Introduction and Overview of the Synchronization System

European XFEL RF Synchronization User Workshop

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Outline

- Our team
- Introduction to synchronization
- Types of synchronization signals and definitions of synchronization accuracy
- Planned layout of the XFEL synchronization system
- Short introduction to subcomponents of the RF synch.
- General difficulties and system limitations
- Expectations for user requirements

Our Team

- Holger Schlarb (DESY) – MSK group leader
- Krzysztof Czuba (ISE) – RF synchronization design and planning
- Frank Ludwig (DESY) – Concepts, drift compensation
- Henning Weddig (DESY) – RF hardware
- Wojciech Wierba (IFJ) – Installation and cabling
- Dominik Sikora (ISE) – RF distribution system, measurements, documentation
- Łukasz Zembala (ISE) – RF hardware
- …

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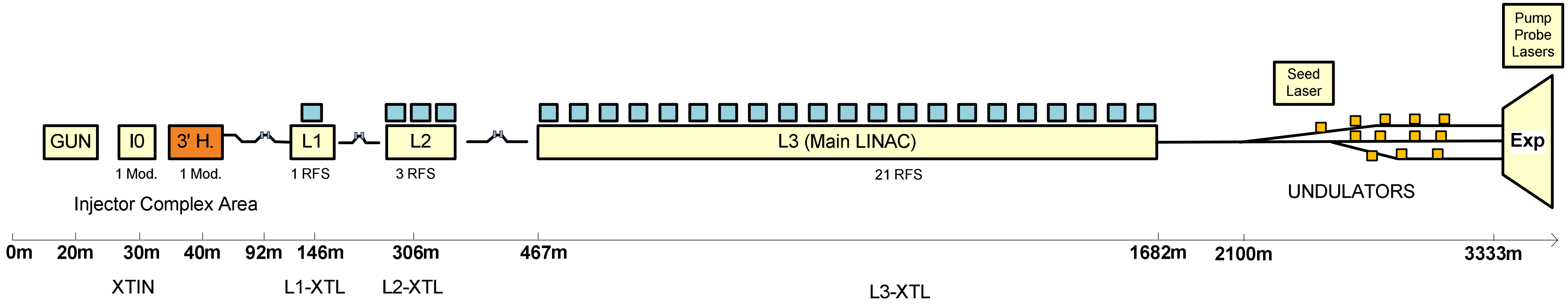
Need for Synchronization at XFEL



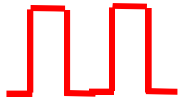
- Subsystems of the machine must run synchronously
- Very high precision of synchronization is required (down to fs for most critical subsystems)
- There will be several thousands of electronic, RF and optical devices in the machine that require synchronization
- The system length of over 3 km make the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

Types of Synchronization Signals

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

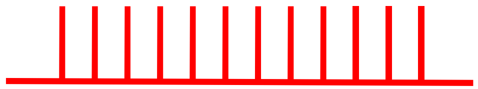
- Analog (RF phase reference, VM, LO)

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



- Trigger signals (digital subsystems, CPU)

- Optical pulse trains (lasers, diagnostics, experiments)



Phase Reference vs Clock

People often confuse:

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

Harmonic Signal With Noise Components

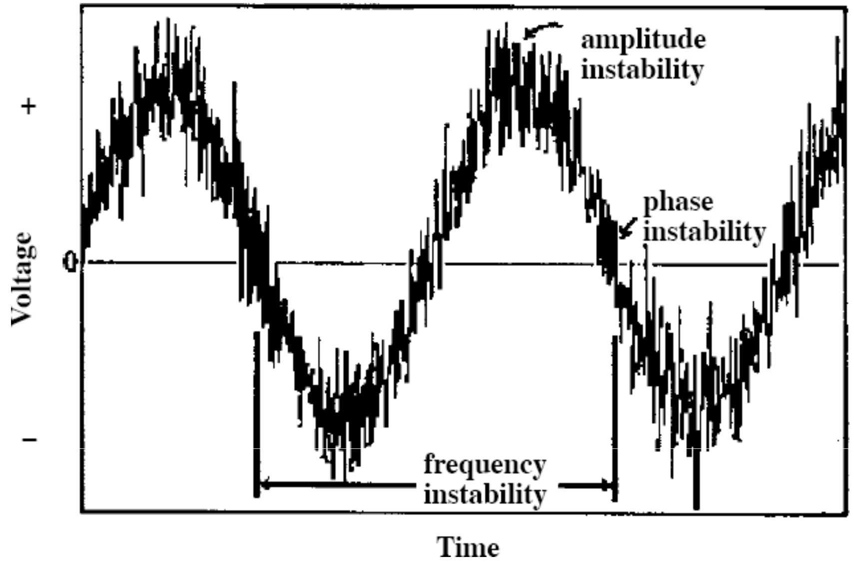
In Time Domain

Ideal Signal

$$v(t) = V_0 \sin(2\pi v_0 t)$$

Noisy Signal

$$v(t) = [V_0 + \varepsilon(t)]\sin[2\pi v_0 t + \phi(t)]$$



V_0 - the nominal peak voltage amplitude

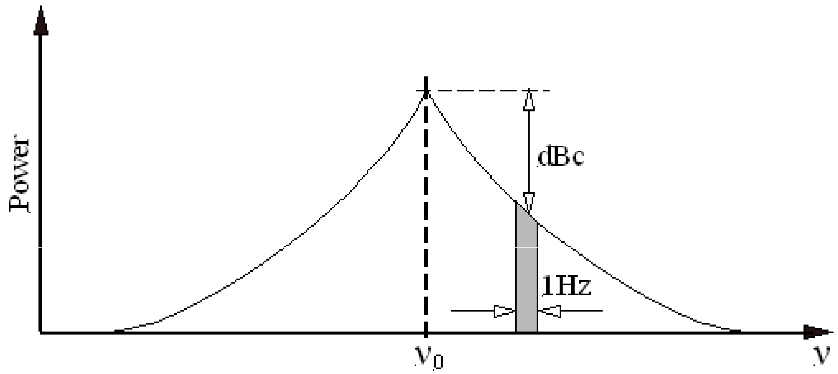
v_0 - nominal frequency, called also instantaneous

$\varepsilon(t)$ - 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

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

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

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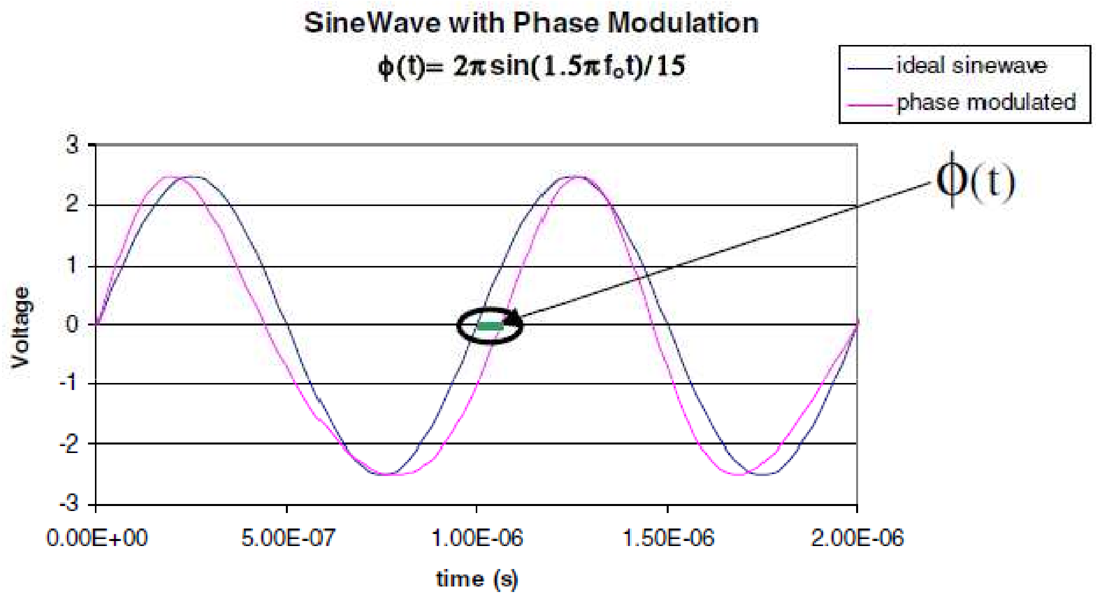
Phase and Timing Jitter

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

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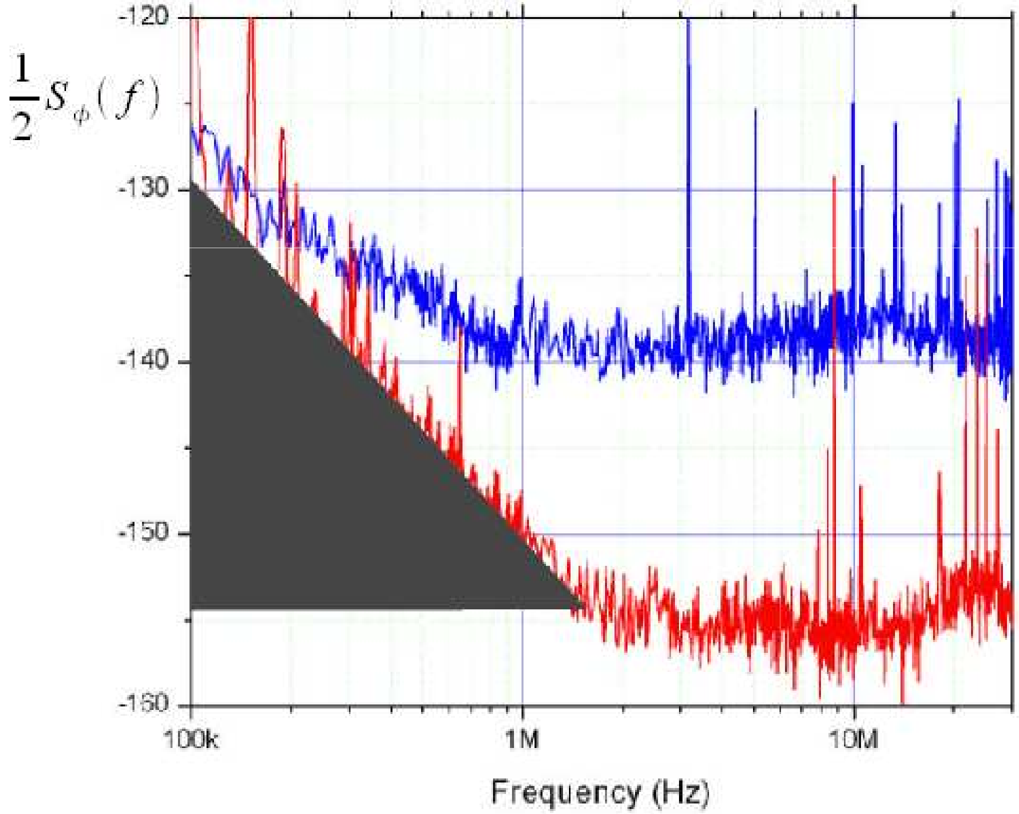
Phase Noise and Jitter Relationship

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

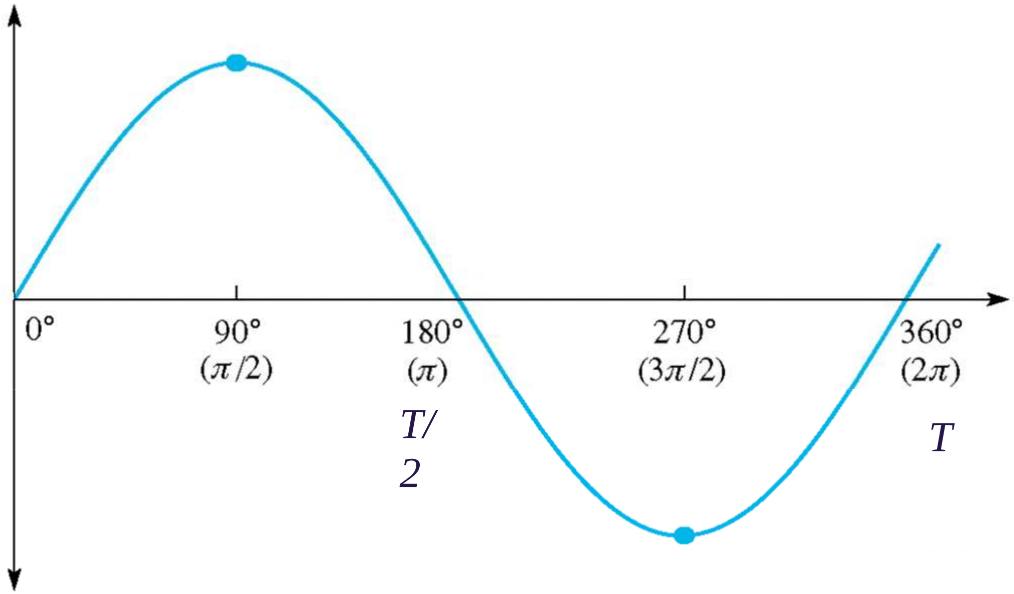
$$\phi_{jitter}^2 = \int_{f_1}^{f_2} S_\phi(f)\,df$$

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



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 $\rightarrow$ T = ~769ps, 1^o $\rightarrow$ 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

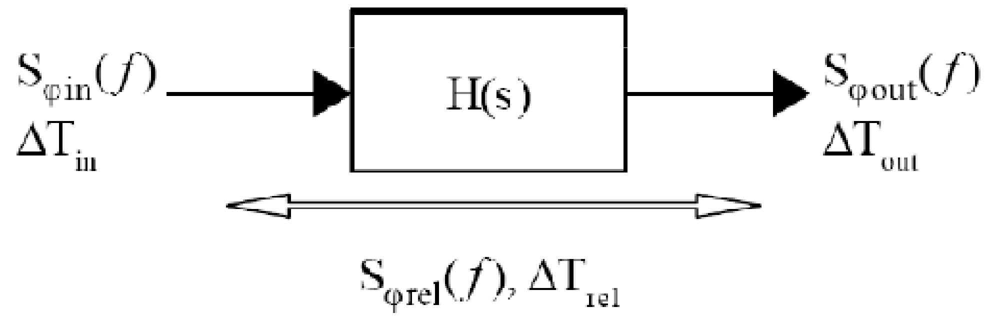
- derives from slow processes like long term frequency drifts, aging and susceptibility to environmental parameters like temperature
- expressed in units of degree, second or ppm per time period (minute, hour, day ...)

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

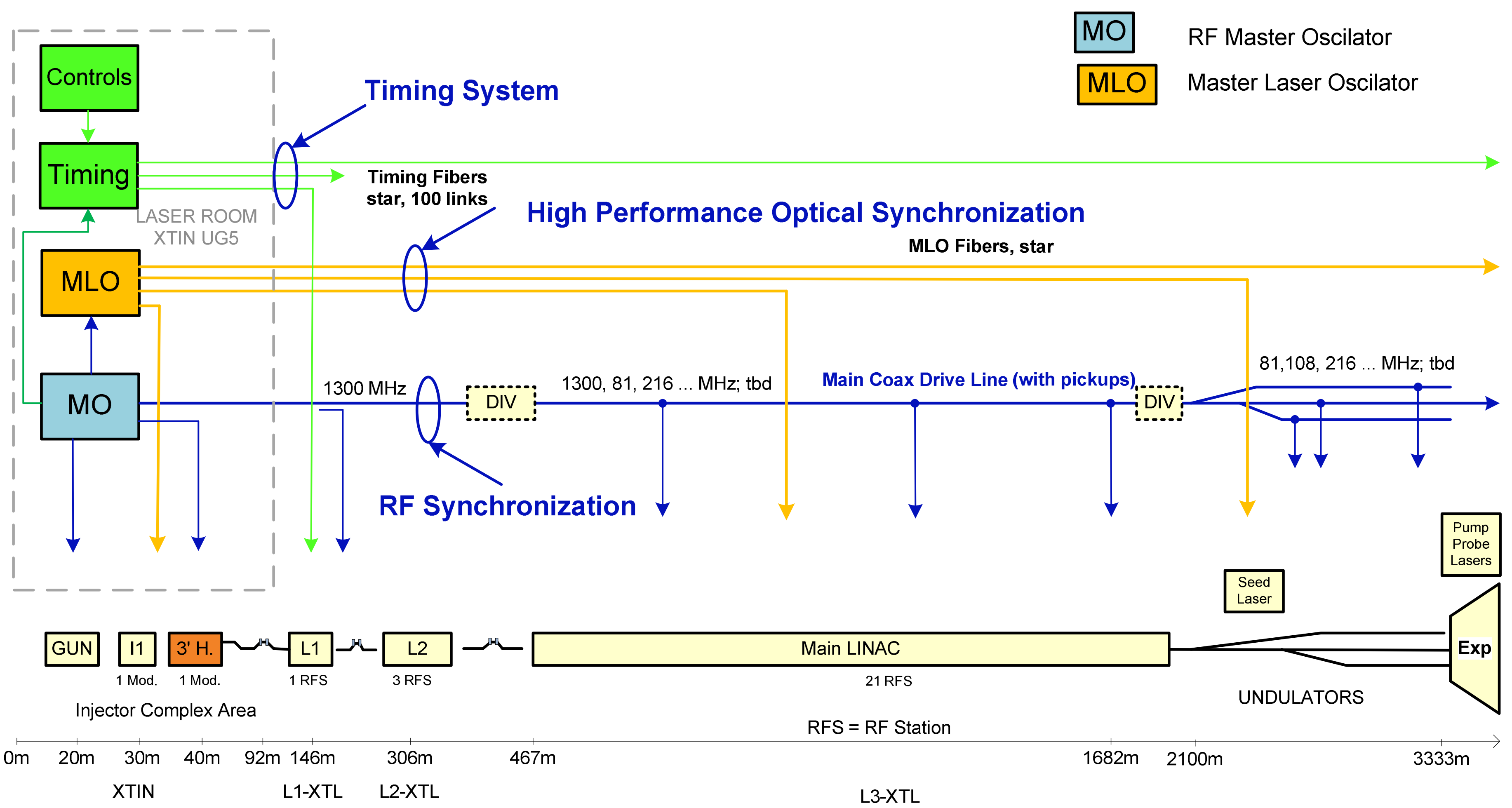
Residual Phase Noise and Jitter



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

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

XFEL Synchronization System Layout (General)



XFEL Synchronization System Characteristics

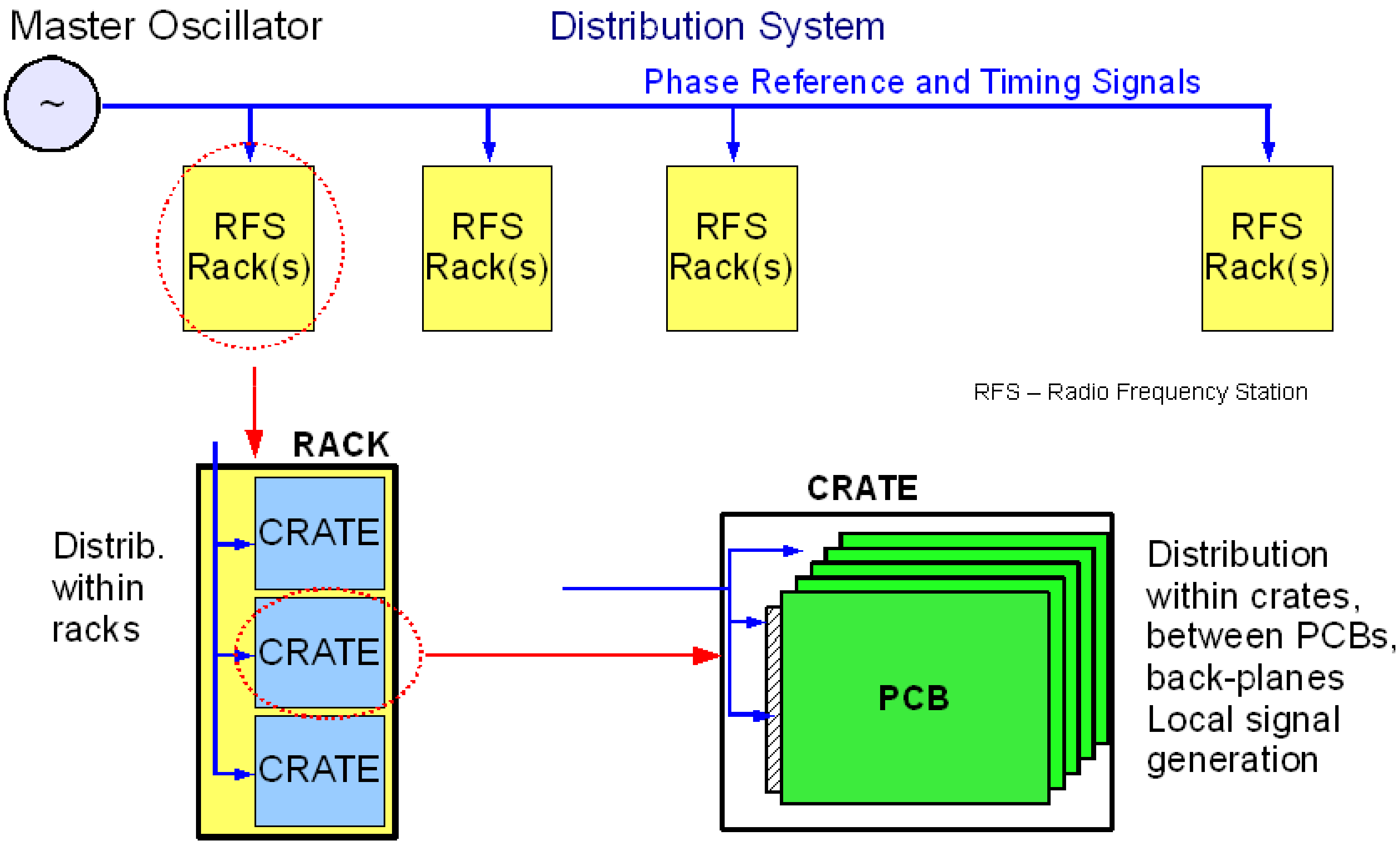
- The high performance optical links will provide optical pulses with <10fs stability
  - There is possibility to generate RF signals
- The RF system will deliver RF signals with stability <100 fs
- The digital, coded timing signals will carry event trigger codes and lower performance clocks (few ps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

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**

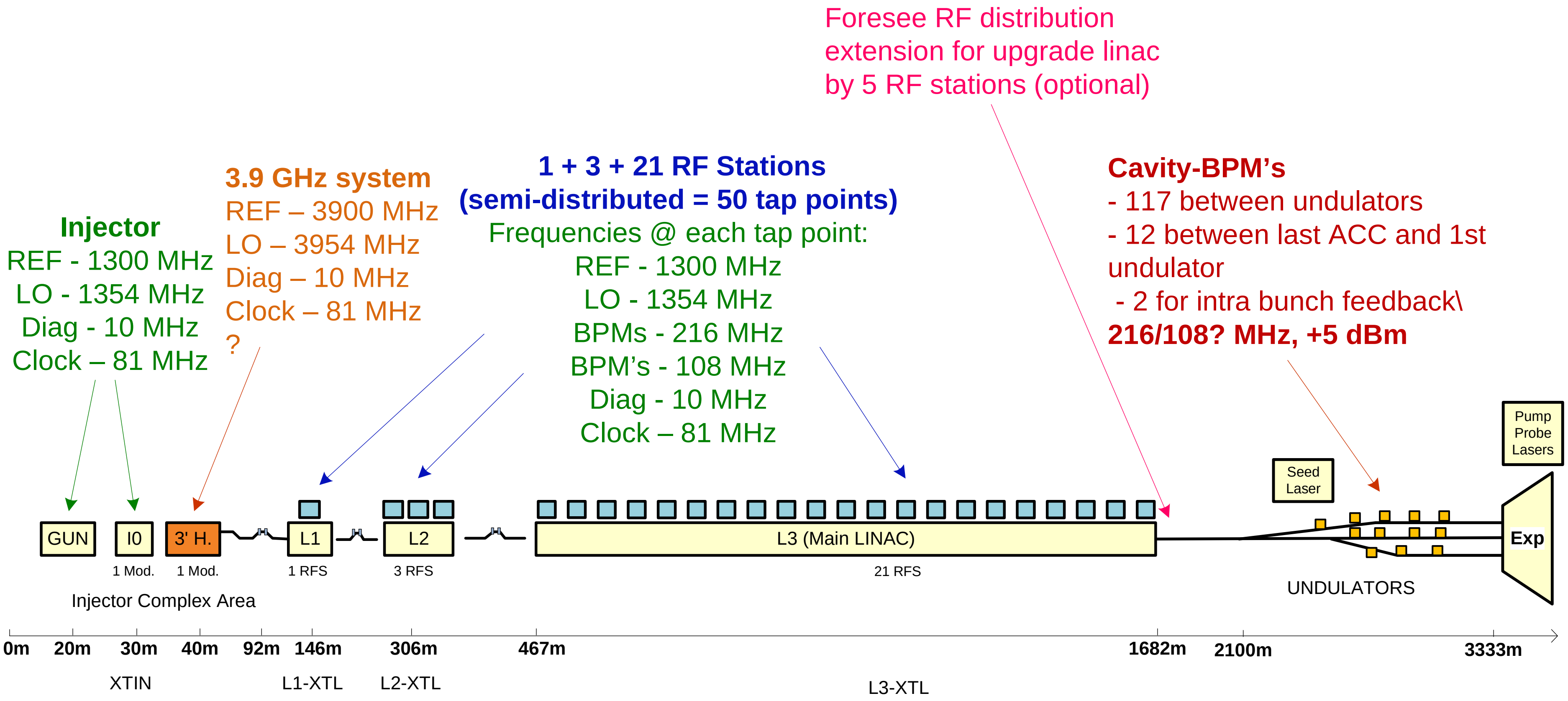
- Numbers in the last column indicate the required synchronization accuracy
  - Not straightforward! (contribution of control system components and feedback loops) but can give a good approximation
- 0.01 deg @ 1.3 GHz corresponds to roughly 20 fs of jitter

RF Synchronization – general components



Overview of Required RF Signals

- More complete picture should be created after this workshop

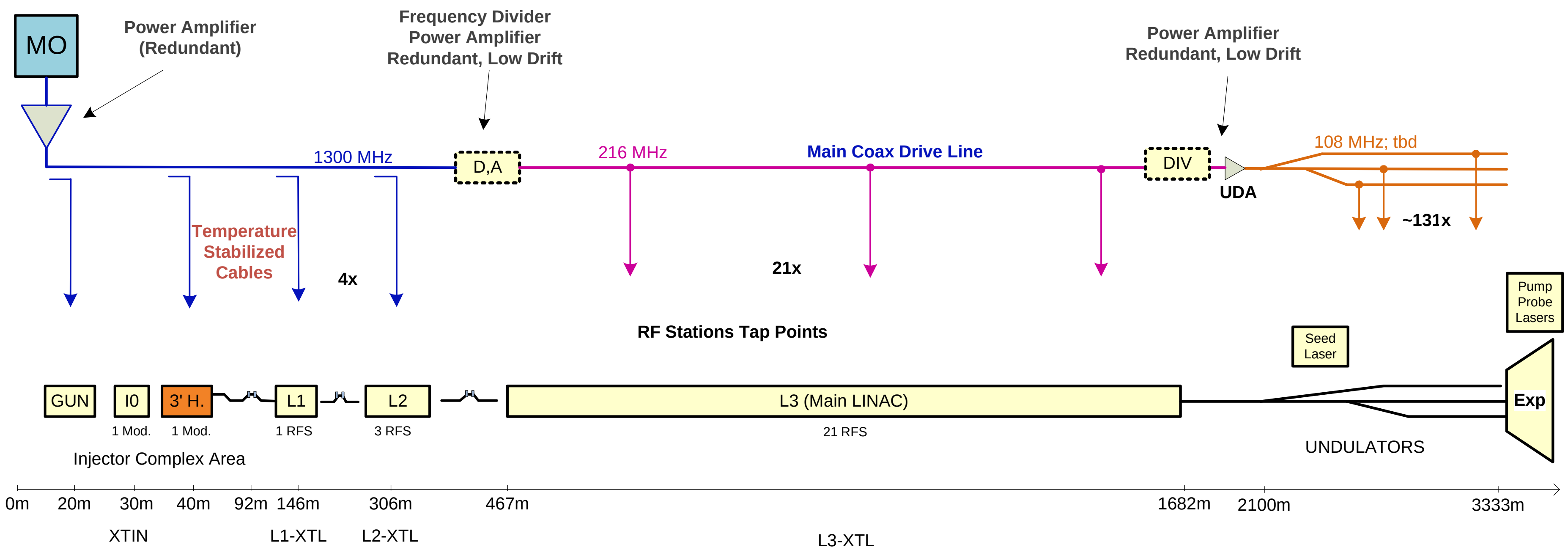


Frequency Distribution Scheme

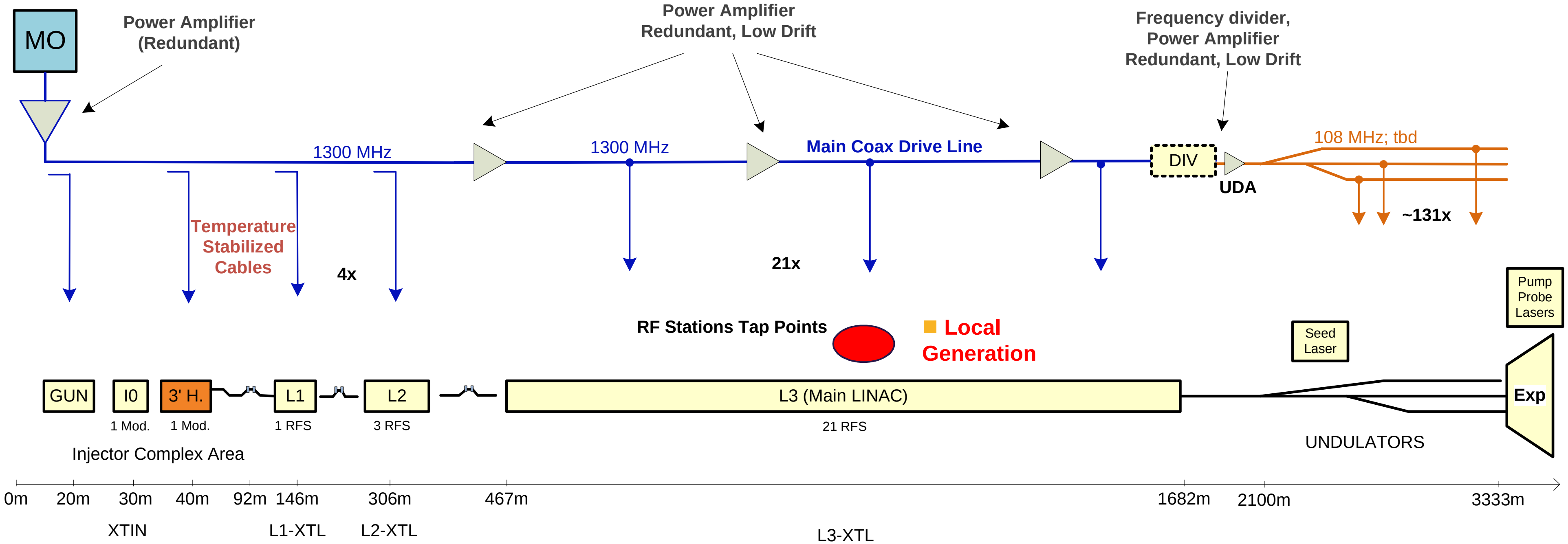
- Due to machine length and stability requirements only single frequency distribution and local generation of other frequencies is acceptable

- Consequence: The RF MO will generate single frequency (1.3 GHz) to be distributed along the machine

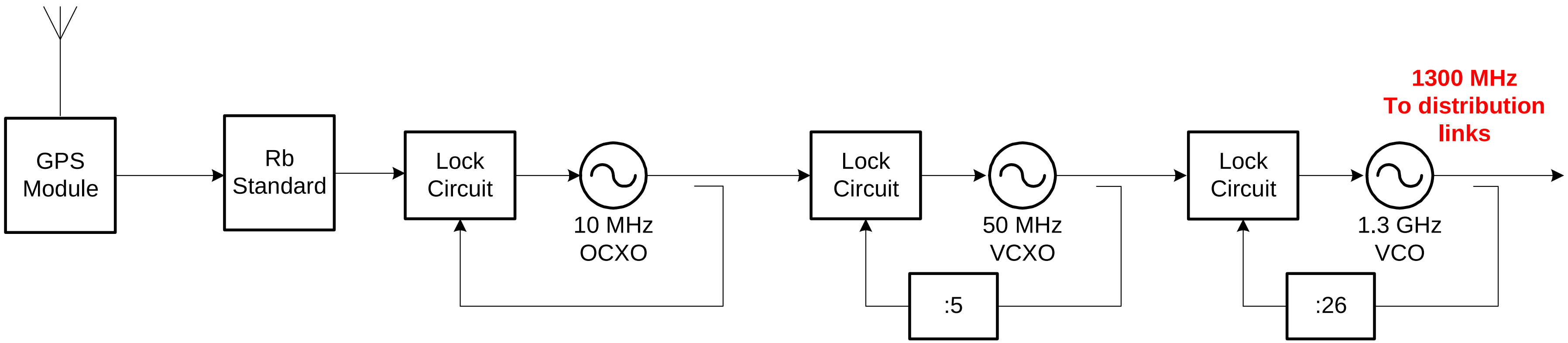
Main Frequency Distribution Proposal – ver. 1



Main Frequency Distribution Proposal – ver. 2



Master Oscillator Architecture



- The MO System must be redundant
- Locked to atomic standard for long term frequency stability
- Low phase noise and drift solutions are investigated
- Very good results achieved (jitter ~30fs @ 1.3 GHz) – experience with FLASH MO
- Phase drifts of the chain are of lower importance because the output will be the reference point

Frequency Distribution

- Transport phase reference signals
- Main difficulties
  - Assuring power levels (link losses)
  - Phase drifts
  - Transportation of phase noise
- Assure high availability of signals

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

Cable Attenuation

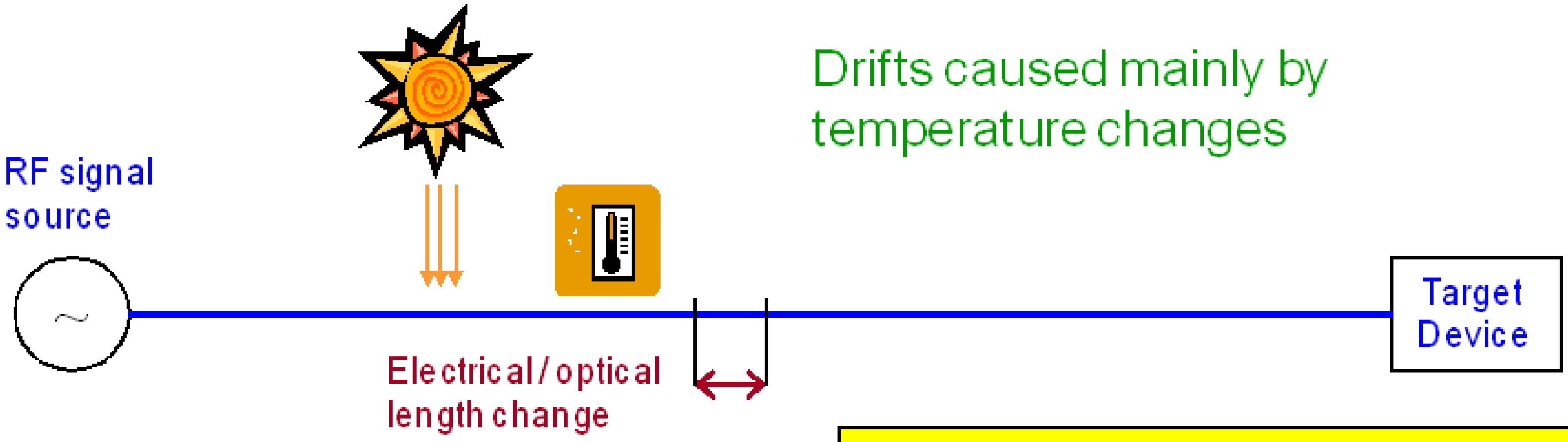
DIAMETER	1/4”	1/2”	7/8”	1-5/8'
CABLE	FSJ1-50A	CELFEX	LDF5-50A	LDF7-50A
Attenuation [dB/100m] 9MHz 30MHz 108MHz 1300MHz 2885MHz	~1.8 3.19 6.13 ~23 ~33	1.17 ~9 ~13	~0.35 0.64 1.24 ~4.80 ~7.60	~0.15 0.35 0.69 ~2.9 over f_{max}

Practically cable attenuation limits distribution distances to 600 m (for 7/8” cable) without using amplifier repeaters

Thin cables (used locally) exhibit even higher attenuation

Phase Drift Problem

Drifts caused mainly by temperature changes



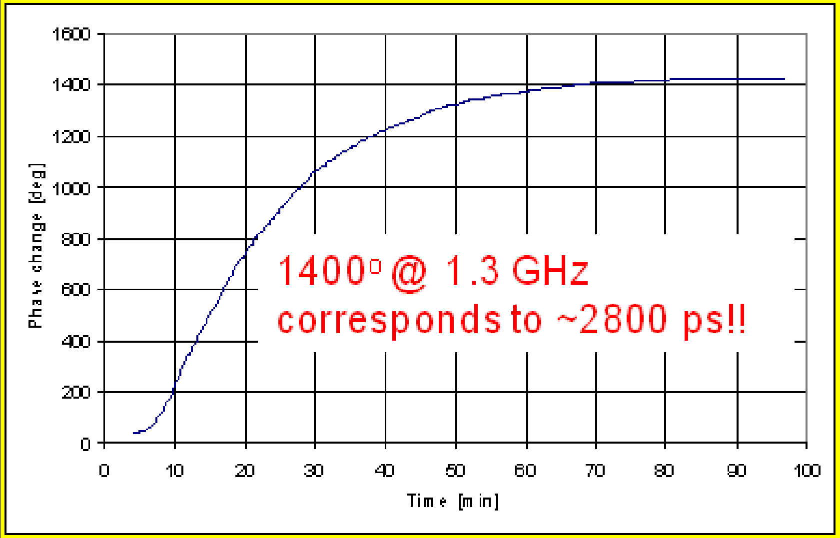
Reason of drifts:

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

Temperature coefficient: 56 [fs/K/m]

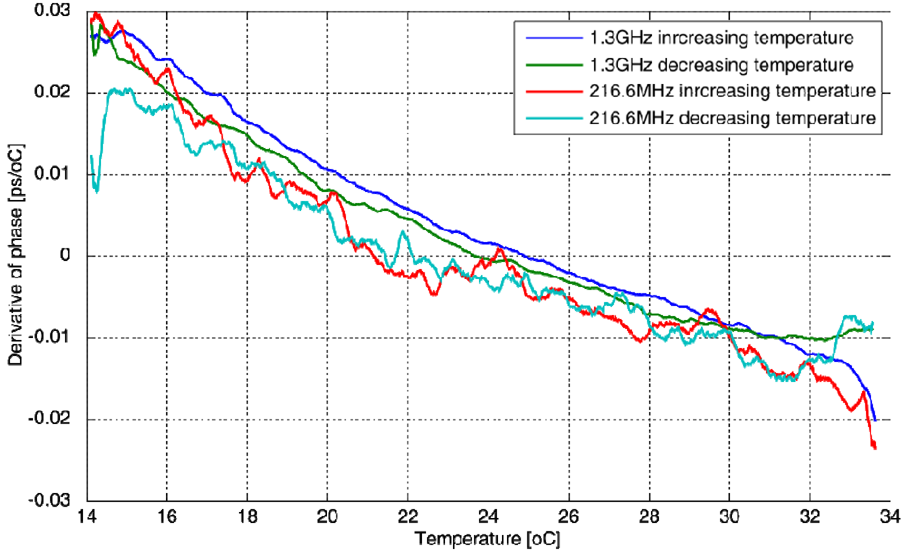
Feedback on phase required!!

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

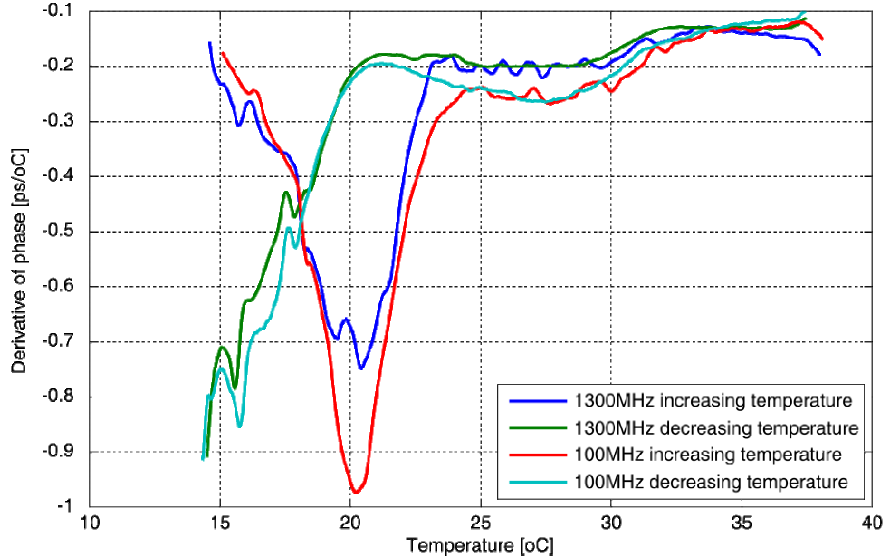


Phase Drifts in Coax Cables

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!**

XFEL Tunnel Temperature Variations

- Recent simulations (Joerg Eckoldt) show that temperature will vary significantly along the tunnel:
  - In LINAC sections temperature values may change of up to 10K!
  - Temperature will depend on the power dissipation in accelerator subsystems (switching on or off the power devices)
  - After breaks in operation, temperature will stabilize over significantly long time (days)
- The best cable without phase compensation will cause drifts of min. 10 ps/km -> required 100 fs for some subsystems!

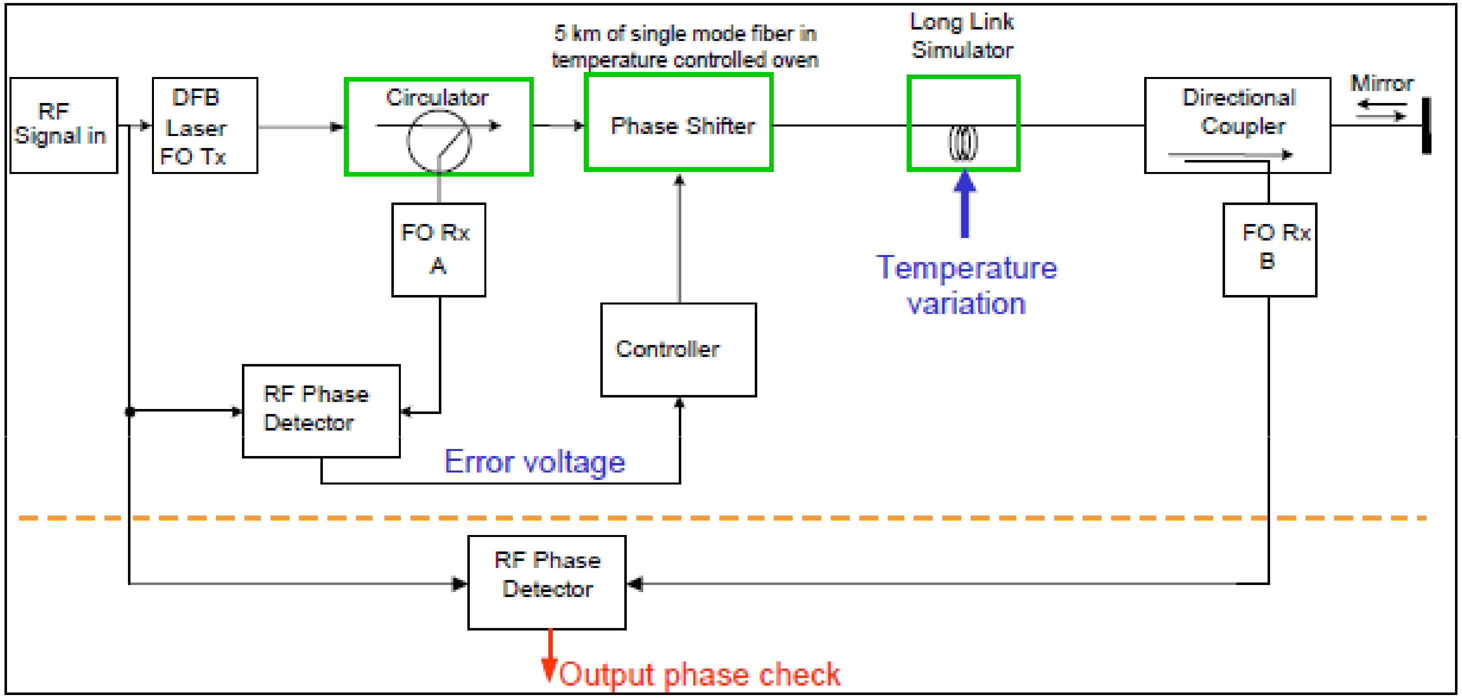
  -> Active phase stabilization necessary (quite complex and increases cost)

Phase Stabilization

- By temperature regulation of distribution media
  - Very expensive and difficult for long distances
  - No direct influence on distributed signal

- By interferometric techniques
  - May become complex for high accuracies
  - Significant suppression of drifts
  - Can be used for both optical and RF distribution (developments are pending)

Interferometric Distribution Link



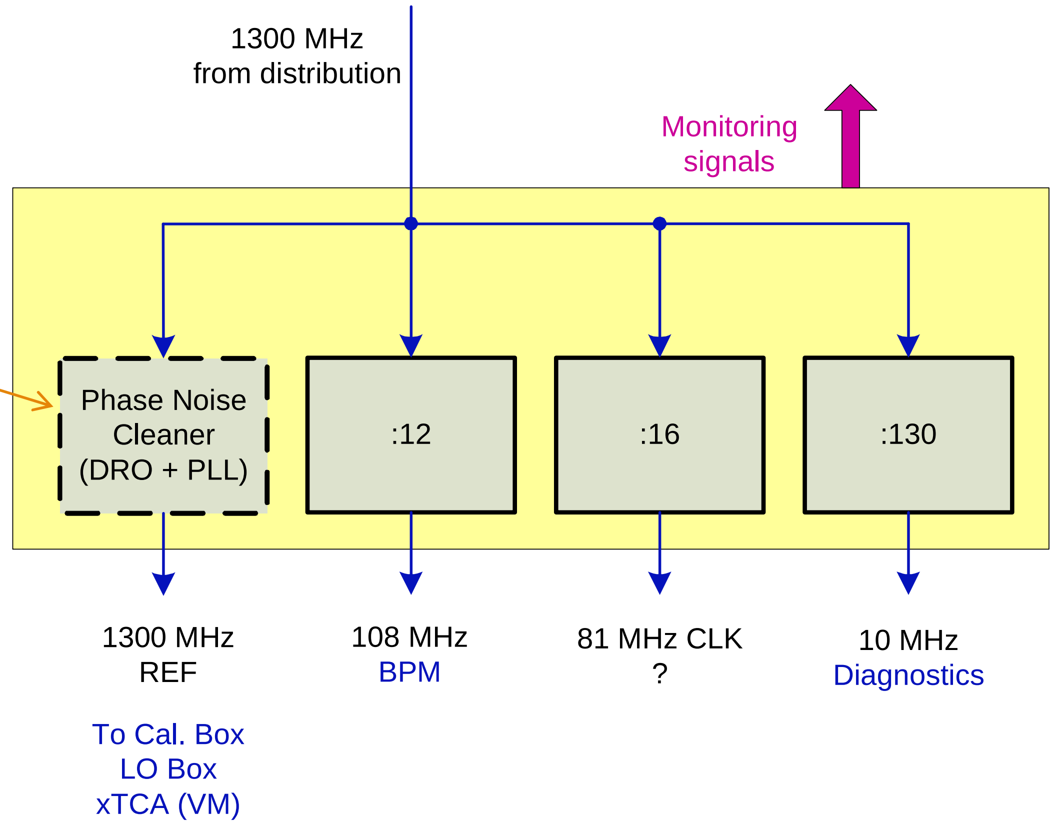
- Principle valid for both coax cable and optical fiber based systems
- Active drift suppression of 10 to 100 possible relatively easy
- Experiments on both schemes pending
- Coax cable solution limits the distribution distances to few hundred of meters

Local Generation and Distribution

- Subsystem frequencies will be derived locally from 216 MHz or 1300 MHz signal
- Relatively easy and cheap is achieving short term stability of >100 fs and drifts 1ps/K
- Reduction by factor of 5 to 10 is possible but quickly increases cost and complexity of local generation and distribution devices
- We will willingly help users with local signal distribution within their devices (cable, component and connector selection)

Local Frequency Generation – RF Station Example

Maybe it will be possible to skip this for the main linac



Possible Diagnostics

- The synchronization system will incorporate diagnostics, eg.
  - Signal availability
  - Power levels
  - Phase locks
  - Amplifer phase drifts
  - Device Temperature
  - …
- Information will be available on-line

Please consider if such information will be useful for your subsystem

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

Thank you for attention!