Synchronization of accelerators

Status and perspectives

Schlarb, Holger

KfB Perspectives
Karlsruhe, 27.04.2018

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

DESY.

Synchronization is ….

- … the coordination of events to operate a system in unison. Systems that operate with all parts in synchrony are said to be synchronous or in sync.

→ Controlling systems in time to one another!

Rem: Prediction of systems time behavior sometimes sufficient

But: little overlap to frequency metrology (… atomic clocks).

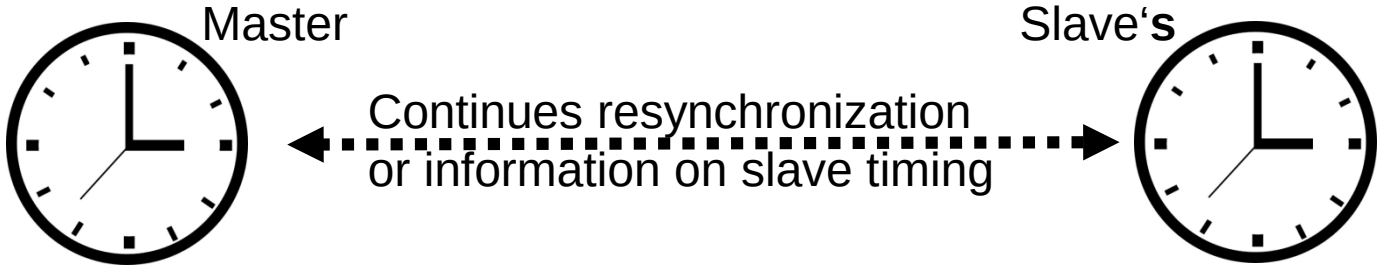
We look for 1fs/1day → 10^{-20} relative frequency instability

Examples:

RF Oscillators
Laser Osc.

Examples:

Local RF Oscillators
Laser systems
Diagnostics
RF controls



Low-phase noise clocks help → reduces locking bandwidth

Accelerator with high synchronization needs

Three main reason:

Beam stability | Pump-Probe Configration | Beam-laser interaction

Examples:

Is post sorting possible?

- Free Electron Lasers (FELs) — SASE: YES, but… Seeded: No
- Ultra-fast Electron Diffraction (UED) — Sometimes, not desired
- e^- driven THz sources (e.g TELBE) — YES,, with restrictions, but
- Compton source (e.g. ELBE) — No
- Plasma acceleration (e.g. SINBAD) — No

Synchronization vs. Timing

There are various types of signals, frequently confused

rms jitter

Trigger signals (digital subsystems, CPU)

~ 100 ps
(10-100Hz)

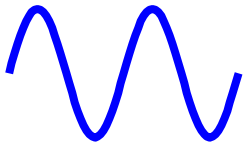
Clocks (digital subsystems, ADC, DAC, CPU)

~ 5–20 ps
(1-100MHz)

e.g. X2TIMER ~ 10ps rms jitter
(may also be used for synchronisation
if RF filtered

Exeption
Clocks for fast ADC
40fs….200fs

Analog (RF phase reference, VM, LO)

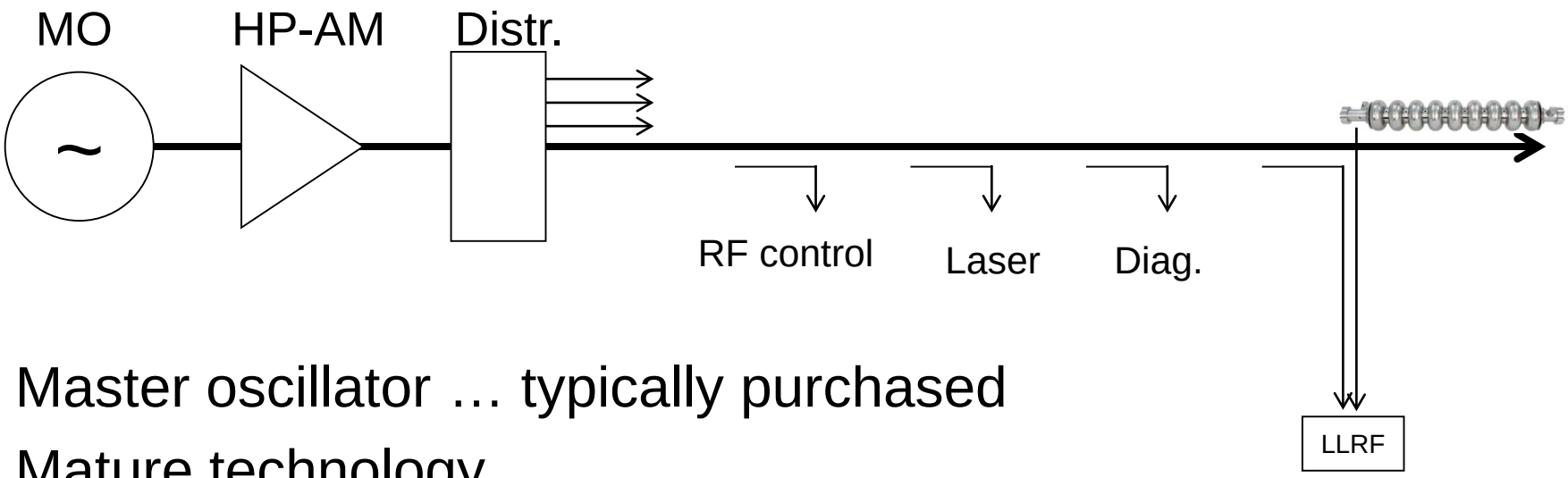


~ 10fs – 10ps
(~0.1-10 GHz)

Optical (laser, diagnostics, experiment)
e.g. laser pulse train

< 10 fs

Synchronization classical approach

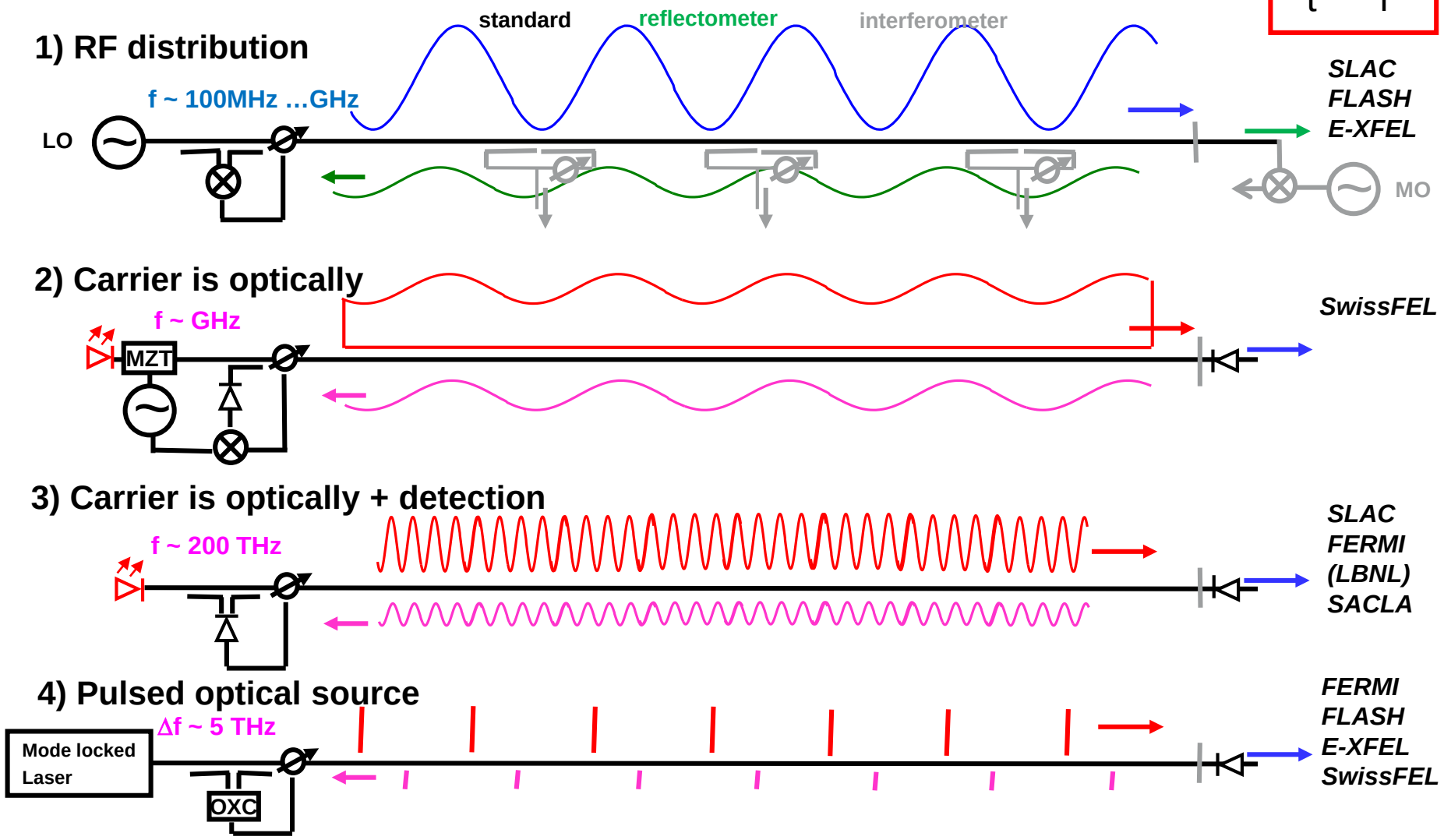


- Master oscillator … typically purchased
- Mature technology….
- Synchronization excellent on short time scales (~ms)… fs
- Issues:
  - Interconnected system
  - Phase drifts (RF components/Cables) → temp stabl. /common
  - Losses for long distance … (km for GHz)

Advanced Synchronization Methods

Various approaches:

$$\frac{\Delta t}{t} = \frac{\Delta f}{f}$$



What are the challenges?

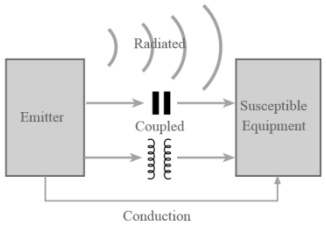
Environmental perturbations…

Vibration

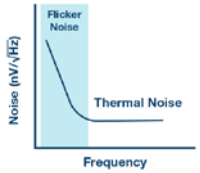
Ground Motion

Temperature

Humidity

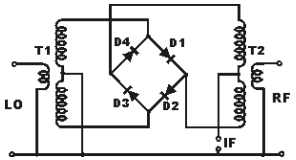


EMI



Noise Limits

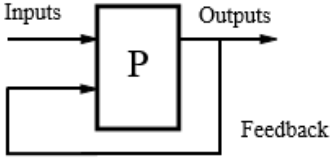
State-of-the-art designs….



Electronics

Optics

Lasers



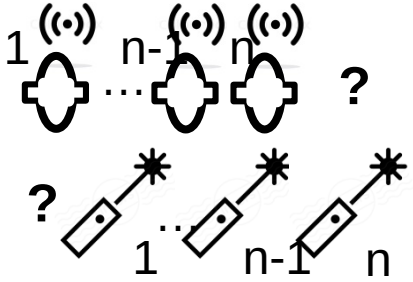
Feedbacks

Automation

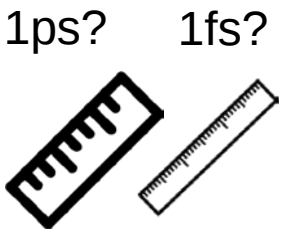
& achieving performance, reliability and maintainability simultaneously

Synchronization system choice?

Distance



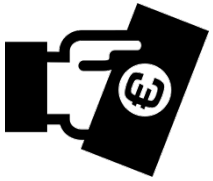
End-stations



Precision

Duration

Infrastructure

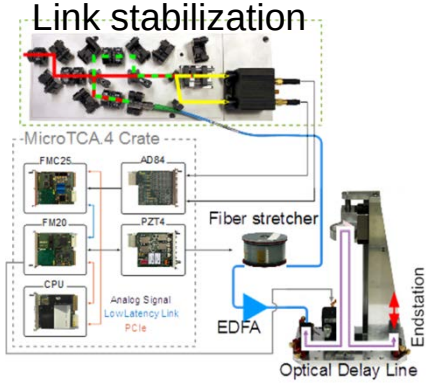


Budget

Examples 1: European XFEL

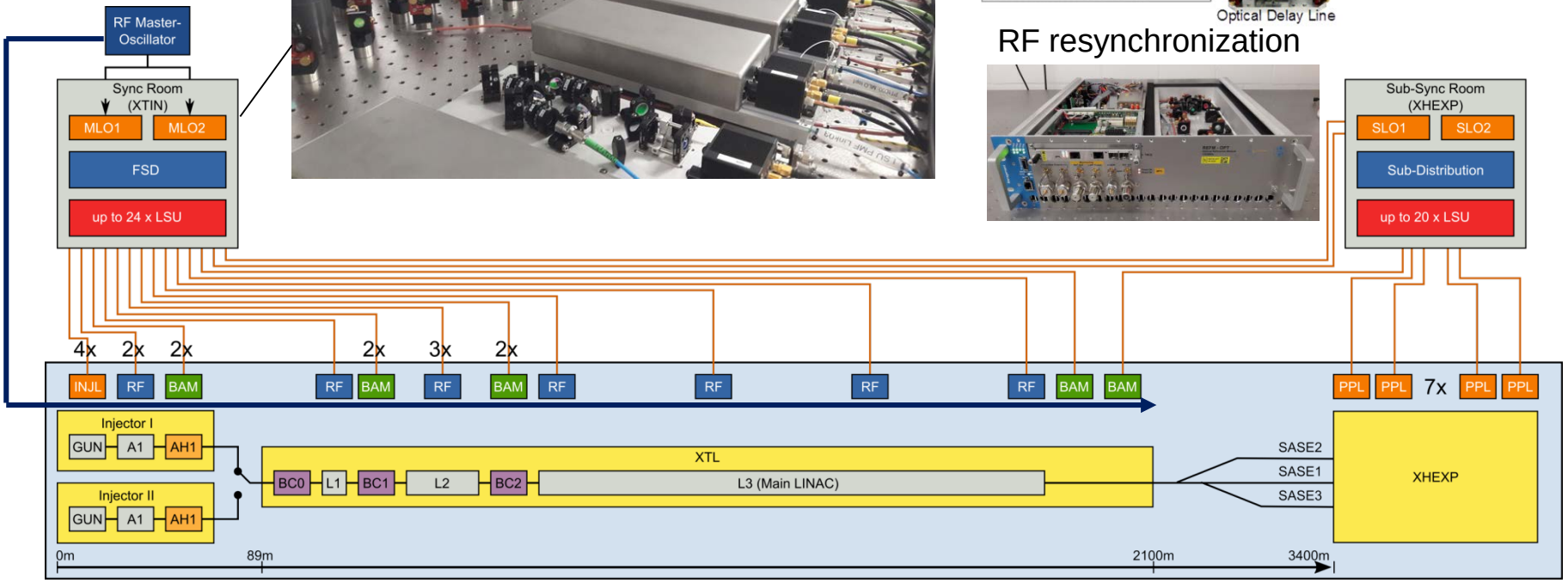
hybrid system, RF distribution + pulse optical + beam based FB (intra/pulse-to-pulse)
→ Robustness + Performance

Link stabilization

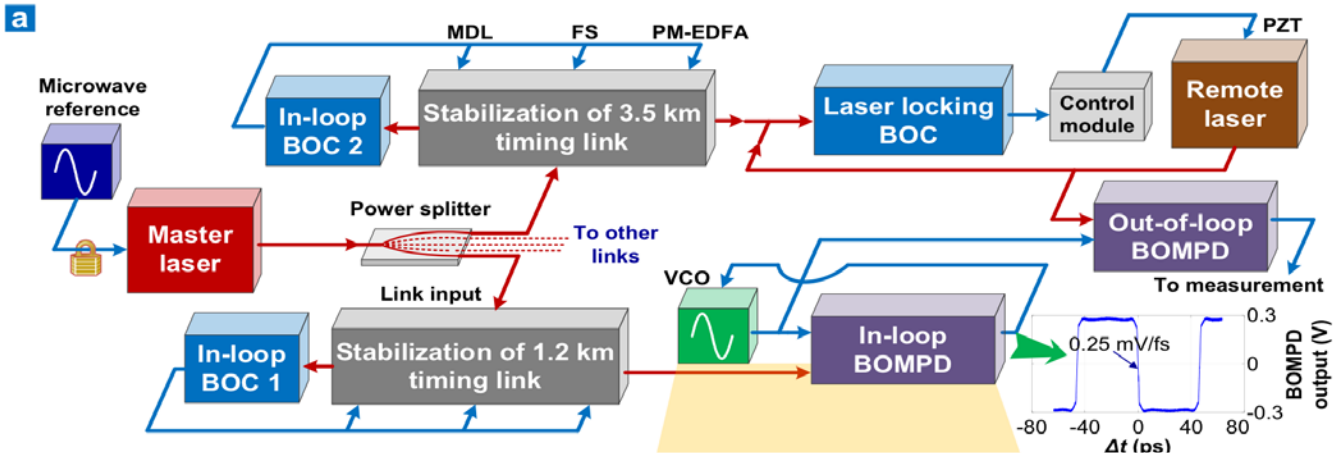


Master Oscillator, Distribution and Links

RF resynchronization

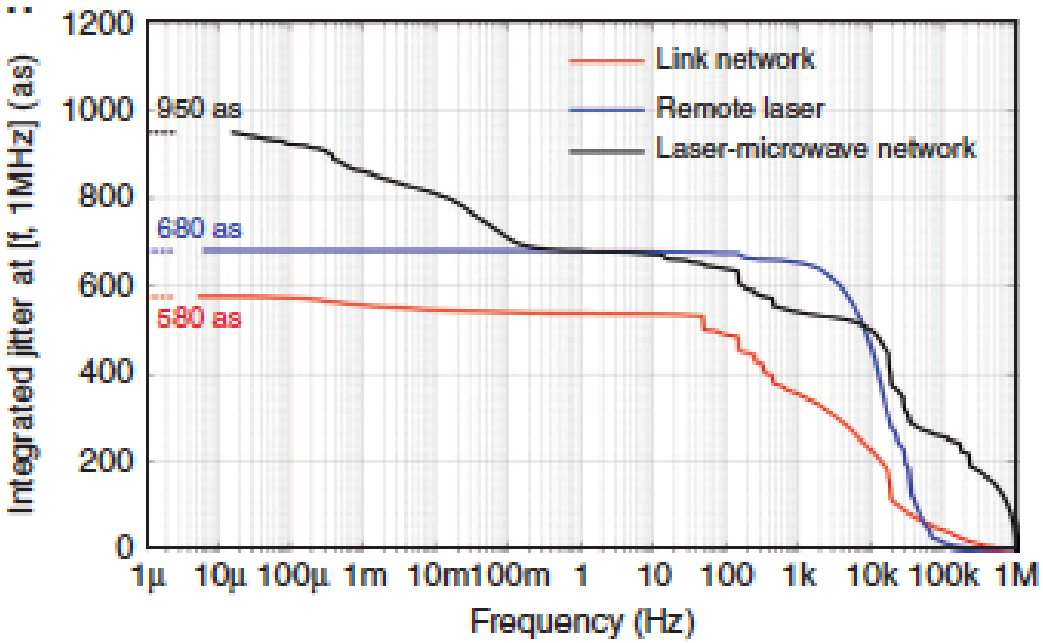


Example 2: Studies toward ultimate performance



- Well controlled environment
- Suited sub-systems
- Optimized designes

➔ sub-fs can be achieved



Courtesy: F. Kärtner

RF Measurement Equipment

- Phase noise & signal source analyzer
- Essential for R&D
- Required for evaluation in facility
- 10 year ago: do it yourself…
- Today: excellent equipment exists
- Strong interplay: technology progress ↔ measurement equipment
- But: rather expensive…

E5052B SSA Signal Source Analyzer,
10 MHz to 7 GHz, 26.5 GHz, or 110 GHz

R&S®FSWP-B1
Spectrum Analyzer, 10 Hz to 26.5 GHz

Low Phase Noise RF Sources

- Enormes progress over past decade (almost x10)
  - Oven Controlled Crystal Oscillator (OCXO) & up-multiplied
  - Dielectric Resonance Osc. (DRO)

Jitterperformance 1kHz .. 10MHz: **0.61** fS

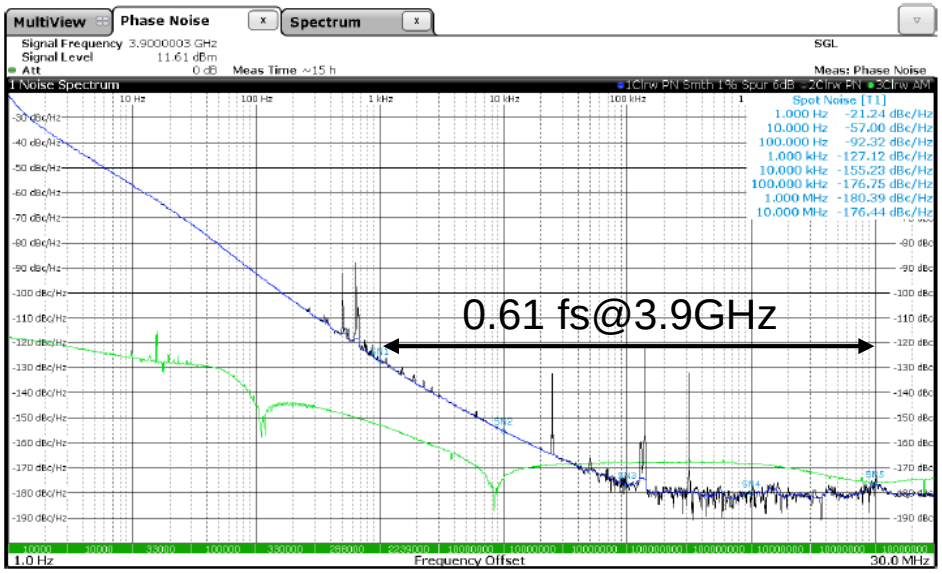
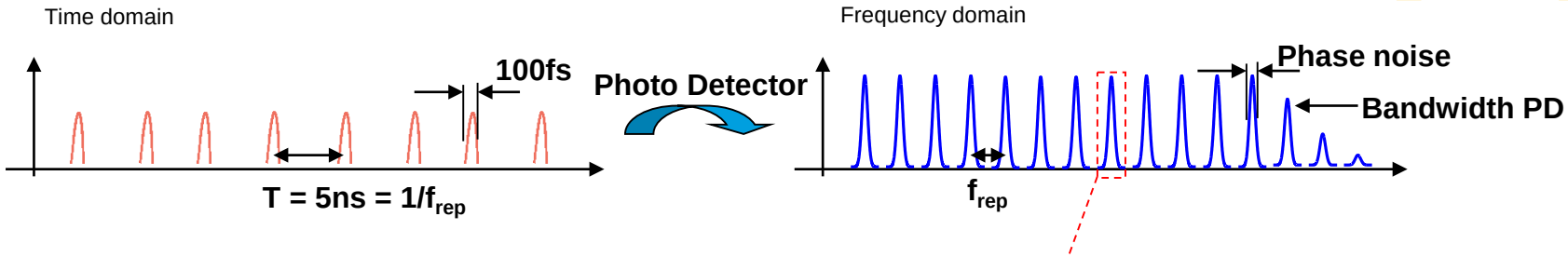


Diagram 1: Phase Noise / AM-Noise **Blue: Phase Noise** **Green: AM-Noise**

LAURIN AG

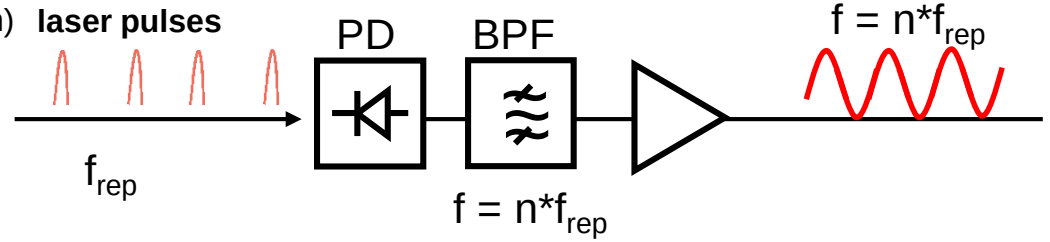
RUPP tronik
Beratung und Vertrieb • HF - und Mikrowellentechnik

Laser-to-RF & visa versa



Direct conversion with photo detector (PD)

– Low phase noise (to be proven at end-station)
– Temperature drifts (0.4ps/C°)
– AM to PM conversion (0.5-4ps/W)
– Potential for improvement
(corporation with PSI)

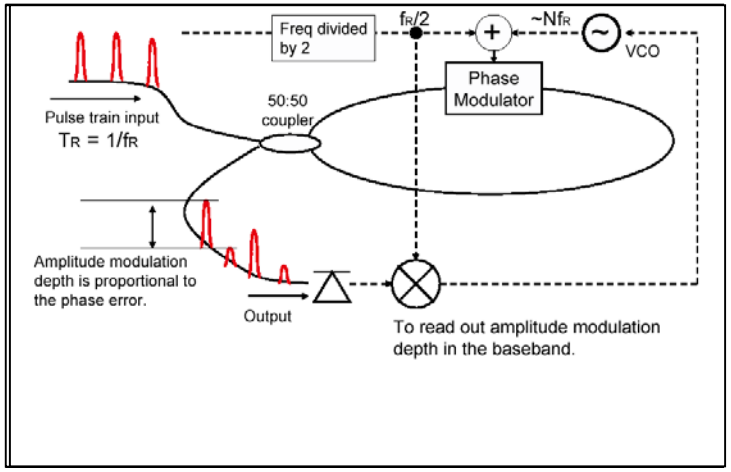


Sagnac loop interferometer

– balanced optical mixer to lock RF osc.
– insensitive against laser fluctuation
– Very low temperature drifts

MZI based balanced RF lock

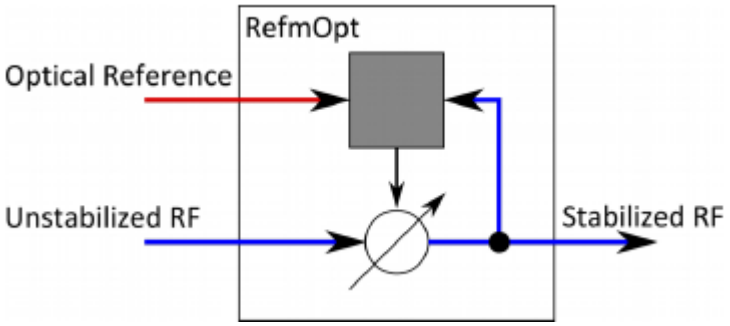
– new scheme, also well suited for lower frequencies e.g. 1.3GHz
– very robust and flexible



Laser to RF locks & visa versa

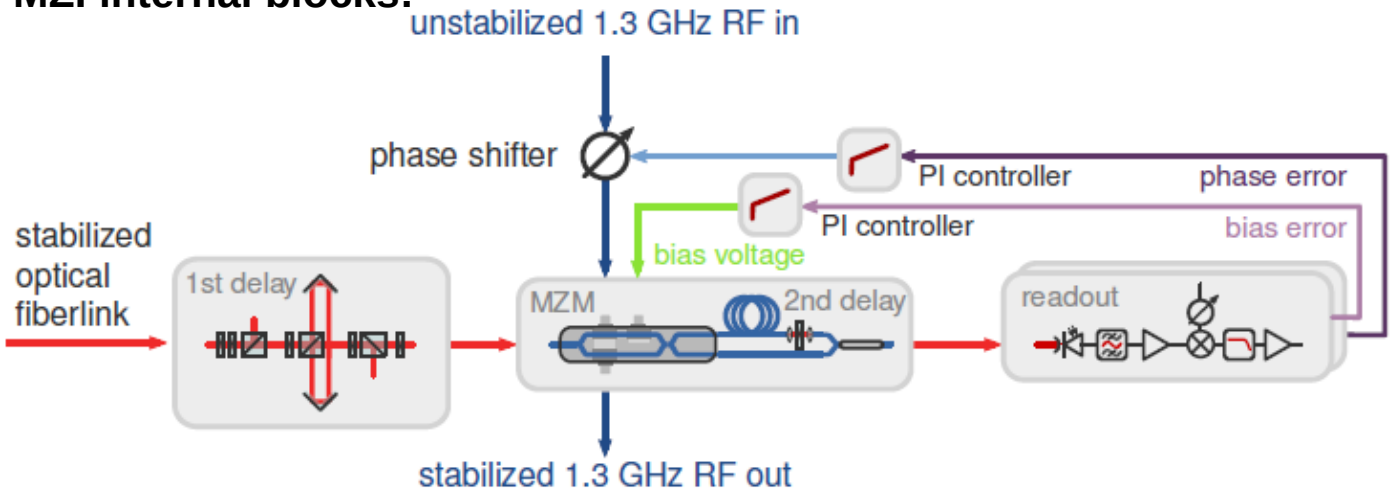
MZI based balanced optical-RF phase detector

Functionality:

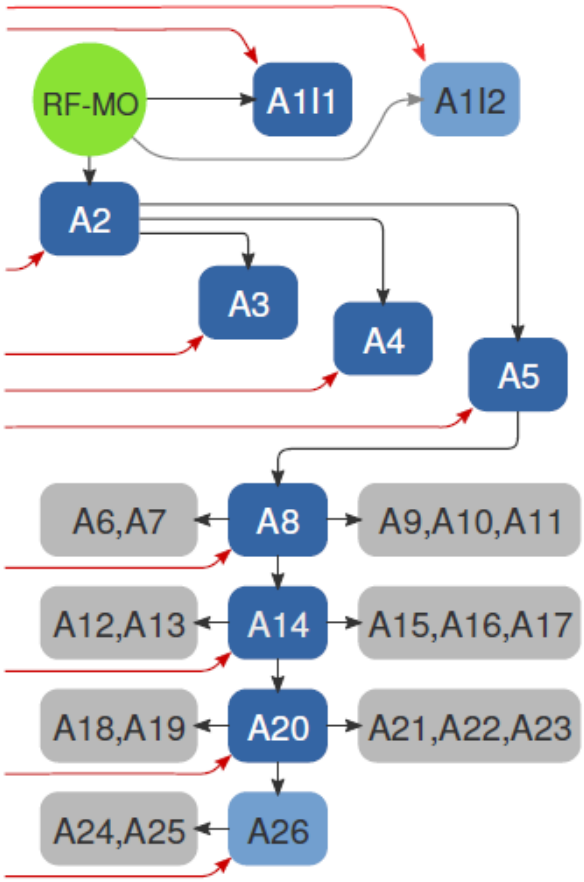


Humidity sealed / temp. stabilized

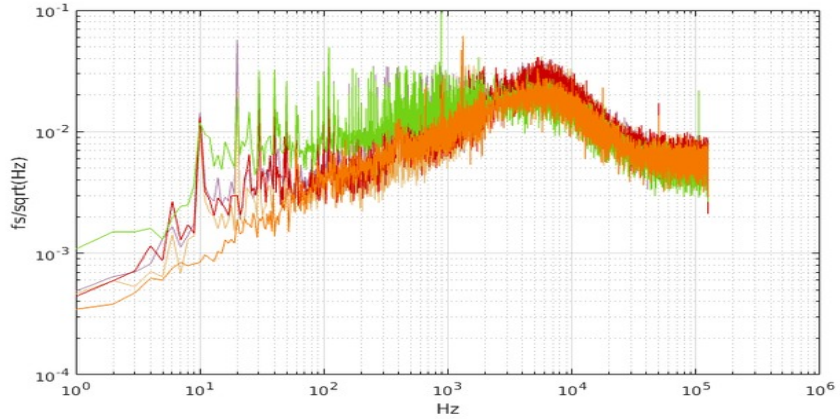
MZI internal blocks:

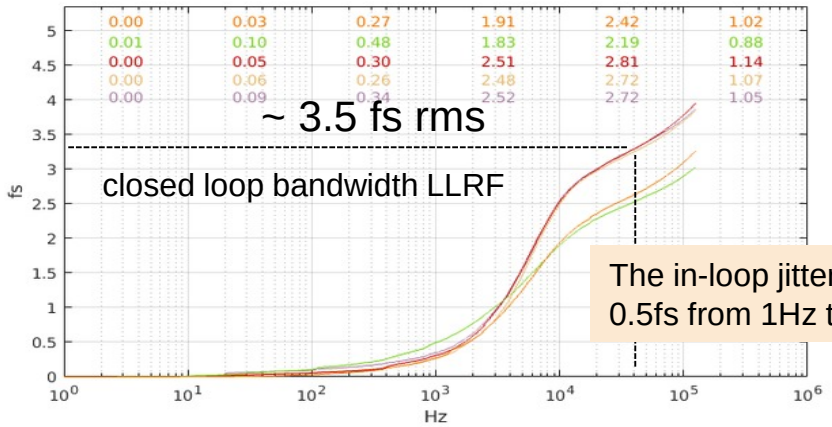


RF distribution resynch. by opt. reference

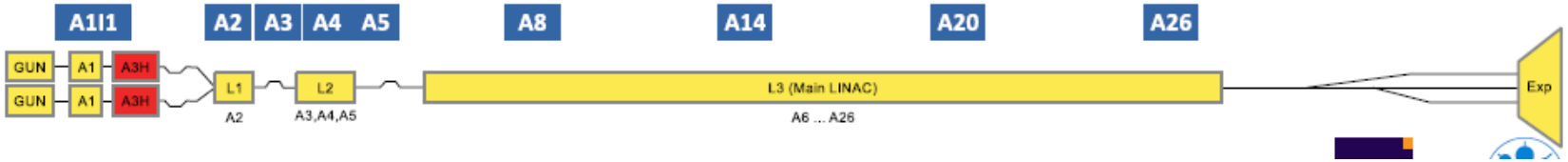


I1 (orange), A2M (green). A3M (red), A4M (yellow) and A5M (purple)



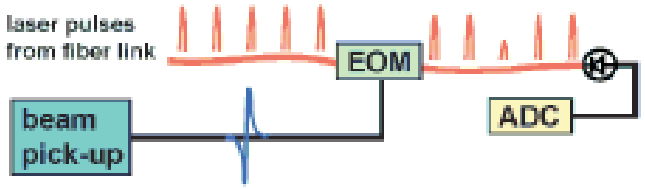


The in-loop jitter to less than 0.5fs from 1Hz to 1kHz.



Bunch arrival diagnostics

- **At European XFEL/FLASH**

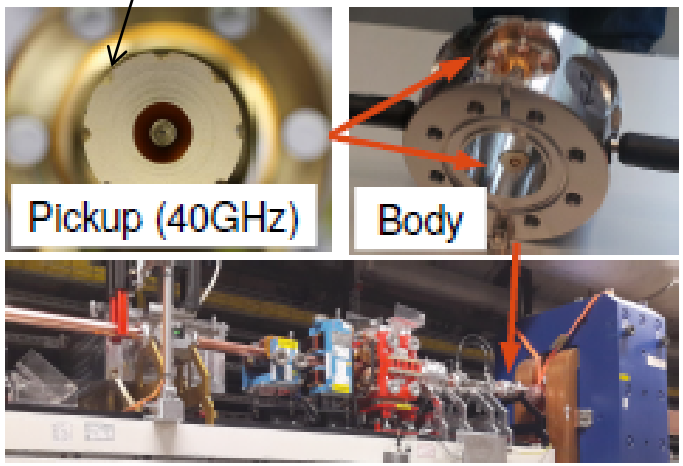


Target specs:
<10fs@20pC resolution
(not yet achieved…)

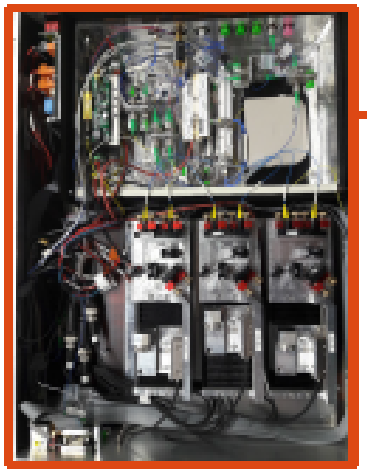
Desired: 1fs@10pC

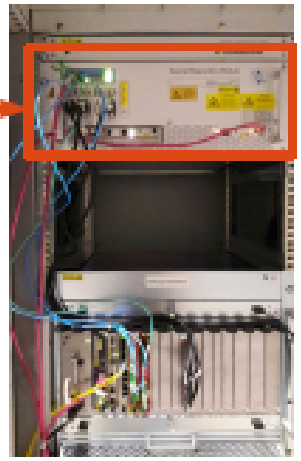
Charge (pC)	Sensitivity (fs/%)	Resolution (fs)
50	120	24.0
100	84	16.8
140	67	13.4
200	38	7.6
450	27.8	5.6

Verbundforschungsantrag



Beamline Installation


BAM Front-End


Rack Installation

(✓)

- **REGAE / SINBAD: Bunch arrival cavity + RF processing (expected < 10fs@1pC)**

➔ **New techniques to be explored…**

To Do

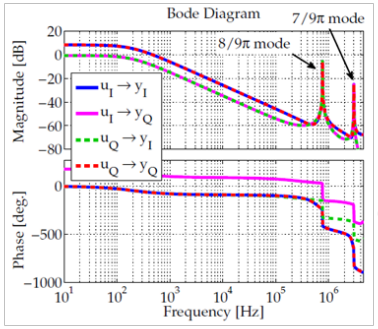
➔ **BMBF**

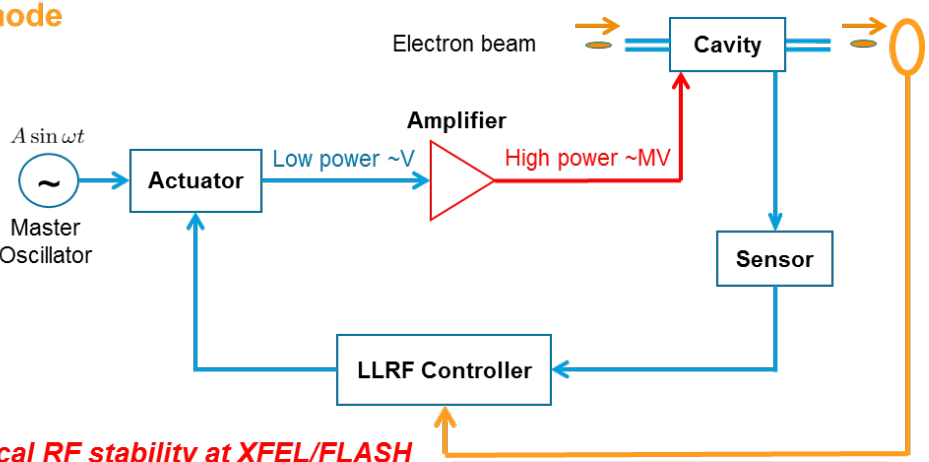
Precision RF controls

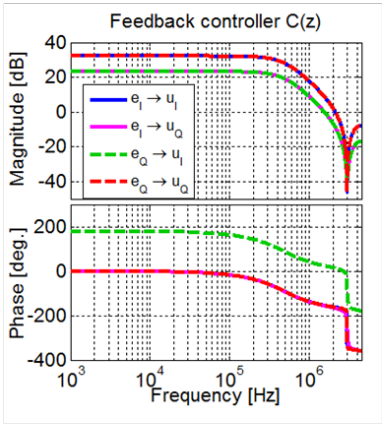
Specification for RF Field Control
ΔA/A < 0.01 % and Δφ < 10 mdeg.

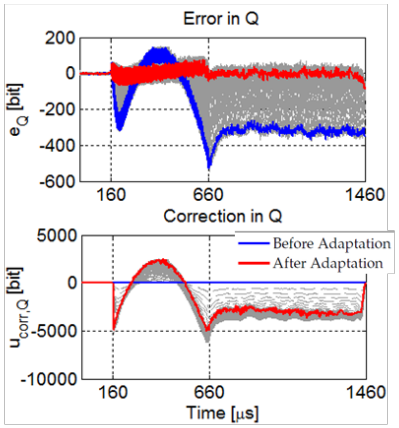
Example at FLASH and European XFEL operated in pulsed mode

1. System characterization
2. RF Feedback controller design [1]
3. Iterative learning controller design
4. Beam-based feedback [2]

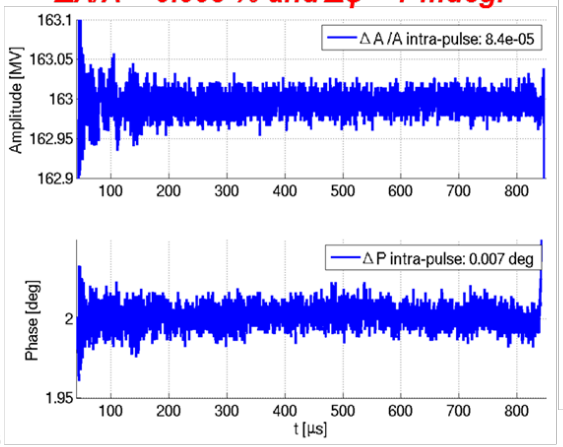


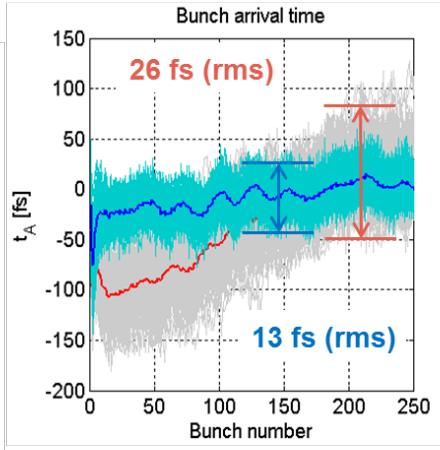






Typical RF stability at XFEL/FLASH
ΔA/A ≈ 0.008 % and Δφ ≈ 7 mdeg.





[1] PhD Thesis, C.Schmidt, 2010
[2] PhD Thesis, S.Pfeiffer, 2014

- **Improvement x 10 every decade… now ~ 10 fs**
- **Controlling drifts one of main challenges (still elements out-of-loop)**
- **We dont trust pickups anymore….on 1e-5 levels (other passband,…)**
- **For NRF 1-2 us RF pulses → temp. reg. / pulse compressors / modulator stability**

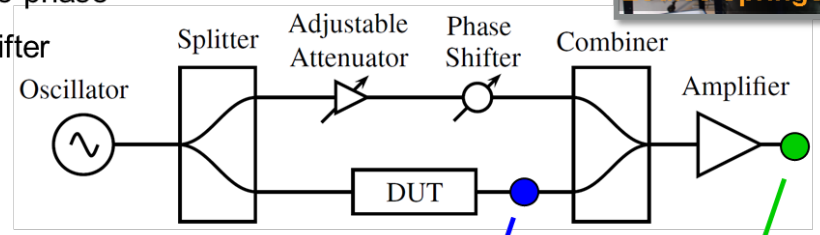
→ BMBF

RF Controls …. next generation

Study: Receiver with attosecond-resolution

In cooperation with TU Hamburg-Harburg (master student)

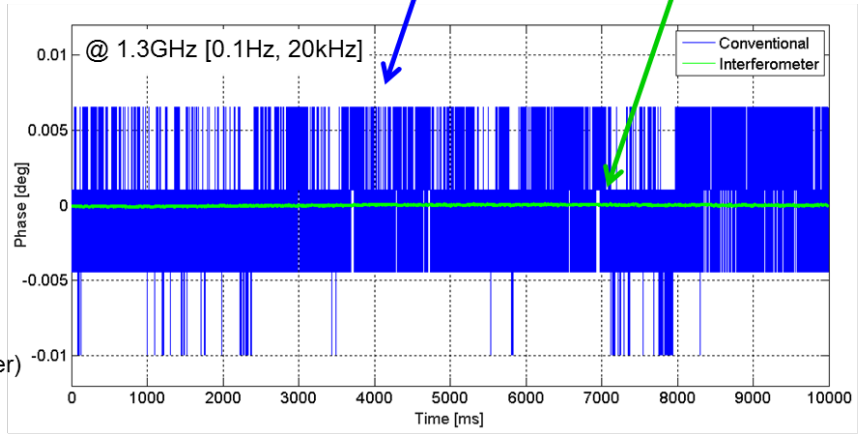
- Laboratory measurement setup to precisely measure the phase
- Device Under Test (DUT) is voltage controlled phase shifter
  - Cavity probe signal in application
- Interferometer based method to suppress the carrier



Reduction factor >50: 2.6mdeg (rms), ≈5.5fs | 0.045mdeg (rms), ≈96as

Outlook: Technical realization (2018-20??):

- Many challenges to be addressed → long-term development
- Pulsed mode vs. continuous mode operation
- Carrier tracking algorithm, ...
- Development of ultra low noise attenuator and phase shifter
- …

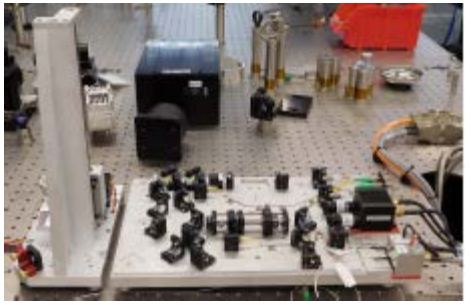


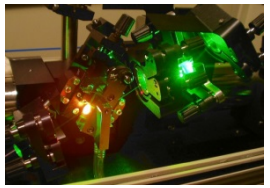
Blue: signal in front of the interferometer (non-suppressed carrier)
Green: signal behind the interferometer (suppressed carrier)

→ **BMBF**

External Laser systems

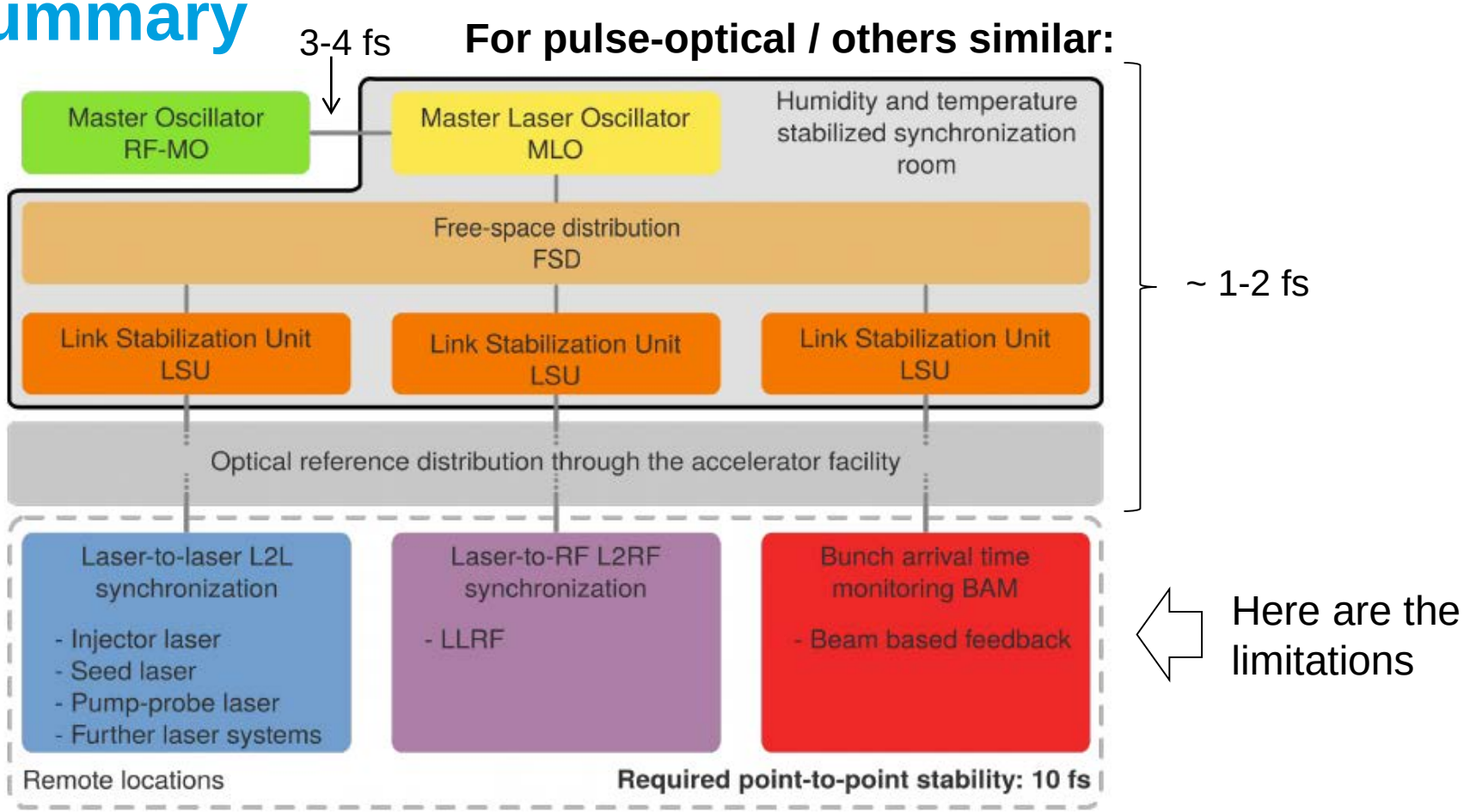
- Synchronization detectors based on optical cross-correlation (precision < fs)
- Laser osc. performance very different
  - Erbium …. + engeering …
  - TiSa … often have problems
  - Strong boundaries (choice not free)
  - Designs are not made for precision synchronization
- High power system… main problems
  - Ti:Sa … several loops required, 10 Hz …
  - OPA … have their own challenge
  - Transport to experiment





→ **BMBF**

Summary



High power chain
Laser transport

RF controls → 1 fs
Drifts

Resolution
New Techniques

+ system understanding as a whole
+ costs and complexitiy

➔ Will be still topic of R&D for next decade

Thank you