

Timing Distribution for LLRF Systems

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LLRF Topical Workshop on
Advanced feedback Control



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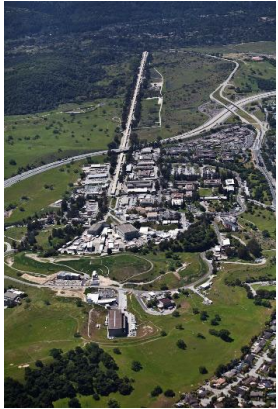
Femtosecond precision timing distribution & synchronization

- Founded in 2015 in Hamburg by Prof. Franz X. Kärtner
- Spin off from DESY, German accelerator research center
- 30+ people
- Delivering turnkey femtosecond precision synchronization and F&T solutions worldwide

Proven systems across demanding applications

F&T Generation · Transfer · Distribution · Comparison

Particle accelerators and free-electron lasers



Application : Facility wide synchronization of RF cavities and lasers with < 10 fs

Free Electron Lasers

- [European XFEL](#), Germany
- [SLAC Linac Coherent Light Source II](#), CA USA



Space ground segments and radioastronomy



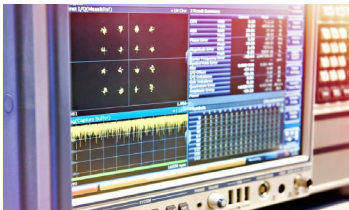
Application: Distributing reference clock signals (F&T) between control room and antennas



Space telescope networks:

- [ESA ESTRACK](#)
- [KSAT LUNAR network](#)
- [SSC Space Ground Stations](#)

Quantum



Application: Distributing RF frequency signals over campus or experiment nodes

Quantum computing

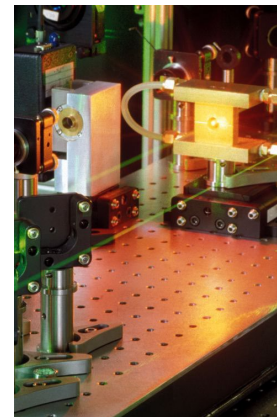
- OEM Integration of RF transfer for microwave qubit control

Quantum networks

- Synchronization for Quantum Networks and Key Distribution



Femtosecond laser sources



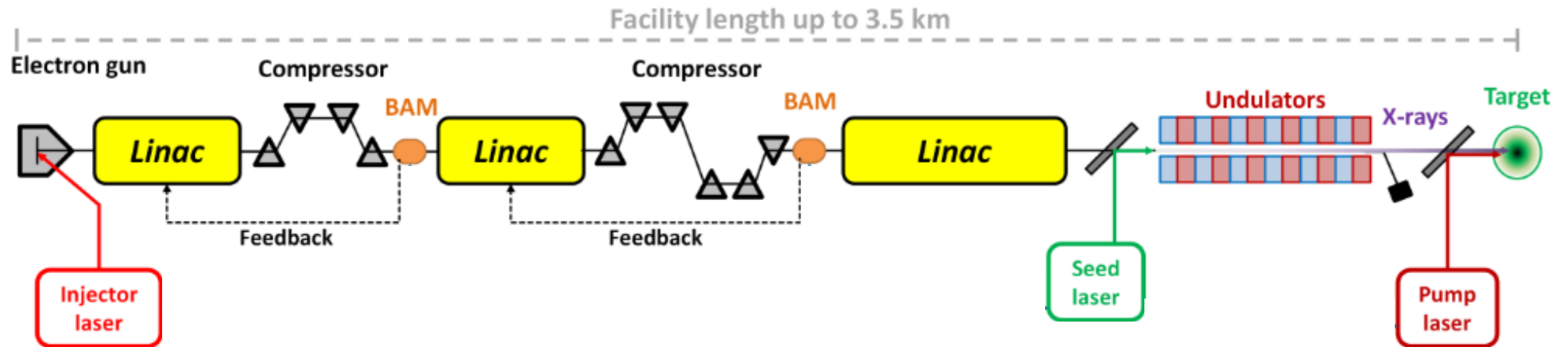
Application : Facility wide synchronization of High-power lasers with < 10 fs

Femtosecond laser facilities

- [Plasma physics](#)
- [Ultrafast metrology](#)
- [High-power laser fusion](#)

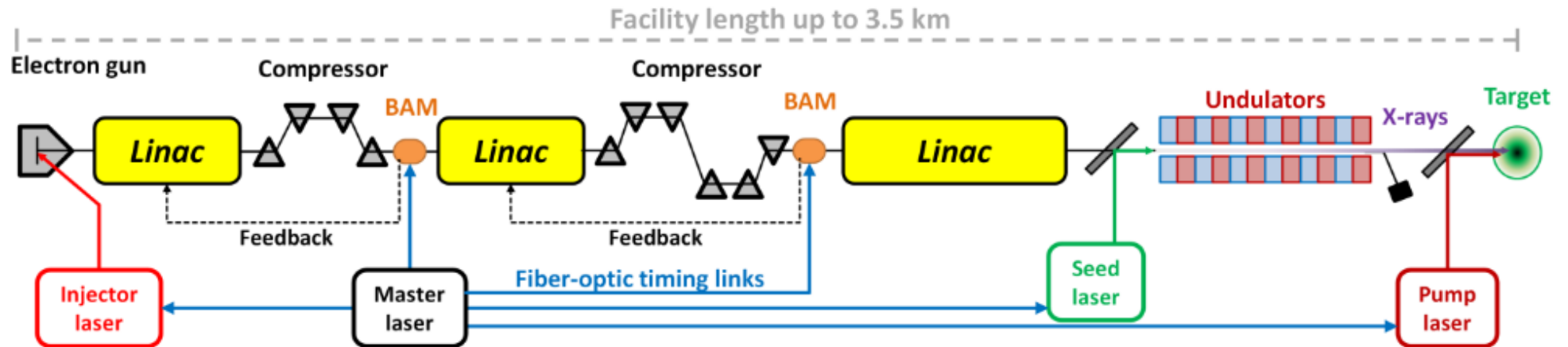
Facilities with demanding synchronization requirements

Schematic of an externally seeded and optically synchronized X-ray Free Electron laser



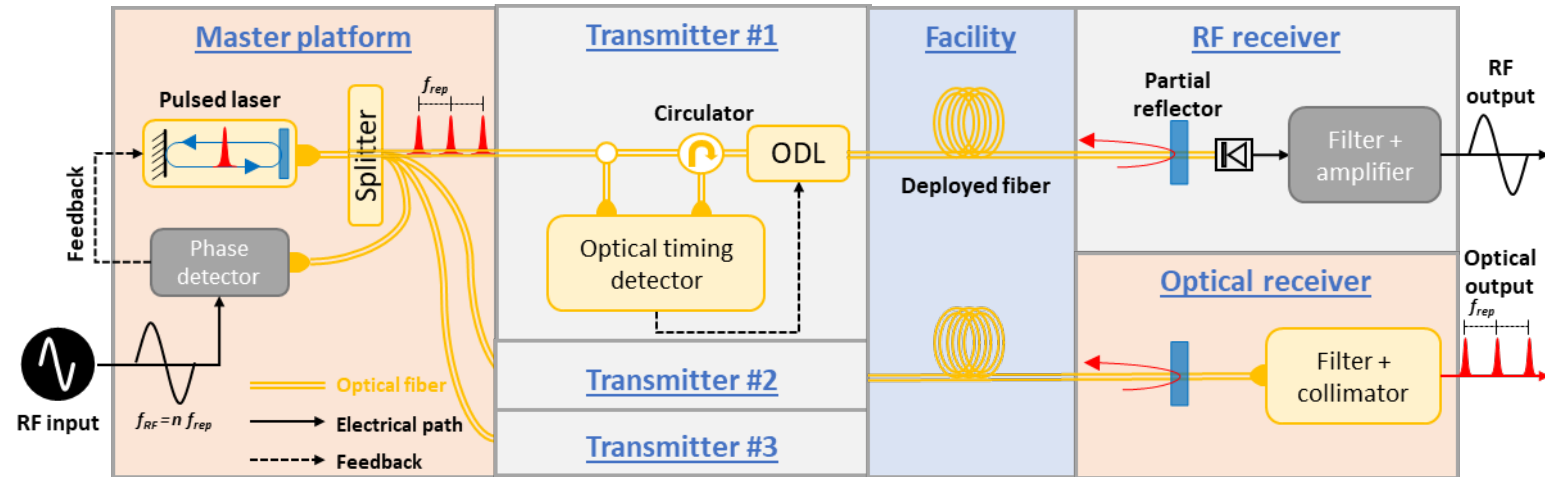
Facilities with demanding synchronization requirements

Schematic of an externally seeded and optically synchronized X-ray Free Electron laser



Femtosecond laser approach based on optical timing detection

Cycle PULSE System: sub-femtosecond optical timing distribution



~ 6U Master + Transmitter

≤ 3U Receiver



Advantages

Highly sensitive phase detection in the optical domain

<5fs integrated jitter [35 μ Hz - 1 MHz]

Compatible with current and future femtosecond lasers and frequency combs

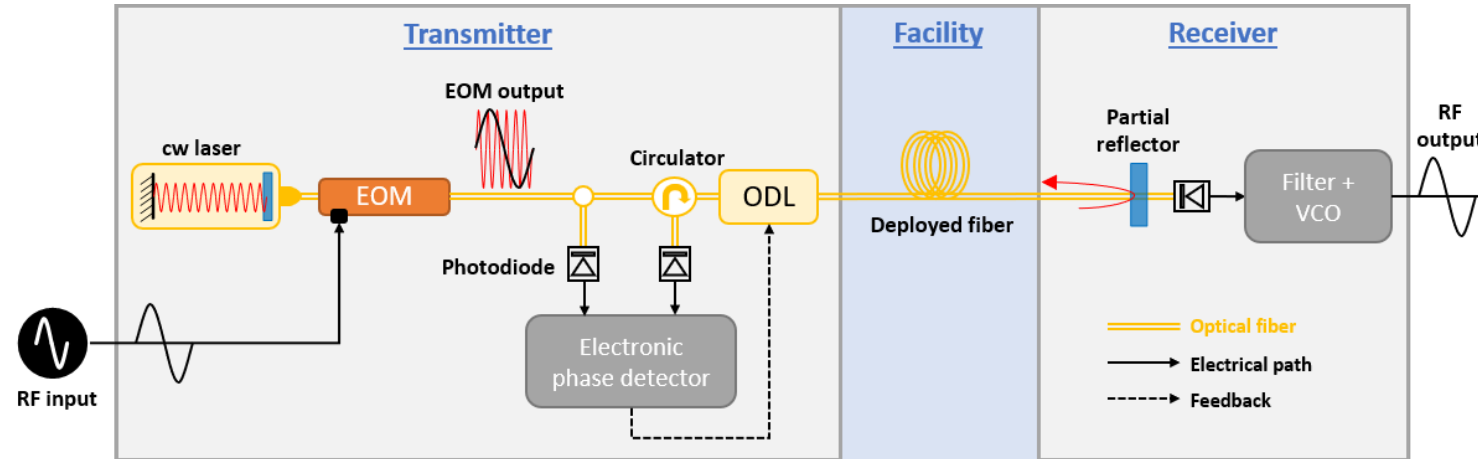
Disadvantages

Relatively complicated front-end

Requires dispersion-compensation

CW laser approach based on electronic phase detection

Cycle WAVE Link: maser-grade RF over Fiber transmission



≤ 3U Transmitter



≤ 3U Receiver



Advantages

Highly compatible with electronic phase detection and microwave equipment

Simple front-end

Relatively cost effective

Disadvantages

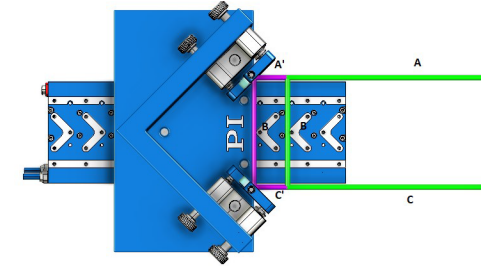
Requires up and down conversion electronics to reach high frequencies

Relatively noisy (compared to PULSE links)

Active phase/delay stabilization dilemma

One-way phase/delay stabilization based on round-trip error detection

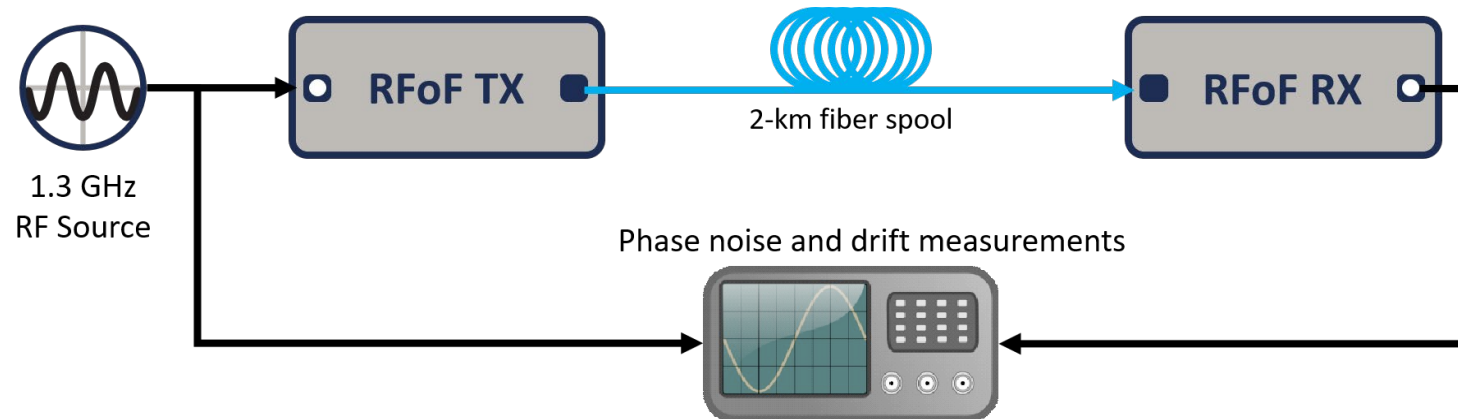
- assumes symmetrical forward and backward phase/delay error,
- requires a bi-directional symmetrical delay mechanism for feedback.



Solution	Advantages	Disadvantages
Matched electronic delay lines ⁶	• Large delay range • Compact • Compact footprint (i.e., PCB)	• Not commercially available (highly specific design) • Requires delay matching • Temperature sensitive
Thermally controlled optical fiber delay lines ⁶	• Bi-directional & fully symmetrical • Wide RF transmission bandwidth • Improved performance	• Limited range (does not scale with RF) • Large footprint • Long warm-up time / temperature sensitive
Our approach: motor-controlled optical delay line	• Bi-directional & fully symmetrical • Wide RF transmission bandwidth • Robust against temperature • Superior long- & short-term performance • Short warm-up time	• Limited range (does not scale with RF) • Large footprint • Long delay line → high optical signal loss

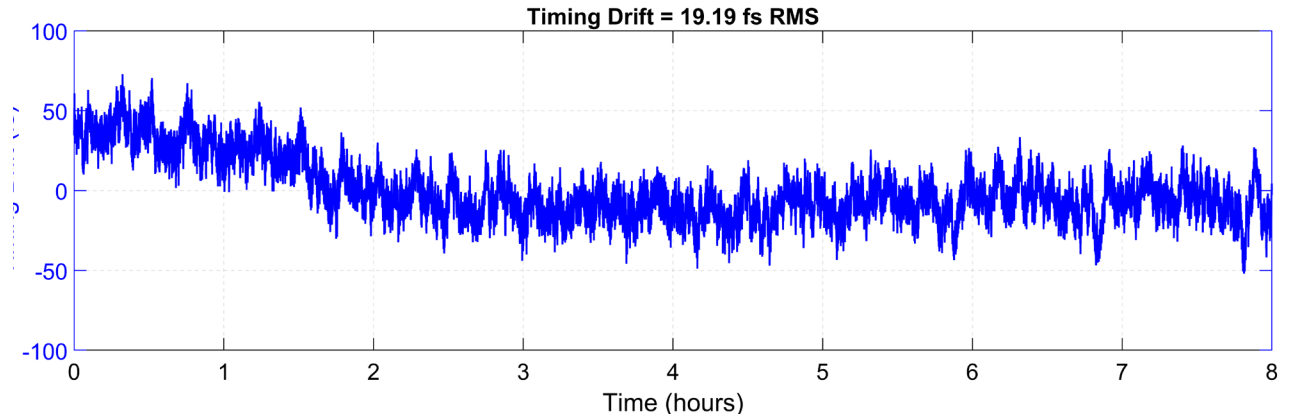
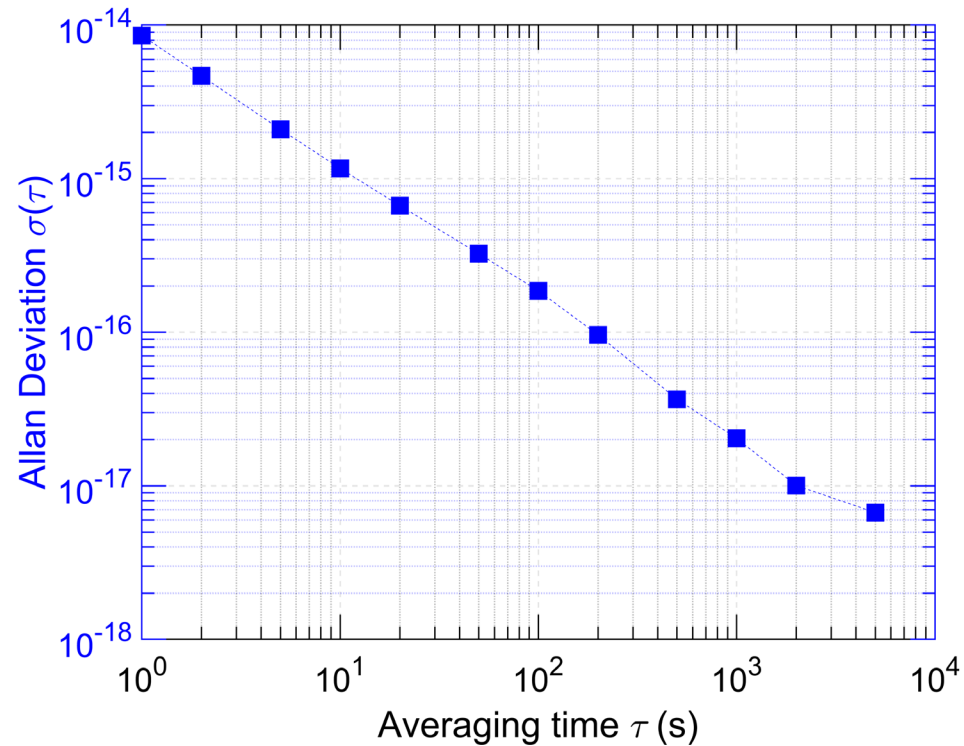
Validation setup in FEL facility

2-km fiber link for 1.3GHz transfer

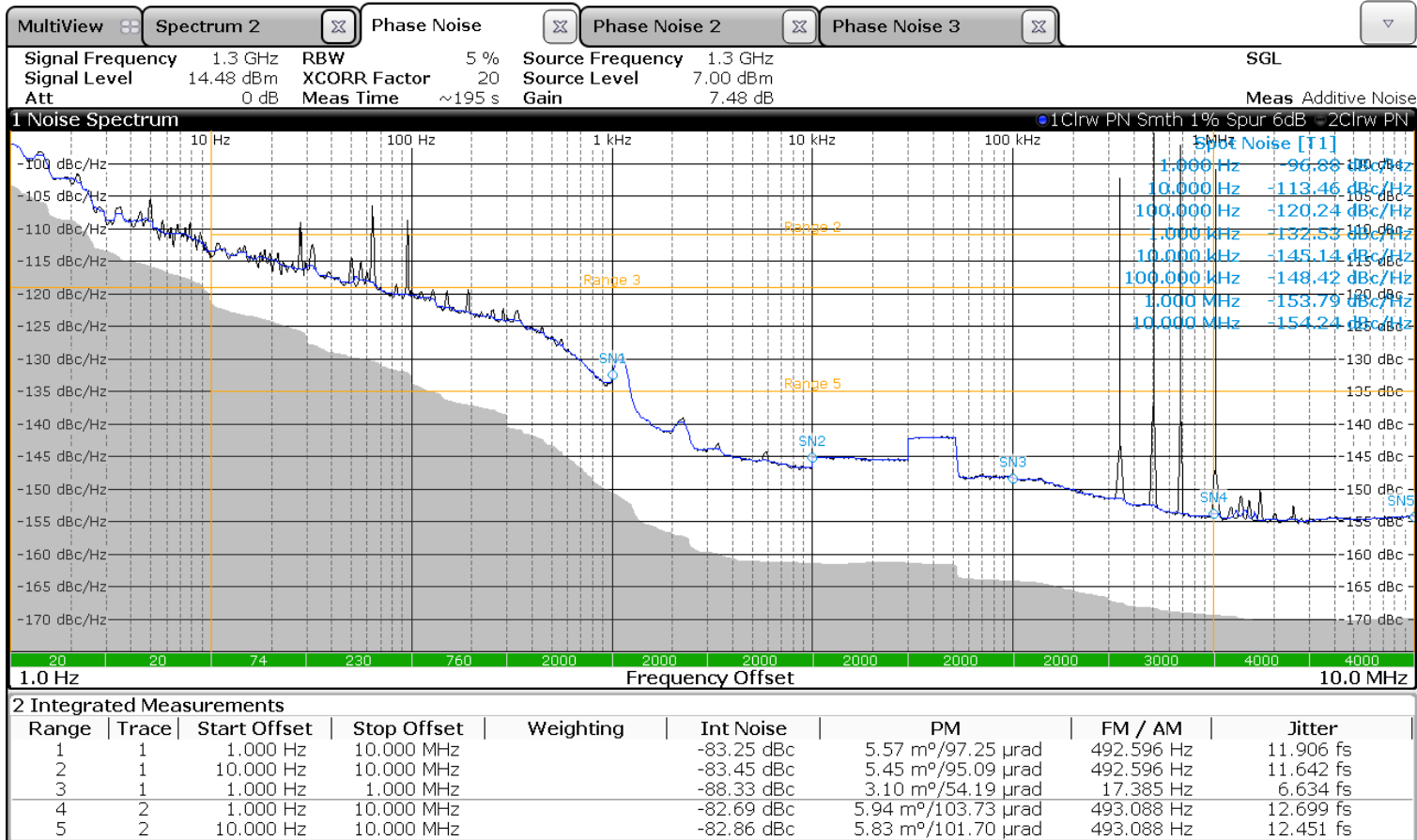


- Stabilized RF-over-fiber link evaluated using a 2 km fiber spool.
- Link performance characterized in terms of additive phase noise and phase drift using a phase detector and phase noise analyzer.

Out-of-loop timing jitter and drift for 1.3 GHz phase reference distribution



- < 20 fs RMS residual phase drift
- Fractional frequency transfer instability < 9E-15 at 1s and < 7E-18 at 5000s.



- Only 6.6 fs RMS additive timing jitter [1 Hz - 1 MHz].
- Phase noise:
 -97 dBc/Hz at 1 Hz
 -145 dBc/Hz at 10 kHz.

What can we do for
you?



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