EPAC‘08, Genoa, Italy

RF Reference Signal Distribution System for FAIR

M. Bousonville, GSI, Darmstadt, Germany
P. Meissner, Technical University Darmstadt, Germany

Dipl.-Ing.
Michael Bousonville

Overview

- Introduction
  - Goal
  - Phase synchronisation
  - Reference Signal
- System
  - Basic Principle
  - Optical Network
  - Delay Measurement
  - Reference Generation
- Performance
- Summary

Reference Distribution

Goal

- Cavity synchronisation

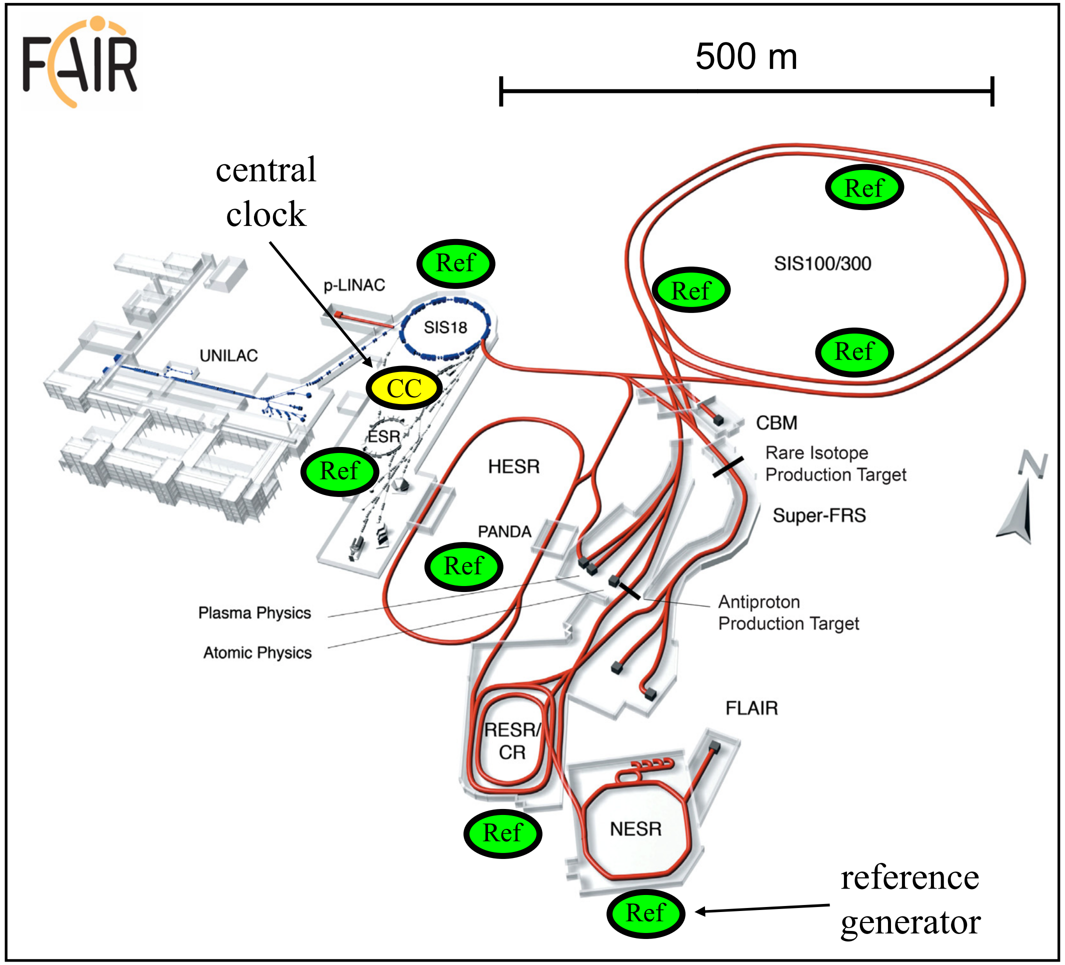
  ⇒ signal generator (DDS) synchronisation

$$\text{Ref} \rightarrow \boxed{\text{signal generator}} \xrightarrow{f,\ \varphi} \boxed{\text{cavity}}$$

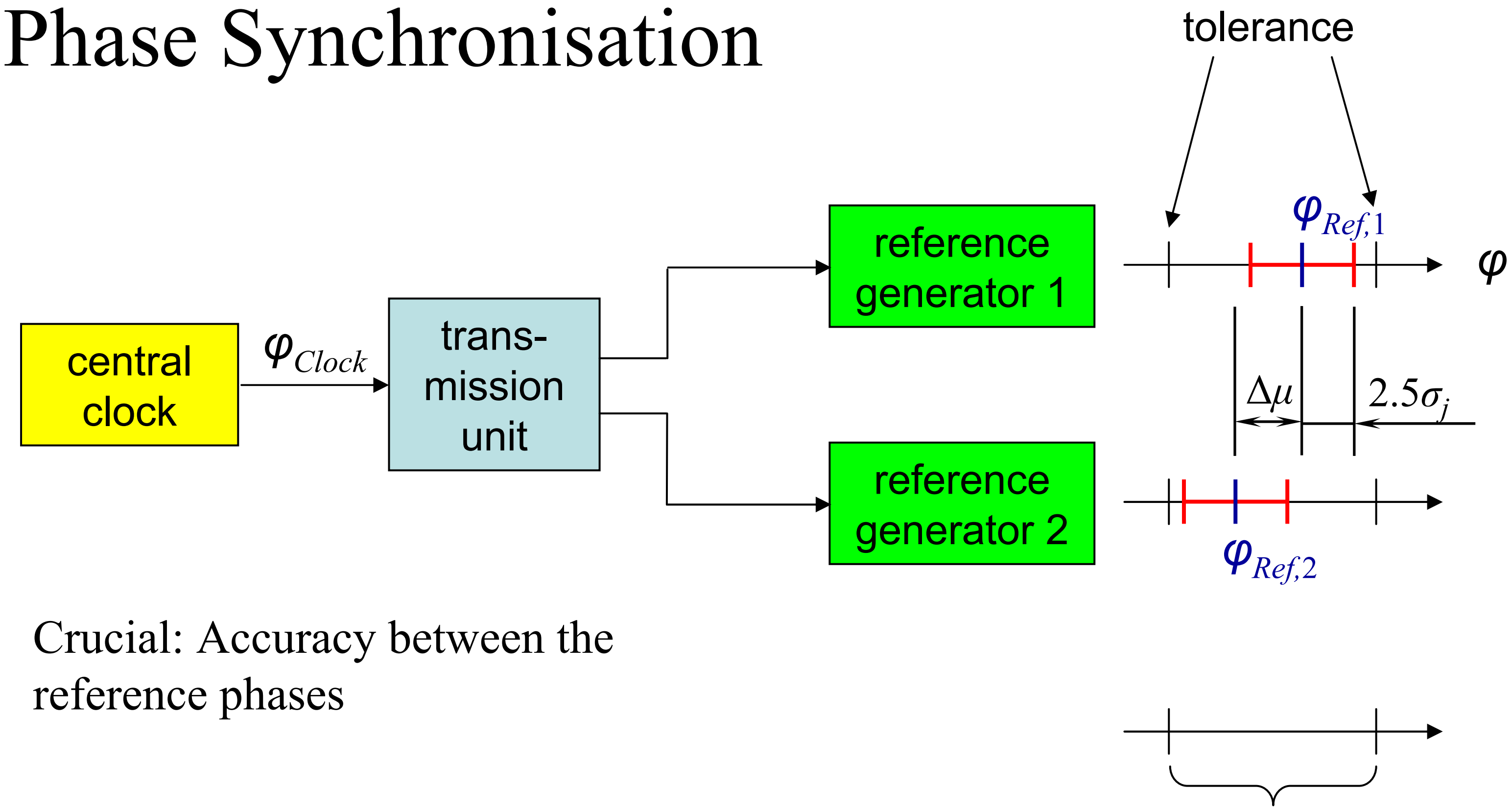
- Therefore necessary:
  - Distribution of
    phase synchronous reference signals

- Problems:
  - Different distances
    ⇒ different time delays
  - Time delays not constant

$$\tau = f(L, T, \ldots) = f(t)$$



Phase Synchronisation



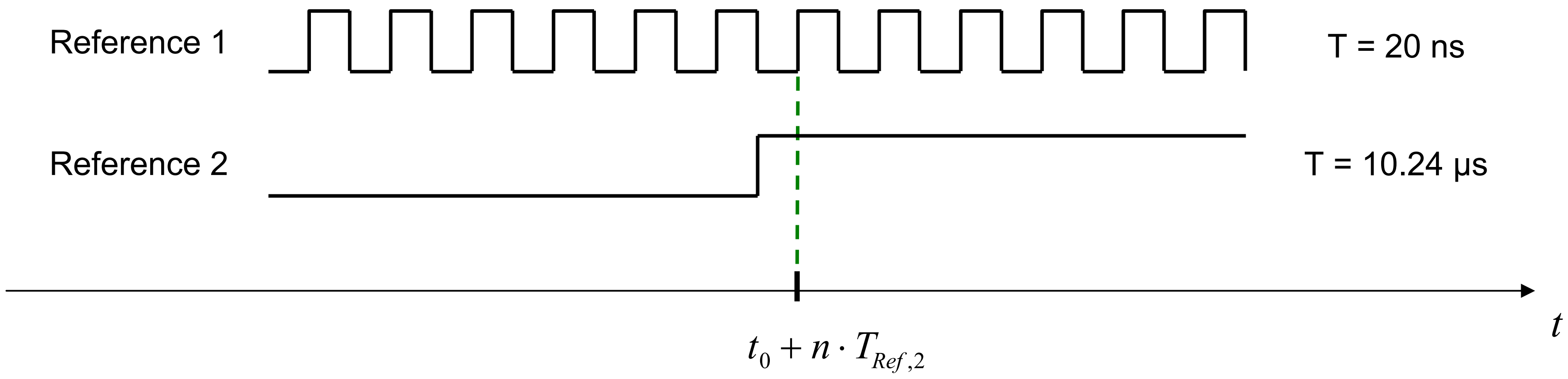
Crucial: Accuracy between the reference phases

Accuracy requirement: 1° at 5.4 MHz $\longrightarrow$ $|\Delta\mu + 5\sigma_j| < 514\,ps$

Optimisation Parameter: $\Delta\mu \downarrow$ *and* $\sigma_j \downarrow$

Reference Distribution

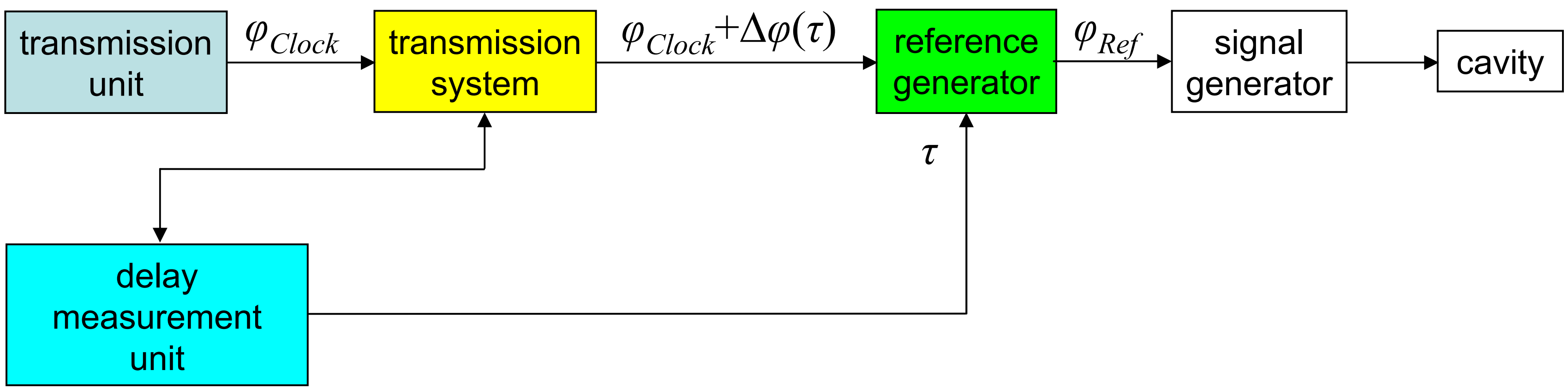
Reference Signal



$$\left.\begin{aligned} f_{Clock,1} &= 200MHz \\ f_{Clock,2} &\approx 97.7kHz \end{aligned}\right\} \Rightarrow \begin{aligned} f_{Ref,1} &= 50MHz \\ f_{Ref,2} &\approx 97.7kHz \end{aligned}$$

Basic Principle

Assembly of one system branch



Any delay variation can be compensated

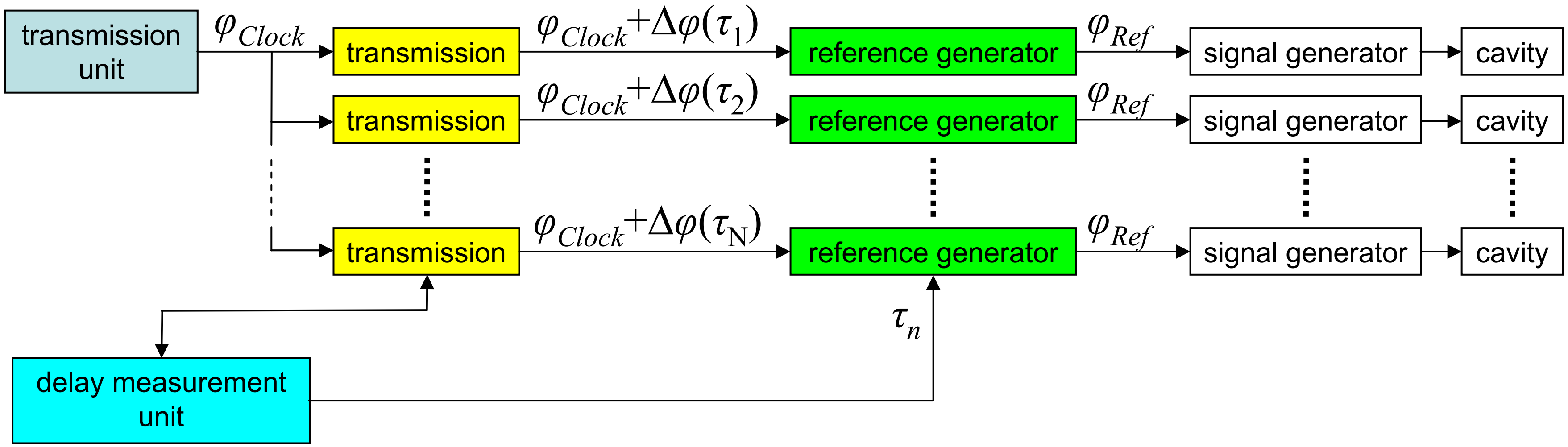
$\Rightarrow$ absolute delay drift irrelevant

$$\varphi_{Ref} = f\left(\varphi_{Clock}\right) \neq f\left(\tau\right)$$

Reference Distribution

Basic Principle

Star-shaped distribution



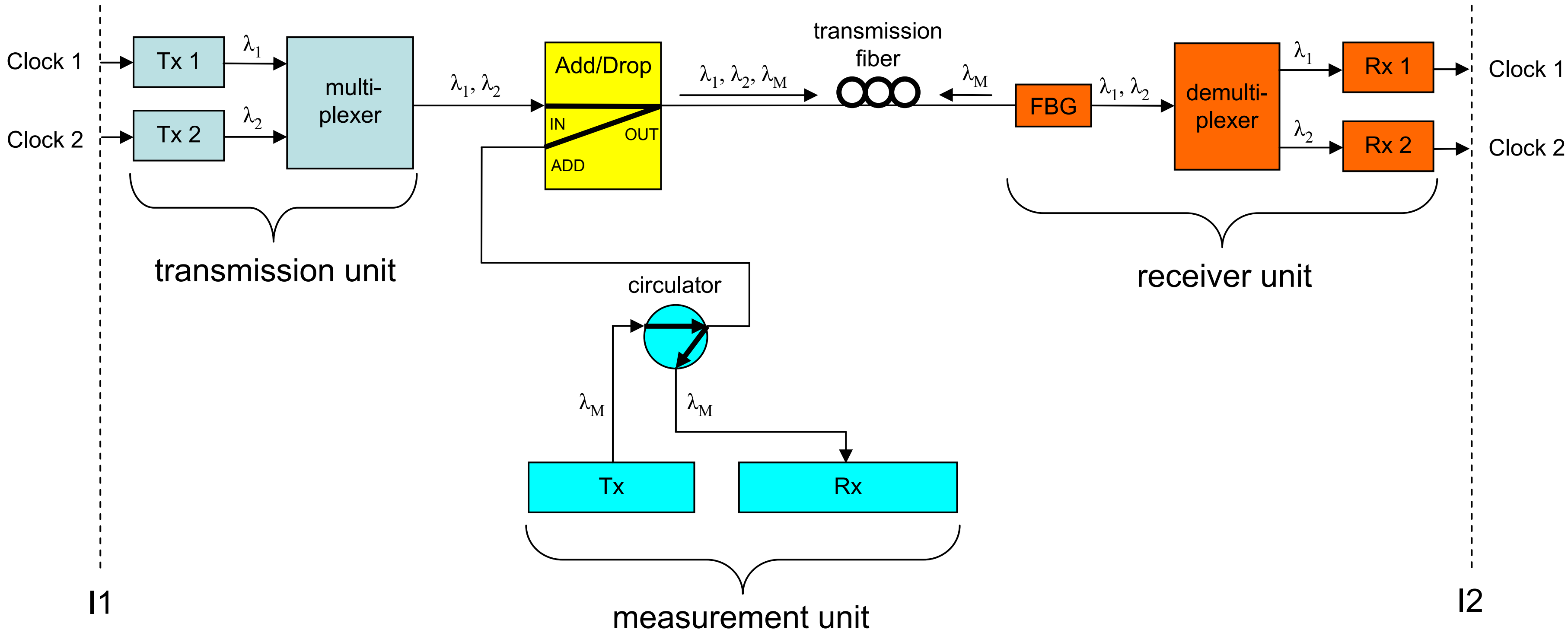
One instead of N transmission units $\Rightarrow$ no different time drifts

One instead of N measurement units $\Rightarrow$ systematic error irrelevant

$\Rightarrow$ much less effort

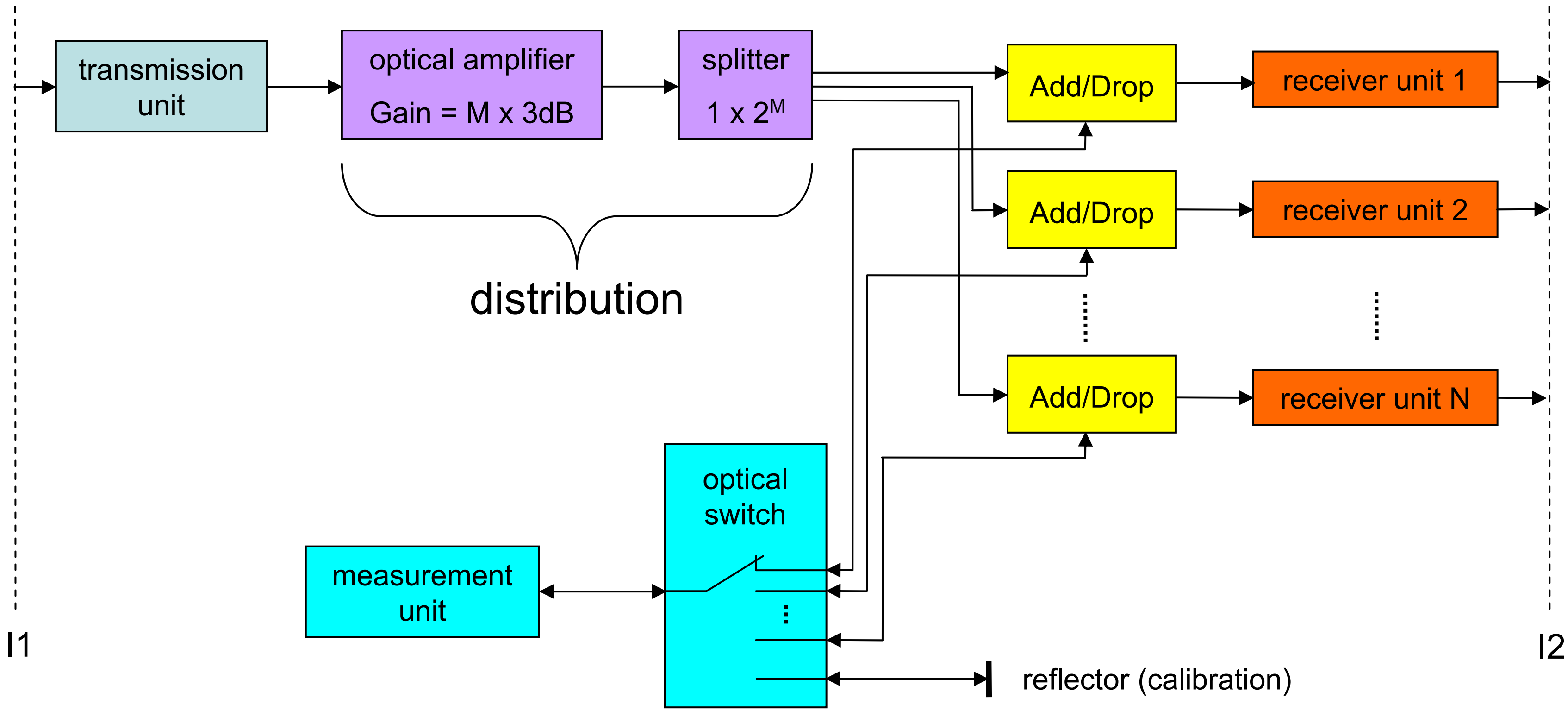
Optical Network

Configuration of one transmission branch



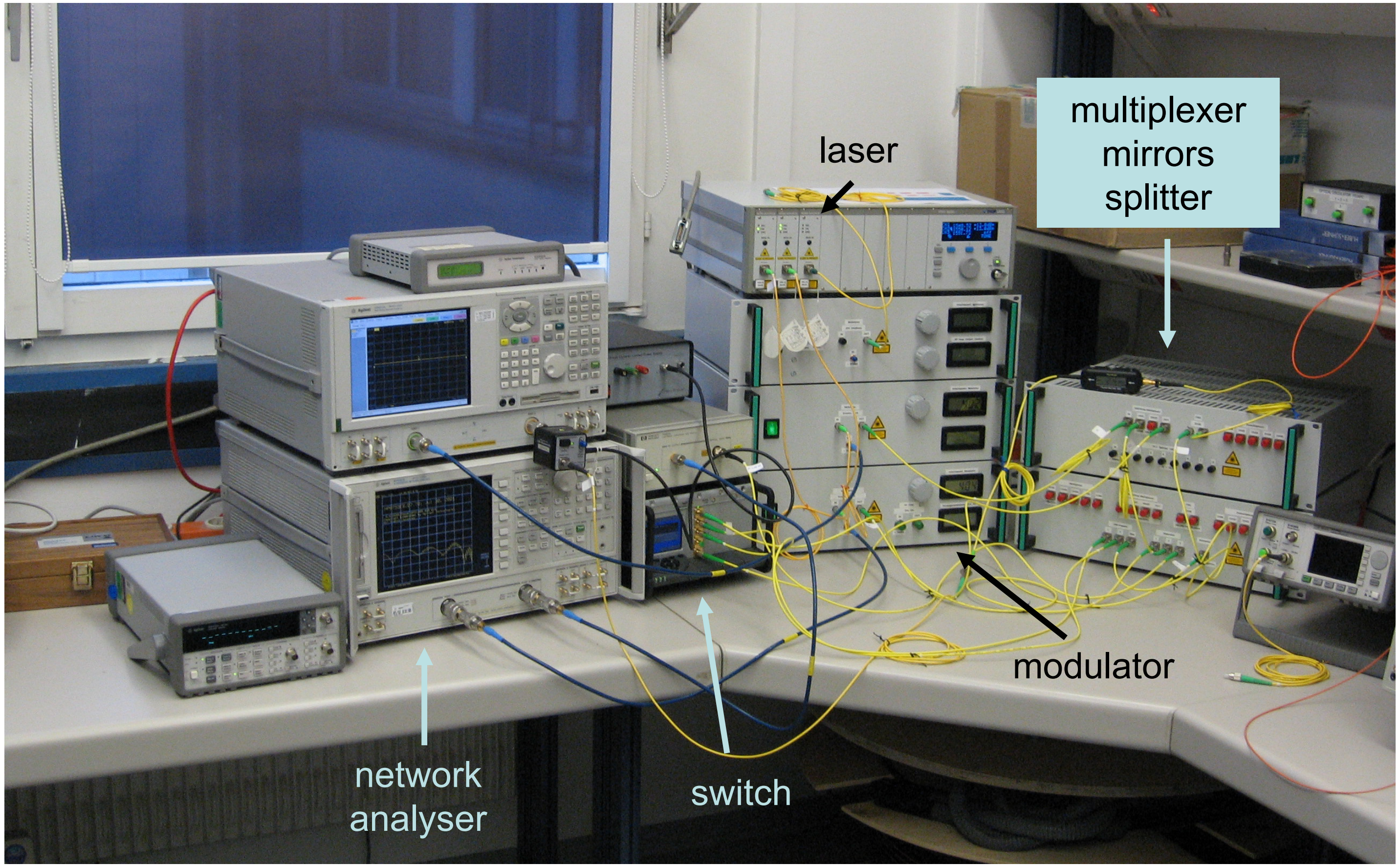
Optical Network

Star-shaped distribution



Reference Distribution

Optical Network - Prototype



Optical Network - Performance

1. Transmission Channels
   - *bandwidth* = 1.2 *GHz*
   - *more channels possible*
   - 0 dBm_{opt} *receiver input*

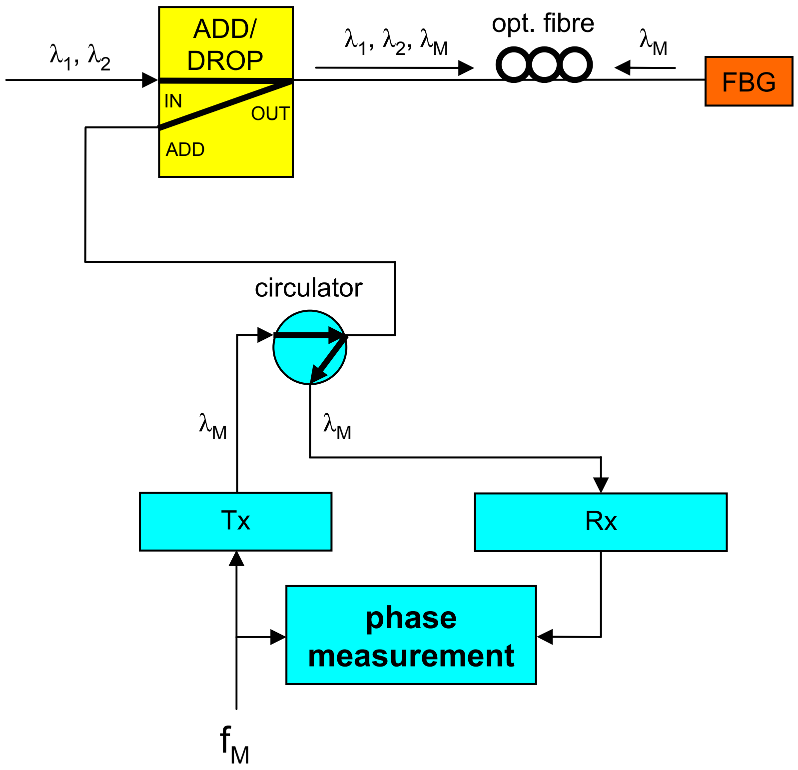
$$\left.\begin{array}{l} noise < -143\dfrac{dBc_{ele}}{Hz} \\ crosstalk < -70dB_{ele} \end{array}\right\} \Rightarrow \quad \sigma_{j,trans} < 305\,fs$$

2. Measurement Channel
   - *bandwidth* = 10 *GHz*
   - 0 dBm_{opt} *receiver input*

$$crosstalk < -130dB_{ele} \quad \Rightarrow \quad total\ decoupling$$

3. Low Costs
   - *only standard components*
   - *only one transmission unit*
   - *only one measurement unit*

Delay Measurement



Delay determination via phase measurement

$$\mathbf{F_M} = \{f_{M1}, f_{M2}, \ldots, f_{MN}\}$$

$$\downarrow$$

$$\Phi_\mathbf{M} = \{\varphi_{M1}, \varphi_{M2}, \ldots, \varphi_{MN}\} \quad \Rightarrow \quad \tau = f(\Phi_\mathbf{M})$$

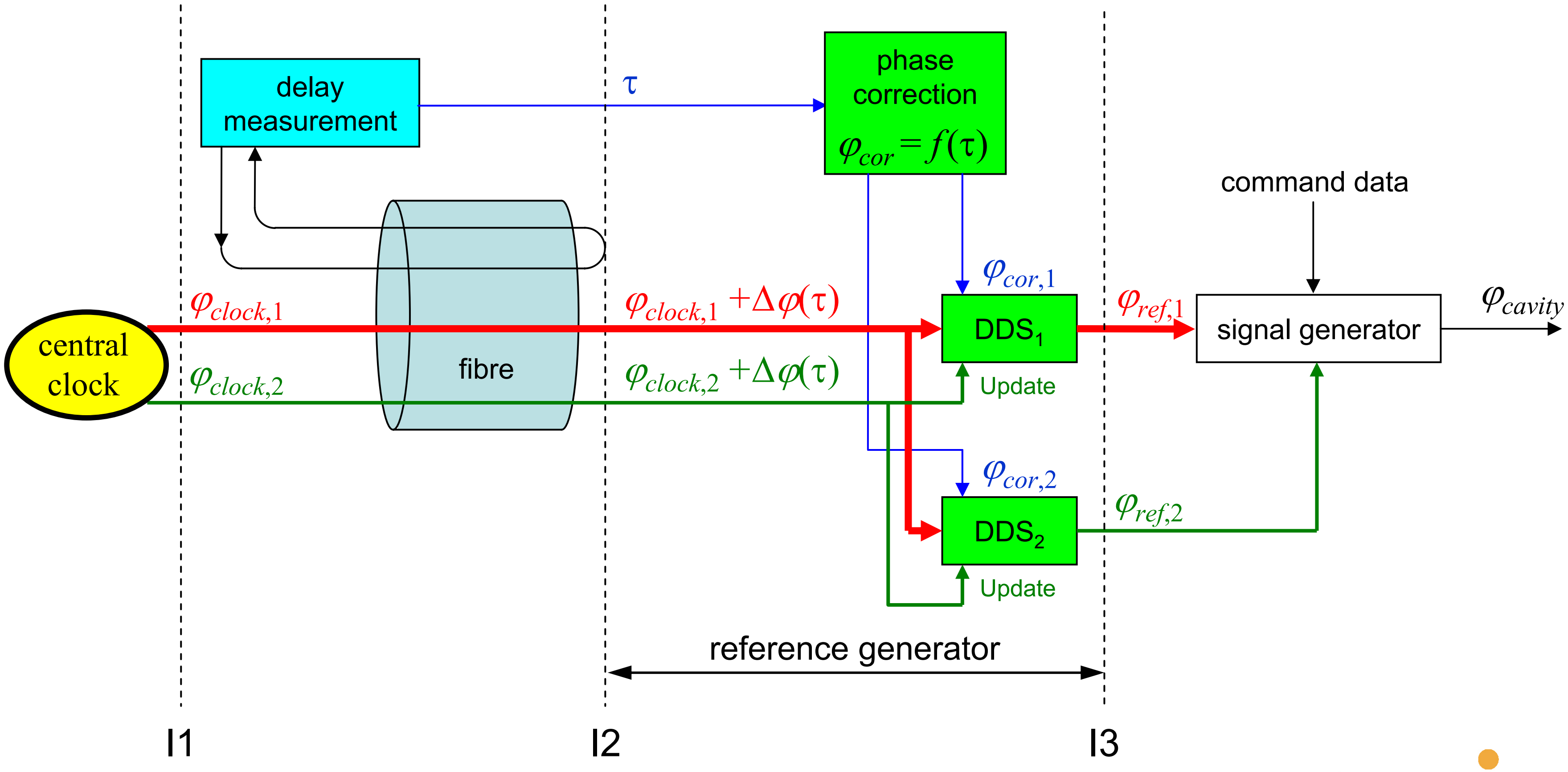
$$boundary\ condition: \quad \frac{1}{f_{M,\min}} > 2\tau$$

$$\boxed{\tau_{accuracy} = \frac{1}{f_{M,\max}} \cdot \frac{\varphi_{accuracy}}{2 \cdot 360°}}$$

$$\varphi_{accuracy} < 0.4°$$

$$\Rightarrow \quad \mathbf{F_M} = \{50kHz, 500kHz, 50MHz, 6GHz\} \quad \Rightarrow \quad \tau_{accuracy} < \frac{1}{6GHz} \cdot \frac{0.4°}{2 \cdot 360°} = \underline{\underline{92{,}6\,fs}}$$

Reference Generation

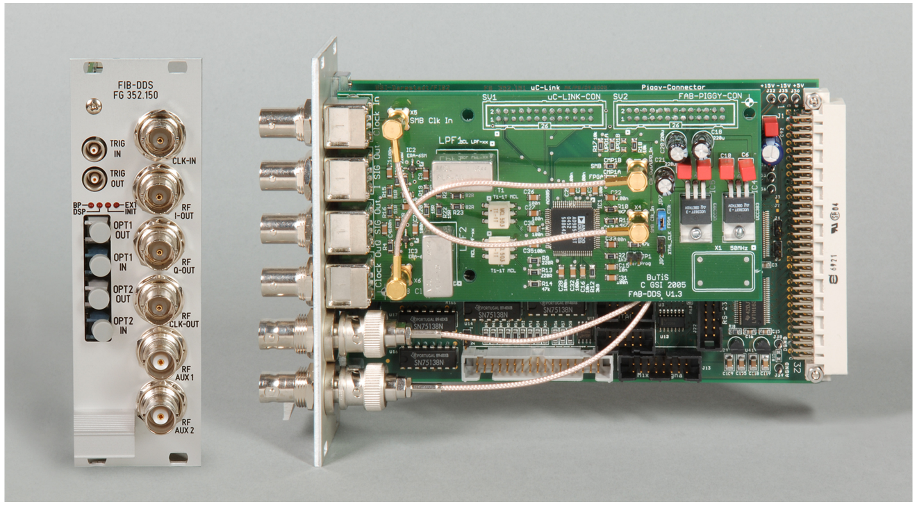


Reference Distribution

Reference Generation

Reference Signal Generation via DDS

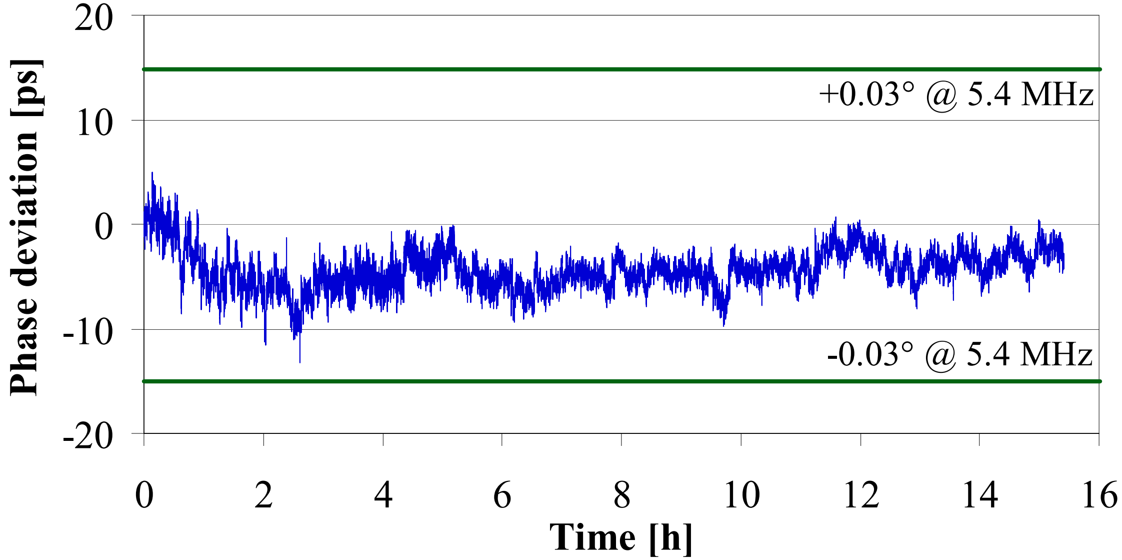
1. No phase adjustment limit
2. Resolution of phase adjustment 1.22 *ps* (Reference Signal 1)
3. Jitter $\leq$ 7.6 ps_{RMS} (Reference Signal 1)
4. Standard components



Reference Distribution

Performance

- Two reference points
- Distance from center clock ≥ 1 km each
- Average interval 1 s



Current performance

$\Delta\mu < 15\ ps$

$\sigma_j \leq 7.6\ ps$

$\varphi_{Stability} < 1\ ps$

change of DDS-model
temperature stabilisation Rx

Anticipated performance

$\Delta\mu << 15\ ps$

$\sigma_j < 250\ fs$

$\varphi_{Stability} << 1\ ps$

Reference Distribution

Summary

1. Transmission of two clocks with DWDM

   $$noise < -143 \frac{dBc_{ele}}{Hz} \quad \Rightarrow \quad \sigma_{j,trans} < 305\, fs$$

   $$crosstalk < -70 dB$$

   more transmission channels possible

2. Separate measurement channel

   $$crosstalk < -130 dB_{ele} \quad \Rightarrow \quad total\ decoupling$$

   measurement accuracy better than 100 fs

3. Reference generation via DDS

   $$\sigma_j \leq 7.6 ps$$

4. Phase deviation between two reference points < 0.03° of cavity frequency

5. Only standard components are used

Reference Distribution

M.Bousonville@gsi.de

Reference Distribution

Additional Slides

Reference Distribution

Interfaces

Interface 1

$\varphi_{Clock,1}$

$\varphi_{Clock,2}$

Interface 2

$\varphi_{Clock,1} + \Delta\varphi(\tau)$

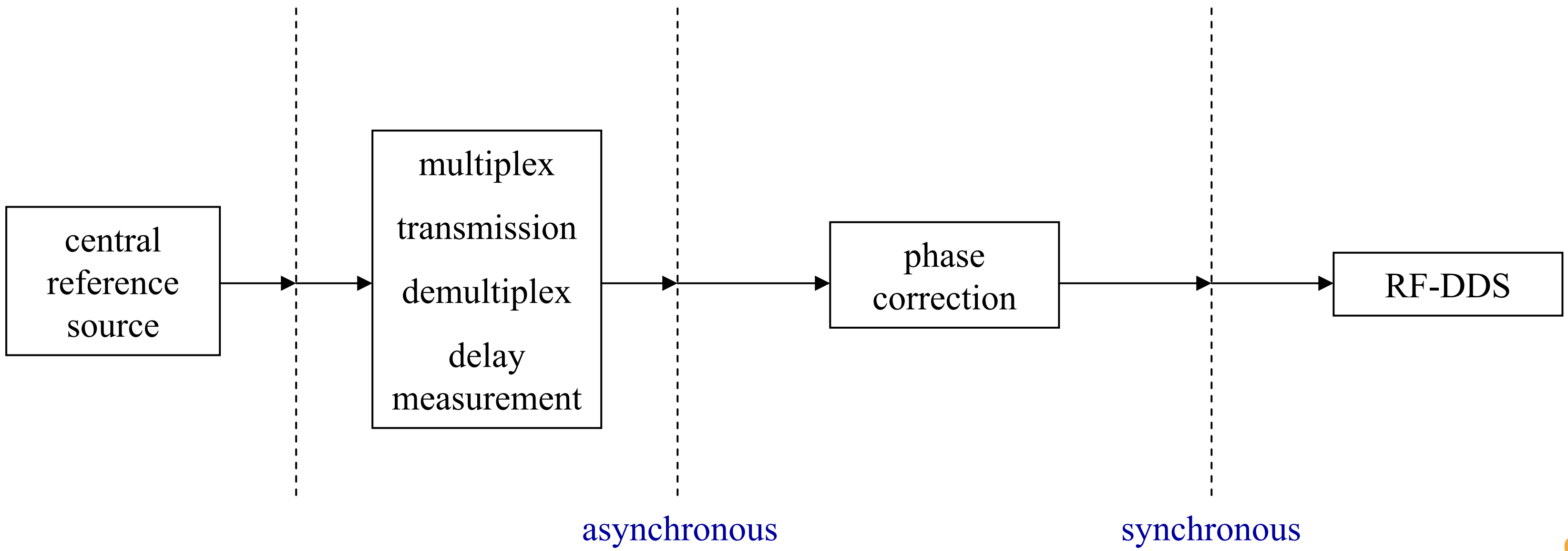
$\varphi_{Clock,2} + \Delta\varphi(\tau)$

τ

Interface 3

$\varphi_{Ref,1} = f(\varphi_{Clock,1}) \neq f(\tau)$

$\varphi_{Ref,2} = f(\varphi_{Clock,2}) \neq f(\tau)$



System Design

1. WDM (Wavelength Division Multiplex)
2. Optimal input power at the optical receiver (0 dBm)

   This is possible for two reasons

   a) Low insertion loss of the passive WDM-components

   b) High transmitter power
3. Crosstalk attenuation >> SNR

   a) No effect on jitter

   b) Measurement do not influence the reference signals

$\Rightarrow$ maximum SNR

$$jitter \propto \frac{1}{\sqrt{SNR}}$$

$\Rightarrow$ minimum jitter

Reference Distribution

System Design

1. One instead of N transmission units
   ⇒ No different time dirfts in different branches
2. One instead of N measurement units
   ⇒ Systematic error irrelevant
      ⇒ Much less effort

Reference Distribution

Realisation

WDM-Laser

- 13 dBm output power
- RIN < -145 dB/Hz

	channel (ITU-norm)	opt. frequency ν [THz]	opt. wavelength λ [nm]
λ_1	32	193,2	1551,72
λ_2	**34**	**193,4**	**1550,12**
λ_M	**36**	**193,6**	**1548,51**

Reference Distribution

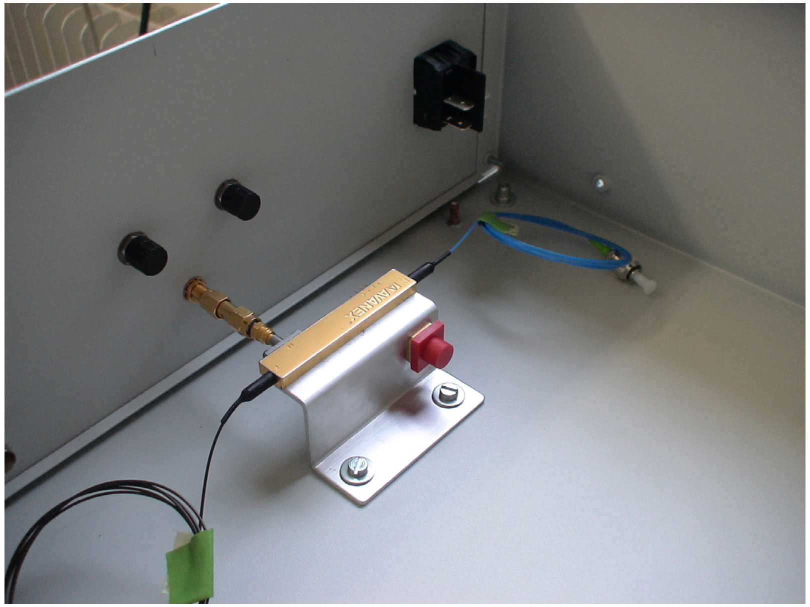
Realisation

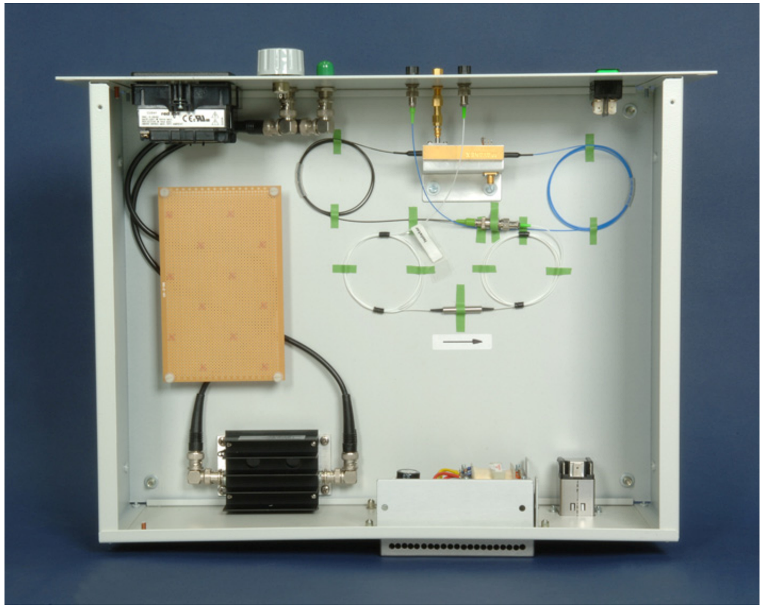
External Modulator

Realisation

External Modulator

• 10 GHz bandwidth – under proper conditions no jitter will be added

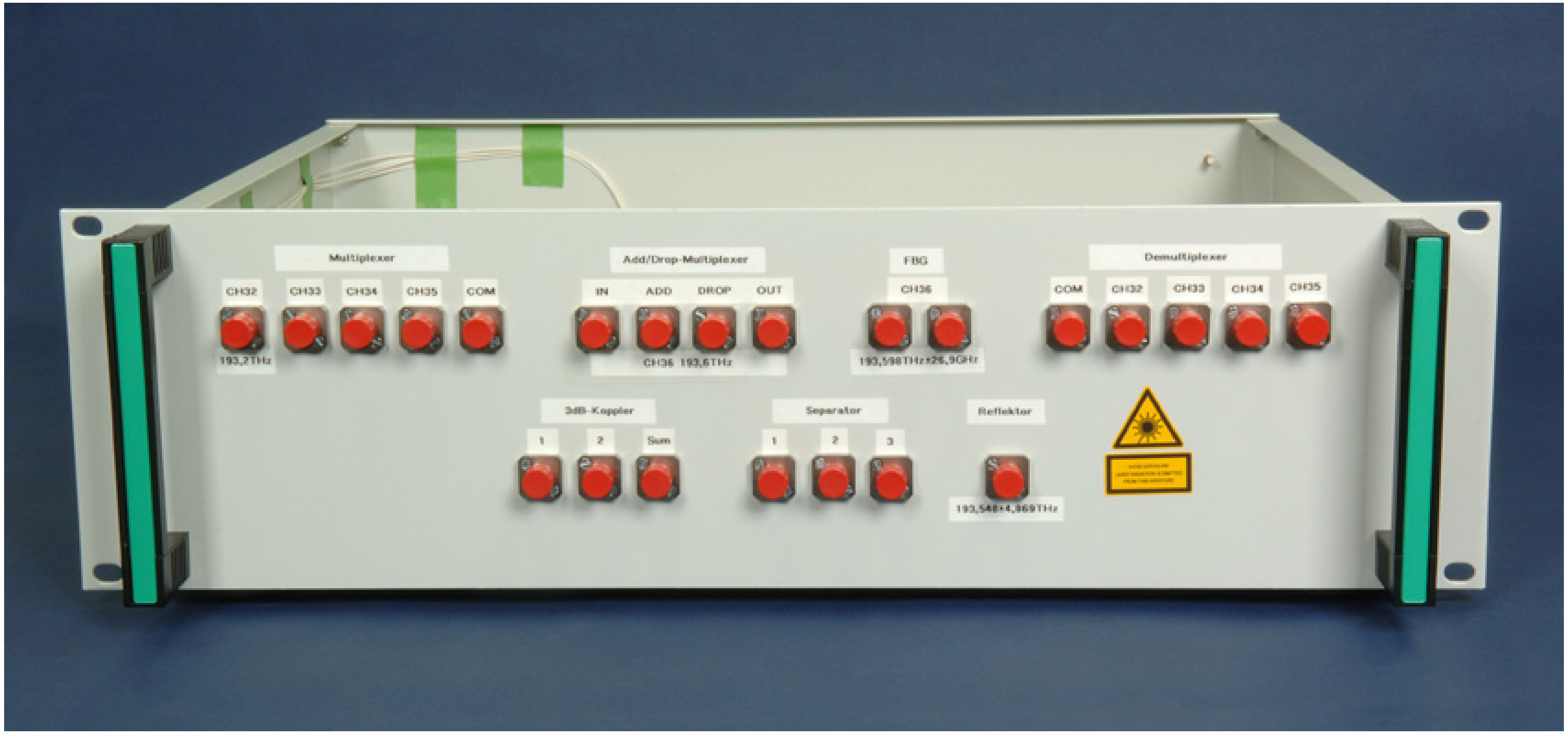




Reference Distribution

Realisation

Passive optical components



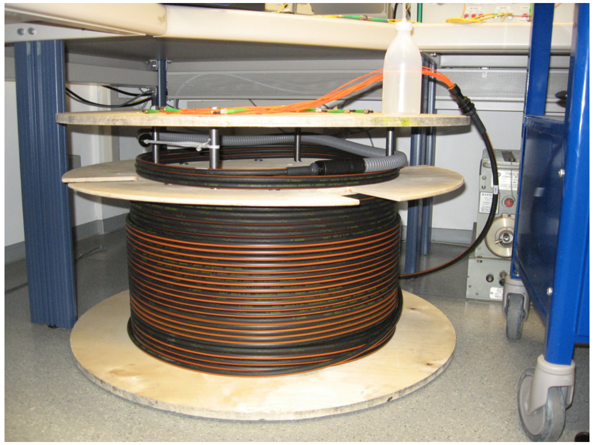
Reference Distribution

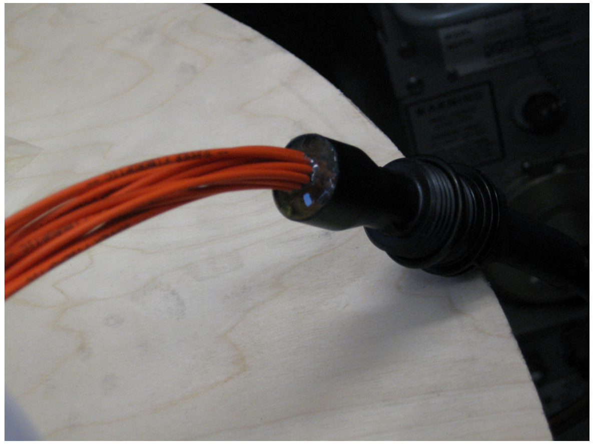
Realisation

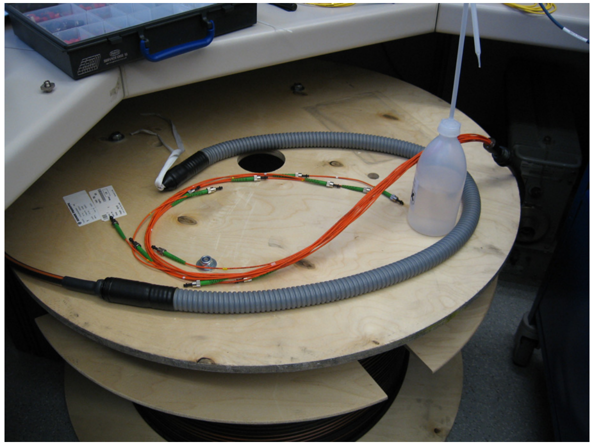
Passive optical
components

Reference Distribution

Realisation – fibre optic cable







Low drift velocity

$$\frac{d\tau}{L\cdot\Delta T_S\cdot dt} < 6\,\frac{ps}{km\cdot K\cdot min}$$

(calculation: analytical and finite element method)

Virtually strain proof

$$\frac{d\tau}{L\cdot dF_G} = 0\,\frac{ps}{km\cdot N}$$

$$for \quad F_G < 4500\,N$$

Reference Distribution

Realisation

Optical receiver

- The biggest noise source other than RIN (Relative Intensive Noise)

Reference Distribution

Realisation

Results Reference Signal Transmission

1. Bandwidth transmitter: 10 GHz
2. Bandwidth receiver: 1.2 GHz

System bandwidth: 1.2 GHz

3. Noise

$$\rho_N < -143.2 \frac{dBc}{Hz} \quad \Rightarrow \quad SNR > 52.4dB$$

4. Crosstalk < -70 dB << Noise

$$\sigma_{j,trans}\left(s_N = 5.56 \cdot 10^9 \frac{1}{s}\right) \approx \frac{10^{-\frac{SNR_{dB}}{20}}}{s_N \cdot \sqrt{2}} < 305\, fs$$

Optimisation Parameter Jitter: $\sigma_j = f\left(\sigma_{j,trans}\right) \quad \Rightarrow \quad ok$

* Sine wave
Standard deviation

Delay Measurement

General

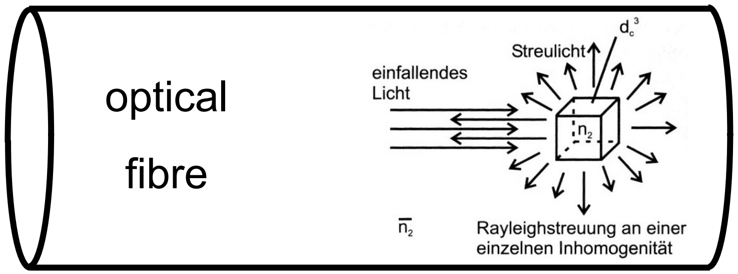
1. One separate measurement channel
2. Bandwidth = 10 GHz
3. Measurement channel totally decoupled form the reference channels
4. Nearly all measurement methods are applicable

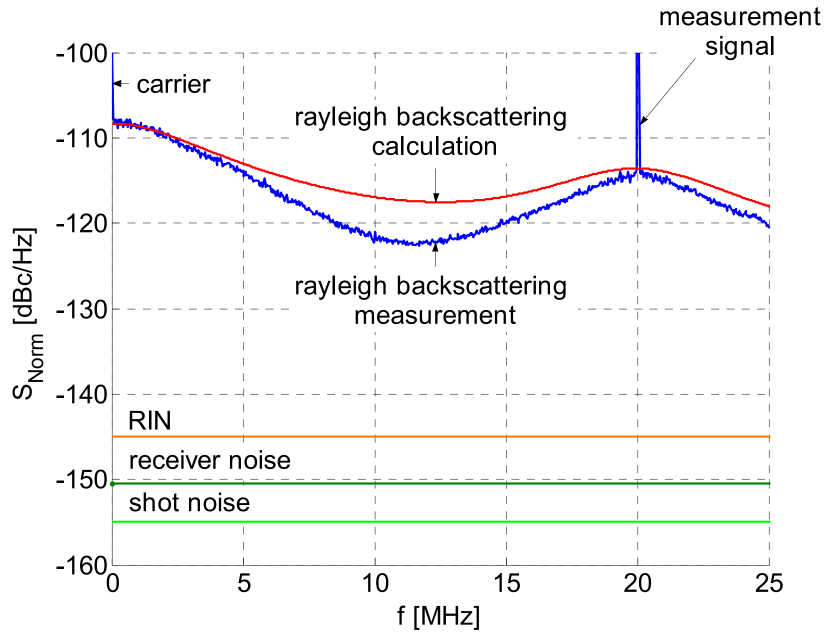
Reference Distribution

Delay Measurement

Noise of the measurement channel

- Amorphous structure of glass
  $\Rightarrow$ Rayleigh Scattering





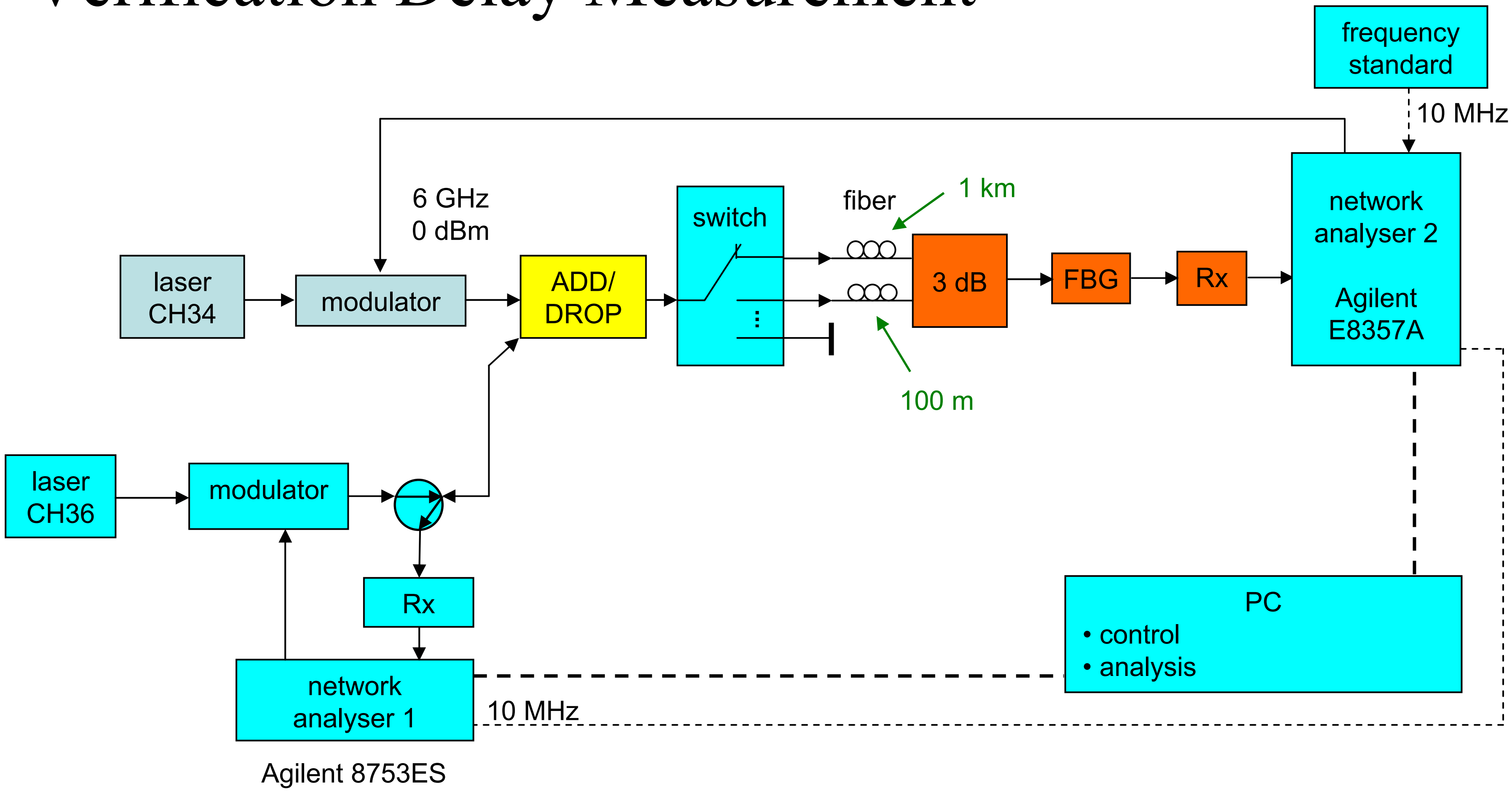
- Noise due Rayleigh Scattering dominates
- Spectrum (calculated analytical/numerical)

$$S_{Norm}(f \geq 0) = \delta(f) + \frac{m^2}{2}\delta(f - f_M) + 1{,}2 \cdot 10^{-4}\left[\frac{2a^2}{\pi}\frac{\Delta f}{\Delta f^2 + f^2} + \frac{2b}{\pi}\frac{\Delta f}{\Delta f^2 + (f - f_M)^2}\right]$$

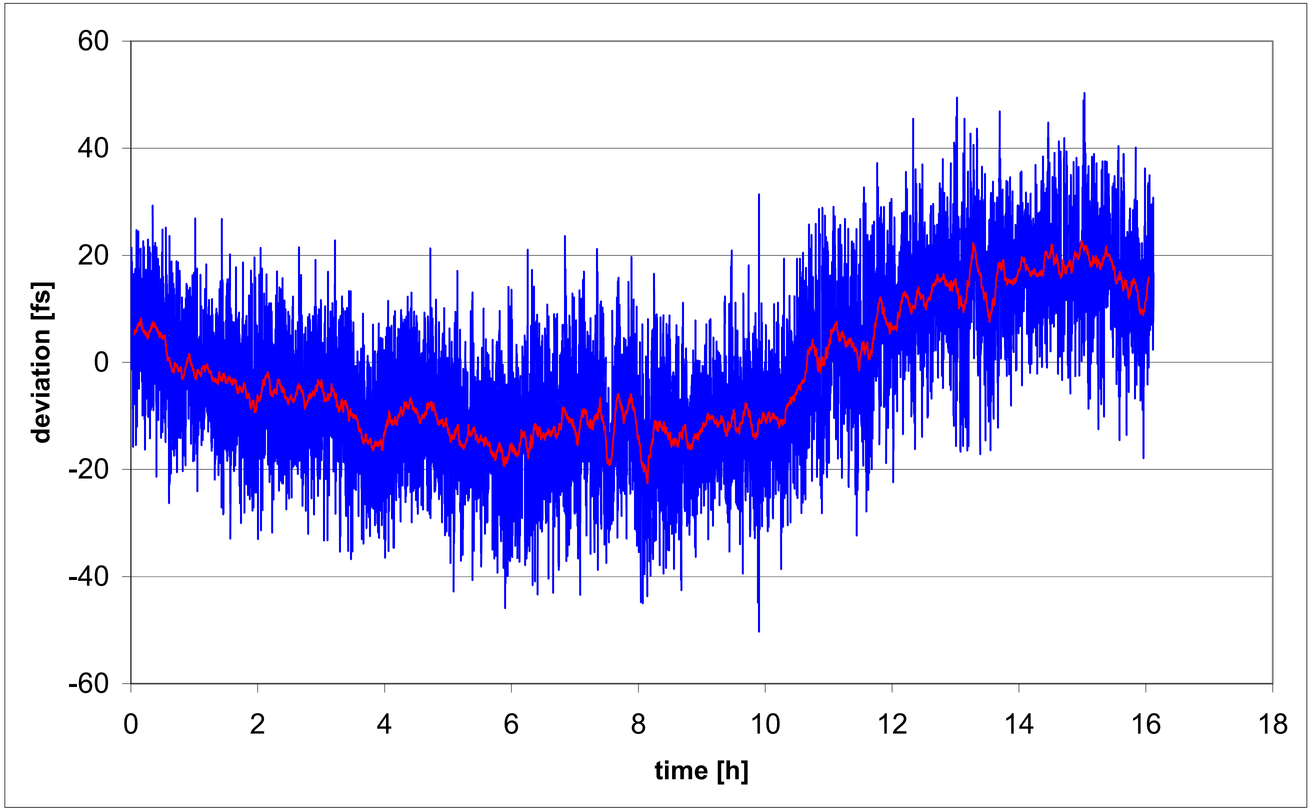
$$SNR(B = 10Hz) \geq 95dB \quad \Rightarrow \quad \varphi_{accuracy} < 1° \quad \Rightarrow \quad \tau_{accuracy} < 1ps$$

Optimisation Parameter Mean: $\Delta\mu = f(\tau_{accuracy}) \quad \Rightarrow \quad ok$

Verification Delay Measurement



Verification of Delay Measurement



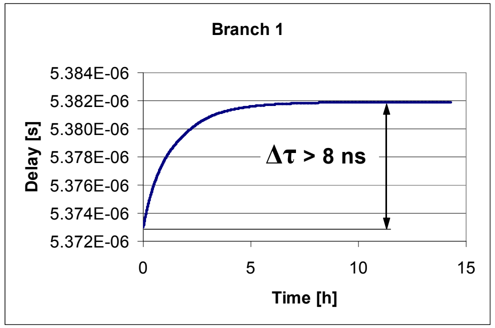
$\Rightarrow$ *accuracy* < 100 *fs*
(*optical domain*)

Prediction correct!

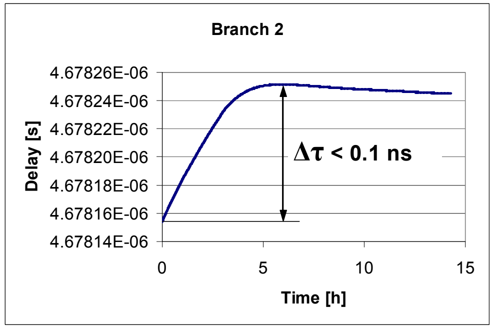
Reference Distribution

Test under extreme conditions

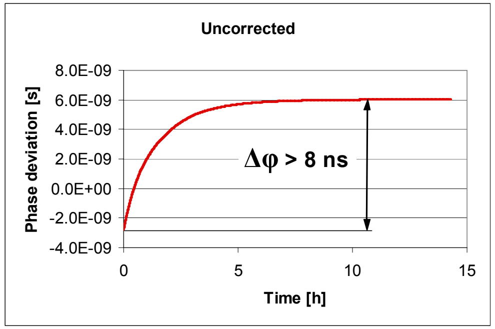
Fiber length > 1 km; temperature change: -26,5°C → 24,5°C



-



=



correction →