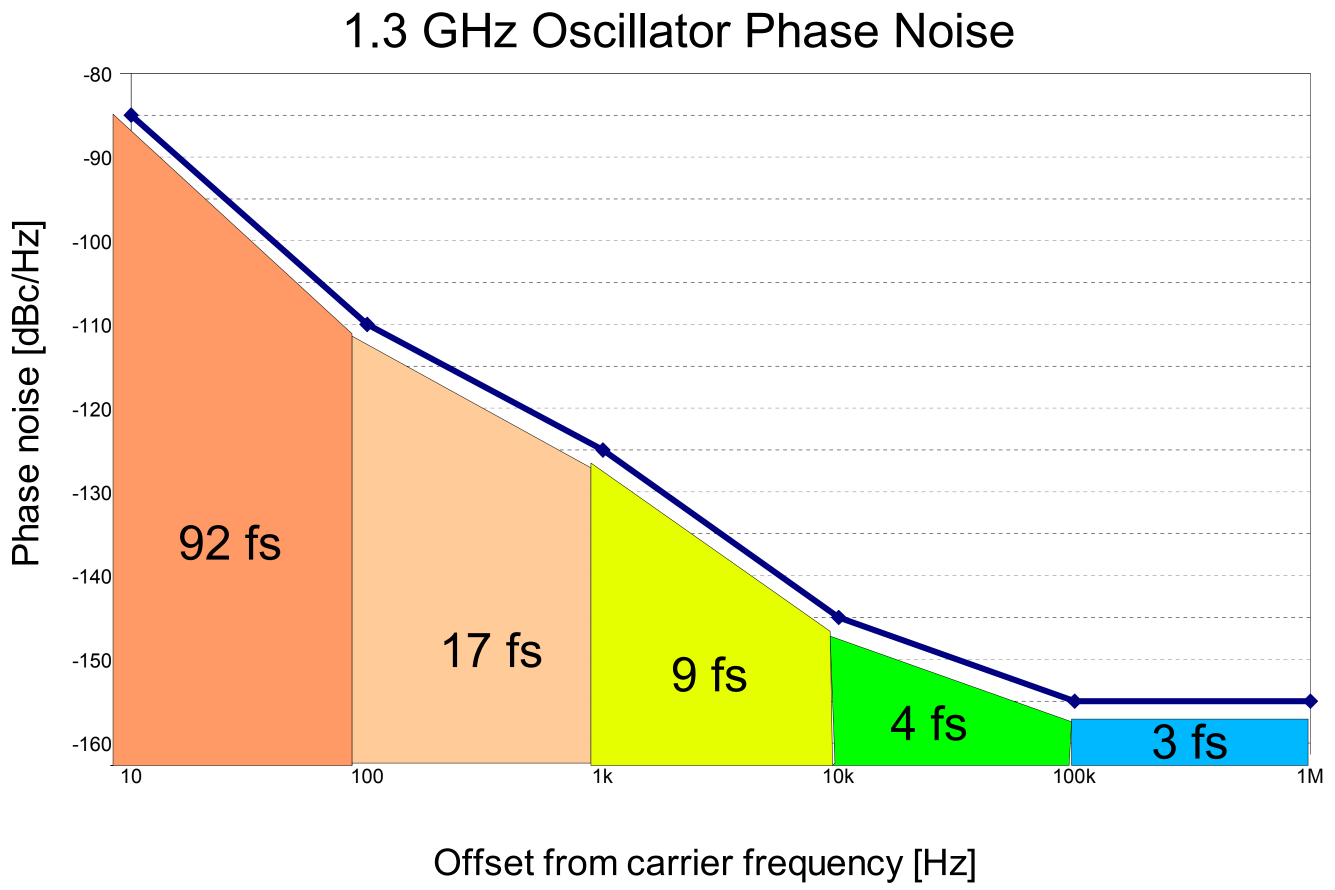
Jitter is the integral of $S_\phi(f)$ over the Fourier frequencies of application

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

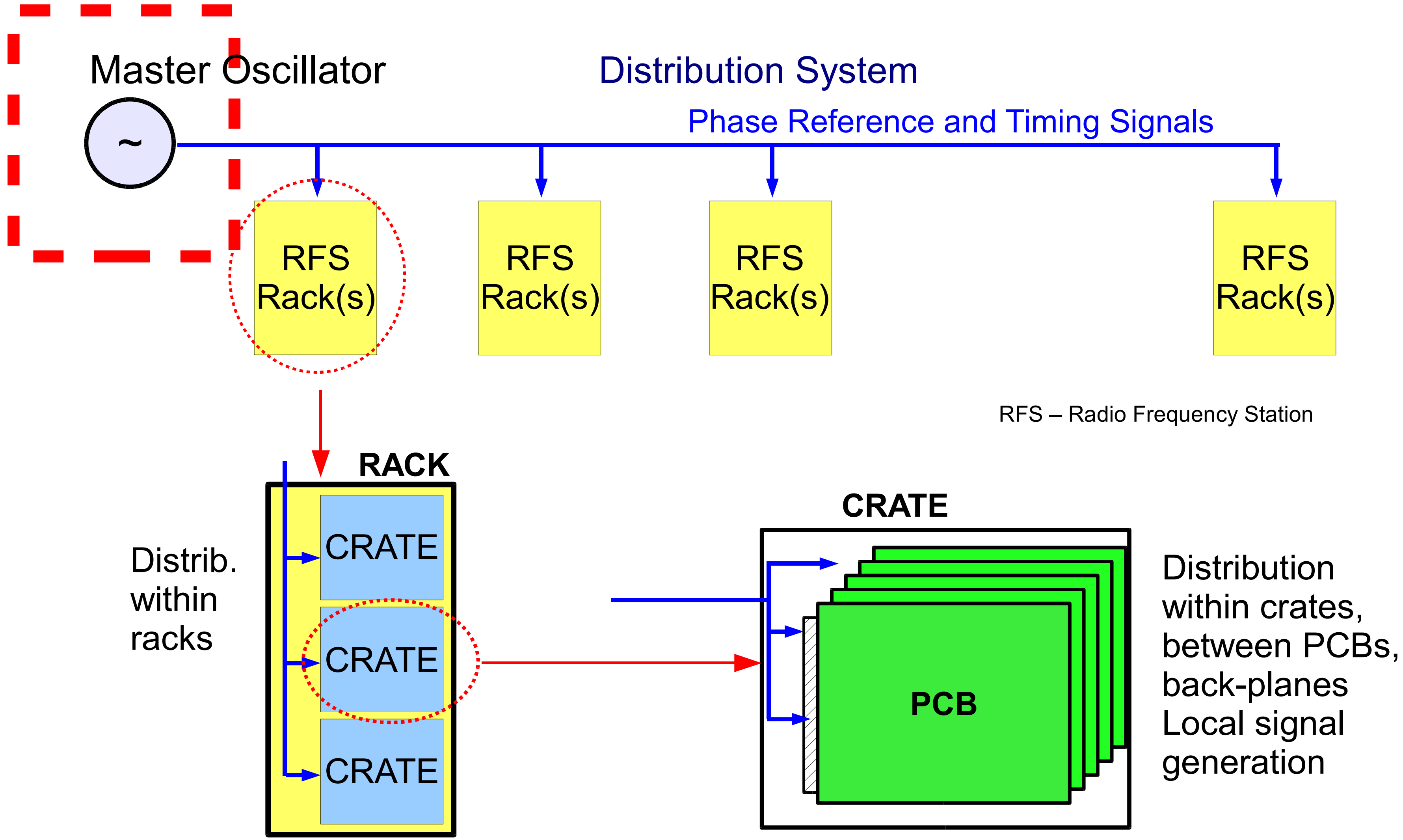
$$\Delta t_{rms} = \left(\frac{1}{2\pi\nu_0}\right)\sqrt{\int_{f_1}^{f_2} S_\phi(f)\,df}$$



Phase Noise Contributions to Jitter



Generic RF Synchronization System - MO



Master Oscillator

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

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Single signal source

↓

But in practice ...

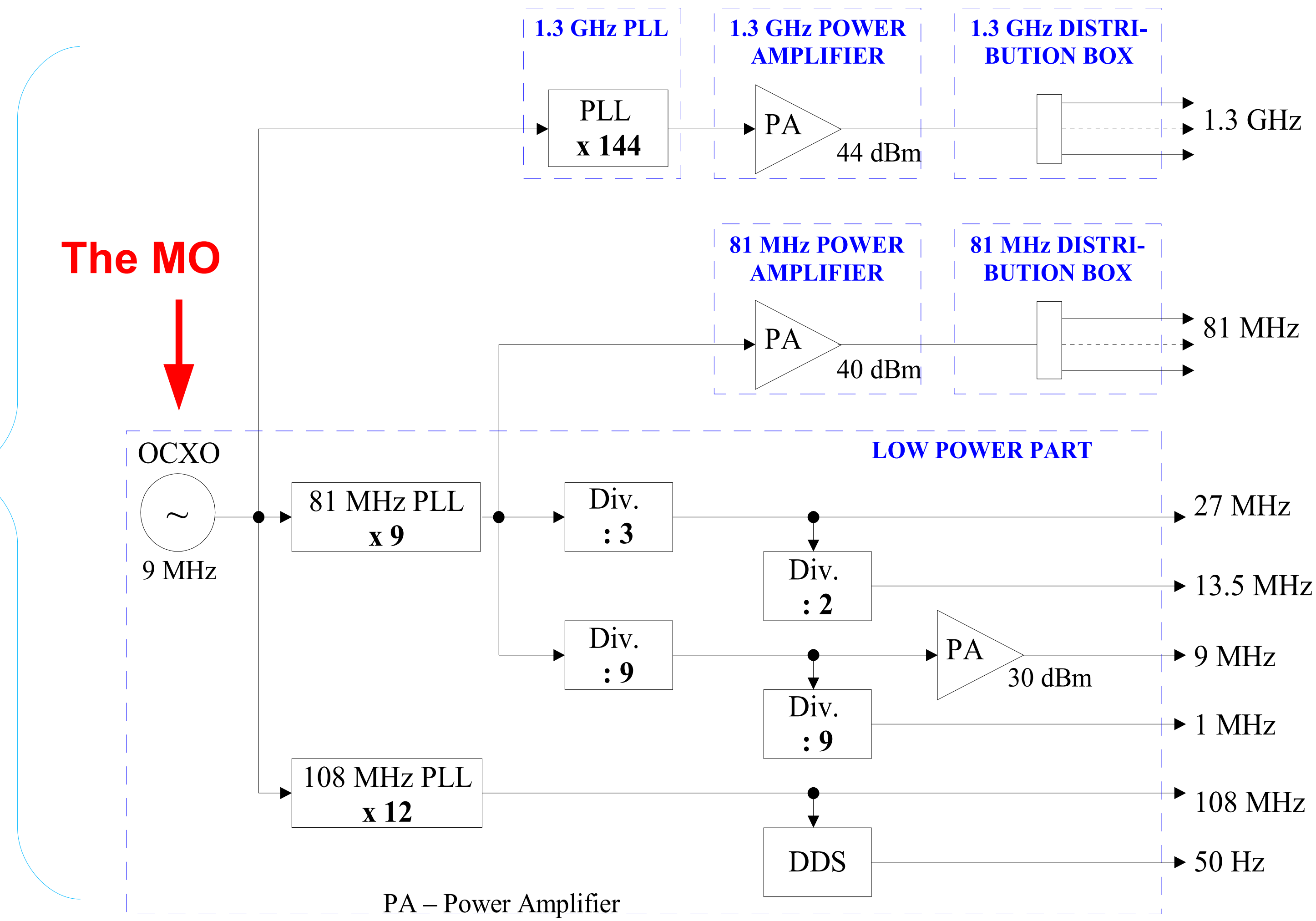
↓

Master Oscillator System Example

FLASH "MO" Scheme*

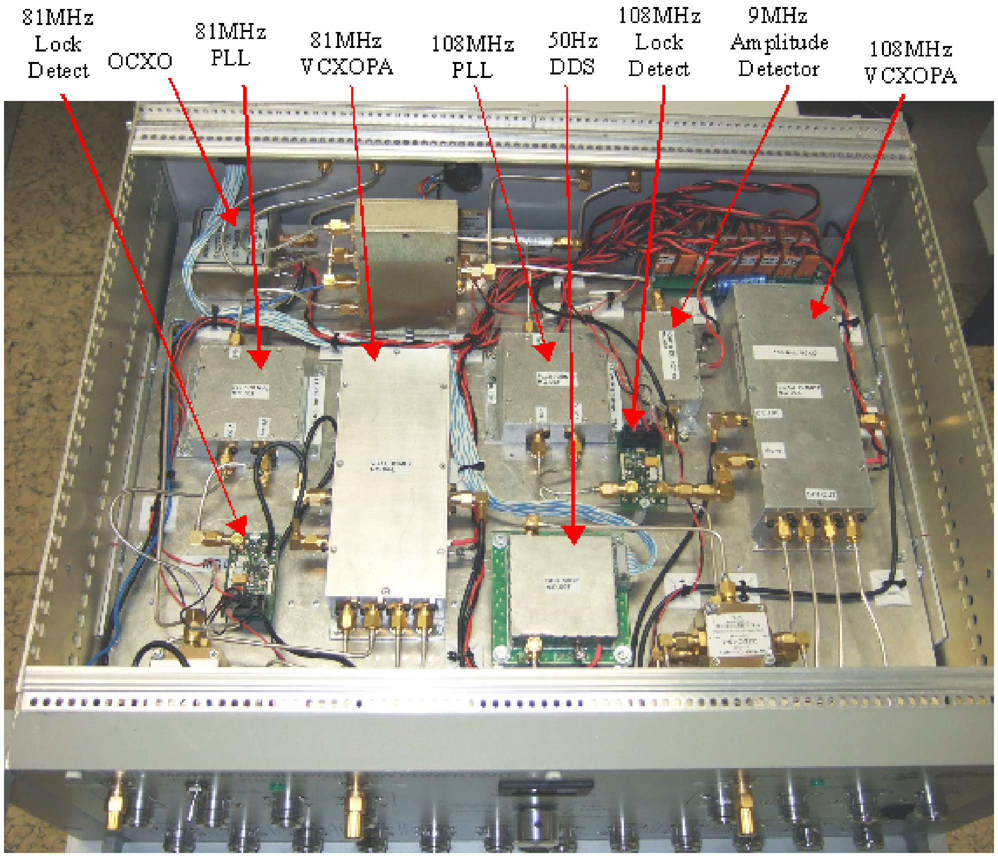
The **MO System**

But for convenience people call it MO



* will be presented in more detail by Henning Weddig

FLASH MO System Racks and Crates



MO System

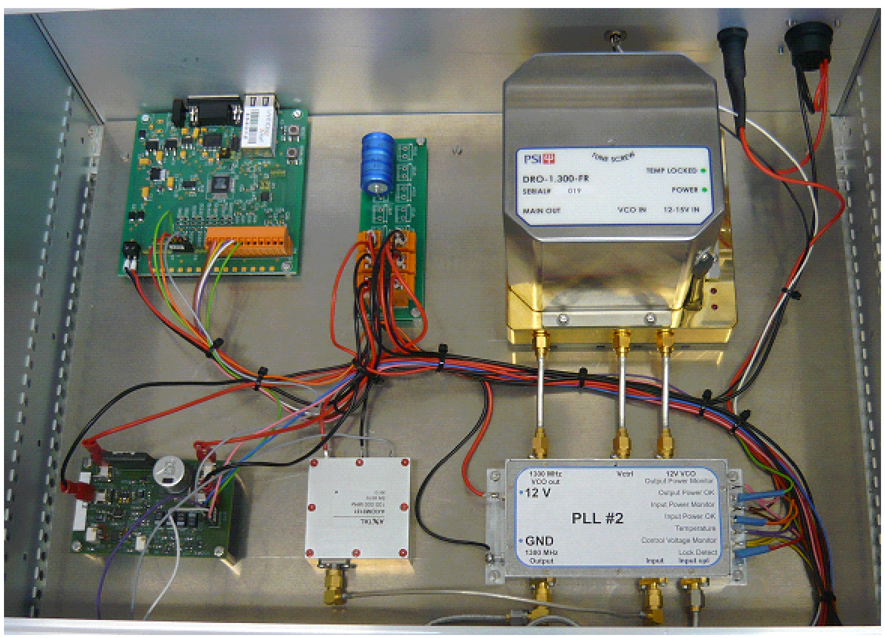
- MO reference generator
- Frequency generation scheme
- Signal level adjustment (power amplifiers)
- Splitters and interface to distribution links
- Power supply (very important issue!), sometimes must be unbreakable
- Diagnostics

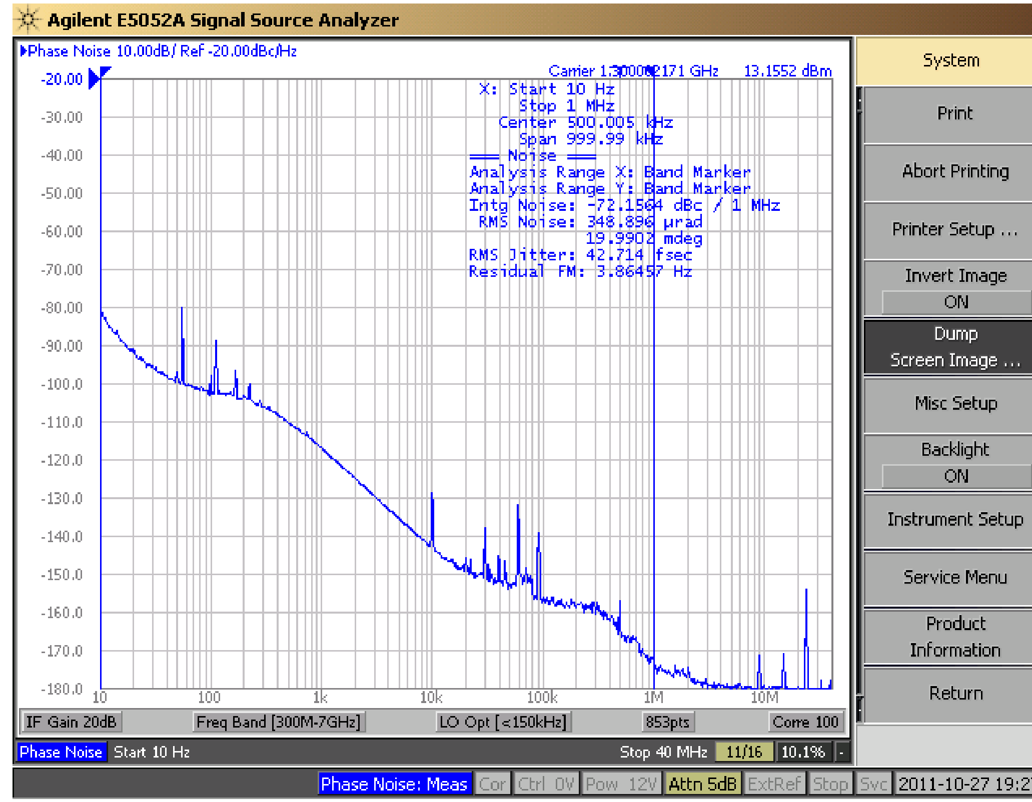
Most Important Task of MO System

- Generate signal with sufficient stability. Usually short-term stability (phase noise) is of concern.
- Well known RF generation techniques (OCXO, PLL, RF Synthesis).
- Stability of ps to ns is easy to achieve (and very cheap)
- No problem to go down to 20 fs (but the last 100 fs gets expensive!)
- At FLASH we demonstrated source with 30 fs of jitter @ 1.3 GHz (10 Hz to 1MHz BW)

Laboratory Prototype of XFEL MO (1.3 GHz)

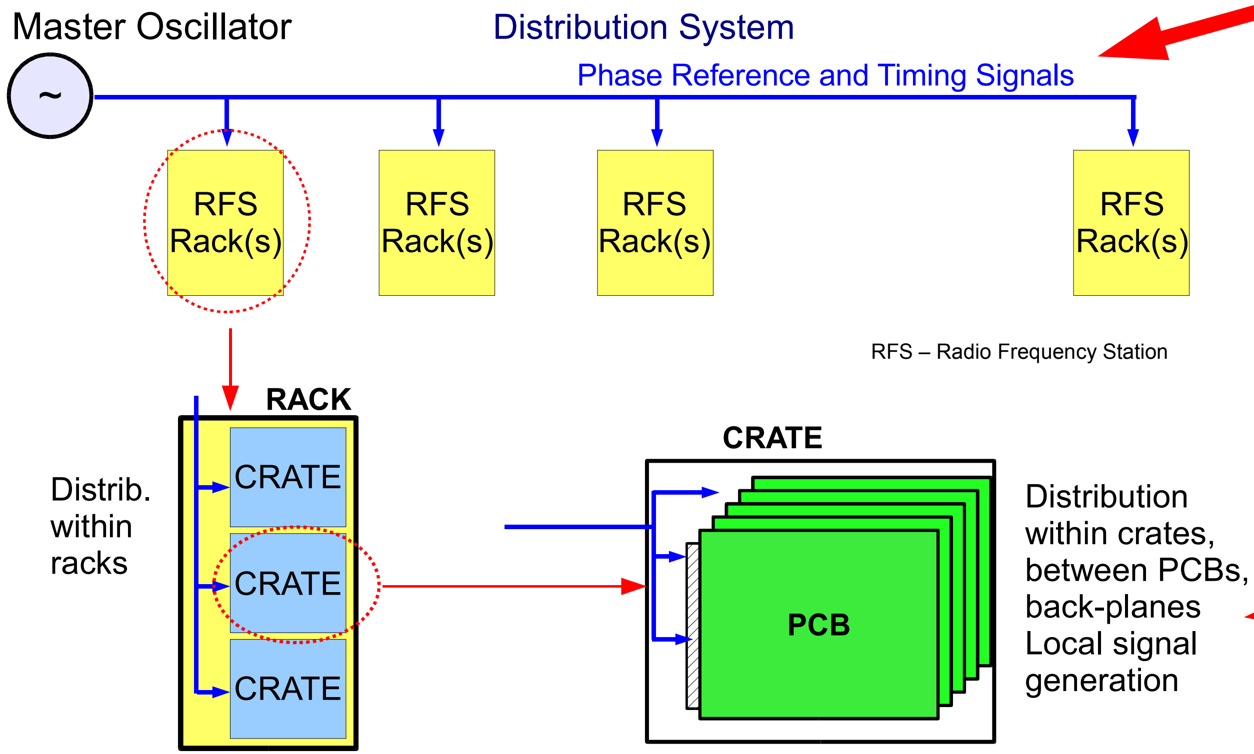
- Reference: OCXO 100MHz
- VCO: 1.3 GHz DRO from PSI
- Output power + 13 dBm
- Jitter 42 fsec RMS (10Hz to 1 MHz)





by (Ł. Zembala, H. Weddig)

Stable Signal Distribution



Main Distribution to RF Stations and other accelerator subsystems

Local Distribution: racks, crates, PCBs

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!

Most Important Task of Signal Distribution

- Deliver the phase reference signal with specified degradation compared to the MO source and with specified output power level
  - Usually phase noise/jitter is not affected significantly in coax cable links
  - Cheap optical links limit jitter performance to few – few tens of ps
  - The biggest problem: long term phase drifts in distribution media

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)
  - high performance systems still under development - reliability not proven

Distribution Media: Cable vs. Optical Fiber

Parameter	Coaxial	Fiber
Attenuation	High	Low at any RF frequency
Distribution distance	short	long
Temperature coefficient of phase lenghth	$\sim 10^{-5}/^{o}C$	$\sim 10^{-5}/^{o}C$
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

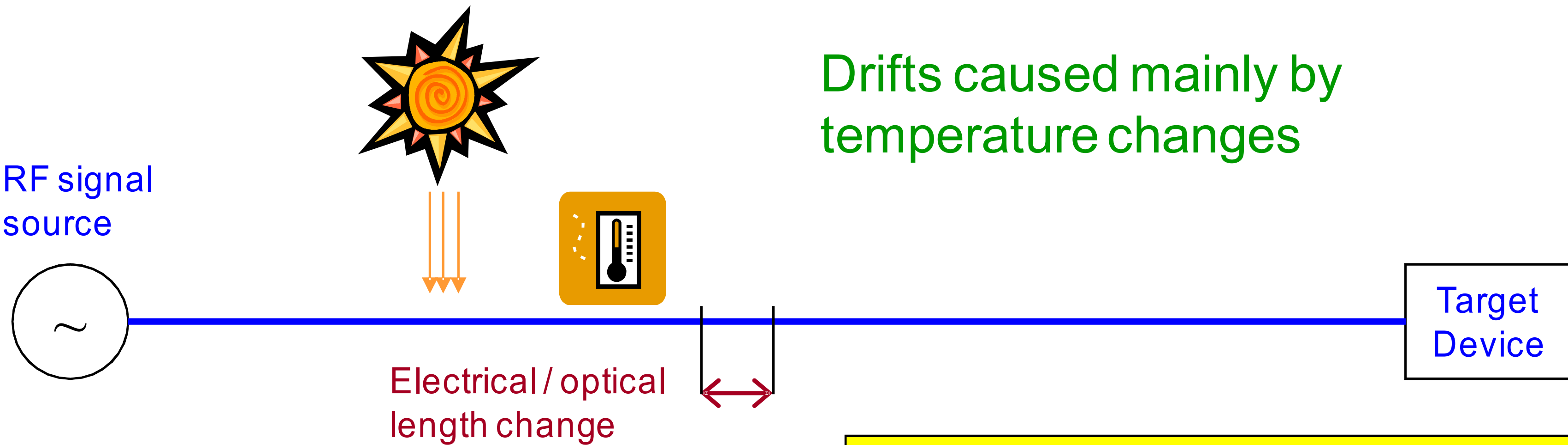
Example: Phase Drift Requirements for European XFEL

- Injector and booster devices: 100 fs p-p drift within 1h. Distribution distance ~150 m
- Main linac: 1 ps (~0.5^{o}) p-p, distribution distance ~1.7 km

- Within 100 fs light travels a distance of ~30µm
- We need to assure sub ~30µm of length stabilization of 150 m long link
- Is this easy to do?

Phase Drifts in Distribution Media

Drifts caused mainly by temperature changes



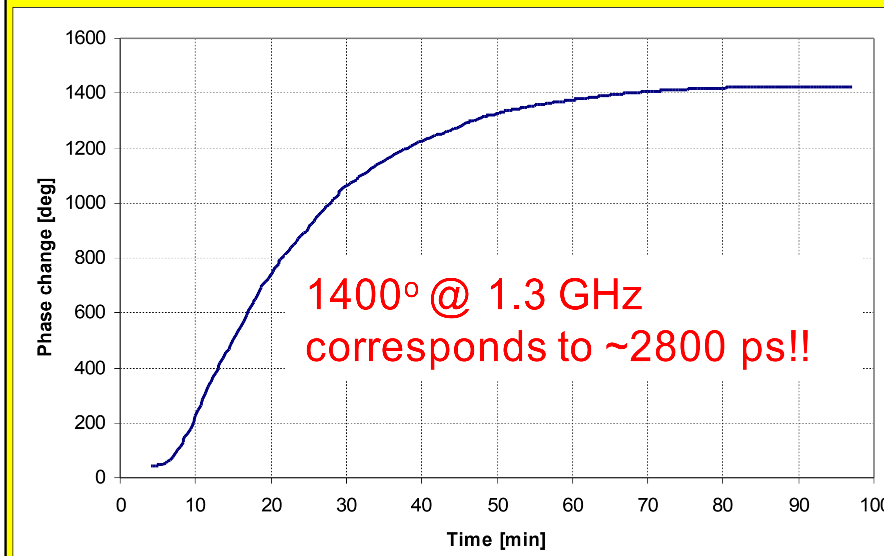
Reason of drifts:

- In fiber: n_{eff} change

- In cable: physical dimension and dielectric properties change

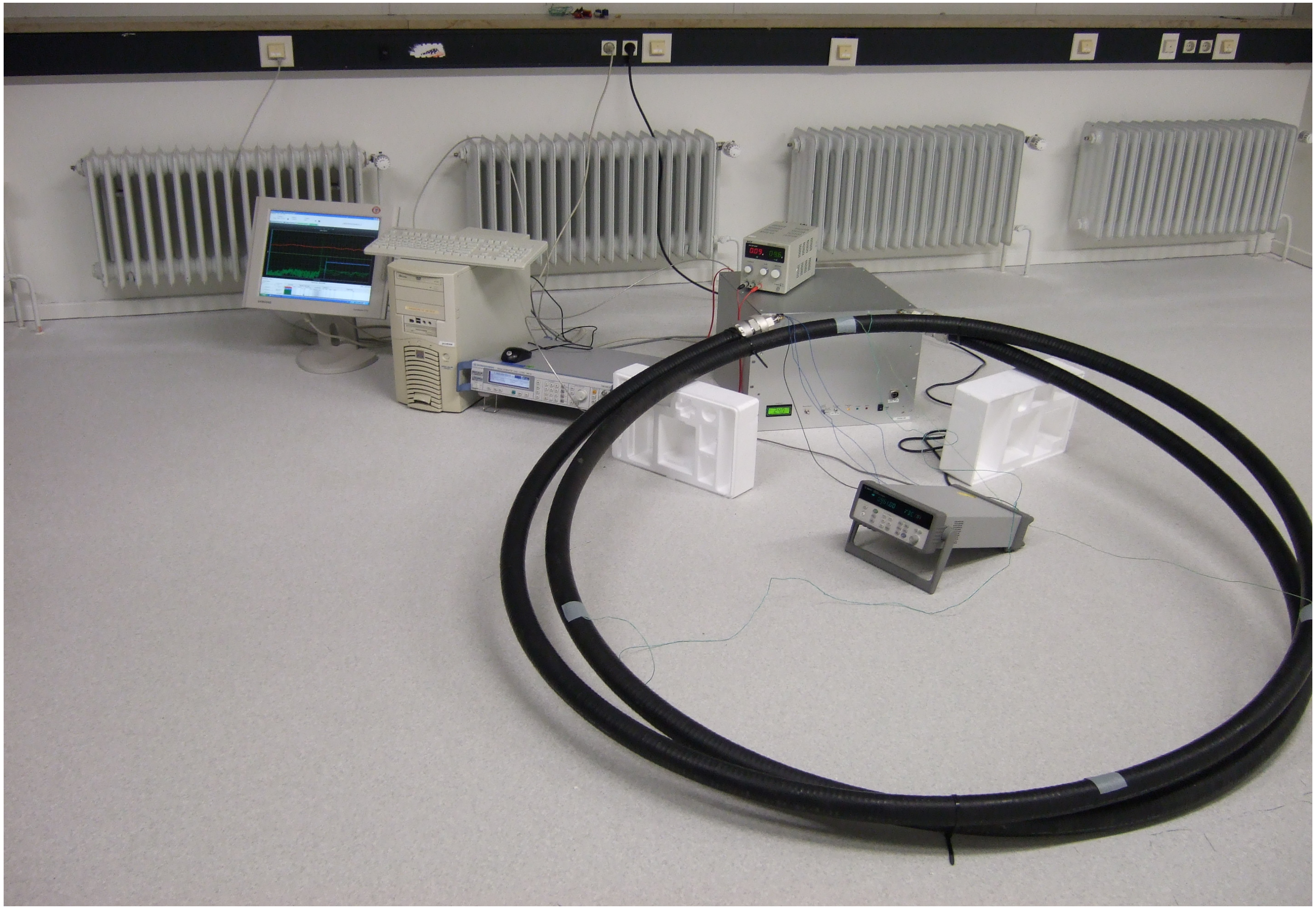
Feedback on phase required!!

1.3 GHz signal phase change in 5km of fiber. 10 °C temperature change



Temperature Measurements of Coax Cables

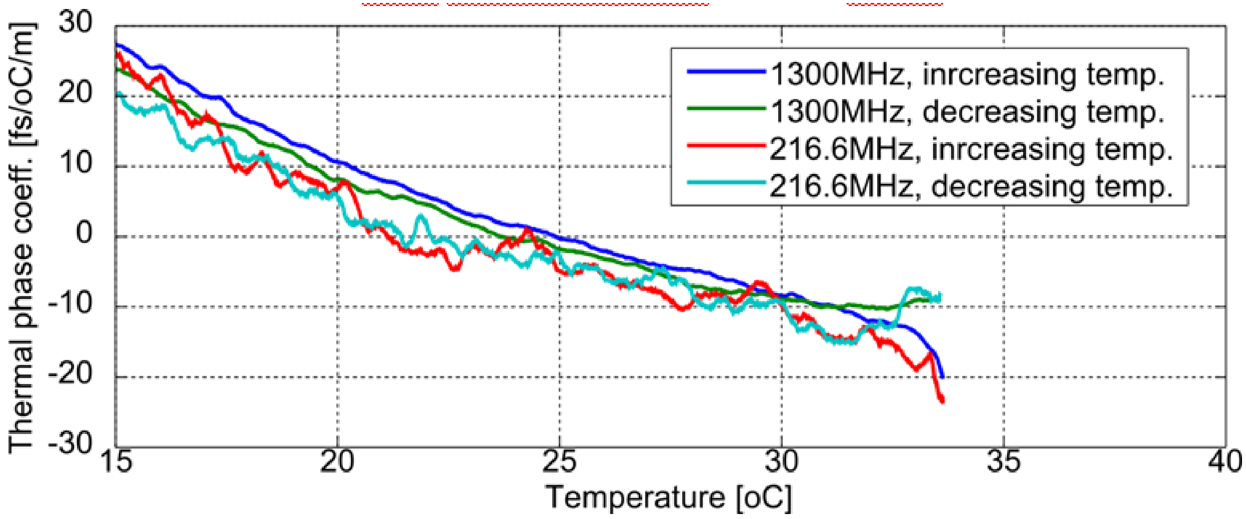
Sometimes is a challenging task...



Phase Drifts in Coax Cables

Cable	Timing drift [fs/m/K]	Loss@216MHz [dB/100m]	Loss@1.3GHz [dB/100m]
coaxial cable 3/8” (Andrew, Heliax)*	-10..25 (opt. at ≈ 25° C to 36° C)*	5	14.2
coaxial cable 7/8” (RFS, Cellflex)*	0..35*	1.7	4.8

Drift measurements of 3/8” cable



More data in: K.Czuba, D. Sikora, “Temperature stability of coaxial cables”, ACTA PHYSICA POLONICA, Vol. 119, Number 4, Warsaw, April 2011, p. 553

Temperature coefficients of poor quality cables reach thousands of ppm/°C → **1 meter of such cable inside of a rack can be worse than hundreds of meters of a thick distribution cable!**

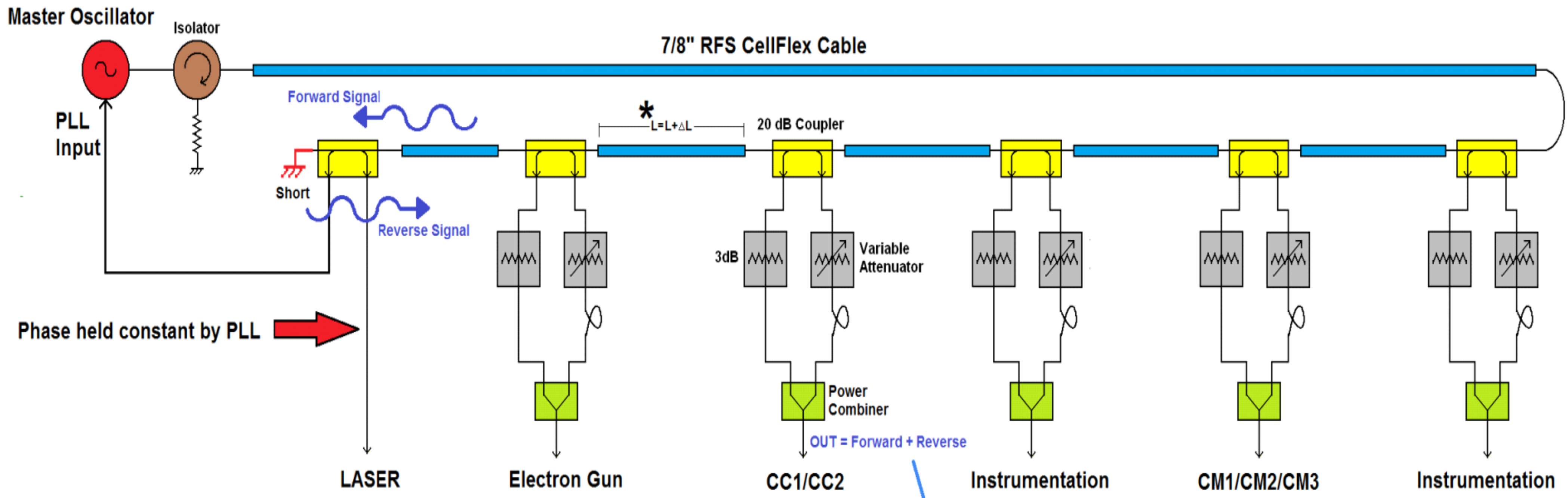
How to Overcome Drift Problem

- Stabilize temperature (cable or fiber)

    feasible for relatively short distances (~100m) and when required long term stability is significantly above 1 ps range

- Active compensation (feedback on drifts)

Active Drift Compensation Example



* changes in cables lengths between tap positions due to temperature changes ($L = L + \Delta L$)

the output becomes: $OUT = A_F \cos(wt + \phi_F + \Delta\phi_F) + A_R \cos(wt + \phi_R - \Delta\phi_R)$

Forward Reverse

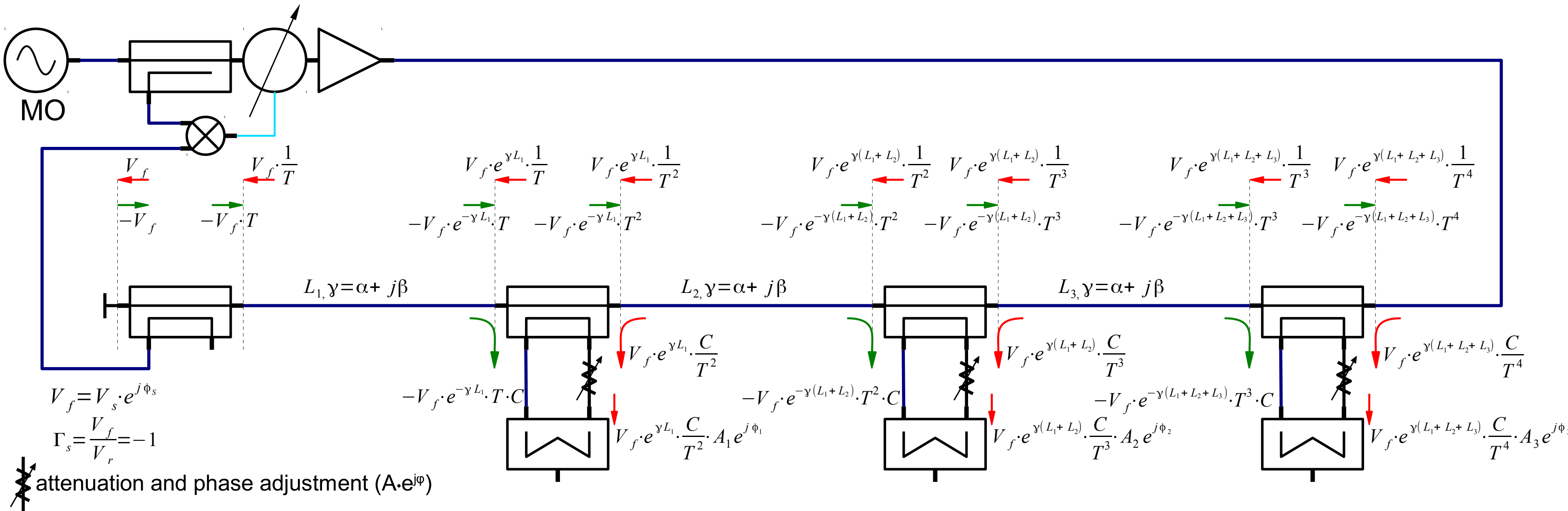
When the phase at the shorted end of the reference line is held constant, $\Delta\phi_F = -\Delta\phi_R$

When $\Delta\phi_F = -\Delta\phi_R$,

$\arg\{A_F \cos(wt + \phi_F + \Delta\phi_F) + A_R \cos(wt + \phi_R - \Delta\phi_R)\} = \arg\{A_F \cos(wt + \phi_F) + A_R \cos(wt + \phi_R)\}$

Idea by Ed Cullerton and Brian Chase (Fermilab), Presented at LLRF2011, DESY

First Experiments



$$V_1 = -V_f \cdot e^{-\alpha L_1} \cdot e^{-\beta L_1} \cdot T \cdot C + V_f \cdot e^{\alpha L_1} \cdot e^{\beta L_1} \cdot \frac{C}{T^2} \cdot A_1 e^{j\phi_1}$$

$$when: \; e^{-\alpha L_1} \cdot T = e^{\alpha L_1} \cdot \frac{1}{T^2} \cdot A_1 e^{j\phi_1} \Leftrightarrow A_1 e^{j\phi_1} = T^3 e^{-2\alpha L_1}$$

$$V_1 = V_f \cdot C \cdot e^{-\alpha L_1} \cdot T \cdot 2j \cdot \sin(\beta L_1)$$

$$when: A_2 e^{j\phi_2} = T^5 e^{-2\alpha(L_1+L_2)}$$

$$V_2 = V_f \cdot C \cdot e^{-\alpha(L_1+L_2)} \cdot T^2 \cdot 2j \cdot \sin[\beta(L_1+L_2)]$$

$$when: A_3 e^{j\phi_3} = T^7 e^{-2\alpha(L_1+L_2+L_3)}$$

$$V_3 = V_f \cdot C \cdot e^{-\alpha(L_1+L_2+L_3)} \cdot T^3 \cdot 2j \cdot \sin[\beta(L_1+L_2+L_3)]$$

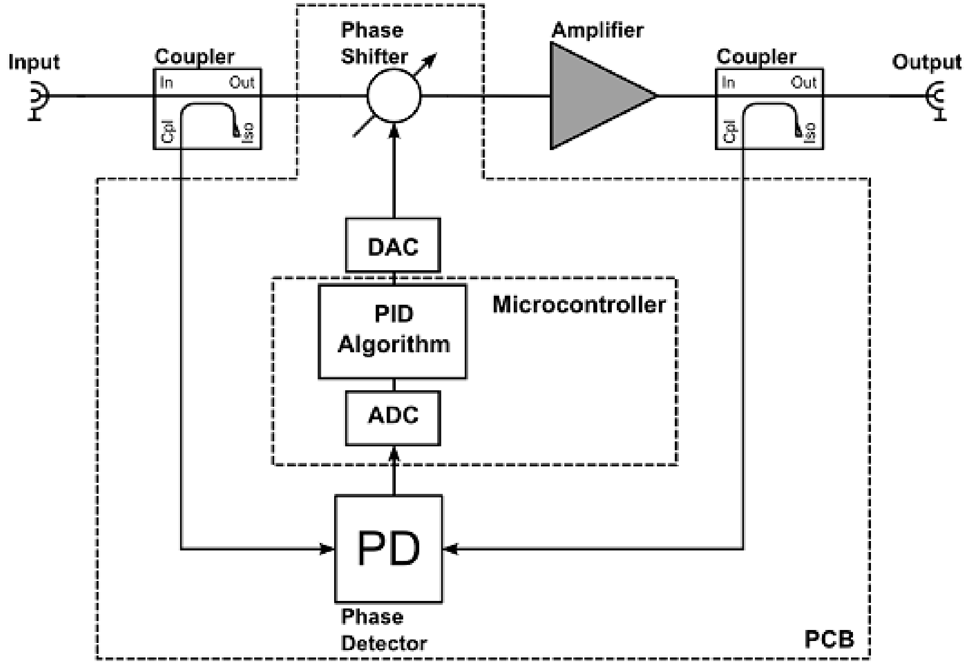
Figure: Courtesy of D. Sikora

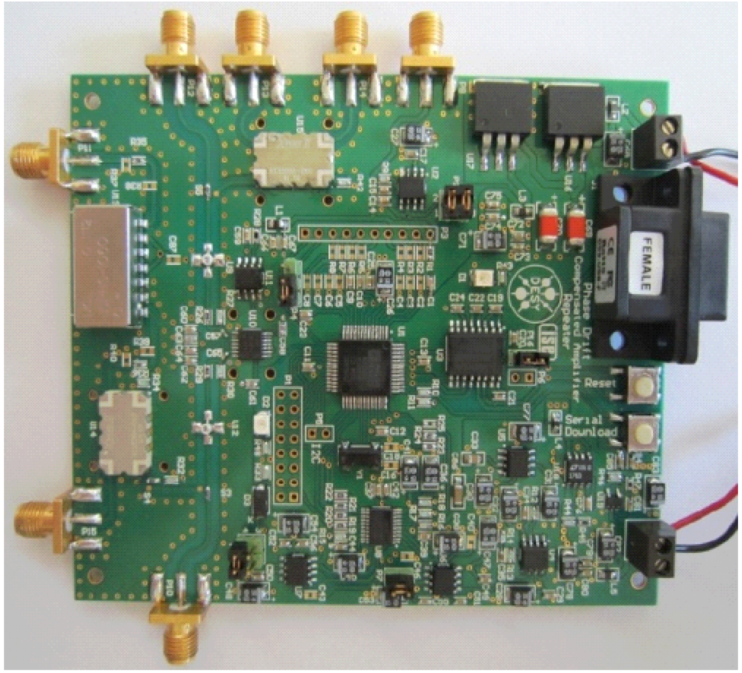
First test setups demonstrated drift suppression factors in range of 10 to 50.
There is still room for improvement.

Phase Drifts in Other Components

- All RF reference distribution system components (like power splitters, attenuators, directional couplers, amplifiers …) introduce drifts on the level of sub-ps to 100 ps/^{o}C
- Again the main reason is temperature change
- We characterized many types of components
- In general it is possible to use components with opposite phase coefficients to compensate
- In some cases temperature stabilization down to +/- 0.1 ^{o}C is necessary

Power Amplifier Phase Drift Compensation





Figures: Courtesy of S. Jablonski

Good experience from FLASH MO with high power modules.
Developed phase compensation circuit.

Demonstrated drift reduction from 350 fs/K to 34 fs/K

Summary

- Main concern of a synchronization system designer is to assure low phase noise and long term drifts
- Phase noise requirements are usually relatively easy to fulfill
- Most difficult task is phase drift stabilization
- It becomes one the most critical problems for large machines

Thank You for Your Attention!