Warsaw University of Technology

Basics of RF Reference Signal Generation and Synchronization Systems

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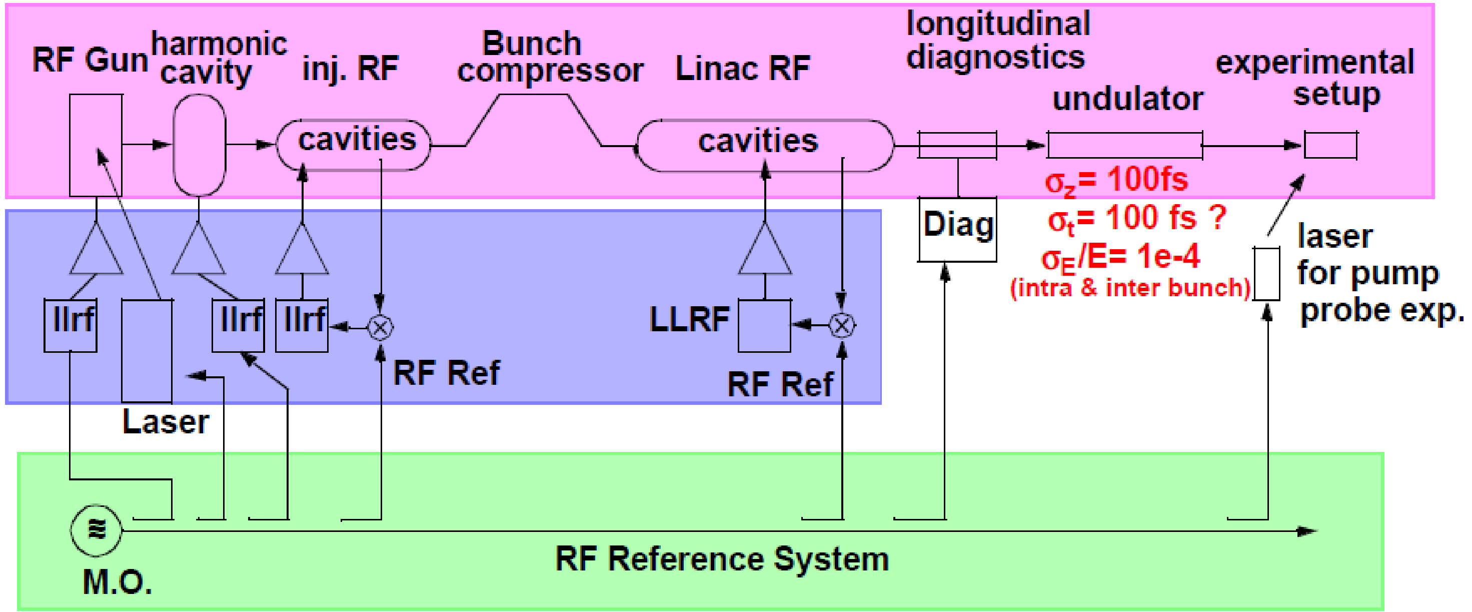
Synchronization

Synchronization is the coordination of events to operate a system in unison [wiki]

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

Accelerator Synchronization

- Accelerating modules
- LLRF systems
- Diagnostics
- Lasers
- Experiments
- …

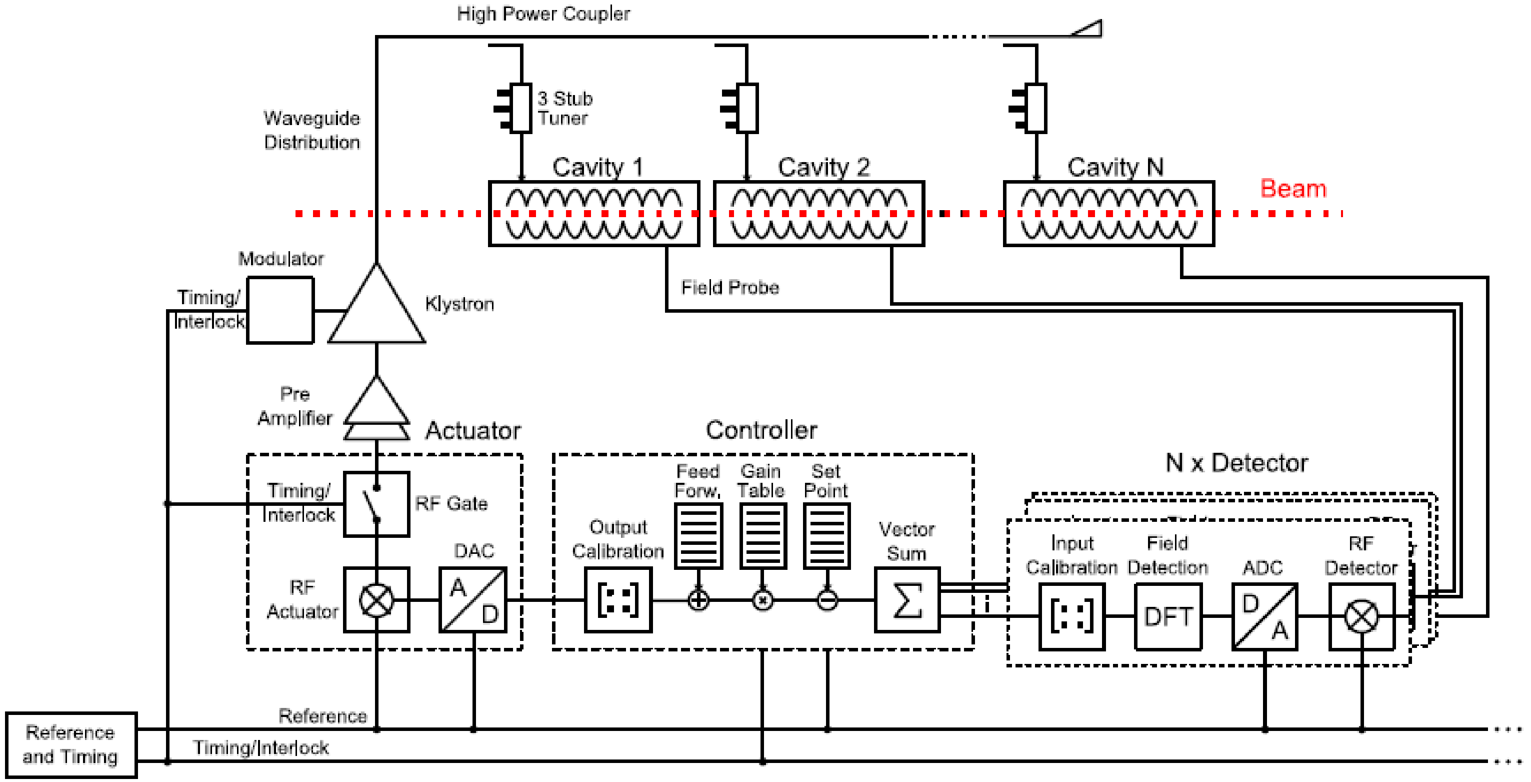


Accelerator subsystems must "play" together in order to achieve desirable particle acceleration and e.g FEL lasing:

- Preparing accelerating fiels before particle arrival
- Releasing particles at a proper time to to travel via accelerator at a proper phase

Accelerator Synchronization – LLRF Example

- RF Phase Reference **(analog)**
- ADC/DAC clocks (**digital**)
- Timing (**digital**)



Simplified (**old**) scheme of a FLASH Accelerating module LLRF system
Courtesy of Matthias Hoffmann

Timing System

- Provides **triggers** initiating specified **events**
  - There is a specified trigger sequence for given event
  - Eg. Initiating filling cavities with RF field, starting RF Gun to produce bunch, running beam diagnostics, … – entire process of passing beam through accelerator
- Provides **coded event name and time** information
  - Allows to correlate data gathered from various subsystems during selected event
- Generates and distributes clock signals

Timing System Example

- Fiducial trigger synchronized with AC mains and a common subharmonic
- Synchronized event triggers with user programmable delays
- Master timing clock, triggers and event codes combined and sent usually by optical fibers
- There are well established solutions available like the White Rabbit

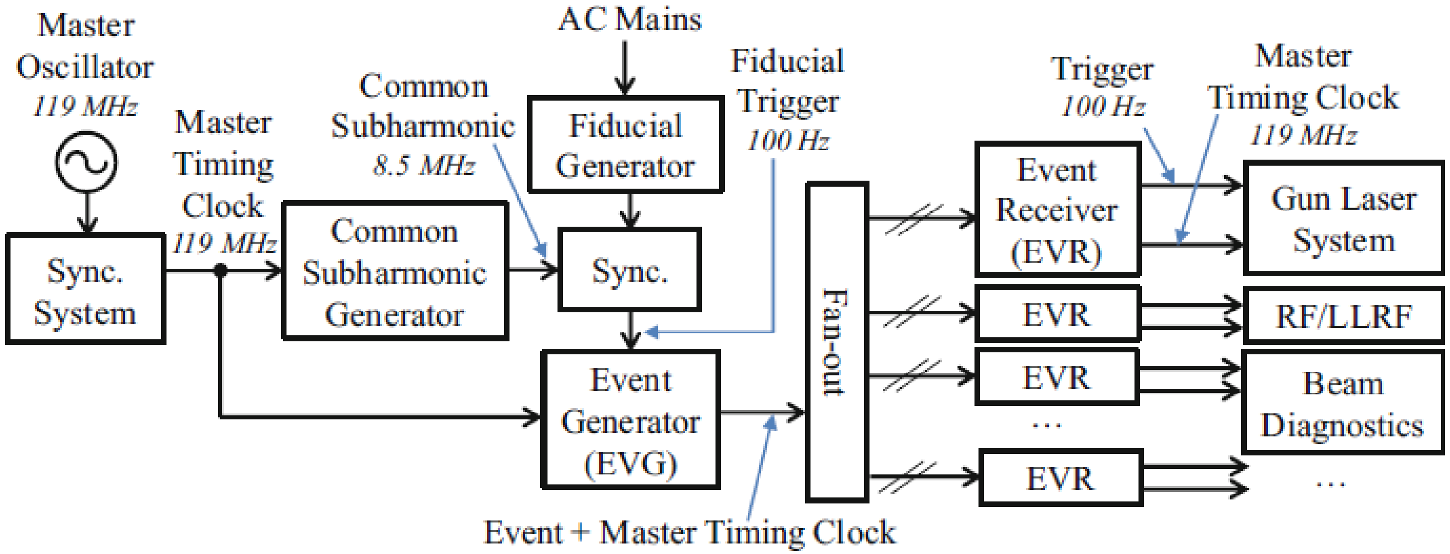
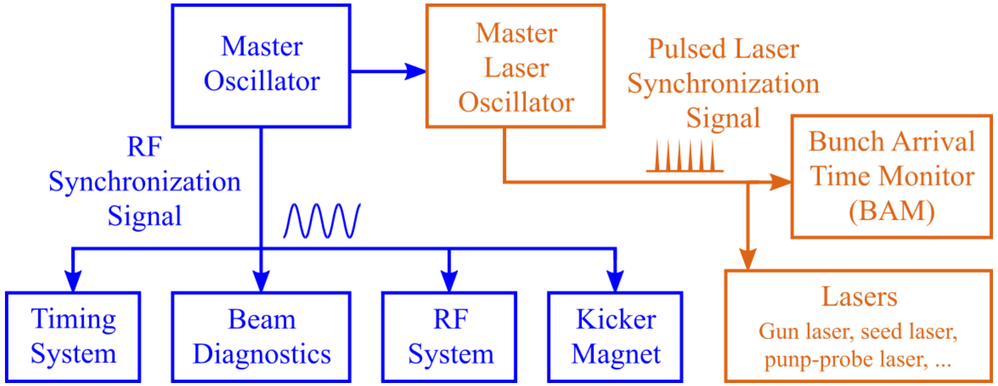


Figure source: S. Simrock and Z. Geng, Low-Level Radio Frequency Systems, 2022

Synchronization System

- **Frequently mistaken with timing system and even with a clock signal**
- Some people claim that timing is above ps regardless of signal type
- Built to distribute phase reference signals (either **harmonic** RF or optical)
- Called also Phase Reference Distribution System (PRDS)
- Consists of a Master/Main Oscillator (MO) and set of signal distribution links
- Sometimes linked with optical Master Laser Oscillator
- Output signals are used at receivers to synchronize phase of devices or to synthesize other signals (e.g., LO for downconverters)



Some Basics

Real sinewave signal

$$v(t) = V_0\big(1 + \alpha(t)\big)\cos(2\pi\nu_0 t + \varphi(t))$$

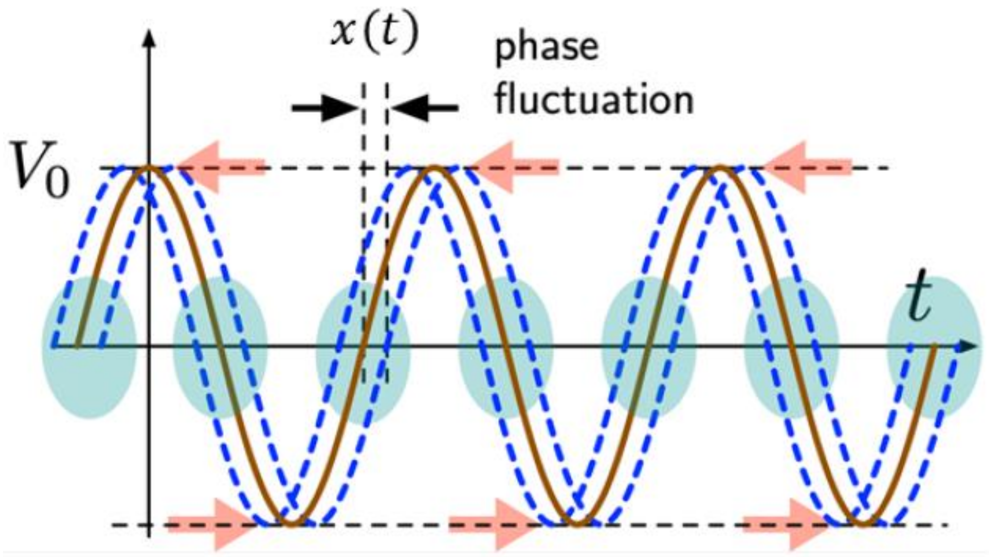


Figure source: IEEE Std 1139™-2022

V_0 - nominal voltage amplitude

$\boldsymbol{\nu_0}$ - nominal frequency, called also instantaneous

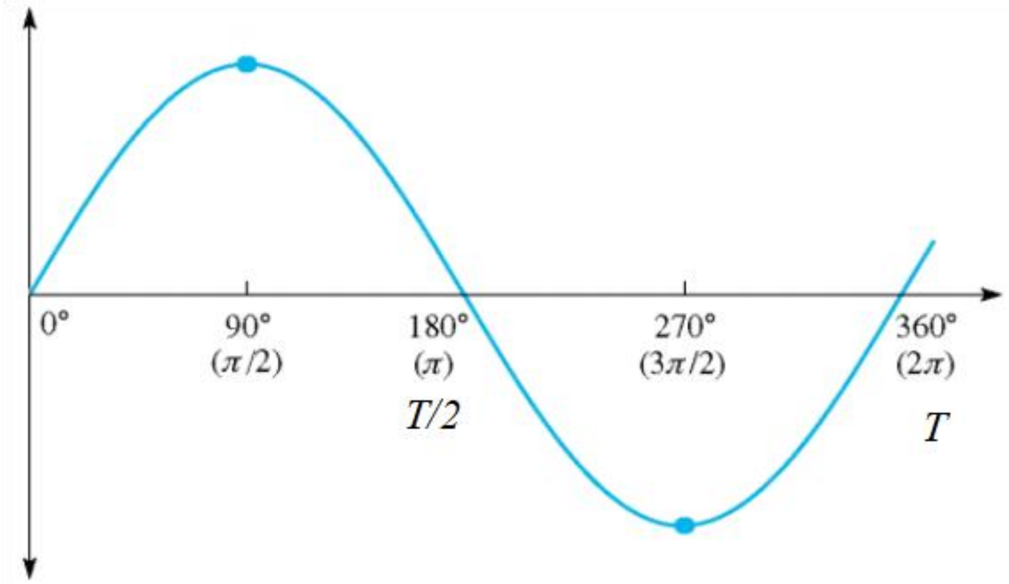
α(t) - amplitude fluctuation

$\varphi(t)$ - phase fluctuation

More details in talk by Maximilian Schütte, Tuesday 11:20

Even More Basics

Expressing phase changes in units of time is convenient for quantifying phase instabilities in distribution media (by means of propagation delay change) - it does not depend on the signal frequency.



$$\Delta t = \frac{\phi T}{360^o}$$

$Example: \nu_0 = 1300\,MHz \;\rightarrow\; T \approx 0{,}769\,ps,$

$\Phi = 1^o \rightarrow \Delta t \approx 2{,}13\,ps$

Phase Stability is Expressed as Instability

Instabilities can be distinguished by:

- **Character:**
  - random (phase noise)
  - deterministic (temperature influence, mains AC harmonics)
- **Reference:**
  - absolute (phase noise/jitter measured at given PRDS output)
  - relative (drifts or residual noise/jitter, phase change between different outputs)
- **Observation time:**
  - short-term
  - long-term

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

- "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 (minute, hour, day ...)
- **Considered either in time >1s or >10s** probably because it is hard to measure phase noise <1Hz

Phase Noise and Jitter

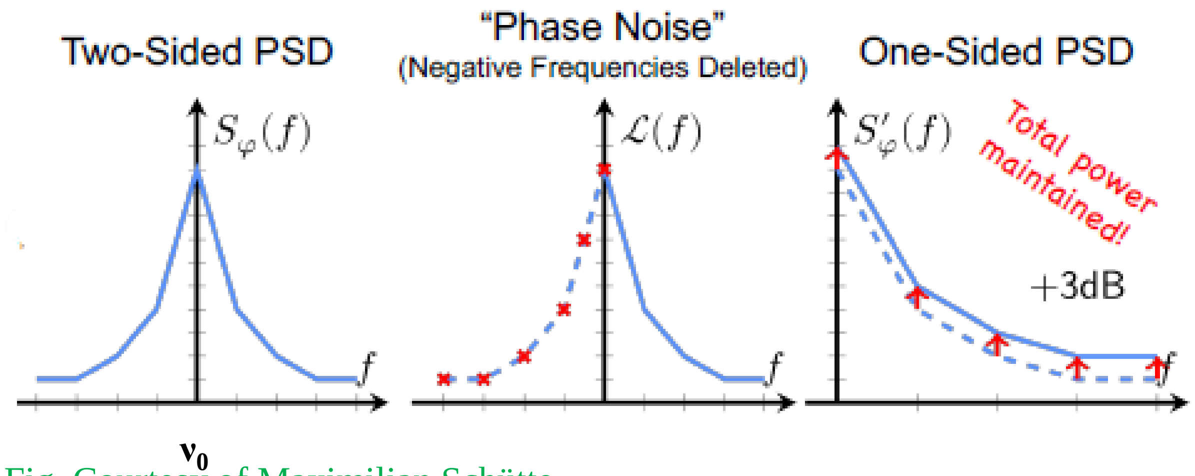
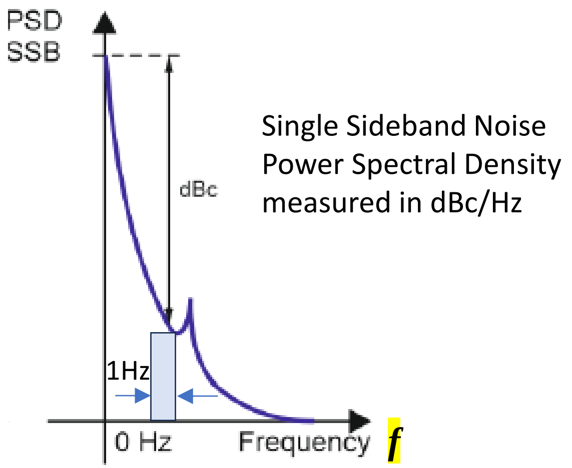


Fig. Courtesy of Maximilian Schütte

Traditional phase noise definition



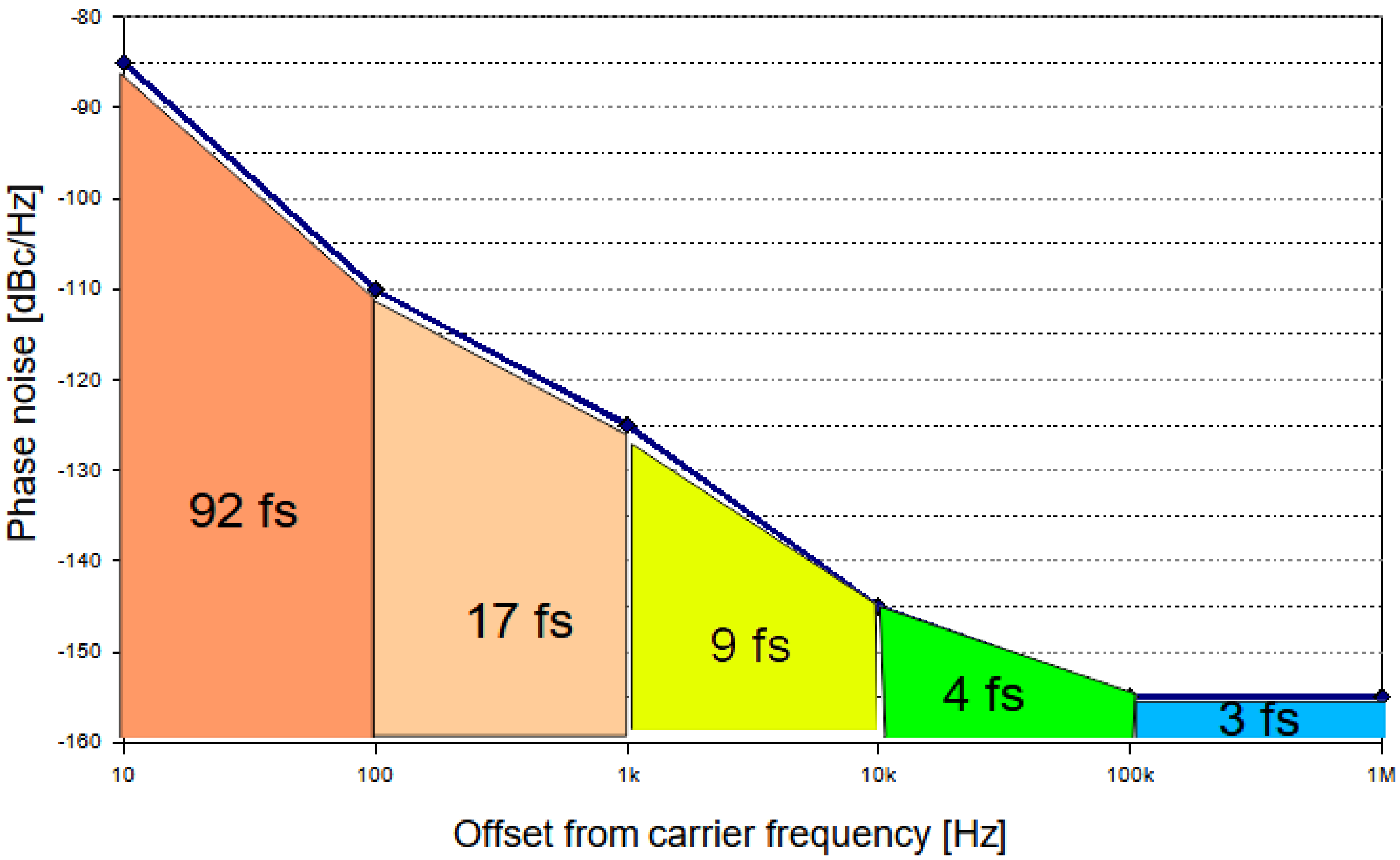
$$\phi_{jitter}^2 = \int_{f_1}^{f_2} S'_{\varphi}(f)df$$ Phase Jiitter

$$\Delta t_{rms} = \left(\frac{1}{2\pi\nu_0}\right)\sqrt{\int_{f_1}^{f_2} S'_{\varphi}(f)df}$$ Phase jiitter in units of time

Note 1/ν_0 – higher frequency results in lower time jitter for the same phase noise levels!

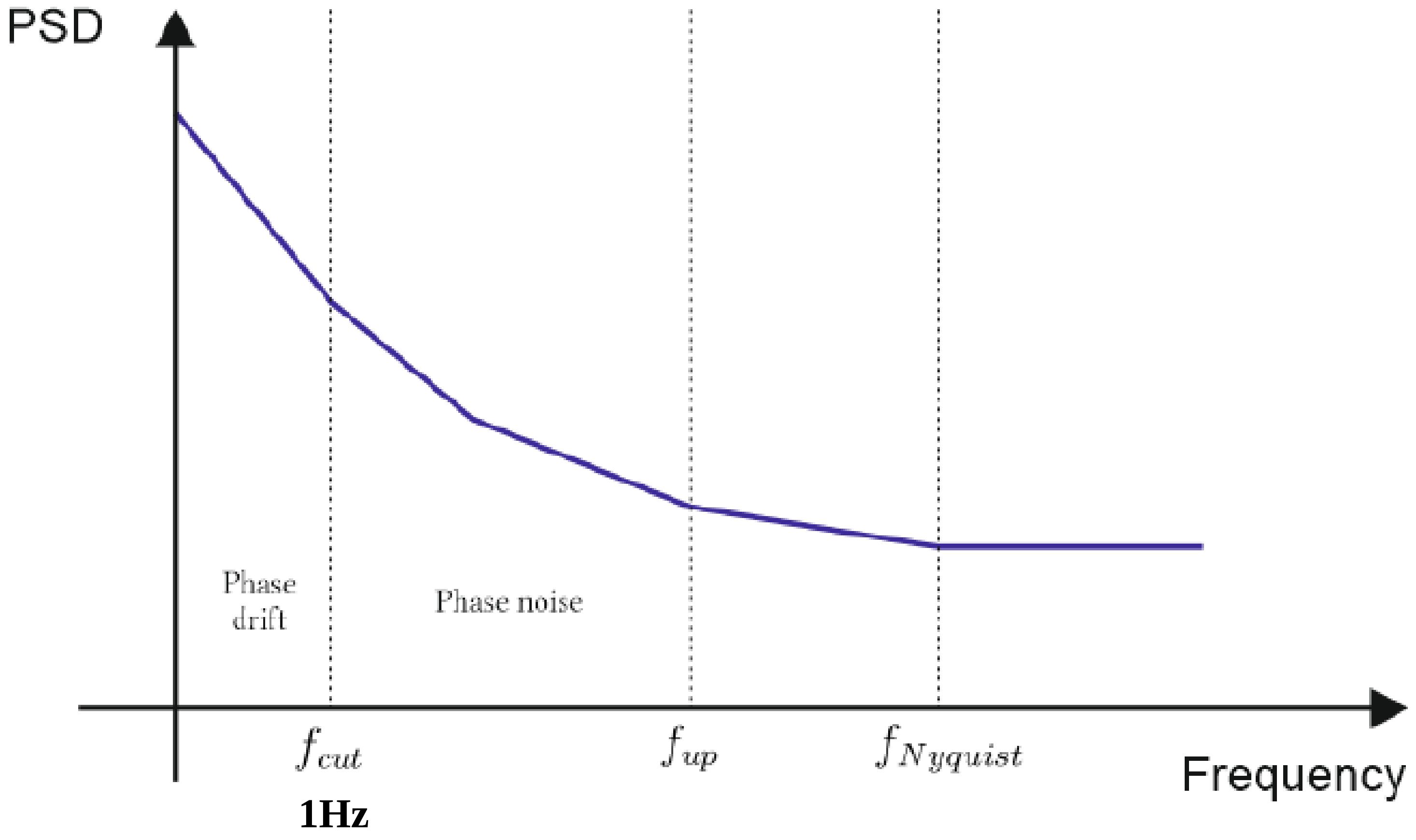
Phase Noise and Integrated Jitter Example

1300 MHz oscillator signal



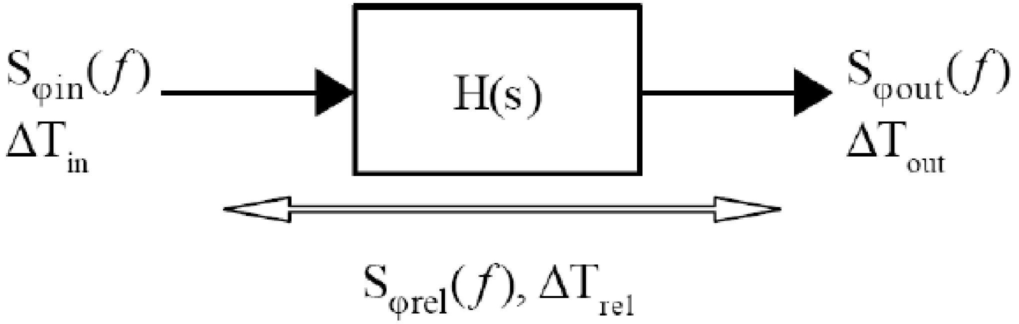
The closer to the carrier, the bigger the phase noise contribution to jitter!

Phase Noise and Drifts



Jitter calculated for frequencies below 1 Hz **(or 0.1 Hz)** is treated as (absolute) phase drift

Residual Phase Noise and Jitter



$$\Delta t_{rel} = \left| \Delta t_{out} - \Delta t_{in} \right|$$

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

May be an issue when using devices introducing significant noise to the signal.

E.g. wrongly designed amplifier with AM/PM noise conversion

Reference Signal Generation

- In most cases the very signal source is a crystal oscillator (OCXO)

- Typical OCXO long term frequency stability is ~10^{-10}
- If better frequency stability is required, the OCXO can be synchronized to:
  - Atomic (Rubidium) clock ~10^{-12}
  - GPS receiver ~10^{-14}

- OCXO frequency rarely exceeds 200 MHz
- Higher frequencies must be synthesized

„Simplest” MO Solution

- **Off the shelf** signal synthesizer
- There are some devices offering high-performance signals
- Phase jitter in range of tens of fs
- Relatively high noise floor (-155 to -160 dBc)
- But still sufficient for many machines

- For higher performance and non typical requirements a custom design is necessary

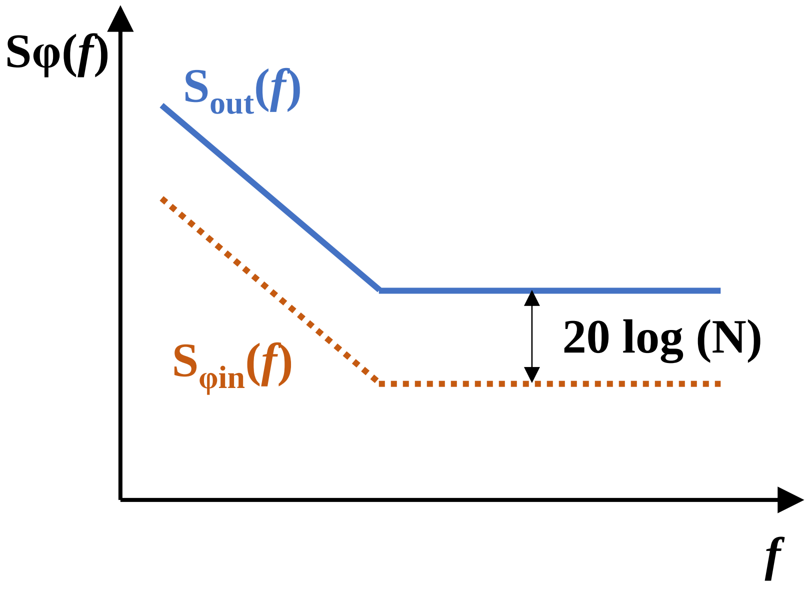
Other MO Requirements

- Low far from carrier phase noise
- Multiple output frequencies
- Many outputs
- Higher power levels
- High-availability (redundancy)
- Included diagnostics

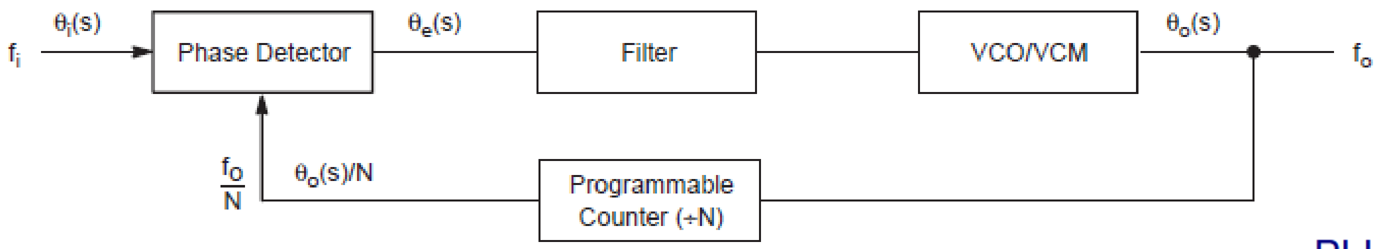
→ Definitely a custom design required

Frequency Synthesis with a Multiplier

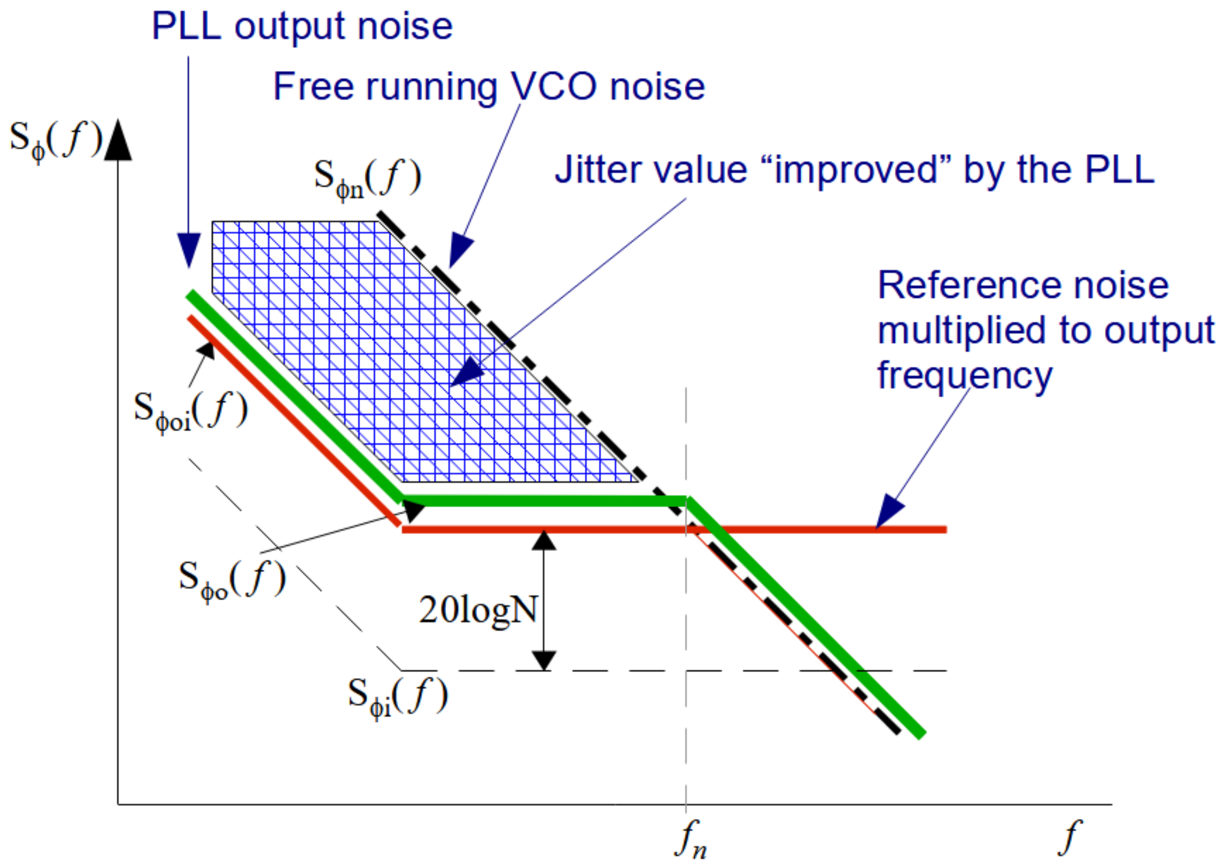
- Usually the multiplication factor N = 2 or 3
- Rather narrow frequency range
- Limited choice of high-performance devices
- Limited flexibility but still possible to make a good design
- Phase noise floor rarely below -155 dBc!
- May drift significantly with temperature



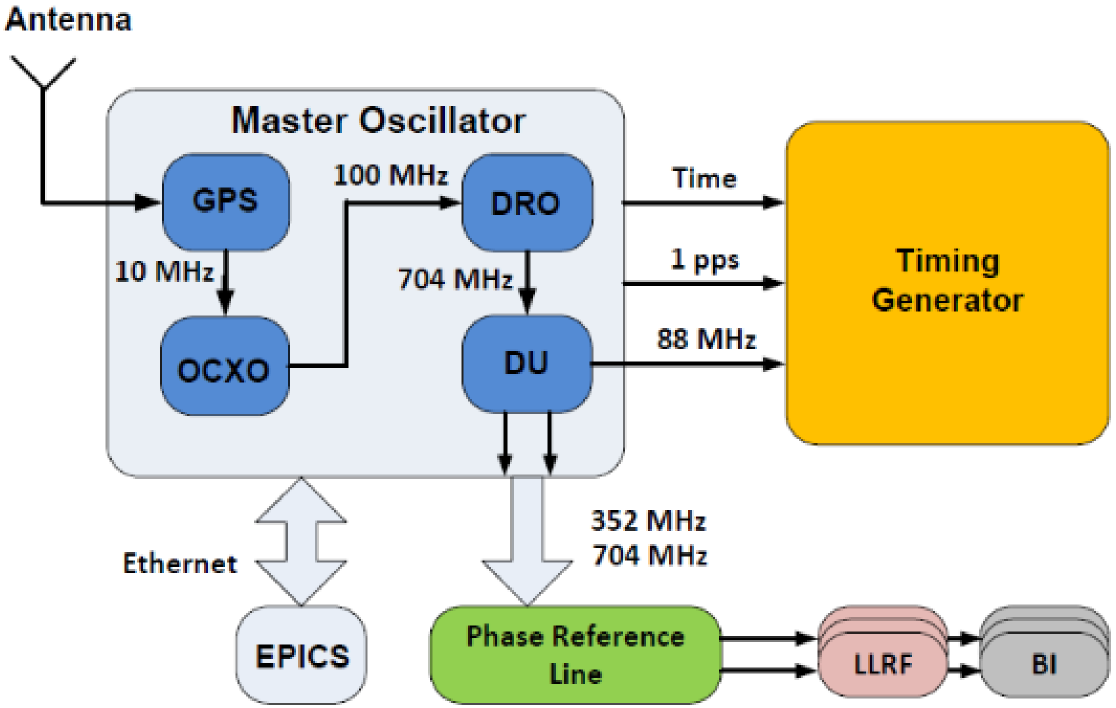
Phase-Locked Loop Synthesizer

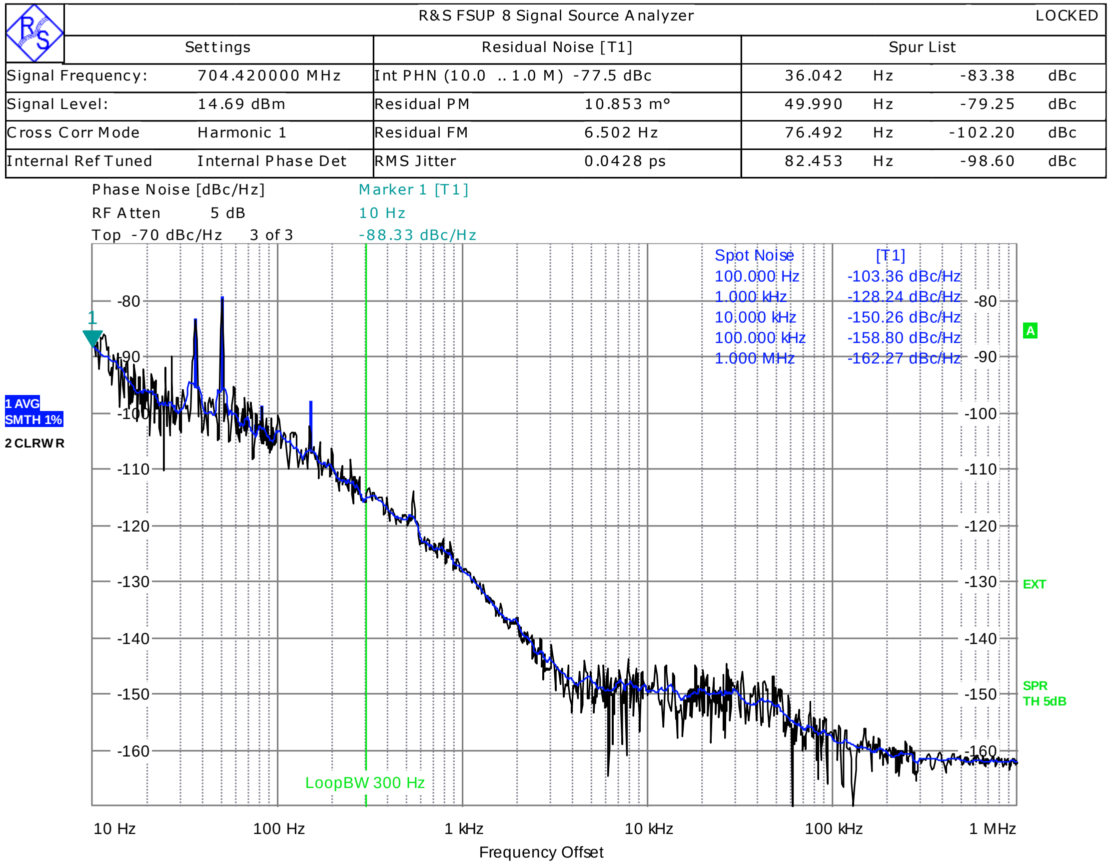


- Phase – locking of a VCO to a reference signal
- Flexibility in selecting output frequency
- Proper selection of PLL components allow for phase noise (jitter) reduction comparing to a standard multiplier



High-Performance MO and RF Synch Scheme

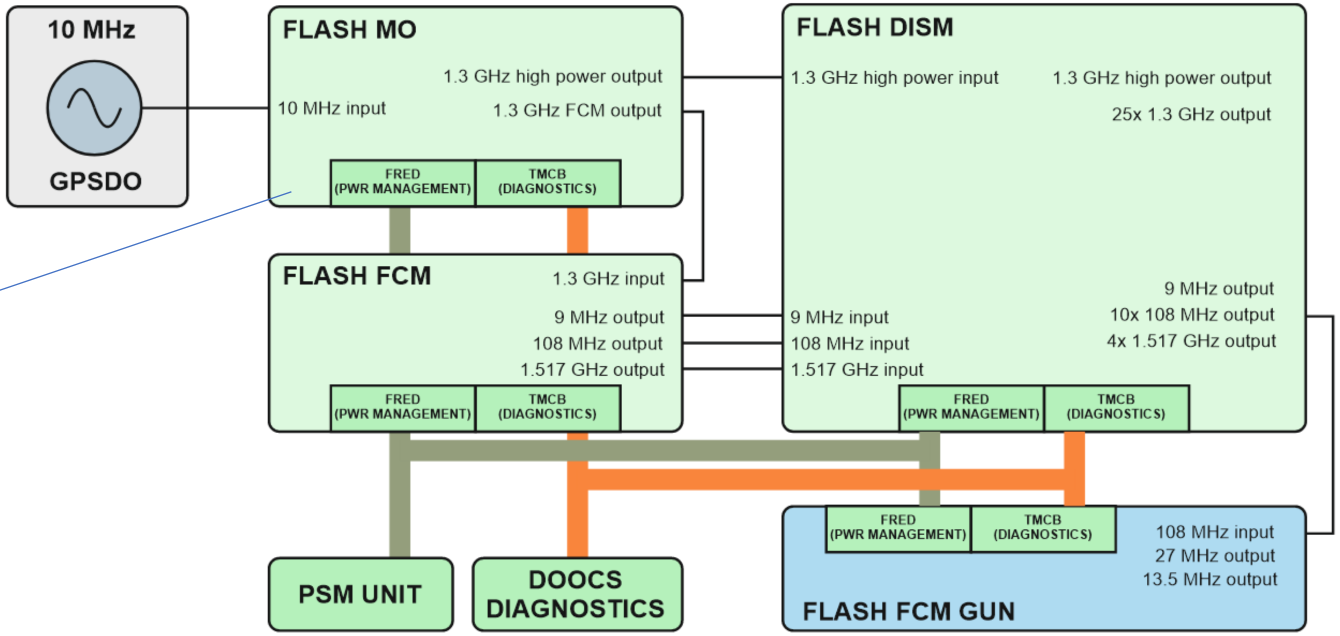




- Design by Lund University and ESS
- Output power +6.3 dBm
- RMS Jitter **laboratory** test (10 Hz – 1 MHz):
  - ~ 80 fs @ 352 MHz
  - ~43 fs @ 704 MHz

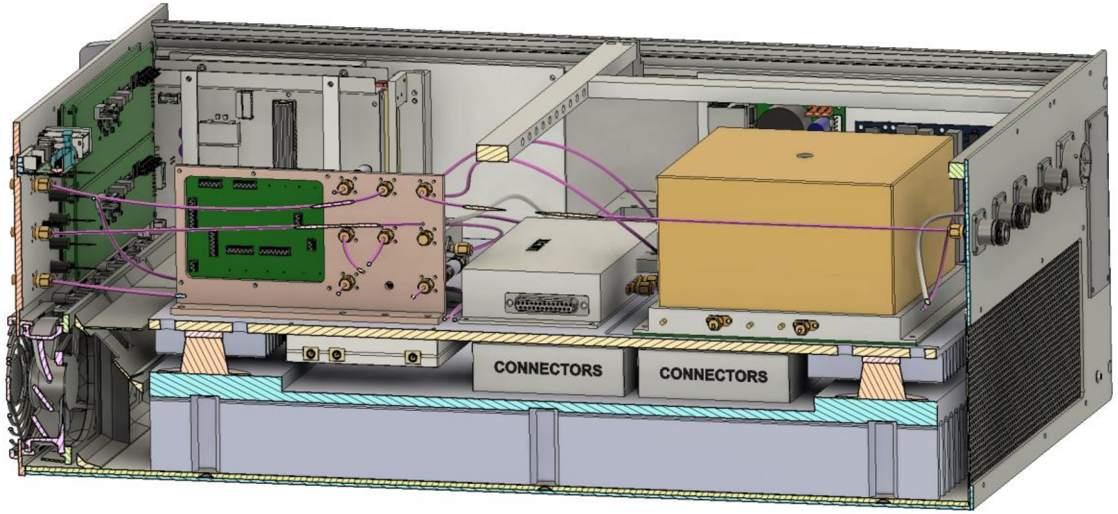
Courtesy of A. Svensson, A. J. Johansson

FLASH 2020+ MO Design - Very High Performance



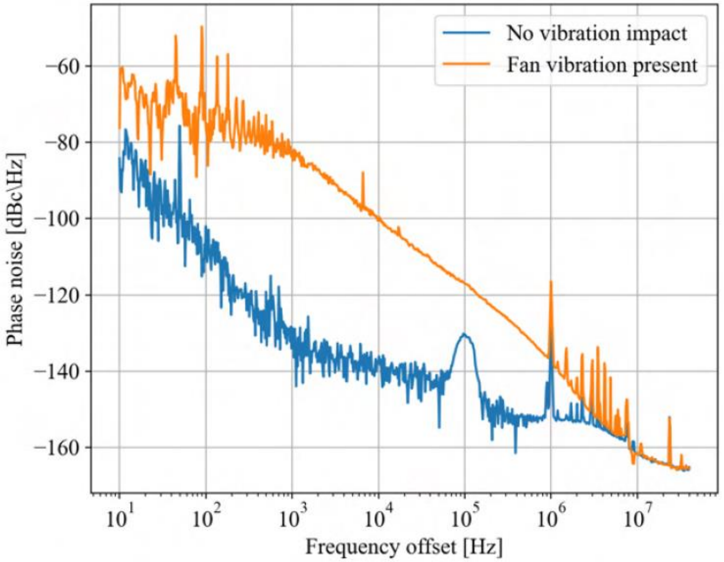
- Design by WUT and DESY
- Distribution by KVG

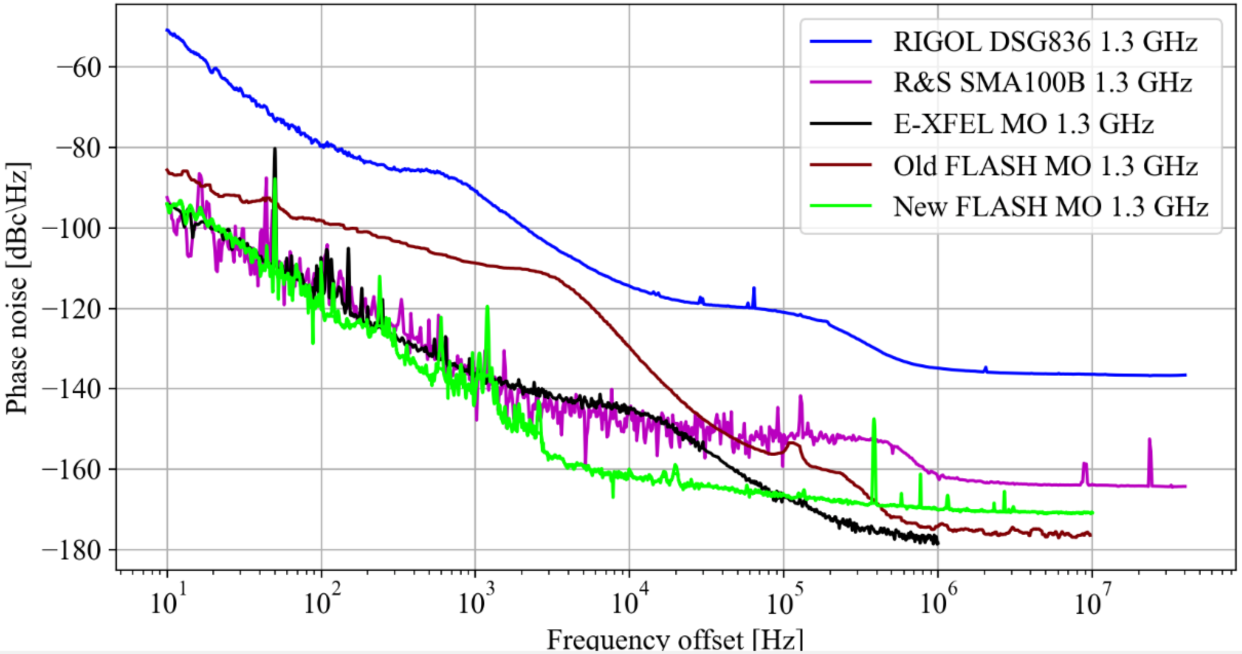
FLASH MO 2020+ Performance



	Phase Jitter (10 Hz do 1 MHz)		
	Old FLASH MO	E-XFEL MO	**NewFLASH2020+ MO**
108 MHz	86.1 fs	-	**27.8 fs**
1300 MHz	55.9 fs	19.5 fs	**10.7 fs**
1517 MHz	1390 fs	-	**45.8 fs**

OCXO phase noise optimization



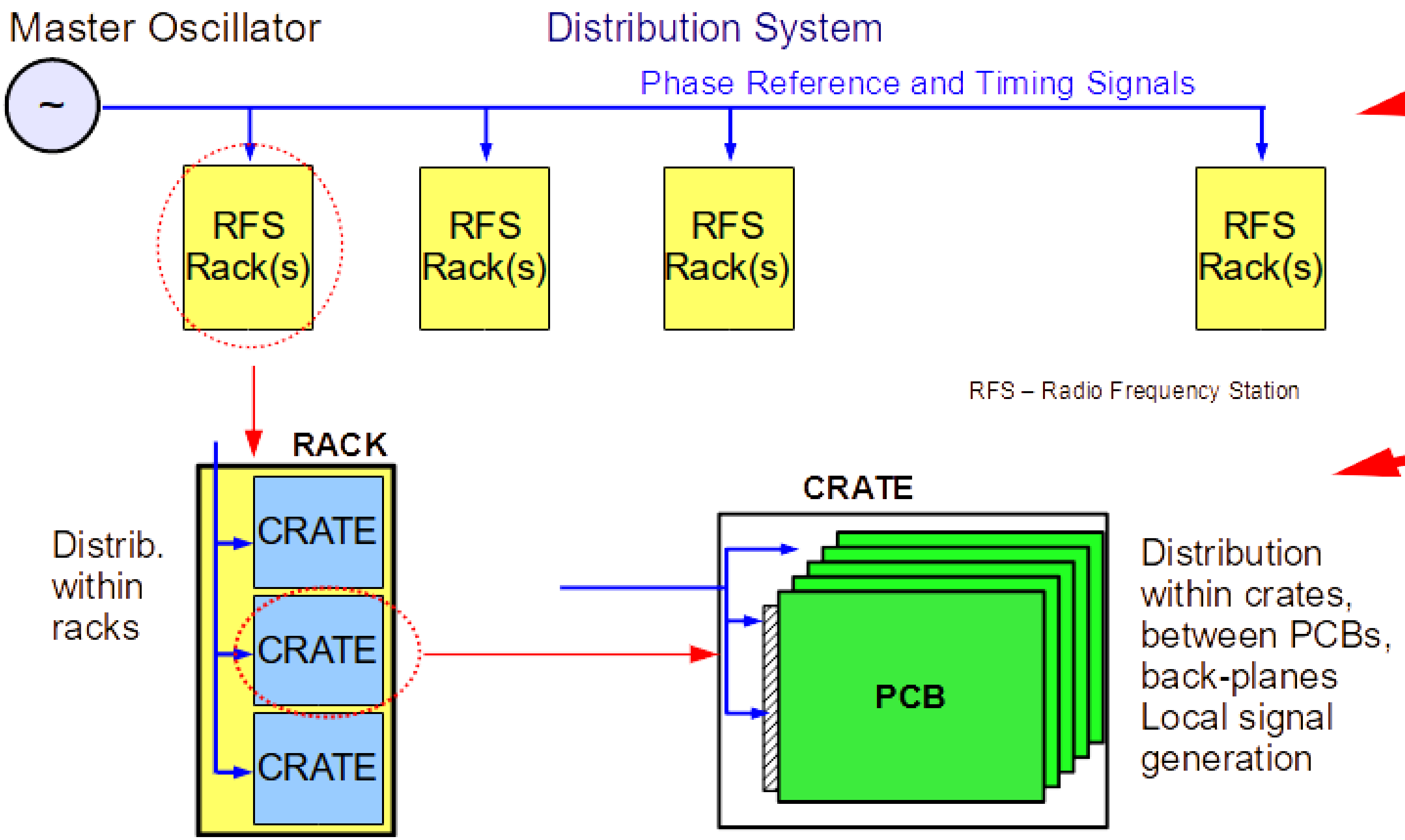


After signal generation …

Instabilities in Practice

- The absolute instability depends mostly on the MO phase noise
- Passive components do not contribute to jitter (well… EMC, low power)
- It is possible to select amplifiers with negligible additive phase noise
- **Well designed distribution „transports" MO phase jitter to user devices**
- Required timing signal stability usually exceeds tens of ps or ns range
- High-performance clocks for fast ADCs are synthesized from the phase reference signal
- <u>Any distribution media introduces phase drifts</u>

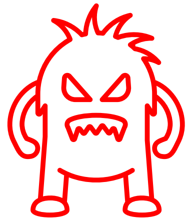
Typical Reference Signal Distribution Scheme



Main Distribution to RF Stations and other accelerator subsystems

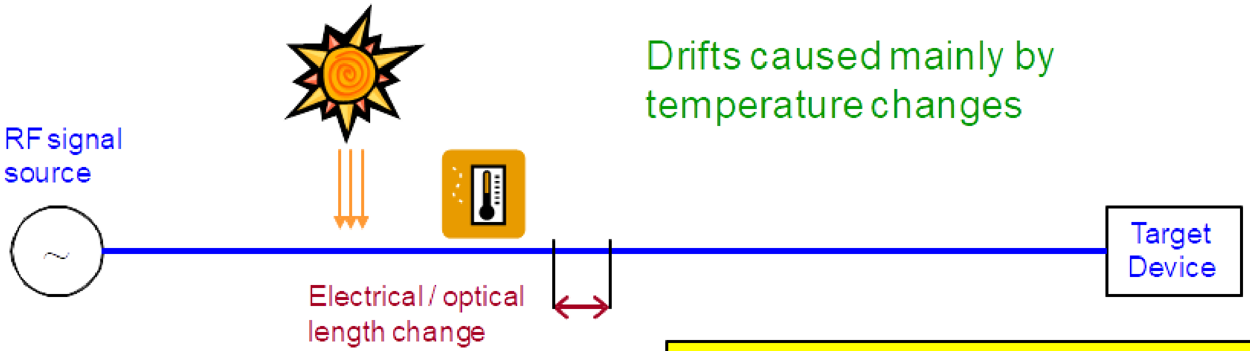
Local Distribution: racks, crates, PCBs

Main Enemy
PHASE DRIFTS



The importance of a local distribution is frequently underestimated

Phase Drifts in Distribution Media

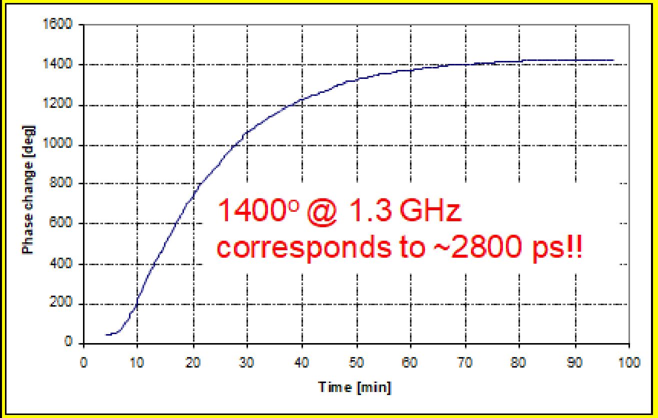


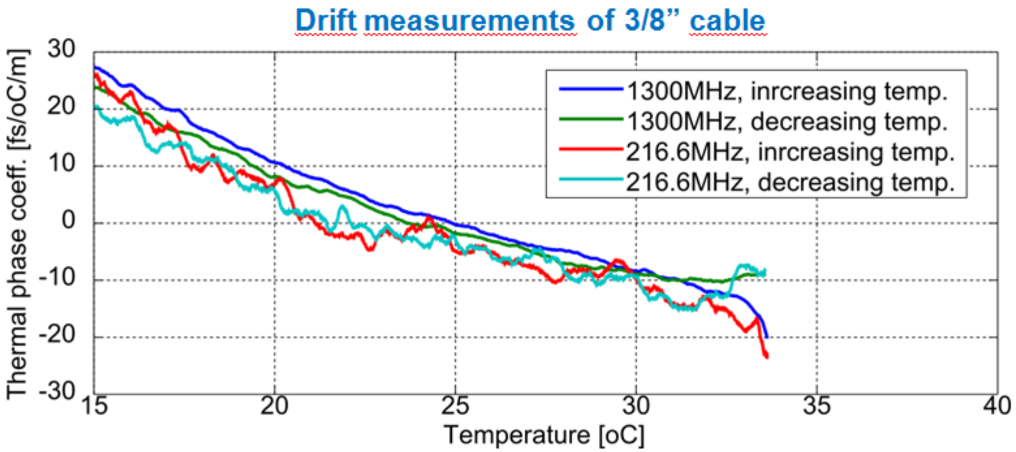
Drifts caused mainly by temperature changes

Reason of drifts:

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

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





K. Czuba, D. Sikora, "Temperature stability of coaxial cables", ACTA PHYSICA POLONICA, Vol. 119 (2011), No. 4, p. 553

Signal phase in cable and fiber can drift by degrees / 1°C per 1 meter!

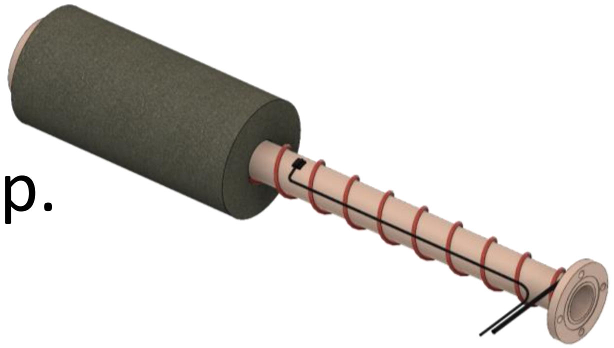
Temperature stabilization or feedback on phase required

Phase Drift Mitigation

- Depends on machine size and stability requirements
- For small accelerators a simple passive distribution may be sufficient

- For larger machines it can be:
  - Passive with cables/fibers selected with opposite temperature coefficients
  - Semi-active by temperature stabilization
  - Active - feedback on phase applied
- See talk by Marie Kristin Czwalinna on Friday 9:05 for state of the art. systems

Cable Temperature Stabilization

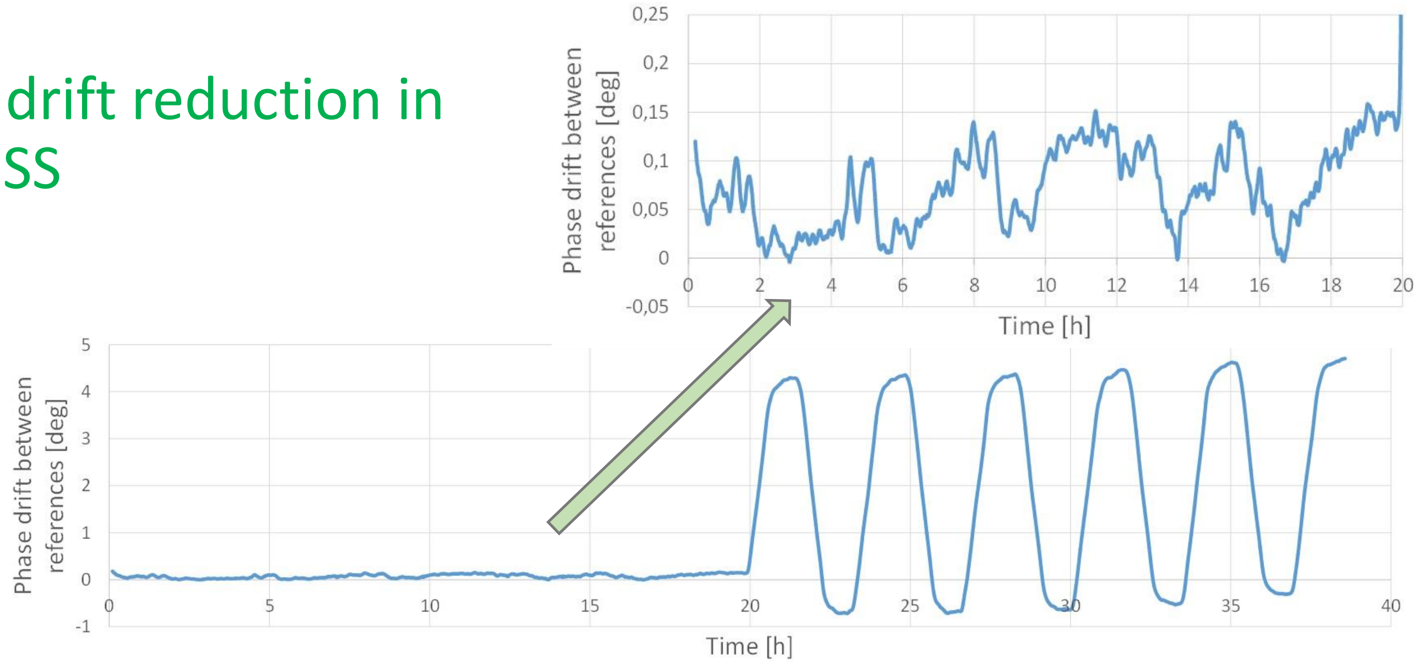


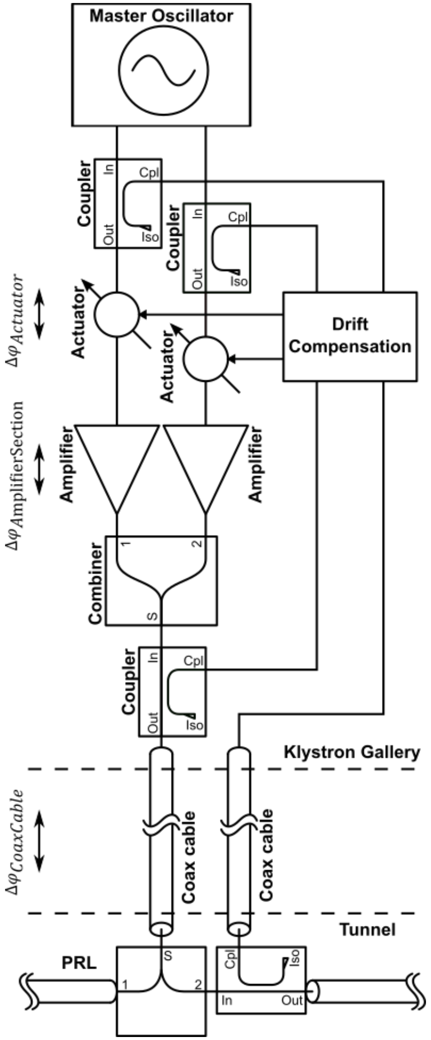
- Either by cooling water or by heating tapes
- Very well known, robust, good performance
- Require a good thermal insulation to achieve good temp. stability far from sensors
- Feasible for up to several hundred meters
- Demonstrated ~0.1^{o} p-p phase stability / 100m @ 704 MHz at ESS
- For longer distances and higher frequencies stability and cost may be compromised

Active Drift Mitigation (1)

By locking phase of a round trip signal

- Either with RF short at the end of the link or 2nd cable for return signal
- Well suited for point-to-point RF and optical links
- Demonstrated 33 x drift reduction in ~40 m long link at ESS

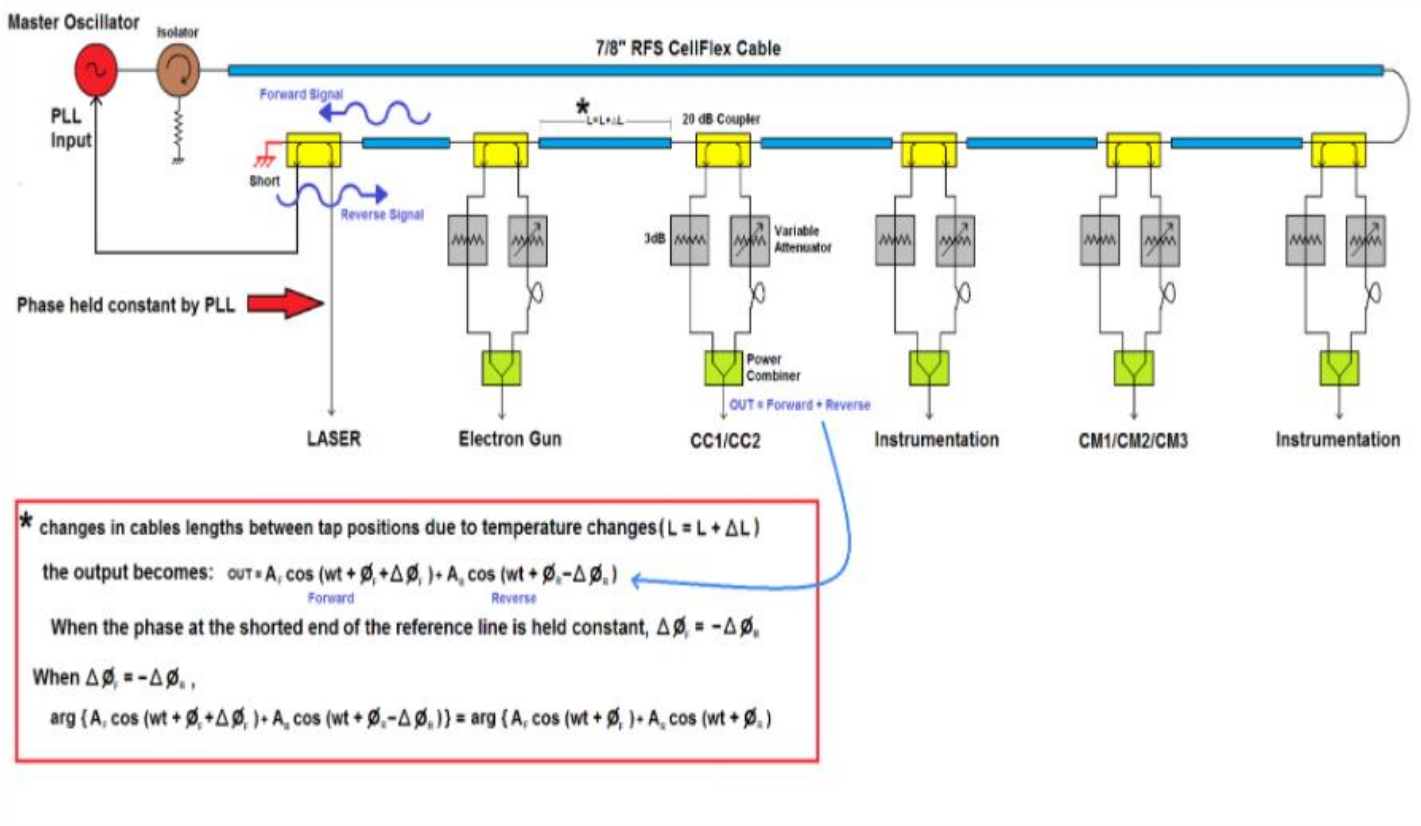




Active Drift Mitigation (2)

Interferometer/phase averaging scheme

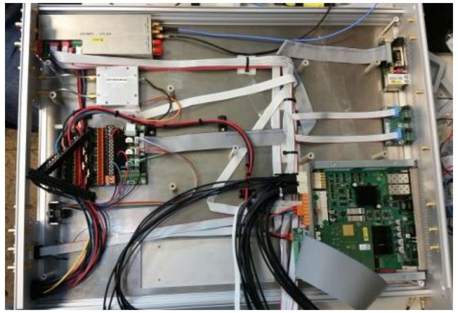
- Round trip signal phase locked at the transmitter
- But also reflected back and summed at outputs of directional couplers
- Signal vector sum averages out phase drifts
- Relatively difficult to setup
- Many problems with parasitic reflections
- Offers excellent performance for up to few hundred meters

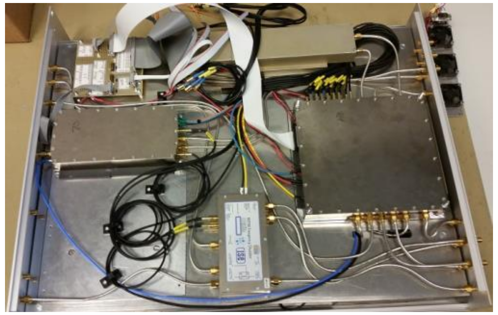


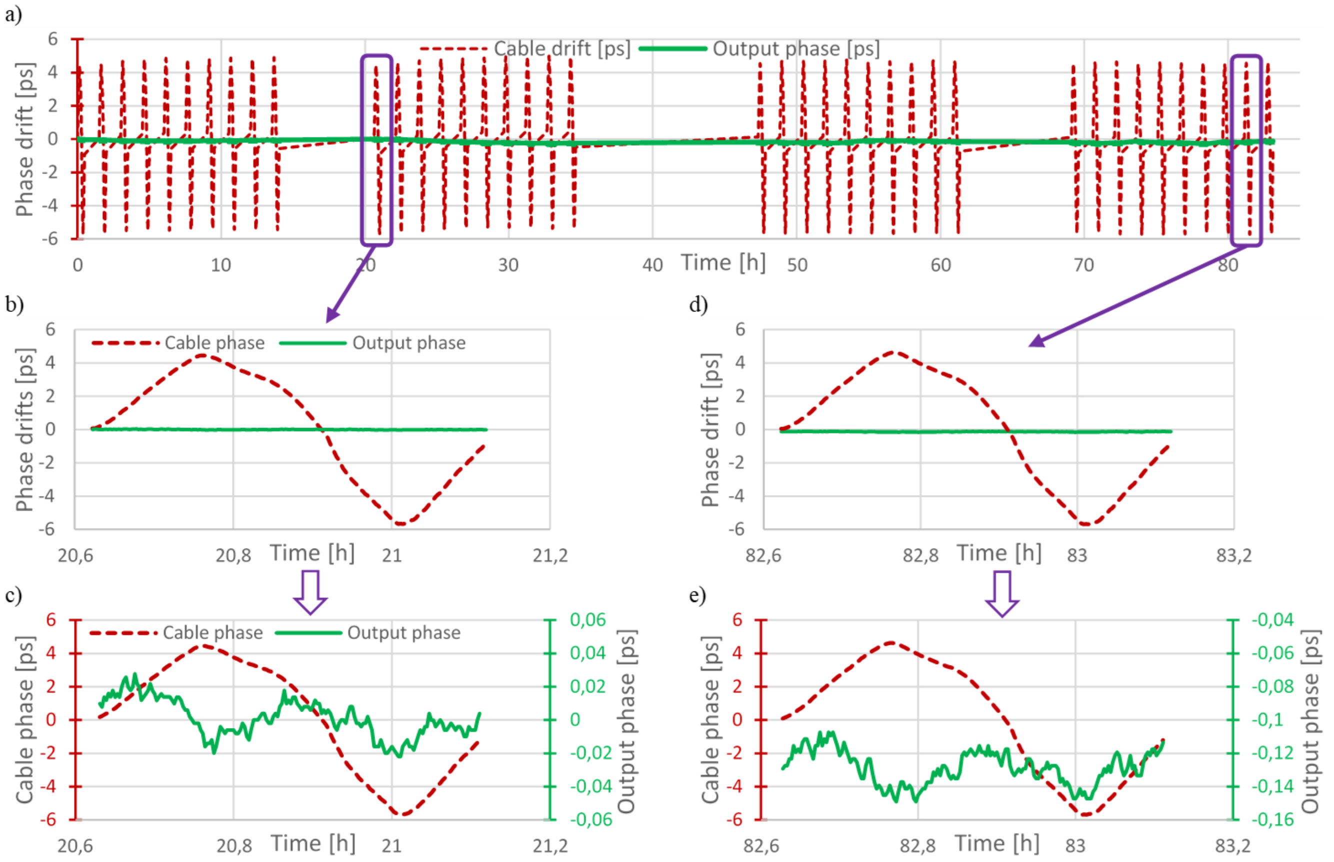
Idea by Ed Cullerton and Brian Chase (Fermilab), Presented at LLRF2011, DESY

Active Drift Mitigation - Example

- WUT and DESY developed interferometric link prototype with automatic calibration
- ~85 h long test
- output vs input phase **with feedback on** and **with feedback off**
- Open loop phase changes in cable (**~10 ps**) compensated to **50 fs p-p**
- Drift reduced ~200 times!







D. Sikora et. Al. "Phase drift compensating RF link for femtosecond synchronization of E-XFEL"

Summary

- Building a „heart" of the accelerator may be a very challenging task
- Timing systems distribute trigger, event information and low/mid performance clocks (ps to ns of jitter)
- PRDS/PRL are used to distribute harmonic RF signals with down to fs precision
- Phase noise is relatively easy to achieve and distribute (short term stability)
- The big problem is mitigation of phase drifts at the level of sub ps on long distances (above hundred meters)
- State-of-the-art (femtosecond) PRDS use active drift stabilization techniques either for RF cables or **optical links**

Thank you for attention!