PHASE DRIFT COMPENSATING RF LINK FOR FEMTOSECOND SYNCHRONIZATION OF E-XFEL

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Abstract

Modern high-energy particle accelerators and free-electron lasers incorporate large quantities of sensitive RF and microwave frequency devices distributed over kilometer distances. Such devices require extreme stable phase and time synchronization by means of high frequency signal distributed along the accelerator facility.

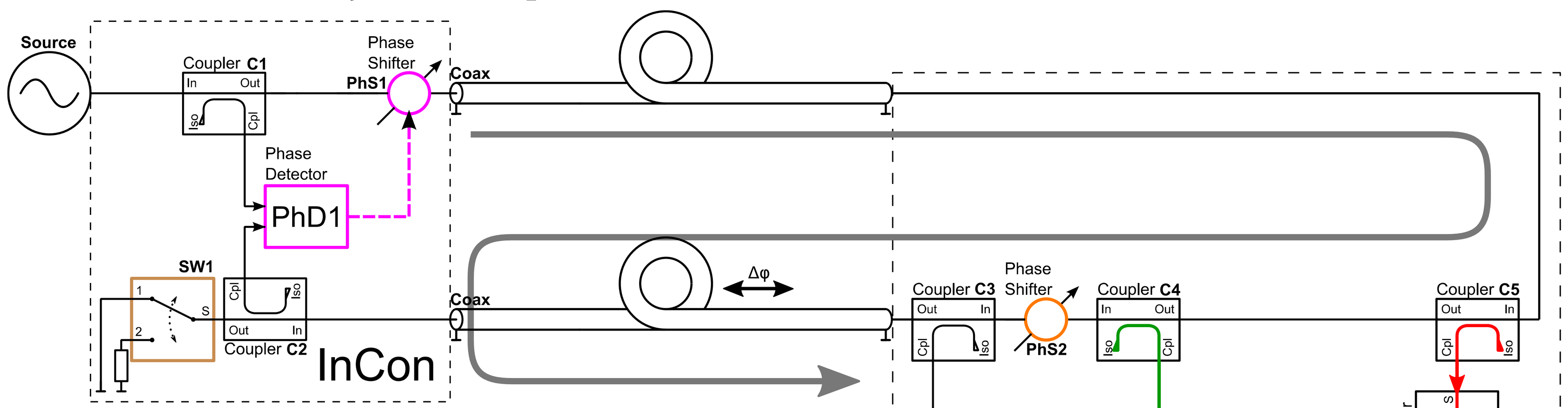
Coaxial cables are commonly used to distribute the reference signal over the large machine to synchronize electronic systems and they are the main source of undesirable phase drifts in the synchronization system. Signal phase drifts in cables are mainly caused by temperature and humidity variations and their values usually exceed required phase synchronization accuracy by more than order of magnitude.

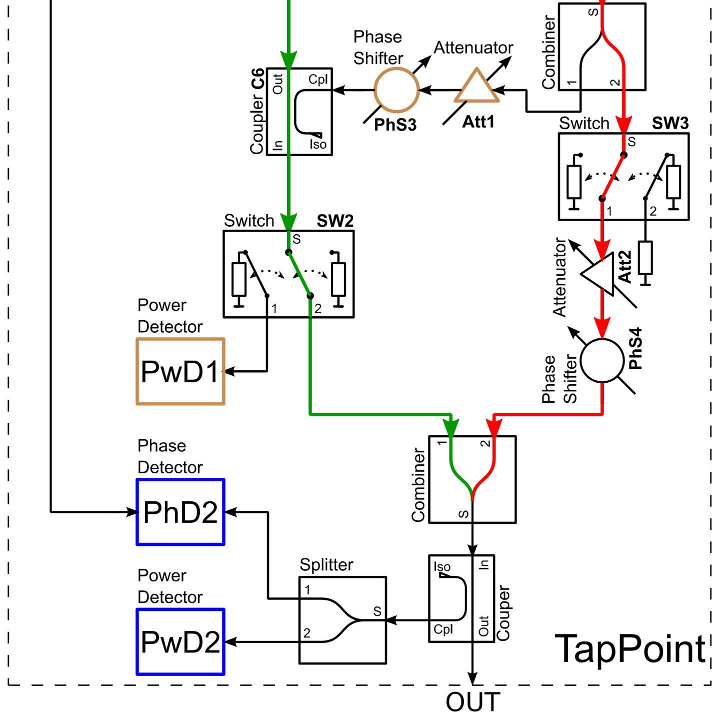
There are several approaches to reduce signal phase drifts in coaxial cables. This paper describes the realization of active phase stabilization system based on interference phenomenon. A phase-locked signal from the transmitter is reflected at the end of a coaxial cable link. Directional couplers placed along the cable pick up the forward and reflected signals and interfere them to cancel out the cable phase drifts. Distributed hardware including interferometer controller/transmitter and receiver modules were built demonstrate system concept and performance. Link input and output devices used FPGA I/O boards with Ethernet interface to control system operation. Specialized firmware and software was developed to calibrate and control the system.

This paper describes the concept of interferometer link, basic control algorithms, designed hardware and performance evaluation results. The link prototype was built to distribute 1.3 GHz signal through a coaxial cable. Measured phase drift suppression factor value exceeded level of 100.

Interferometer Link Concept

Interferometer link concept [1] was developed to provide automatic adjustments of the link without any manual operations.



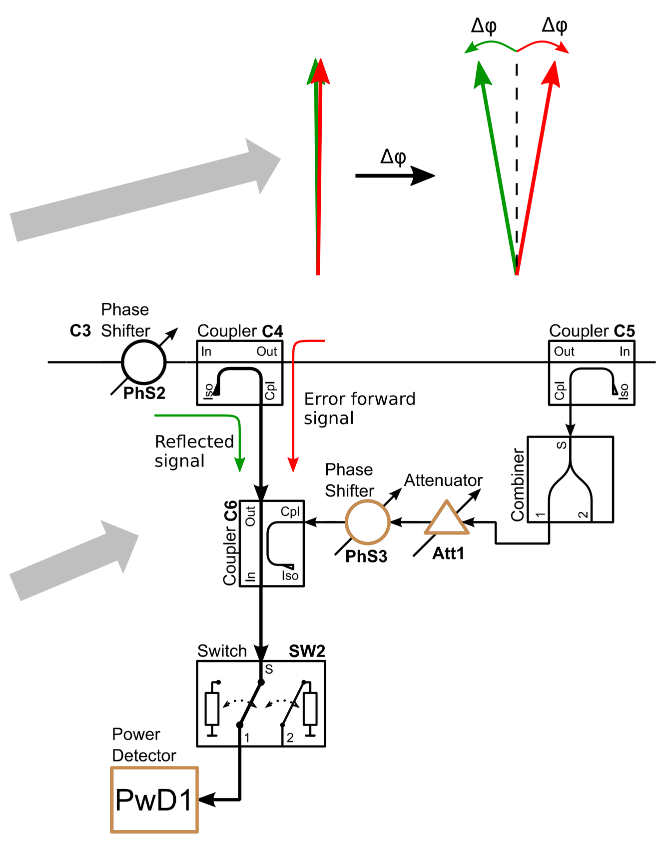


The primary concept requires three basic conditions:

1. Constant phase shift at the end of the coaxial cable link – it is done by InCon phase-lock loop (phase detector PhD1 and phase shifter PhS1 marked in pink),
2. Sum of equal forward and reflected signals at the link output – it is done in the TapPoint by :
   - proper configuration of RF switches (SW2 and SW3),
   - adjustments done by variable attenuator and phase shifter (Att2 and PhS4 in the red path),
   - measurements done by power and phase detectors (PwD2 and PhD2 marked in blue),
3. Appropriate electrical length between InCon and the TapPoint's picking up couplers – it's done by a main line phase shifter in the TapPoint (PhS2 marked in orange) and the control algorithm.

These 3 conditions ensure that any coaxial cable phase drift appeared in forward and reflected signals will have opposite signs. Directional couplers C4 and C5 in the TapPoint pick up the these signals and interfere them to cancel out the coaxial cable phase drifts.

Due to significant level of error forward signal getting via coupler isolation at the C4 the isolation improvement circuit is added (SW1 in InCon and Att1 and PhS3 in TapPoint marked in brown). The procedure minimize the error signal up to 50 dBc below the reflected signal.

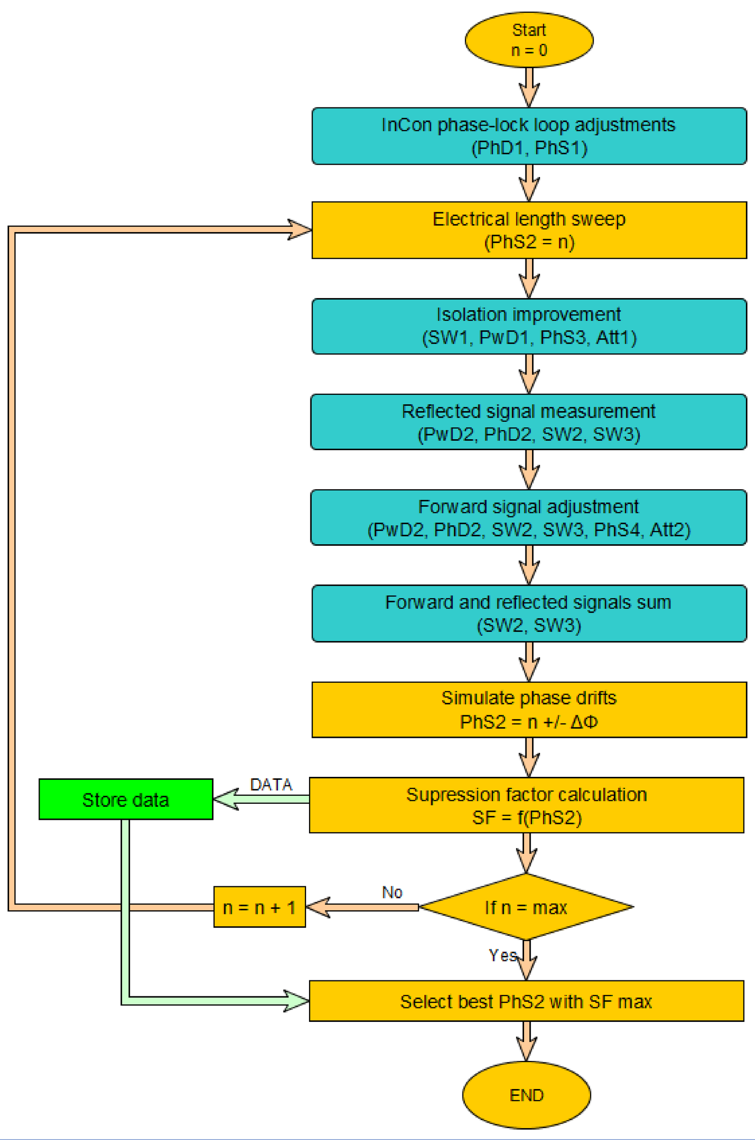


Basic Control Algorithms

Control algorithm steps:

- Set the electrical length between InCon and TapPoint by PhS2,
- Isolation improvement change the short to 50 Ω and the reflected signal is turned off. The variable attenuator and variable phase shifter adjust an additional forward signal to cancel out the error signal,
- Amplitude and phase of the forward and reflected signals are measured with proper configuration of RF switches. The reflected signal (green path) is measured at first and then the forward signal (red path) is adjusted to the reflected one,
- Phase drift simulation by PhS2 and the PhD2 phase detector measures the output phase drift,
- Suppression factor calculation at each electrical length step.

After full scanning the main line phase shifter position is chosen with the maximum suppression factor.



Designed Hardware

The interferometer concept was developed for European XFEL synchronization system. That is why the link components were designed to operate with 1.3 GHz signal, which is a main reference for the E-XFEL accelerator.

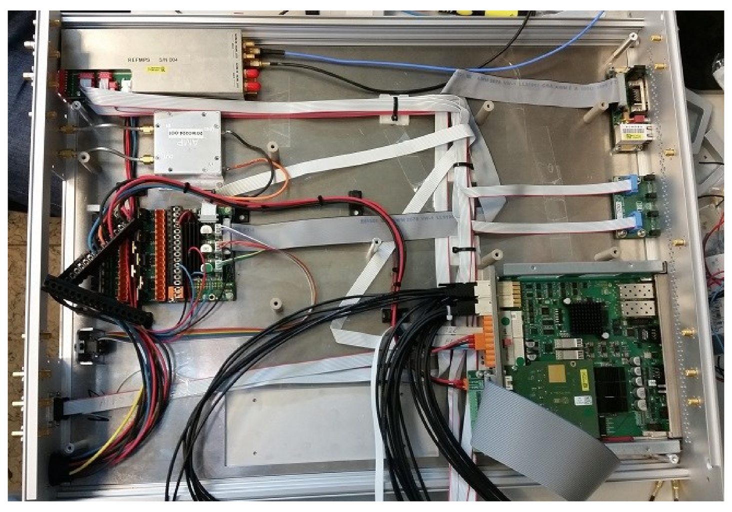
InCon

TapPoint

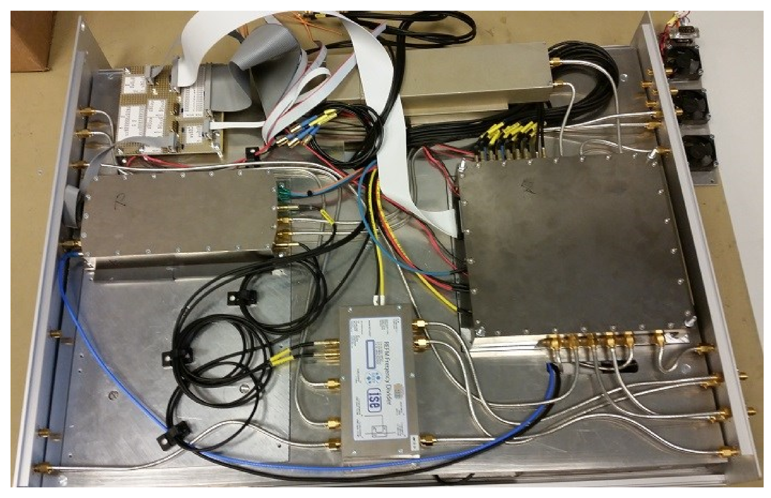
To minimize system own phase drifts the RF sub-modules are:

- closed in sealed (with o-ring) aluminum enclosures to minimize humidity variations,
- temperature stabilized with Peltier modules.

19" modules were built to demonstrate system concept and test the interferometer link performance. Bottom layer of the box contain digital sub-modules and the top layer contain just RF sub-modules. Entire top layer of 19" box is temperature stabilized.



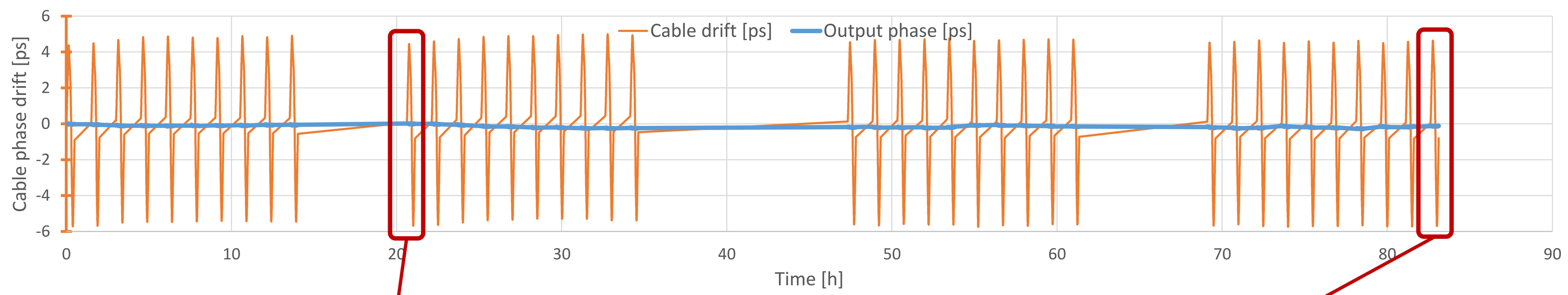
Bottom layer of 19" module



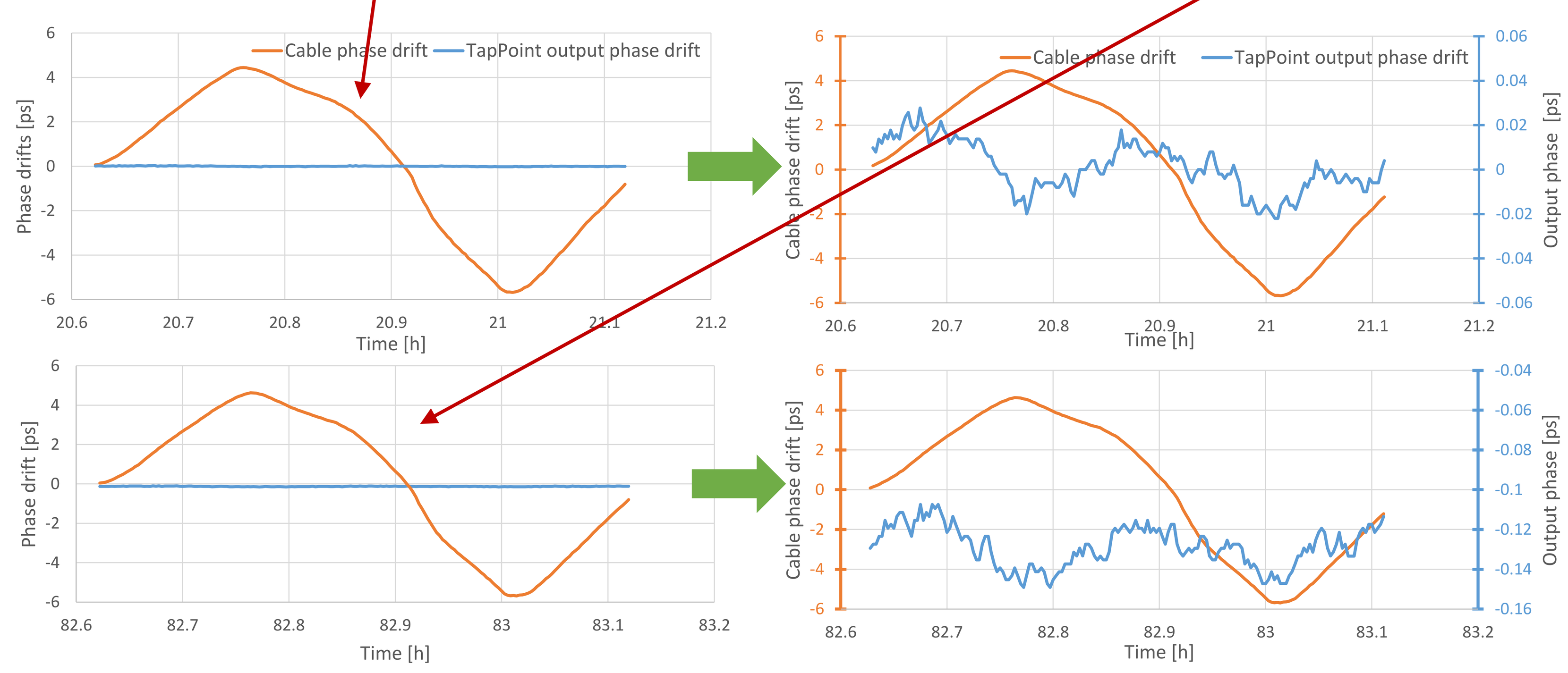
Top layer of 19" module

Interferometer Test Results

- Phase drifts measured during E-XFEL running up after 2 days downtime: 12.3 ps,
- Interferometer link components in the 19" module,
- Long coaxial cable in a climate chamber,
- Temperature changes to force phase drifts of 10 ps,
- The interferometer automatic adjustment done to set the best operating point before the long term tests.



Long term drifts of out of loop phase detector: up to 300 fs in 85 h of measurement.



Cable phase drifts of more than 10 ps are suppressed to less than 50 fs at the interferometer output (suppression factor higher than 200).

References

[1] E. Cullerton, B. Chase, 1.3 GHz Phase Averaging Reference Line

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