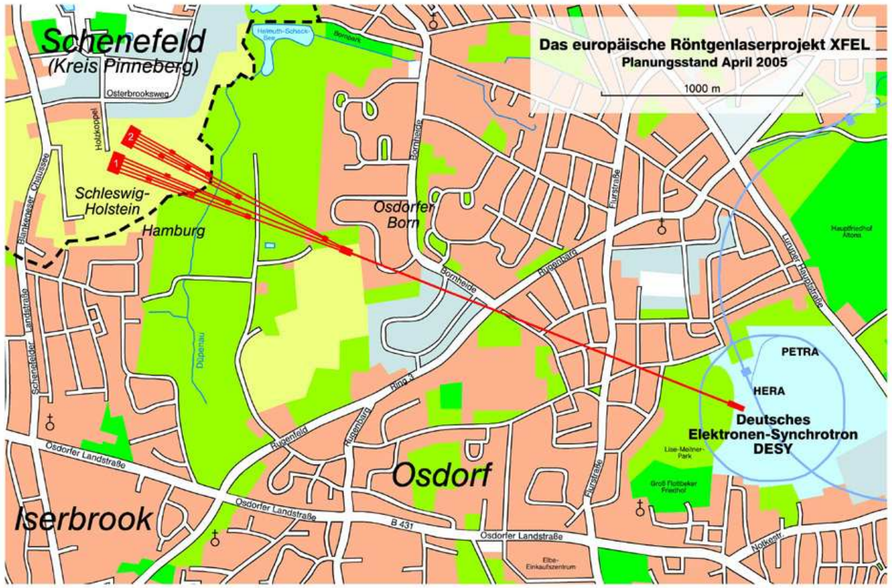
Summary of the European XFEL RF Synchronization Workshop

RF Tech 2nd Workshop

Krzysztof Czuba
ISE/WUT

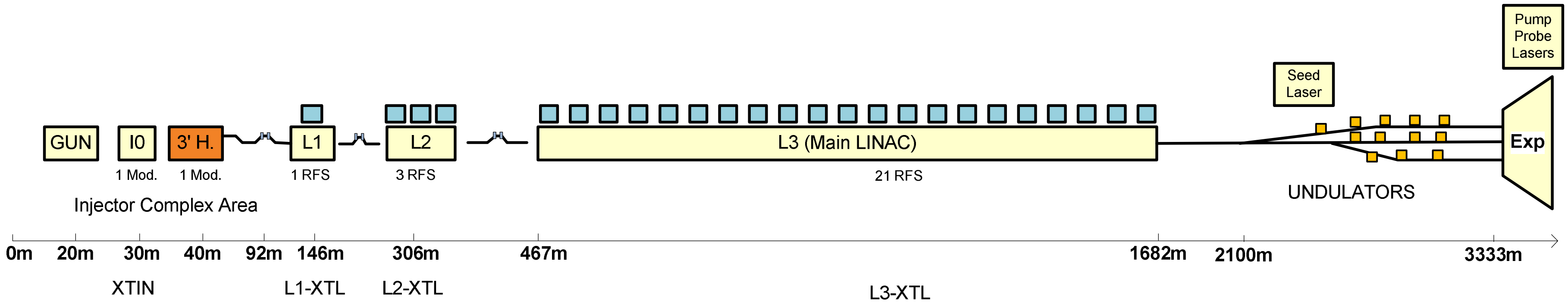
Introduction – European XFEL

- X-Ray Free Electron Laser (XFEL)
- Under construction at DESY in Hamburg
- 3.3 km long machine based on superconducting cavities
- Include numerous RF subsystems



European XFEL

Introduction - Need for Synchronization at XFEL



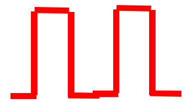
- Subsystems of the machine must run synchronously
- Very high precision of synchronization is required (down to fs for most critical subsystems)
- There will be several thousands of electronic, RF and optical devices in the machine that require synchronization
- The system length of over 3 km make the design of the synchronization system very challenging and difficult task

Types of Synchronization Signals

There are various types of signals, frequently confused by users:

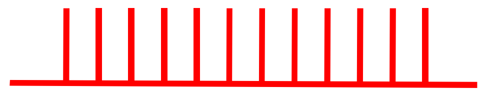
- Analog (RF phase reference, VM, LO)

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



- Trigger signals (digital subsystems, CPU)

- Optical pulse trains (lasers, diagnostics, experiments)



Synchronization System Design

- Works going on since 2008
- Many general issues addressed and solved until now
- A Conceptual Design Report (CDR) is planned for spring 2011
- Gathering and freezing of user requirements is necessary before releasing the CDR
- Workshop with users of the synchronization system signals was necessary for accomplishing of the CDR preparation

Workshop Objectives

Initiated as preparation for ***"Conceptional Design Review"*** (CDR) for the RF Synchronization System (submit spring/summer 2011)

- List of stakeholders
- List of requirements
- Interface definition to other sub-systems
- Functionality of the system
- Principle design and layout
- Capabilities & Limitation
- Interplay to closely related system (optical synch/timing system)

1) Completeness of stakeholders & requirements gather so far!

Workshop Objectives (2)

Initiated as preparation for ***"Conceptional Design Review"*** (CDR) for the RF Synchronization System (submit spring/summer 2011)

- Spread information on the synchronization system(s)
- Provide better understanding of RF/timing/clock/optical synchronization and opportunity for redesign/reconsider layout of subsystem to make optimal use of planned infrastructure
- Migrate functionality from sub-system <-> synchronization system
- Trigger discussion on
  - Optical synchronization system (stakeholder/requirements/layout)
  - Timing/clock system (stakeholder/requirements/layout)

1) Completeness of stakeholders & requirements gather so far!

2) Kick-off for preparing the CRD on optical synch. (own workshop)

3) Come to an optimized overall design w.r.t. synchronization infrastructure

Location and Other Data

- Workshop was held at DESY, Hamburg
- 25 November 2010
- 36 participants
- 12 talks with extended time for discussion
- 2 dedicated discussion sessions

- Workshop indico page: http://indico.desy.de/conferenceDisplay.py?confId=3735

Workshop Timetable

Thursday 25 November 2010

09:00 - 09:10	Welcome Address and General Information 10' Speakers: Holger Schlarb (DESY)	Overview talks
09:10 - 09:55	Introduction and Synchronization System Overview 45' Speakers: Krzysztof Czuba (ISE, Warsaw University of Technology)	
09:55 - 10:10	Possible Operation Modes of the European XFEL 15' Speakers: Winfried Decking (DESY) Material: Slides	
10:10 - 10:35	Optical Synchronization Overview 25' Speakers: Holger Schlarb (DESY)	
10:35 - 11:00	Introduction to XFEL Timing System 25' Speakers: Kay Rehlich (DESY)	
11:00 - 11:20	Coffee Break	Coffee break
11:20 - 11:40	Synchronization System Installation - requirements, constrains, remarks 20' Speakers: Wojciech Wierba (Institute of Nuclear Physics PAN, Cracow, Poland)	Users requirements
11:40 - 12:00	RF Sychronization Requirement from Xray Photon Diagnostics Group – WP74 20' Speakers: Bin Li	
12:00 - 12:20	Timing Requirements for Optical Lasers at XFEL 20' Speakers: Maximilian Lederer Material: Slides	
12:20 - 12:40	Undulator and 40mm Cavity BPM System Synchronization Requirement 20' Speakers: Markus Stadler (PSI) Material: Slides	
12:40 - 13:00	Reentrant BPMs 20' Speakers: Claire Simon (CEA)	
13:00 - 13:30	Lunch Break (Lunch provided to BAH1)	Lunch break
13:30 - 13:50	Synchronization Requirements WP18 "Special Diagnostics" 20' Speakers: Matthias Hoffmann (DESY) Material: Slides	
13:50 - 14:00	Experience with User Experiments at FLASH 10' Speakers: Harald Redlin (DESY/Hasylab)	Review/ experiences
14:00 - 14:20	Temperature Variations and Profile at XFEL Tunnel System 20' Speakers: Hans-Joerg Eckoldt (DESY)	
14:20 - 14:50	Collection of missing items & specifications 30' Speakers: All	Discussion session
14:50 - 15:10	Coffee Break	Coffee break
15:10 - 15:45	Future Demands and Potential Upgrades 35' Speakers: All	Discussion session
15:45 - 16:00	Conclusions and Plans 15' Speakers: Krzysztof Czuba (ISE, Warsaw University of Technology)	

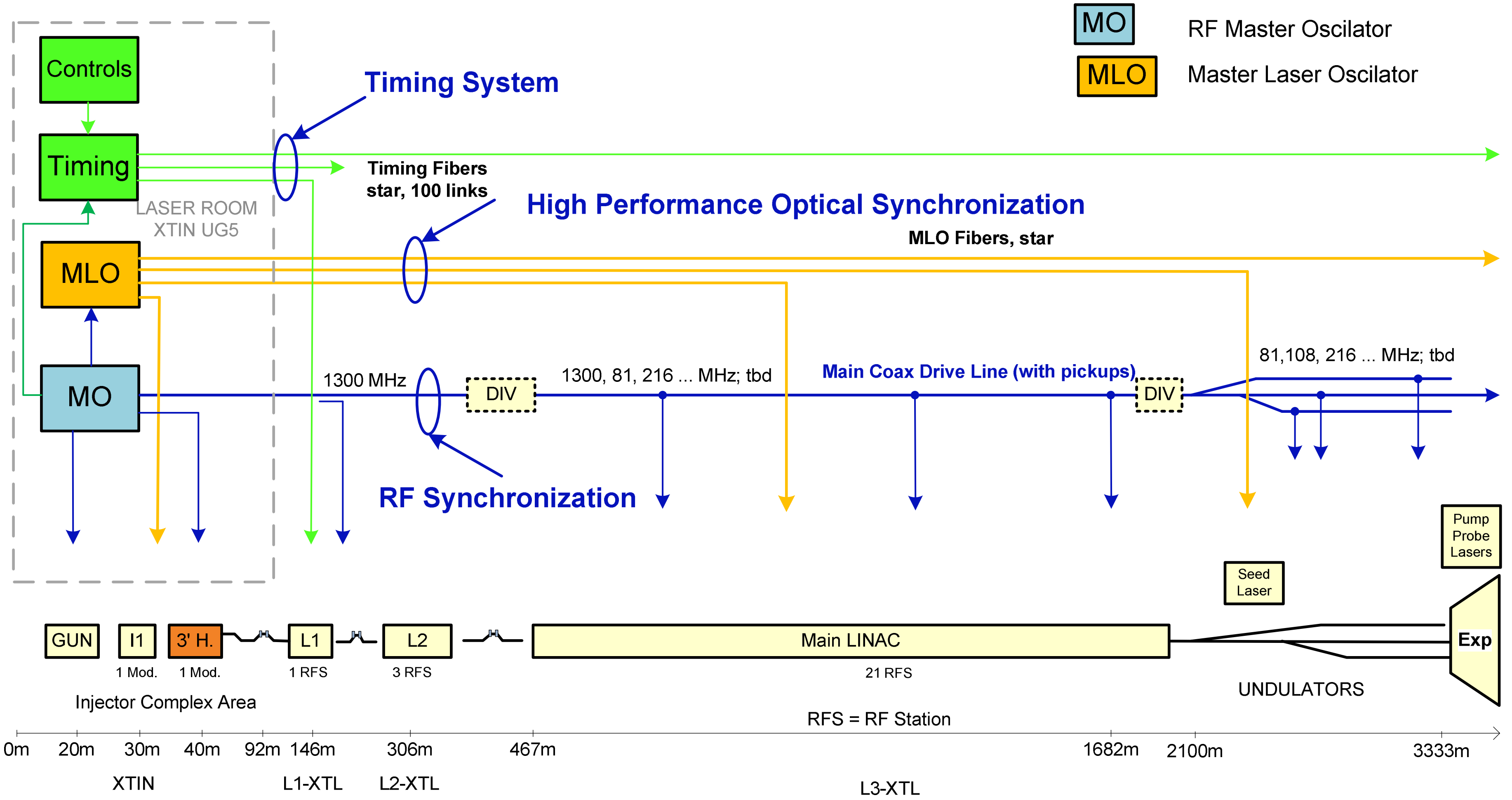
Overview Talks

- **Introduction and Synchronization System Overview**, Krzysztof Czuba (ISE/WUT)
- **Possible Operation Modes of the European XFEL**, Winfried Decking (DESY)
- **Optical Synchronization Overview**, Holger Schlarb (DESY)
- **Introduction to XFEL Timing System**, Kay Rehlich (DESY)
- **Synchronization System Installation - Requirements, Constrains**, Wojciech Wierba (IFJ)

Overview Talks - Summary

- Introduced synchronization basics
- Planned synchronization system layout was presented
- Synchronization system subcomponents were characterized and design plans were presented
- System limitations and estimated performance was shown
- Presented list of requirements that should be provided by users

XFEL Synchronization System Layout (General)



XFEL Synchronization System Characteristics

- The high performance optical links will provide optical pulses with <10fs stability
  - There is possibility to generate RF signals
- The RF system will deliver RF signals with stability <100 fs
- The digital, coded timing signals will carry event trigger codes and lower performance clocks (few ps stability)
- All systems will work complementary – depending on required performance, cost and reliability

User Requirements Expected

- Electrical requirements (frequency value, signal type, level)
- Stability requirements (jitter and drifts, absolute or relative to MO or other subsystem)
- Connectors
- Number of devices in the machine
- Locations (in meters from the beginning of the tunnel)
- Time schedule
- Diagnostic information
- Requests for test sources before installation

User Requirement Talks

- **RF Sychronization Requirement from Xray Photon Diagnostics Group – WP74**, Bin Li (XFEL)
- **Timing Requirements for Optical Lasers at XFEL**, Maximilian Lederer (XFEL)
- **Undulator and 40mm Cavity BPM System Synchronization Requirement**, Markus Stadler (PSI)
- **Reentrant BPMs**, Claire Simon (CEA Saclay)
- **Synchronization Requirements WP18 "Special Diagnostics„**, Matthias Hoffmann (DESY)

European XFEL

User Requirement Talks - Summary

- There are two „big" users of RF synchronization signals: LLRF and BPM's (about 100 and 130 tap points, respectively)
- The undulator cavity BPM'm requirements, jitter <100 fs will be difficult to fulfill on such scale.
- Several systems require synchronization accuracies of 10fs. They will be served by the high performance optical system

- Users were sometimes confusing types of synchronization signals and provided requirements with large safety margin... Discussions helped with identification of those issues

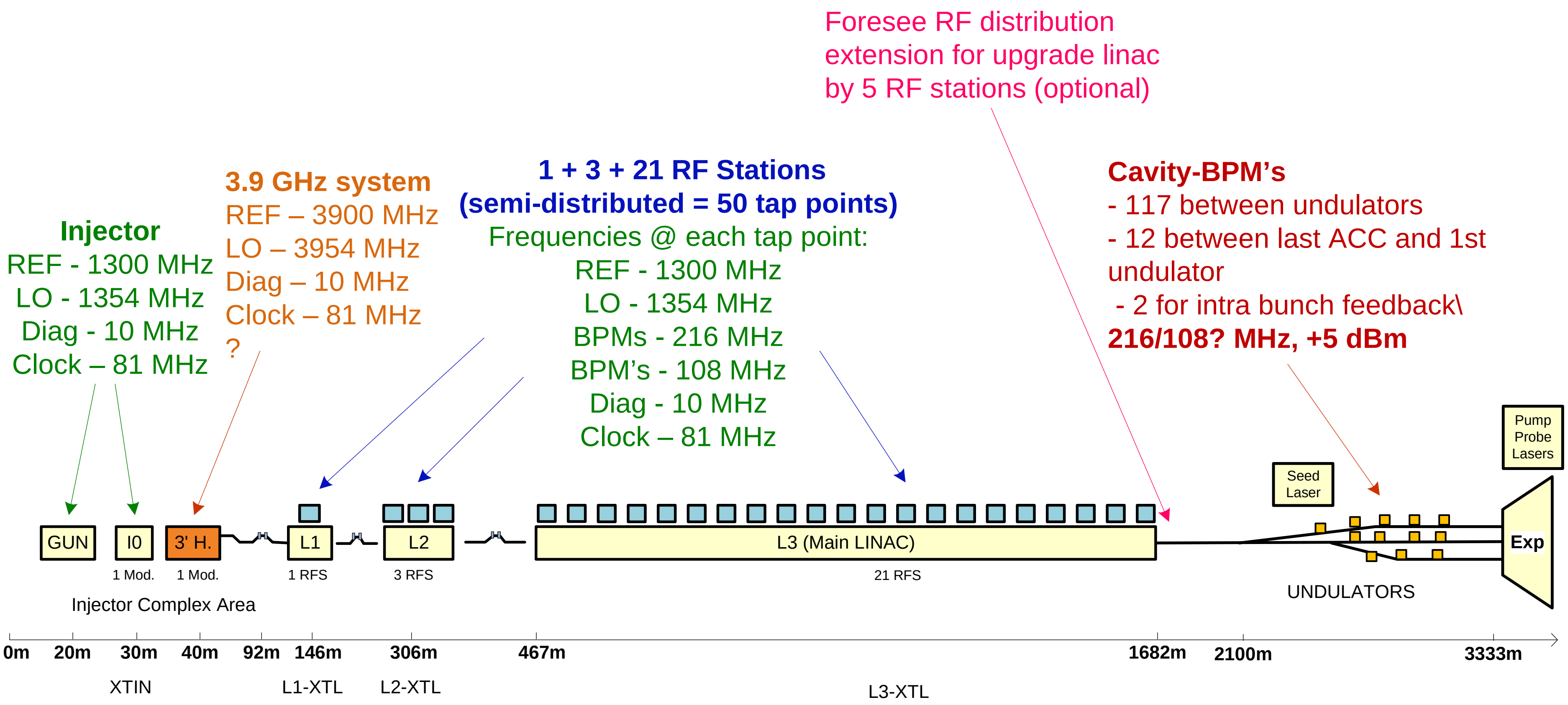
Field Stability Requirements for Accelerating Sections

Accelerator Section	RF Station	Amplitude Stability [%]	Phase Stability [deg]
I1 (GUN)	1300 MHz	0.01	**0.01**
I2 (Injector)	1300 MHz	0.003	**0.005**
I3 (3rd-Harmonic)	3900 MHz	0.005	**0.03**
L1 (Injector Linac)	1300 MHz	0.03	**0.03**
L2 (Booster)	3 x 1300 MHz	0.03	**0.03**
L3 (Main Linac)	20 x 1300 MHz	0.1	**0.1**

- Numbers in the last column indicate the required synchronization accuracy
  - Not straightforward! (contribution of control system components and feedback loops) but can give a good approximation
- 0.01 deg @ 1.3 GHz corresponds to roughly 20 fs of jitter

Overview of Required RF Signals

- More complete picture should be created after this workshop



Review / Expert Talks

- **Experience with User Experiments at FLASH**, Harald Redlin (DESY/Hasylab)
- **Reference Distribution System Plans for SwissFEL**, Stephan Hunziker (PSI)

- The user experiments require jitter smaller than the pulse duration. At XFEL it can be less than 10 fs. Very tough - > largest distance from the Master Oscillator
- Very interesting talk about Swiss FEL synchr. Confirmed many assumptions and ideas for the XFEL synchr. system design.

Summary and Conclusions

- Very successful workshop
- Many positive opinions from participants
- Allowed people from various groups learn about their fields of activities (informative function)
- Increased effectiveness of coordination and preparation of the synchronization system

- There will be follow up meetings about more technical delays and selected substems

Thank you for attention!

Backup Slides

Harmonic Signal With Noise Components

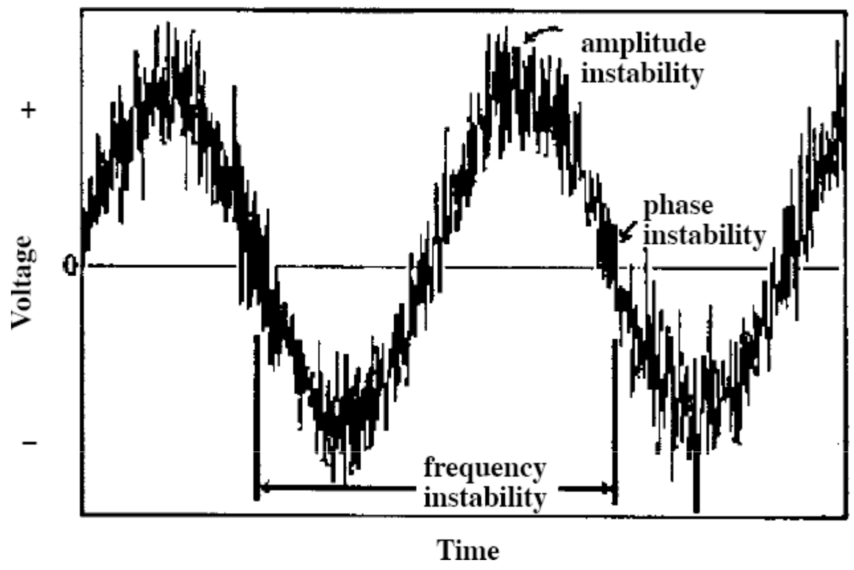
In Time Domain

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

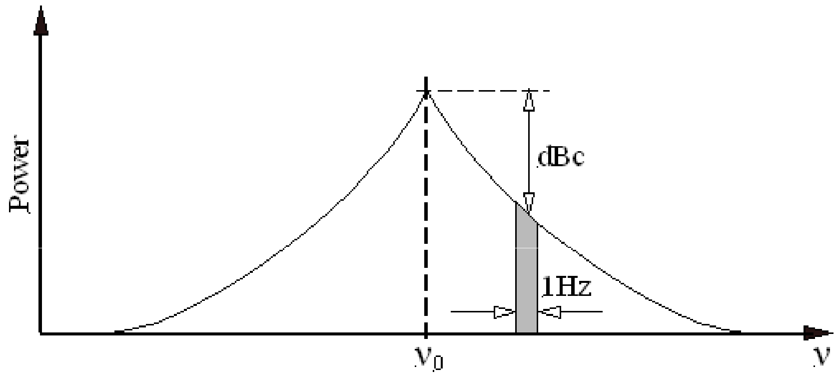
ν_0 - nominal frequency, called also instantaneous

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

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

Phase Noise

A **frequency domain measure** of signal phase instabilities



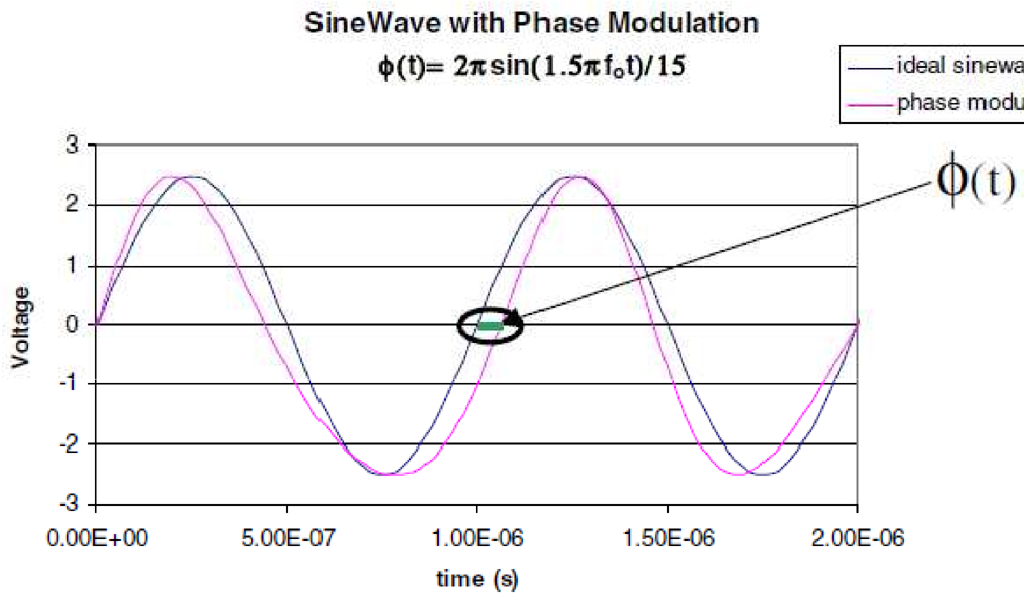
Power Spectral Density measured in dBc/Hz

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

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

Phase and Timing Jitter

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



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

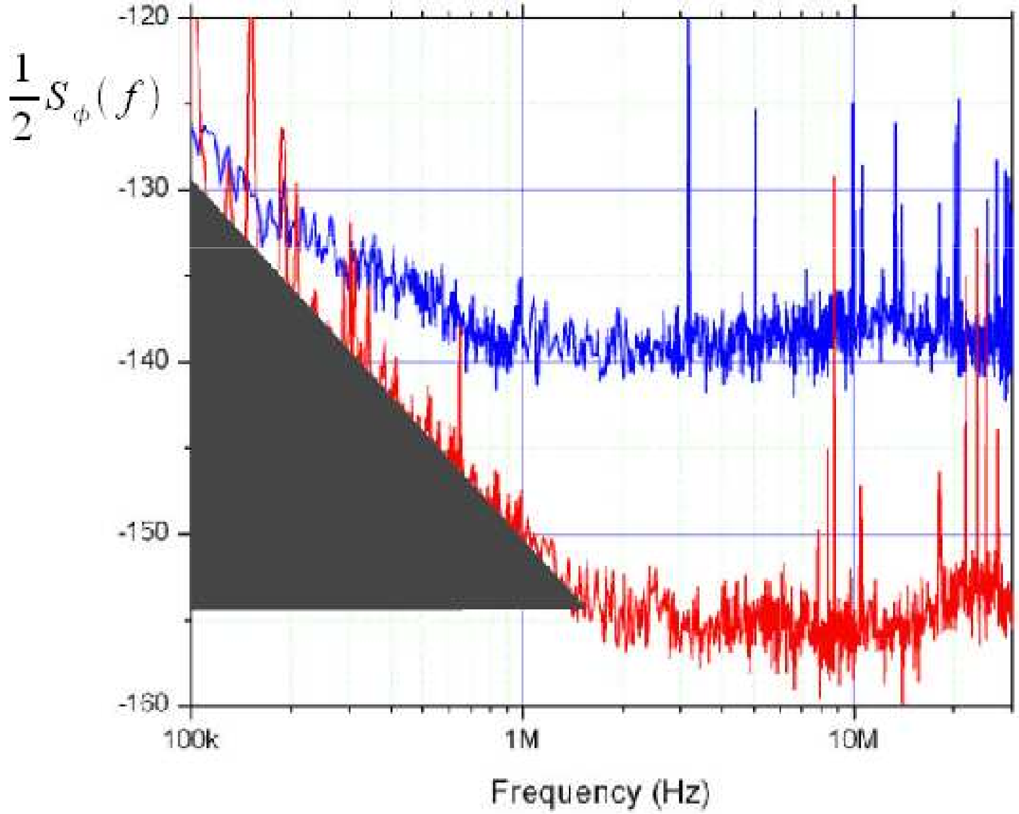
Figure source: Corning Frequency Control

Phase Noise and Jitter Relationship

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

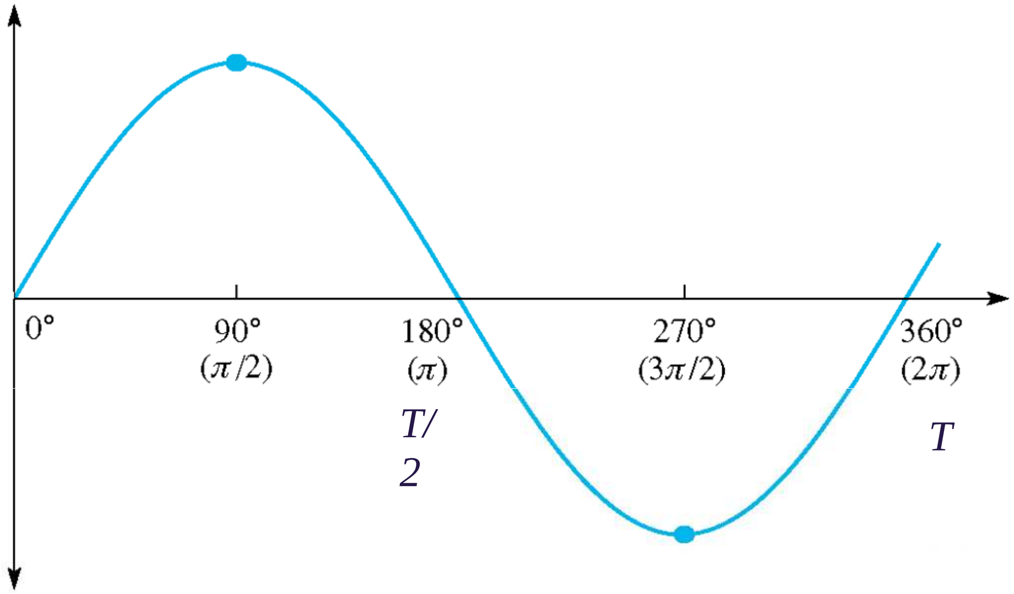
$$\phi_{jitter}^2 = \int_{f_1}^{f_2} S_\phi(f)\,df$$

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



Frequency, Time and Angle – Basic Relationships

Why do we use "ps" when we 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: ν_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.

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 (**Drift**) refers to the phase/frequency variations that occur over time periods longer than a few seconds

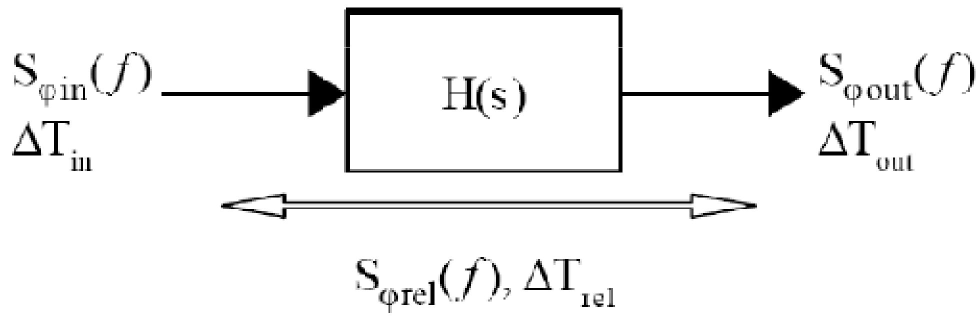
- derives from slow processes like long term frequency drifts, aging and susceptibility to environmental parameters like temperature
- expressed in units of degree, second or ppm per time period (minute, hour, day ...)

Absolute and Residual Instabilities

- **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

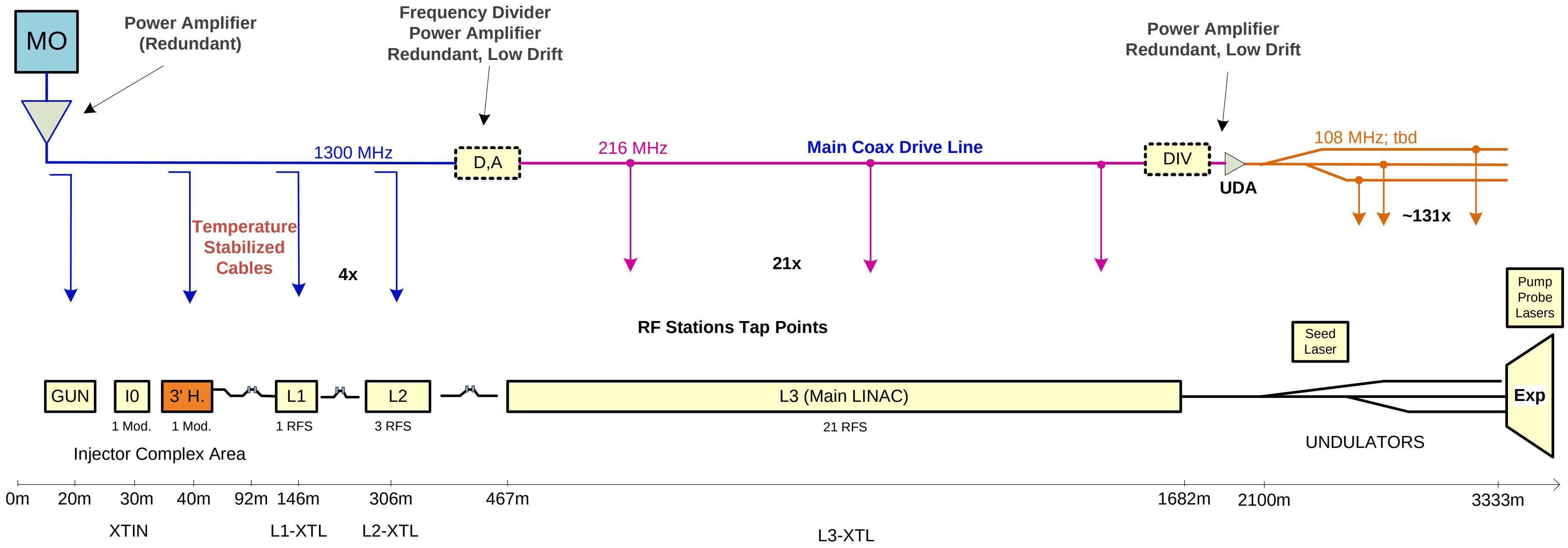
Residual Phase Noise and Jitter



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

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

Main Frequency Distribution Proposal



Frequency Distribution Media – Coaxial Cable vs. Optical Fiber

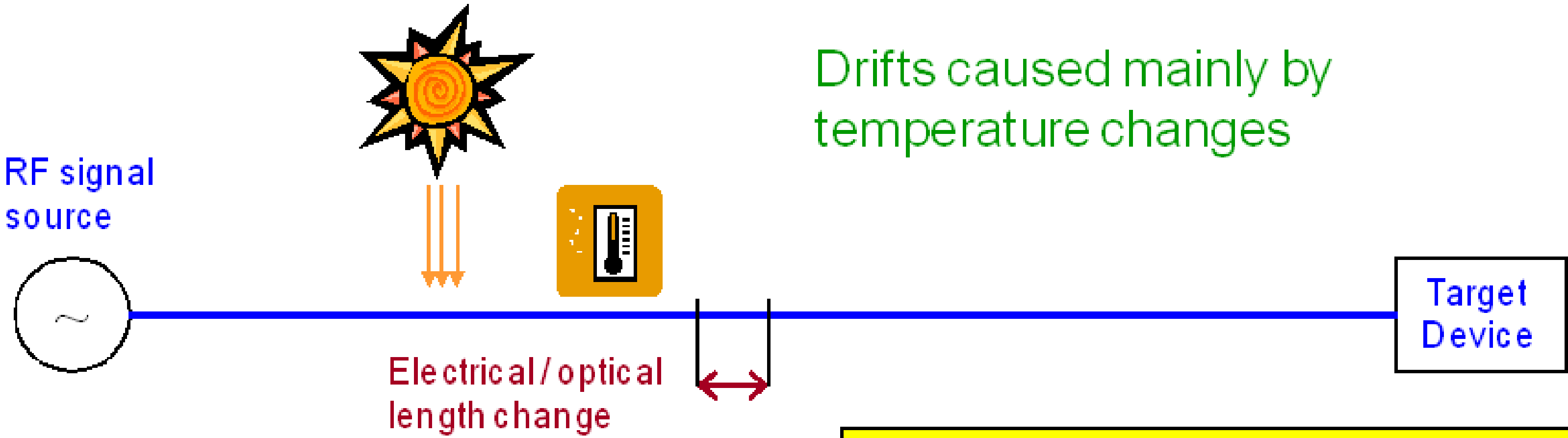
- **Coaxial cable**
  - Robust and radiation immune
  - Passive distribution
  - Very low noise degradation
  - High RF loss
    - ➔ Short distribution distances
  - Distribution with tap points
  - Cost effective

- **Optical Fiber (CW link)**
  - Possible problems with radiation
  - Active components (laser, …)
  - High noise figures
  - Low loss
    - Long distribution distances
  - Point-to-point distribution
  - Fiber is cheap, rest expensive

- Both types of distribution require phase stabilization
- Both undergo significant development, particularly optical links
- The XFEL frequency distribution will use tradeoff between cost, performance and reliability and both media will be used complementary

Phase Drift Problem

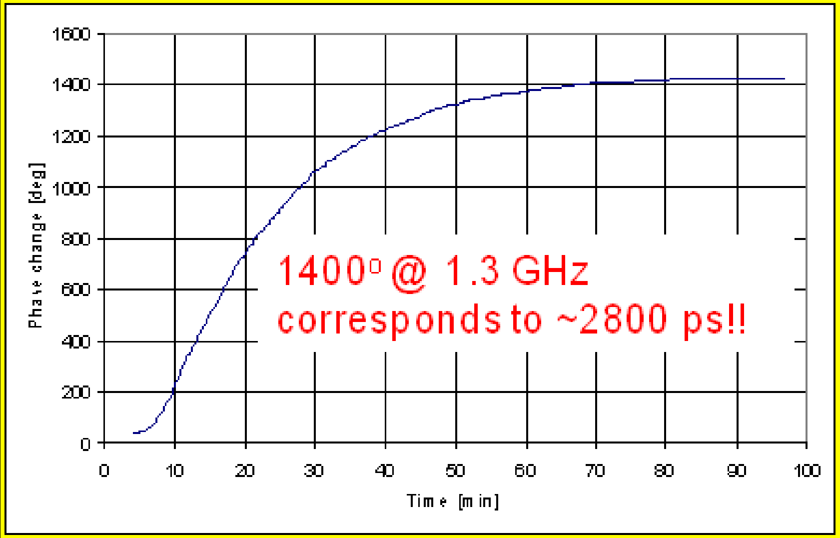
Drifts caused mainly by temperature changes



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



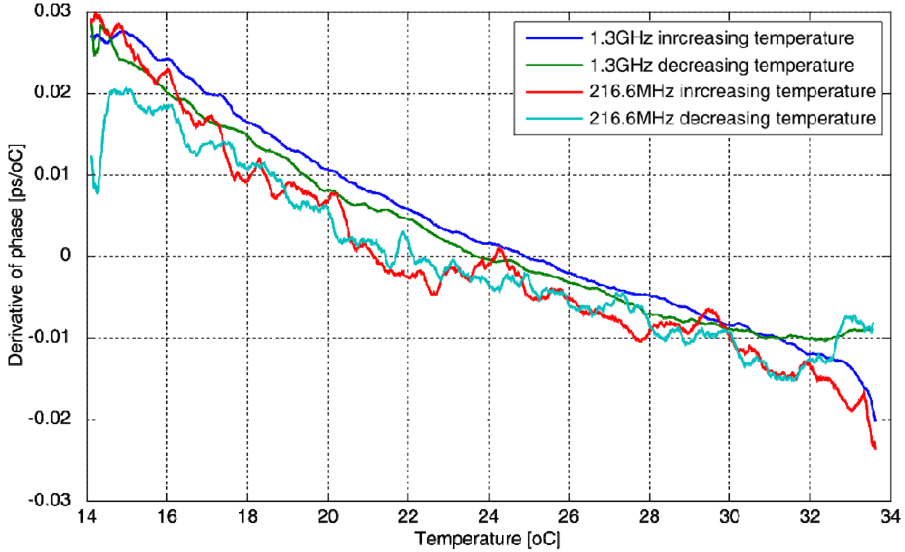
Temperature coefficient: 56 [fs/K/m]

Feedback on phase required!!

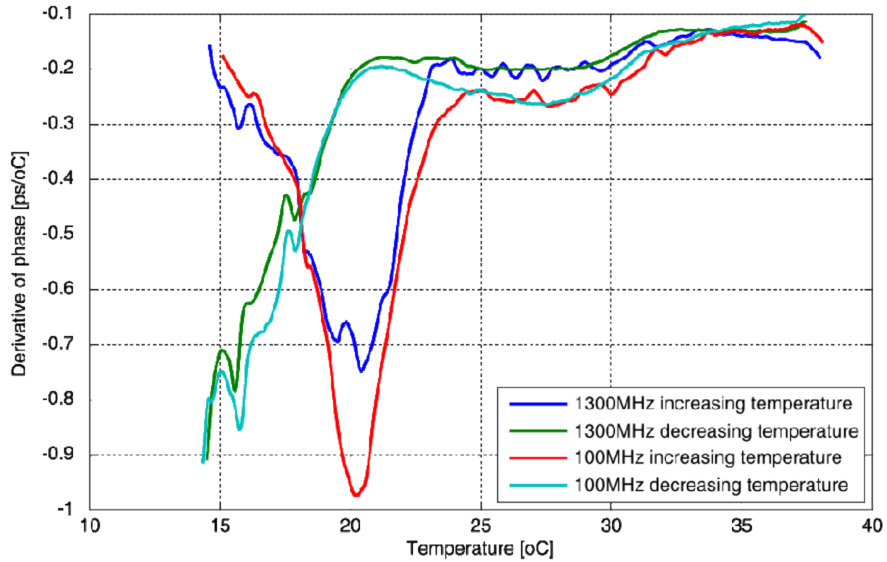
European XFEL

Phase Drifts in Coax Cables

Low loss 3/8” cable



SS402 (Teflon™ Based) Cable



- Max. +/- 10fs/m/K drift in temperature range 20 – 30 °C
- 0 ppm/m/K possible @ 24 °C !

- Up to 1000fs/m/K drift in temperature range 20 – 30 °C
- Local signal distribution is very critical
- **Users must carefully select cables used internally in their subsystems!**