PAUL SCHERRER INSTITUT

PSI

Wir schaffen Wissen – heute für morgen

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Reference Distribution System for SwissFEL

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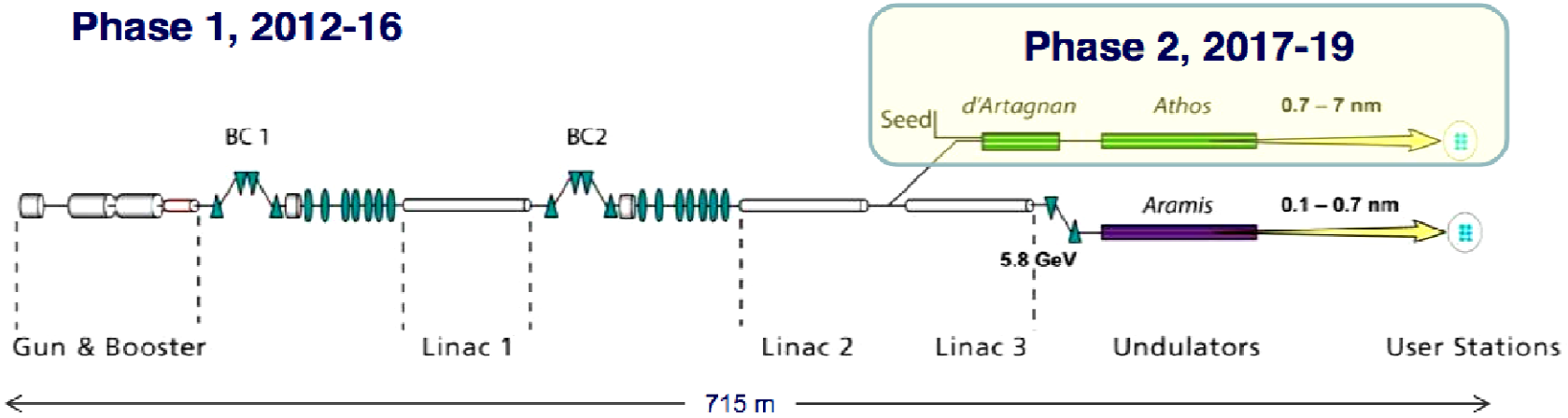
- **Motivation** – Compact X-Ray Free Electron Laser SwissFEL
- **SwissFEL** – Requirements for Timing Stability
- **Reference Signal Distribution** – SwissFEL Layout
- **Critical Issues and Components** – Libera Sync^{+}
- **Status & Outlook**

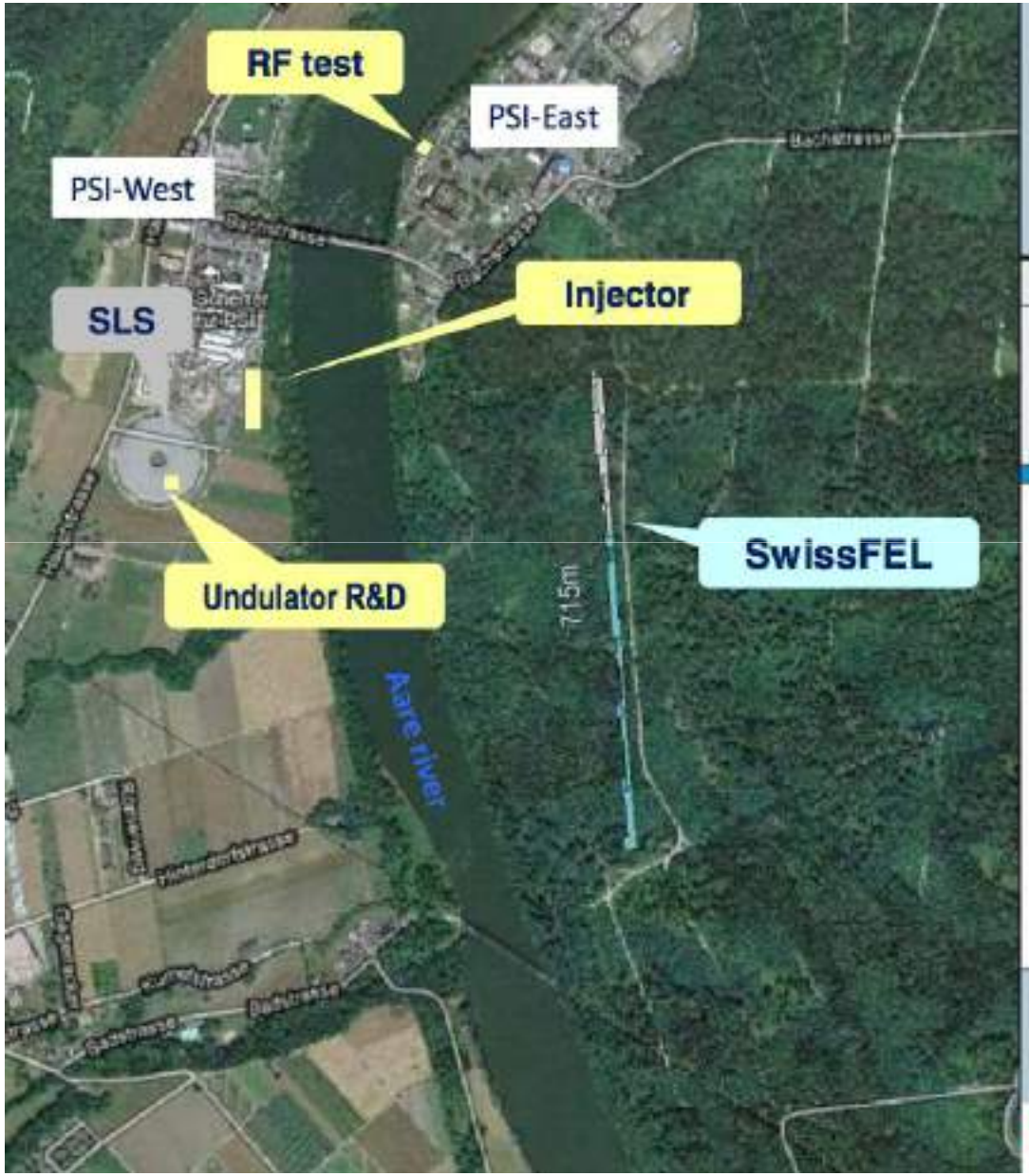
PSI Future Project SwissFEL – A Compact Hard X-Ray FEL User Facility

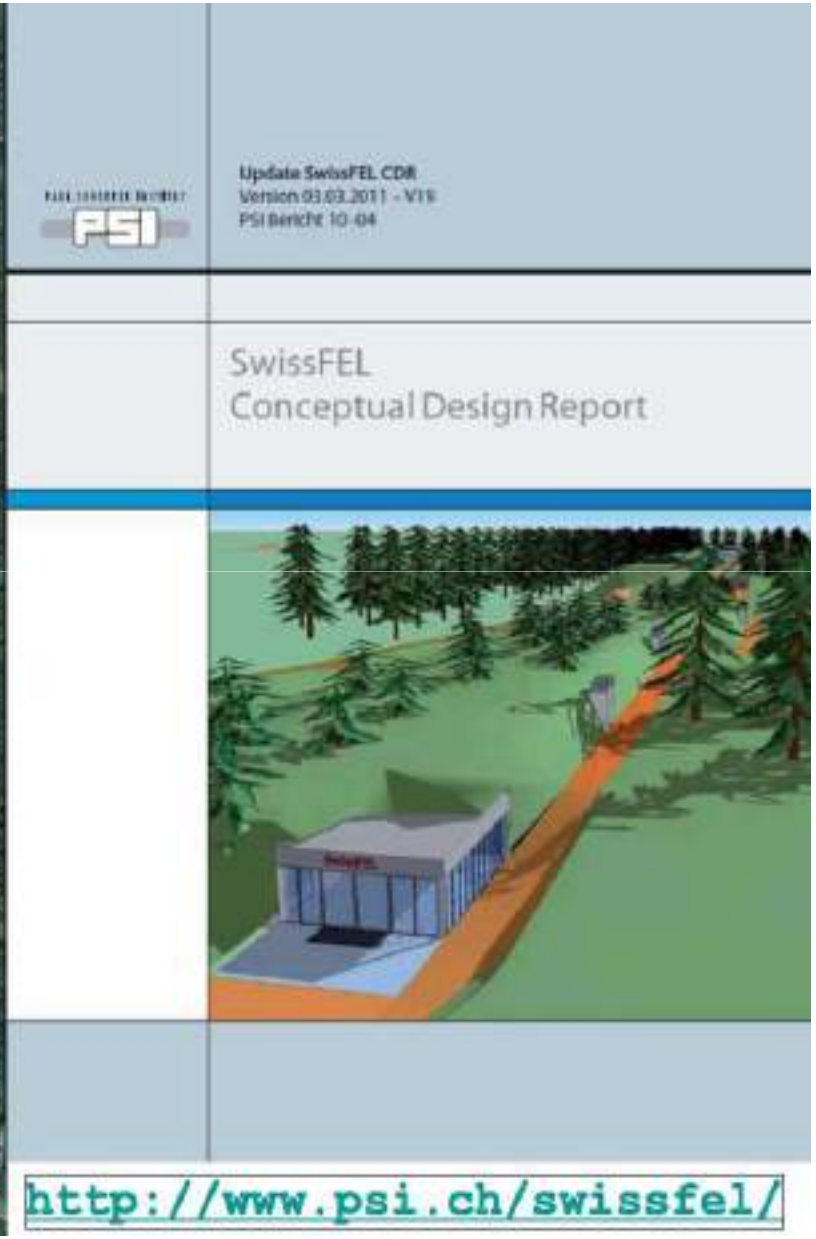


- Max. Beam Energy 5.8 GeV
- Length 715 m
- Norm. Emittance 0.15 – 0.35 μm rad
- Charge Range 10 – 200 pC
- RMS Bunch Lengths 5 – 30 fs
- Peak Current 3 – 5 kA
- Energyspread 350 keV
- Rep.-Rate 100 Hz (2nd Phase: 2 bunches @ 28 ns distance)

- Wavelengths 1 – 7 Å (hard X-ray) planar polarization
  7 – 70 Å (soft X-ray) circular polarization
- Pulse Lengths sub-fs / few fs / 30 fs
- Brilliance $1.3 \cdot 10^{33}$ ph / (s·0.1%bw·mm²·mrad²)

Reference Distribution System for SwissFEL





SwissFEL Longitudinal Tolerances for the Reference Distribution System

SwissFEL longitudinal tolerance budget is driven by peak current stability of 10 – 30 %

- **S-Band RF Photo Gun** — Ti:Sa laser generates photo electrons (τ = 10 ps (FWHM) @ 200 pC / 3.8 ps (FWHM) @ 10 pC)
  → laser pulse stability in reference to S-band RF gun...: 40 fs (rms)

- **Injector S and X-band** — linear magnetic bunch compression in BC-1 ($\tau \approx$ 200 – 300 fs (FWHM) @ 200 and 10 pC)
  → S-band and X-band RF phase stability...: 0.018° and 0.072° (~ 16.5 fs rms)

- **C-Band LINAC** — electron beam acceleration & BC-2 (τ = 18.5 fs (FWHM) @ 200 pC / 1.85 fs (FWHM) @ 10 pC)
  → LINAC 1 / 2 / 3 C-band RF phase stability...: 0.036° (~ 16.5 fs rms)

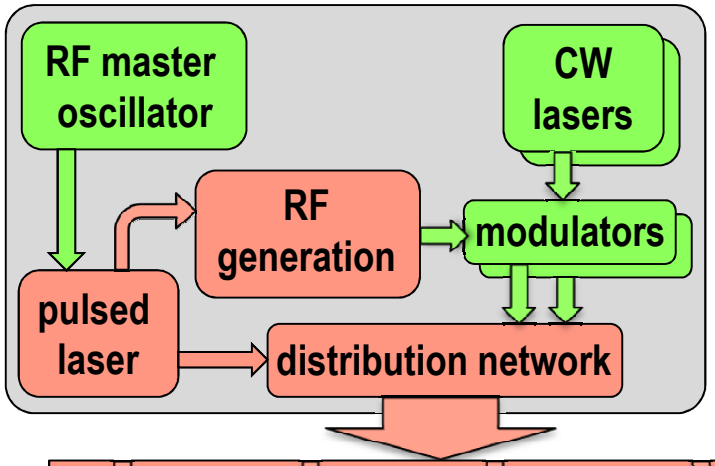
Keep in mind...: the total tolerance budget for RF stations is

$$\Delta\tau_{rms-jitter} = \sqrt{\tau_{sync}^2 + \tau_{LLRF}^2 + \tau_{HPRF}^2 + \tau_{Infra.}^2 + \ldots}$$

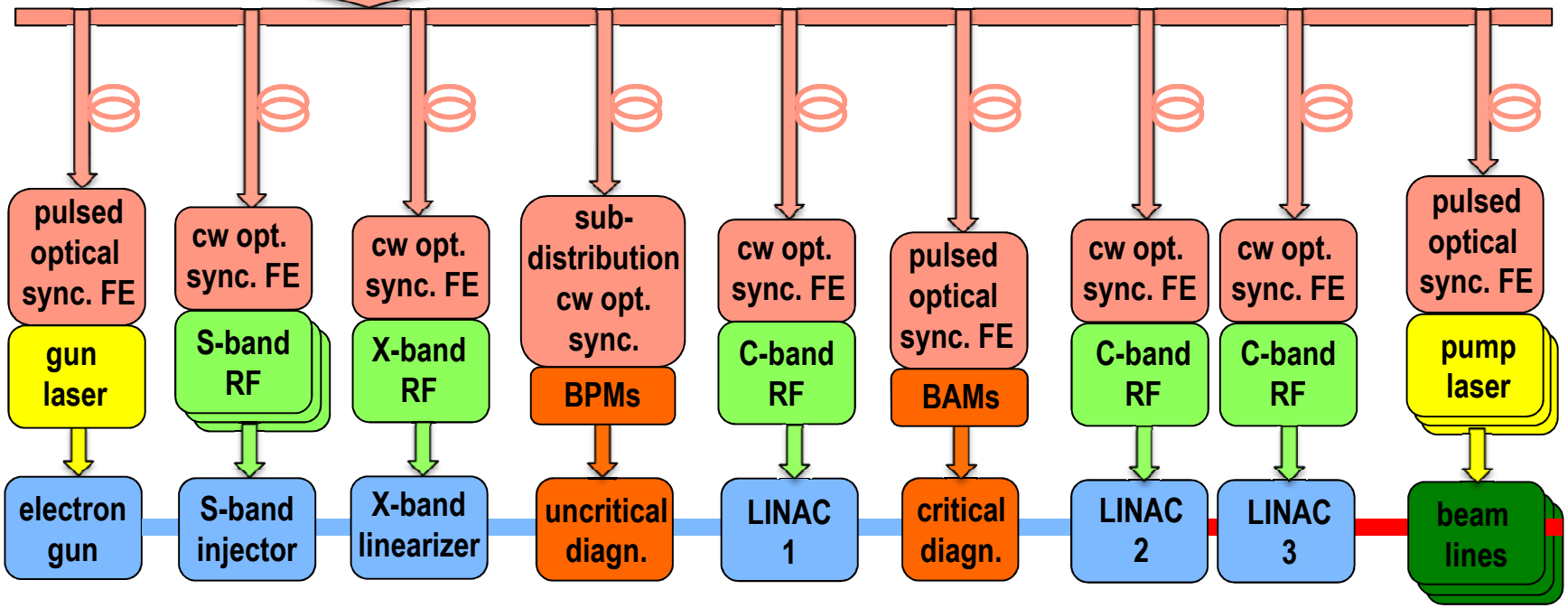
→ τ_{sync} << 10 fs rms

- **Experimental Stations** — (single-shot) laser pump – X-ray probe measurements
  → relative arrival time jitter ~ X-ray pulse length...: < 10 fs (rms)
  → low pump-probe drift...: < 20 fs_{p-p} per day

Schematic of Reference Signal Distribution to SwissFEL Sub-Systems

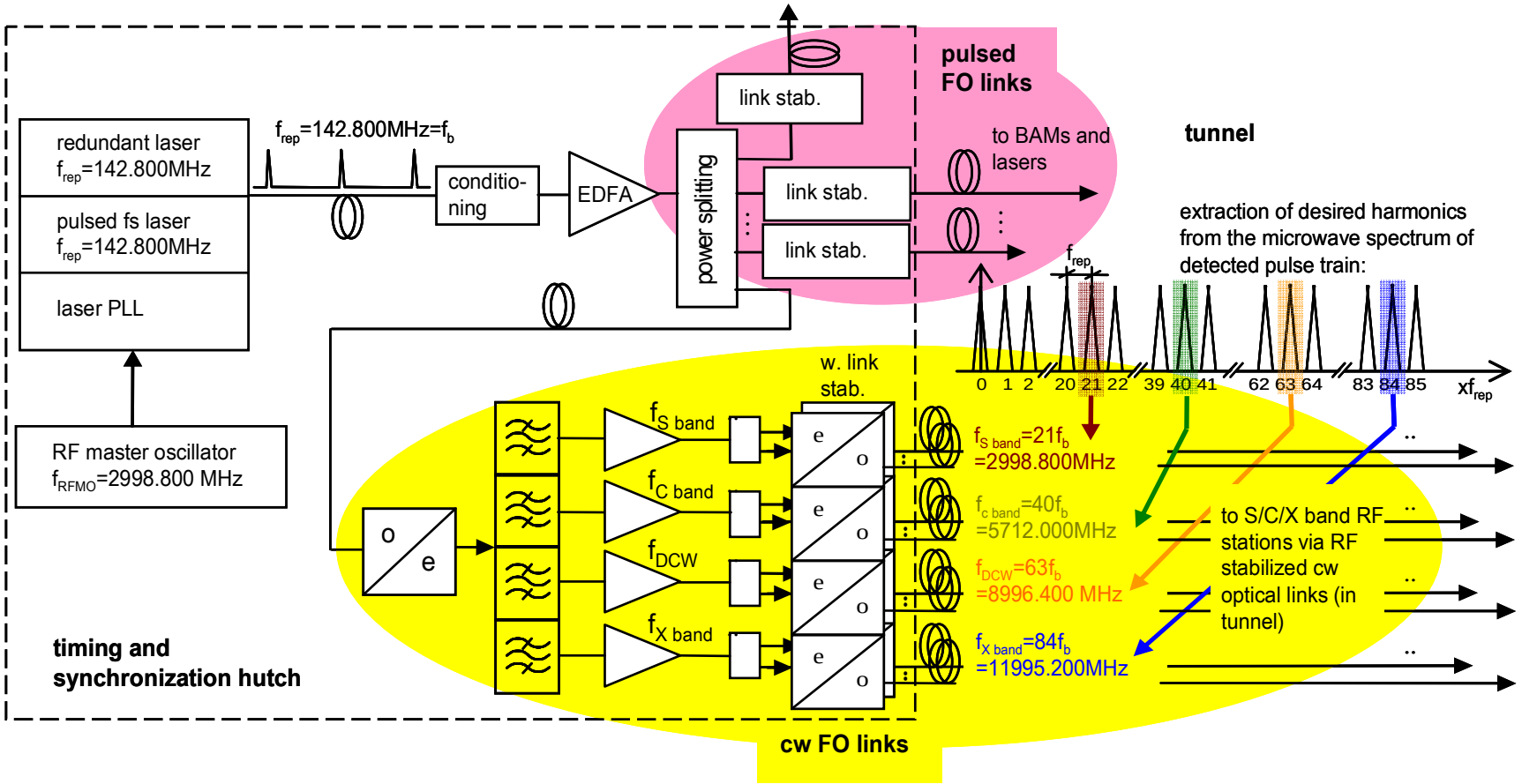


- pulsed optical links → ultimate stability and lowest drift for gun & experimental lasers, BAMs
- cw optical links → high stability and low drift for S-band, C-band & X-band RF stations
- optical sub-distr. → less critical clients like e.g. BPMs



Schematic of SwissFEL Reference Signal Generation and Distribution

- **RF locked pulsed laser** → generate mutually locked RF frequencies (frequency comb)
- **Distribution of…:** → pulse train to pulsed lasers and critical diagnostics (BAM)
  → locked RF frequencies with cw fiber optic links (mainly to RF stations)



Clients of SwissFEL Reference Distribution System

- **gun & exp. lasers, BAMs** → actively stabilized pulsed optical links (EDFL @ 1550 nm, 142.8 MHz, $\tau \approx 200$ fs)
  → optical cross-correlation for highly stable and drift free stabilization
  → performance goals: < 10 fs_{rms} jitter, < 10 fs_{p-p} drifts

- **uncritical sub-distr.** → actively stabilized cw optical link to central sub-distribution station
  → sub-distribution to e.g. BPMs by coax cables

- **RF stations** → actively stabilized cw optical links (Libera Sync+)
  → distribution of sinusoidal microwave reference signals
  → single frequency modulations for S-band, C-band and X-band RF
  → performance goals: < 10 fs_{rms} jitter (10 Hz – 10 MHz), < 10 fs_{p-p} drifts / day

- **"Libera Sync+"** → radio-over-fiber links based on telecom components (laser diodes etc…)
  → high reliability due to proven technology
  → high performance
  → moderate cost
  → simple installation and testing

Starting Point of Collaboration – Original Libera Sync Link Distribution

Transmitter Module Tx

Receiver Module Rx

Libera Sync Original: Stability of 180 m Link

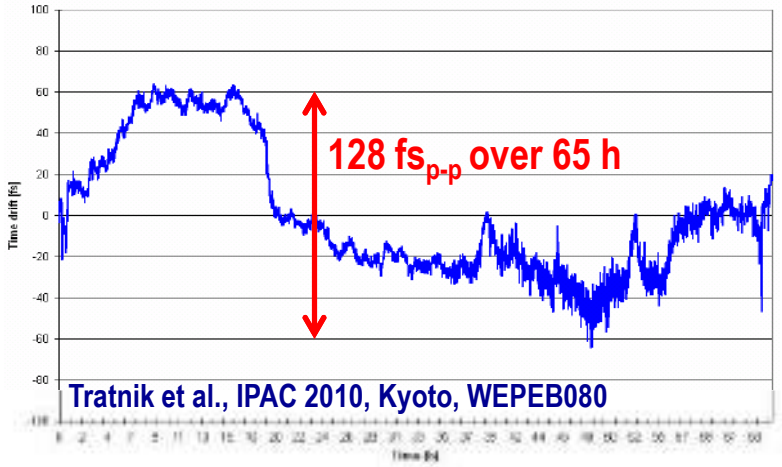


Figure 5: Relative time difference between the master-RF oscillator and the 180 m fiber link is 31.4 fs RMS (128 fs peak-peak) in a 65 h period.

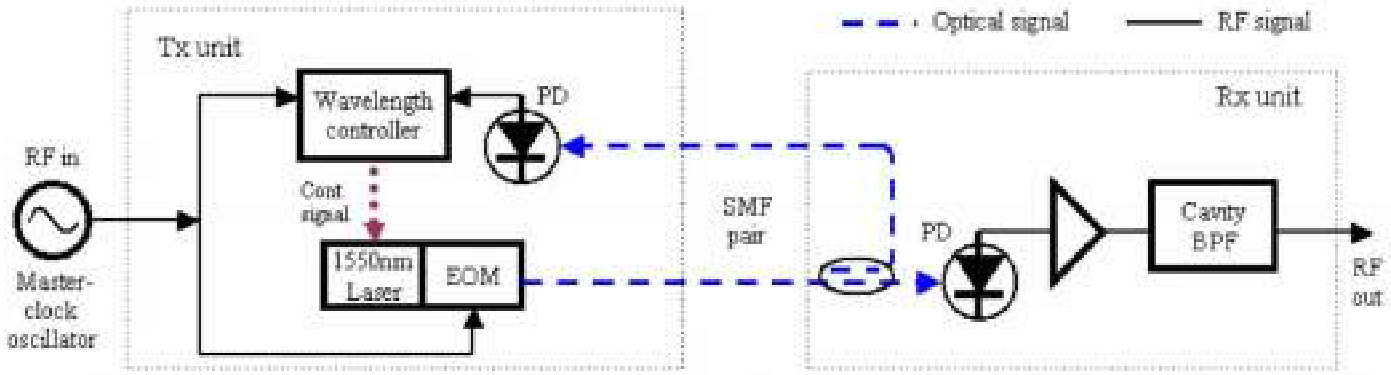


Figure 1: Simplified block diagram of the electro-optical synchronization system.

PSI – I-Tech Collaboration on "Libera Sync+"

Goal: optimize existing Libera Sync length stabilized fiber-optic link system for SwissFEL reference signal stability requirements

- **Motivation (PSI)**
  - → original Libera Sync provides already very good performance
  - → easy and reliable operation due to use of proven technology
  - → well developed firmware, user interfaces and remote control
  - → well established production process and experience in quality control
- **Motivation (I-Tech)**
  - → improvement of existing system for use in future FEL facilities
  - → experienced partner (PSI) with excellent know-how in opto-electronics
  - → shared (development) resources and minimization of risk (costs)
  - → use of PSI lab equipment and tests in SwissFEL Test Injector Facility
  - → market launch with ambitious project (SwissFEL user facility)
- **Collaboration…:**
  - → use of single fiber for up- and downlink
    separate fibers in original system caused "large" drifts due to different fiber characteristics
  - → optimization of components for lowest achievable noise and drift
    phase detectors, cables, photo-diodes, electronic circuits, mechanics…

CW vs. Pulsed Fiber-Optical Links – Main Challenges

cw fiber-optic link…:

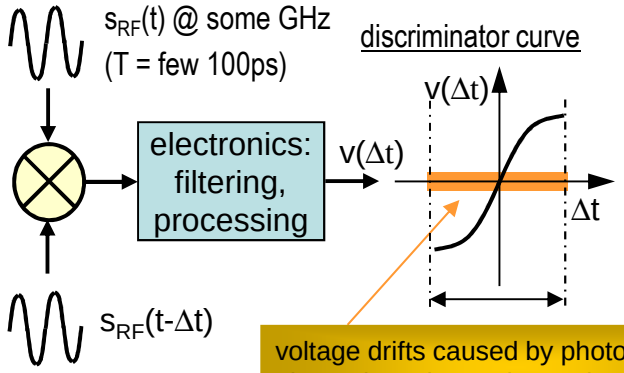
→ lower cost and less complex alternative to pulsed optical-fiber links

→ ultra-high stability of RF phase detection required

→ low drift photo-detection required

RF Phase Detector

(conventional alternative to OXC)

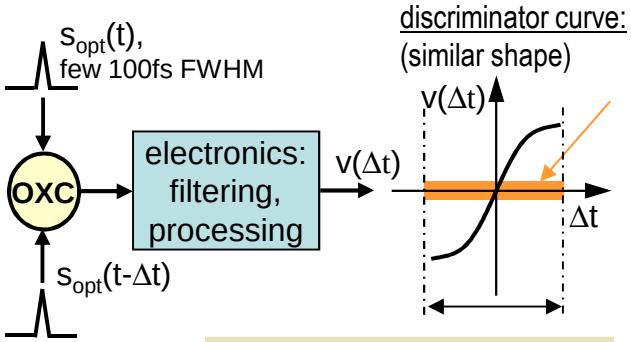


voltage drifts caused by photo-detection, phase detection + electronics:

≈ 0.01% of few 100ps → few **10fs drift**

Optical Cross-Correlator

(pulsed, ultimate phase/timing detector)



voltage drift caused by photo-detection + electronics:

1% of few 100fs → few **fs drift**

[few 100**ps**] ← 3 orders of magnitude lower sensitivity → [few 100**fs**]

⇒ **extremely high demands on detectors and electronics**

Optimized PD and Phase Detector Performance (drift stable part of the link concept)

PD and Phase Detector

→ Peltier stabilized phase detector (temperature stability < 0.01 °C)

→ use of temperature insensitive cables

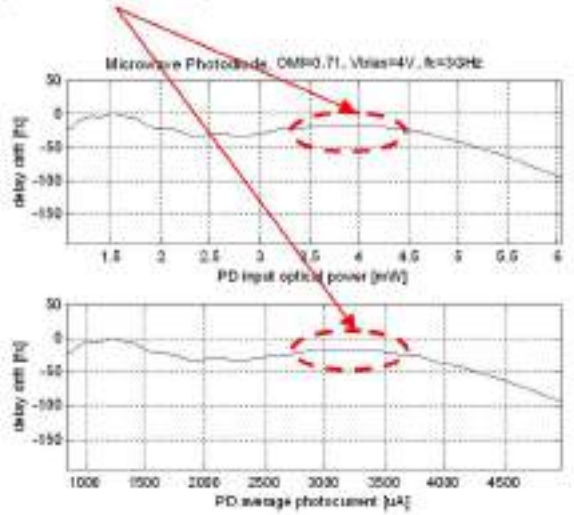
→ laser intensity on PD at vanishing AM/PM conversion spot (sweet spot)
to compensate for changes in laser power due to ΔT and / or polarization changes

→ amplitude stability kept to < 0.2 dB

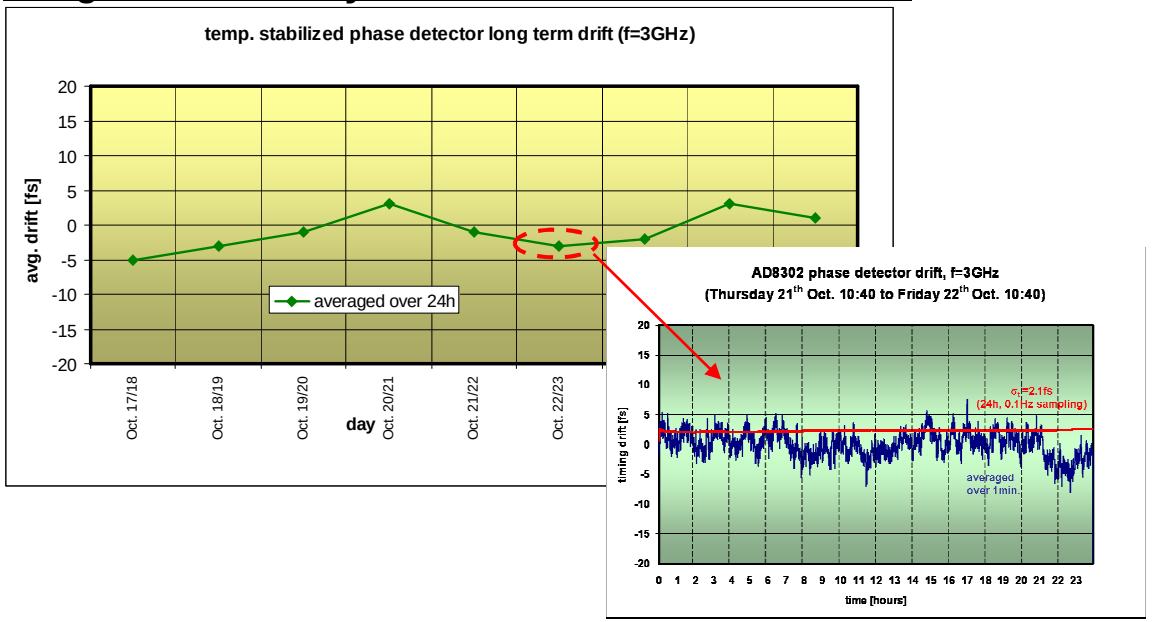
→ set-up under normal (non temp.-stabilized) environmental conditions
only covered with cardboard in electronics lab

PD Operation Point

vanishing AM/PM conversion
("sweet spot")

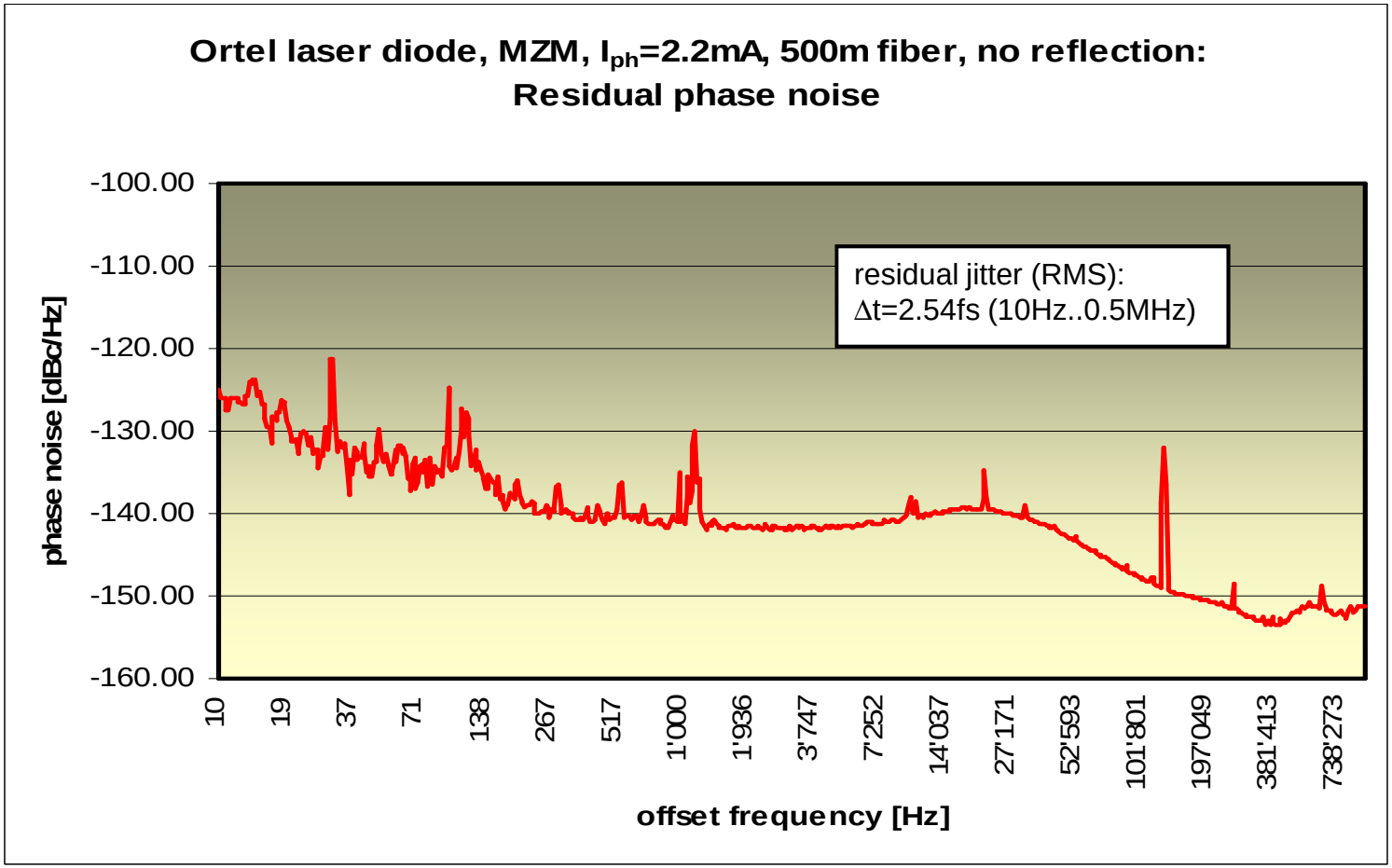


Long Term Stability of Phase Detector < 10 fs$_{p-p}$



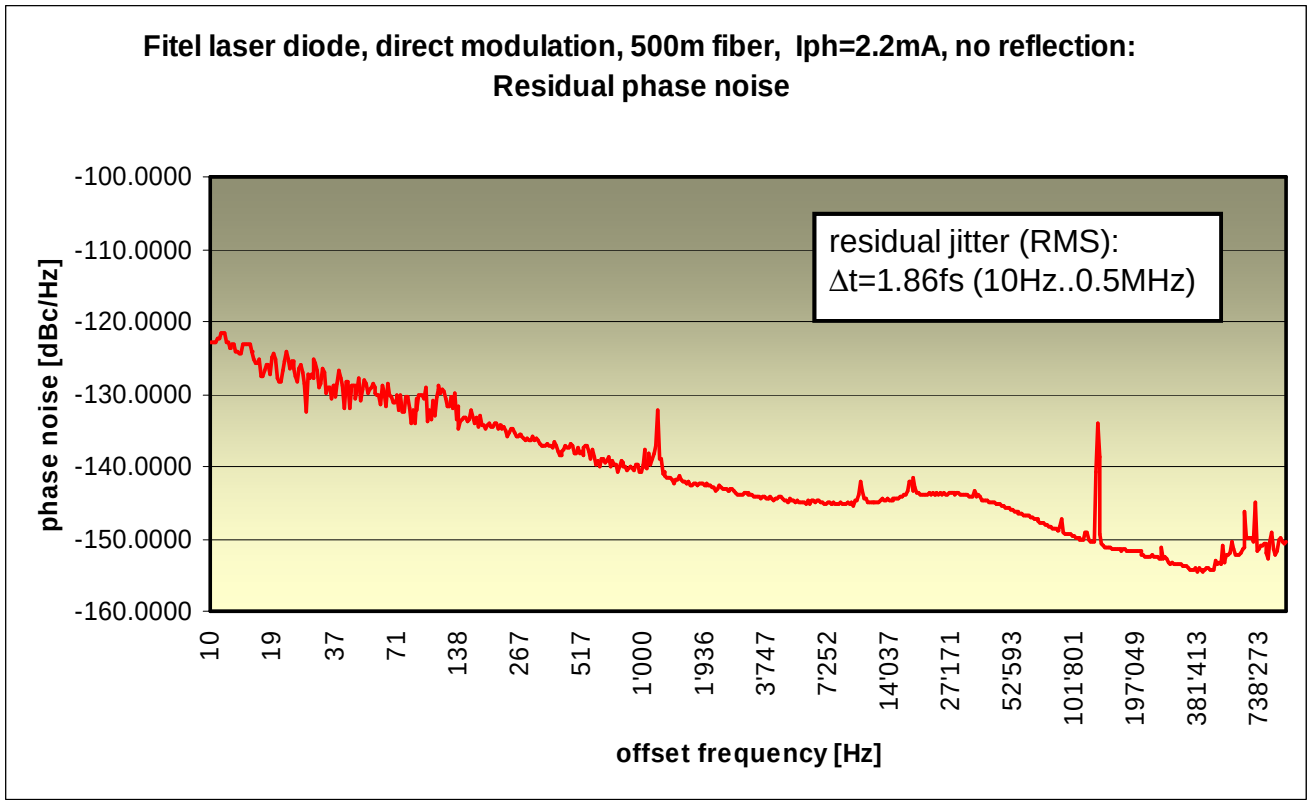
Feasibility of CW Radio-over-Fiber Link Concept – Components (Example 1)

CW Laser Diode & Mach Zehnder Modulator @ 3 GHz (low noise part of the link concept)



Feasibility of CW Radio-over-Fiber Link Concept – Components (Example 2)

Directly Modulated Laser Diode @ 3 GHz (low noise part of the link concept)

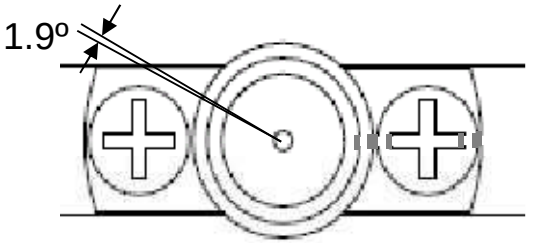


Add. Jitter Contributions → link group delay stabilization (~ 2 fs for 200 Hz control bandwidth)

→ electronics (few fs)

Additional Timing Drifts from "Out-of-Loop" Transmission Media

10 fs ≙ 3 μm in air or 2μm in typical coax cables or optical fibers or **1.9º turn** of SMA



Material		Sensitivity	Timing drift
steel		15ppm/ºC	50fs/ºC/m
standard SM fiber	temperature rel. humidity	8ppm/ºC 25ppm/10%RH	40fs/ºC/m 125fs/10%RH/m
temp. optimized fiber (LCP coated)	temperature rel. humidity	<0.75ppm/ºC 4.1ppm/10%RH	<3.7fs/ºC/m 20.2fs/10%RH/m
std. coax cable (bulk PTFE)		-85ppm/ºC	-425fs/ºC/m
temp. optimized coax cable (air-filled PTFE)		<1..3ppm/ºC	<4.2..12.5fs/ºC/m
air	temperature pressure rel. humidity	-3ppm/ºC 2ppm/10mBar 4ppm/10%RH	-10fs/ºC/m 7fs/10mBar/m 13fs/10%RH/m

Tentative Schedule for PSI – I-Tech Collaboration

- First 3 GHz prototypes of optimized "Libera Sync+" expected for Spring 2013
- Extensive Testing in SwissFEL Test Injector Facility
- 6 GHz prototypes: End of 2013
- 9 GHz and 12 GHz prototypes: Spring 2014
- Delivery of approx. 40 units for SwissFEL: 2015