# Synchronization of Accelerator Sub-Systems with Ultimate Precision

Holger Schlarb

MSK/DESY

- Sources of arrival time jitter
- Synchronization systems
- Low level RF controls
- Beam based feedbacks

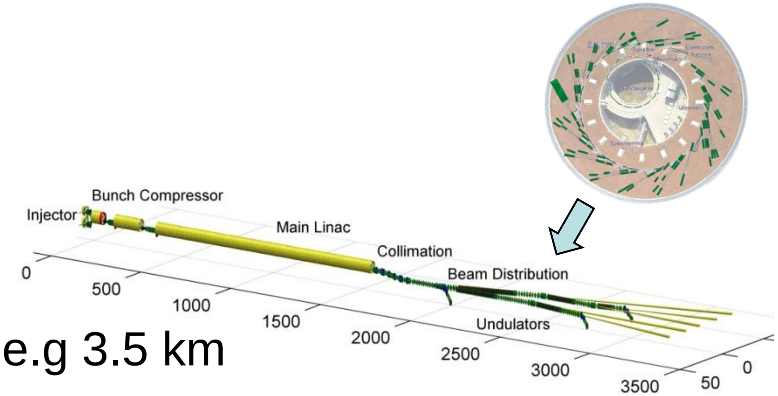
# Increasing demands on synchronization …

## … is driven by stability requirements

⇒ Bunch scale has changed from ns/ps to fs

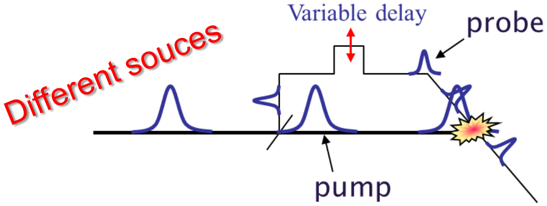
⇒ High accelerator frequencies (e.g. CLIC)

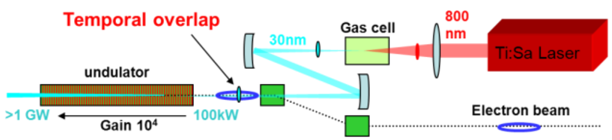
⇒ Accelerator facility length increased ~ 100 m – e.g 3.5 km




### Free Electron Lasers:

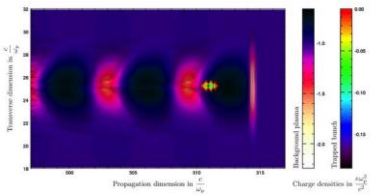
- Compression control (exponential growth)
- Energy control (self seeding)
- Pump-probe experiments (fs-evolution)
- External seeding (efficiency)




### External injection in laser plasma wakefield

- Plasma wavelength



### Picosecond/femtosecond photon sources

- THz / Thomson radiation

**fs-synchronization pre-requisite for new accelerator applications**

# Scope of synchronization …



Synchronization reach into many different physics & engineering disciplines and requires wide range of know-how and technologies

## Radio Frequency:

- RF Master Oscillator and distribution (cables)
- High power RF (modulator, preamp., klystron, waveguide,…)
- Low level RF (field detection, driver, digital feedback loops,…)
- RF accelerator structure (reflection, cooling, phase advance,…)

Wide range of components: phase detectors / mixer / multiplier / divider / low noise amplifier / …

## Optics & Lasers:

- Laser oscillator / amplifier (phase noise, piezo resonance, pump source,…)
- Laser pulse shaping & wavelength conversion & transport
- Optical reference & distribution (fiber optics, opto-electronics, photo-detection)

## Environmental control:

- temperature / humidity / air pressure / vibration / ground motion / EMI / EMC

## Controls & control theory:

- multiple feedbacks / PLL theory / automation / SISO / MIMO / …

## Longitudinal electron beam dynamics

# Sources of timing jitter in accelerator

Arrival time of electron bunch at seed source
Arrival time at entrance to undulator


**Sources of timing jitter (uncorrelated):** $\sigma_t = [\Sigma\,(w_j\,\sigma_j)^2\,]^{1/2}$

| | |
|---|---|
| Photo-cathode laser | w ~ 40-60% |
| RF phase of RF gun (non-relativistic electrons) | w ~ 60-40% |
| Seed and Pump-probe laser | w ~ 100% |

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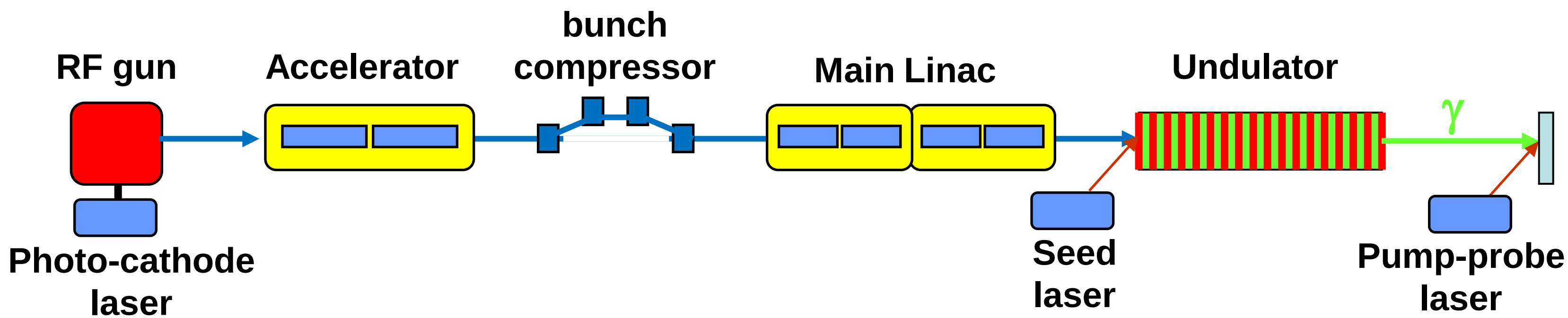
Arrival time at entrance to undulator

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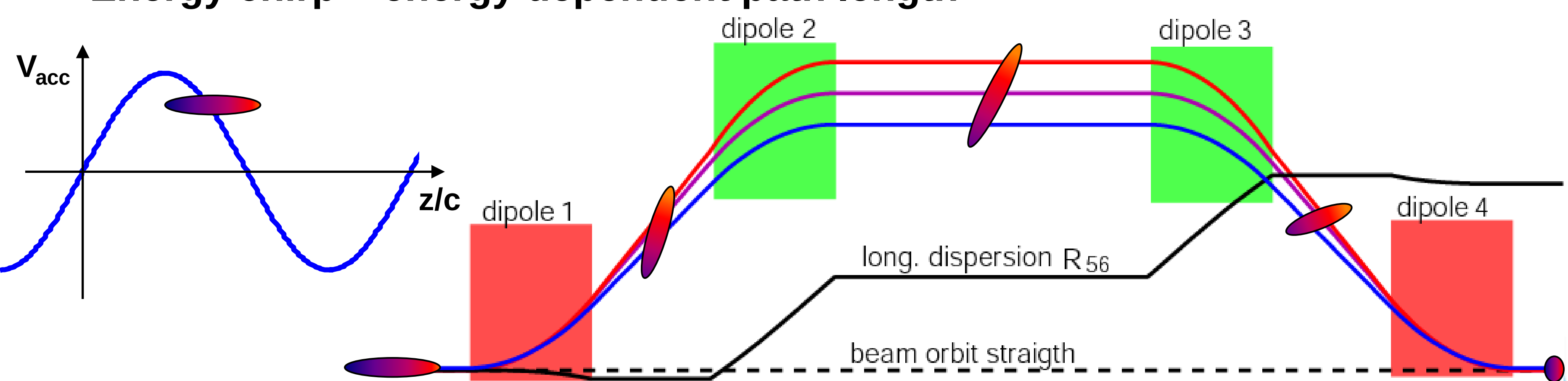
**Energy chirp + energy dependent path length**



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## Arrival time of electron bunch at seed source
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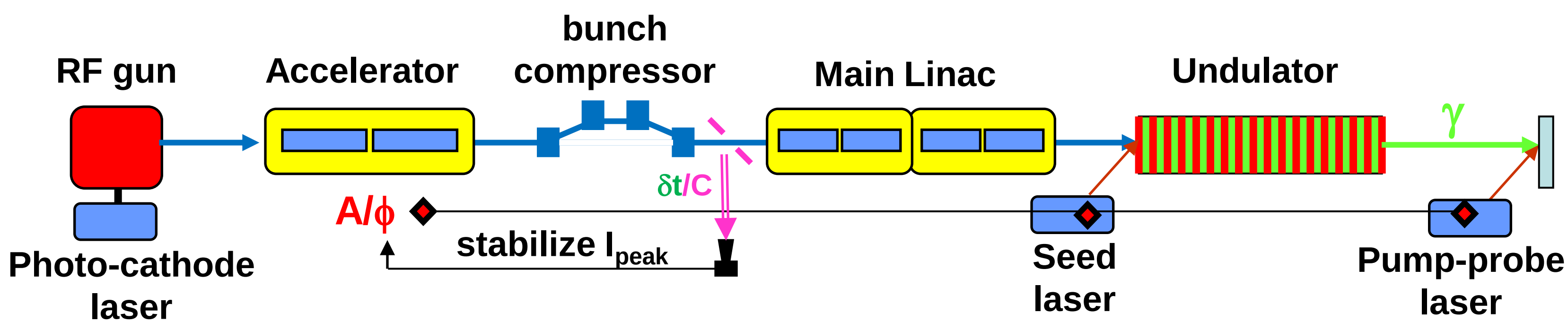


**Sources of timing jitter (uncorrelated):** $\sigma_t = [\Sigma (w\, \sigma_{t,l})^2]^{1/2}$

| | |
|---|---|
| Photo-cathode laser | w < 5% |
| RF phase of RF gun (non-relativistic electrons) | w < 5% |
| RF amplitude and phase | w ~ 100% |
| Seed and Pump-probe laser | w ~ 100% |

Timing jitter behind BC

$$\Sigma_{t,f}^2 = \underbrace{\overbrace{\left(\frac{R_{56}}{c_0}\right)^2 \cdot \frac{\sigma_{V_1}^2}{V_1^2}}^{\text{Voltage}}}_{\substack{\text{XFEL: 3.3 ps/\%} \\ \text{FLASH: 5.5ps/\%}}} + \underbrace{\overbrace{\left(\frac{C-1}{C}\right)^2 \cdot \frac{\sigma_{\phi_1}^2}{\omega_{rf}^2}}^{\text{Phase}}}_{\substack{\text{2 ps/deg} \\ \text{L-band}}} + \underbrace{\overbrace{\left(\frac{1}{C}\right)^2 \cdot \Sigma_{t,i}^2}^{\text{Incoming}}}_{\substack{\text{0.05 ps/ps} \\ \text{C=20}}}$$

compression factor
C ~5 … 20

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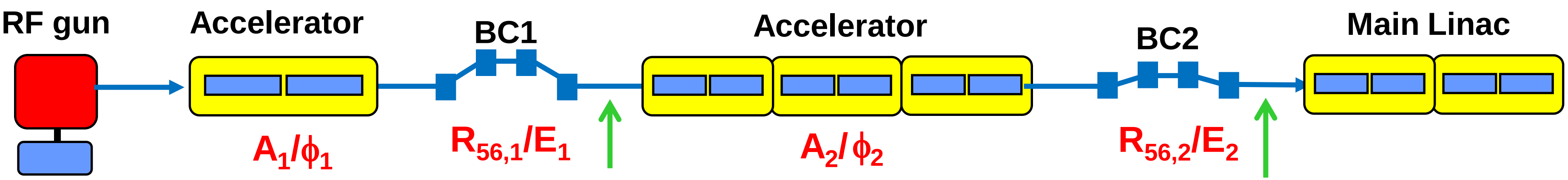


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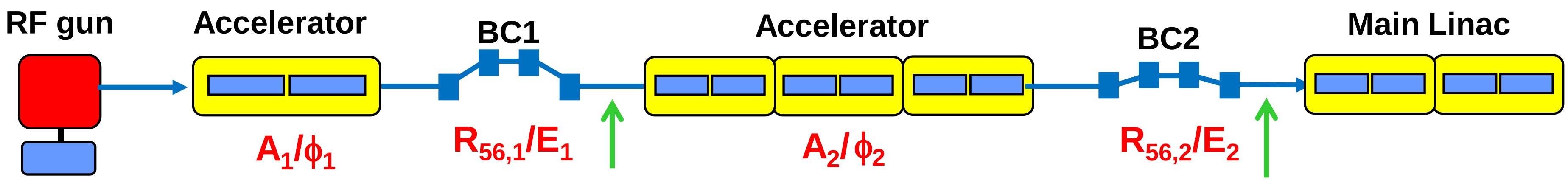


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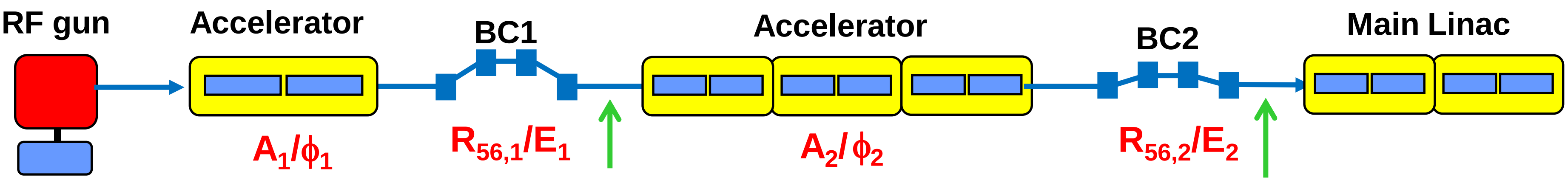


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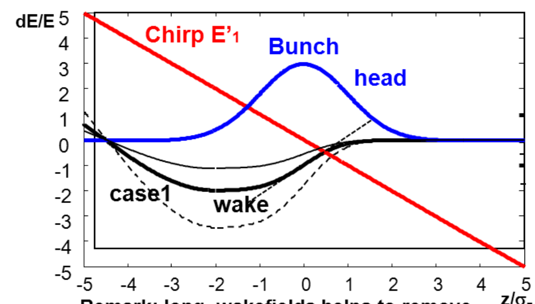


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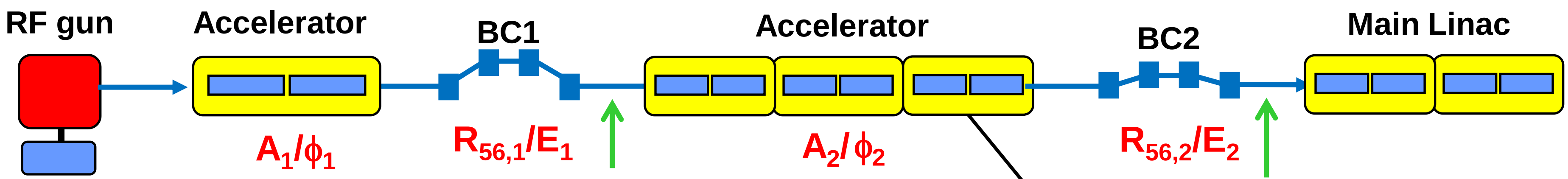


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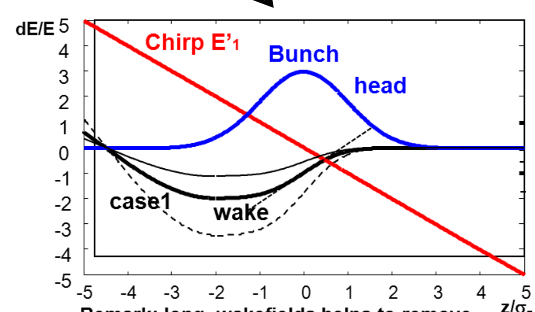


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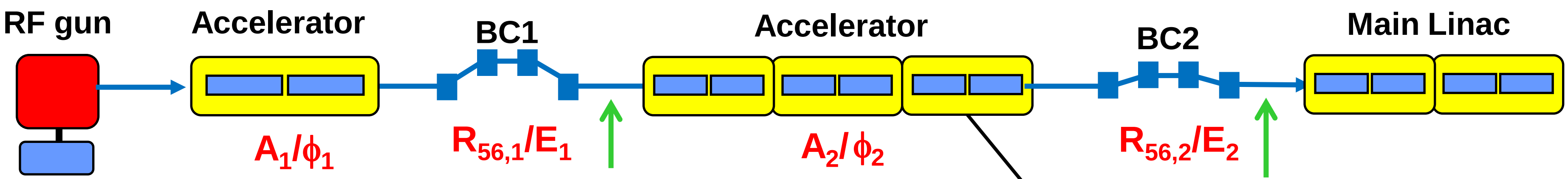


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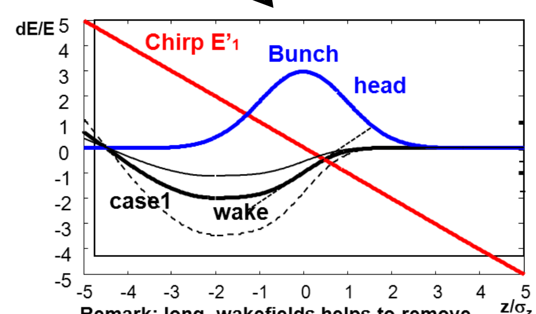


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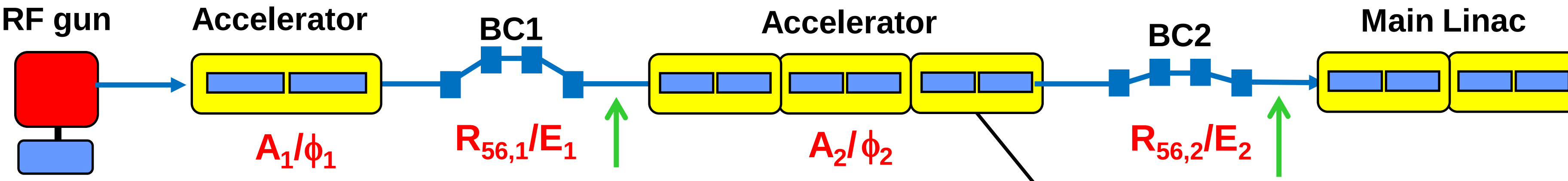


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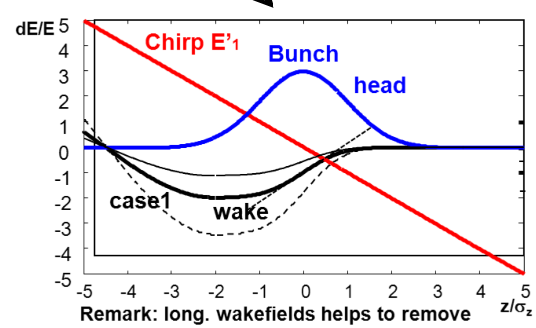


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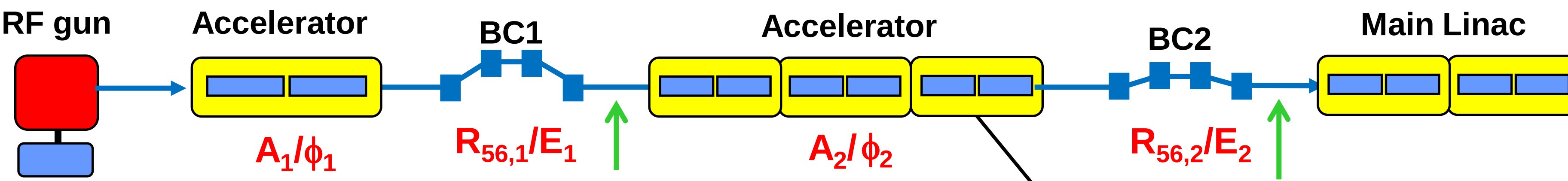


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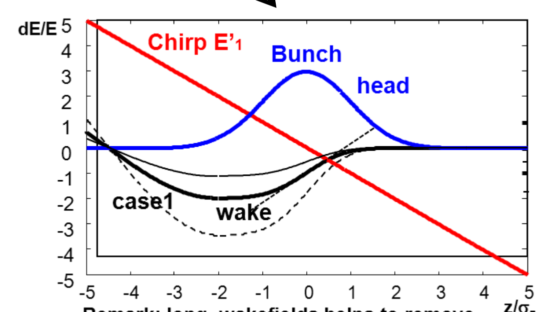


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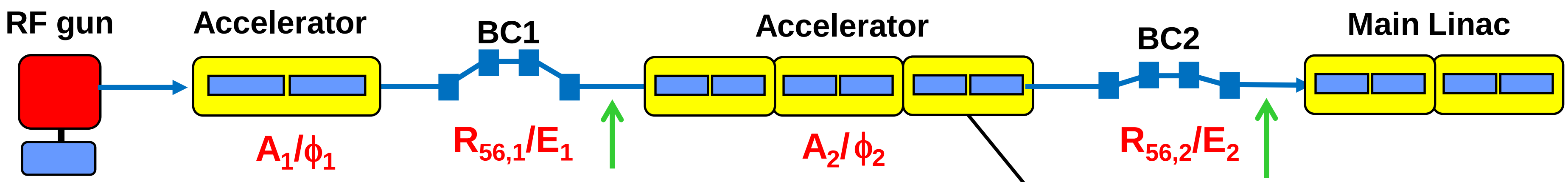


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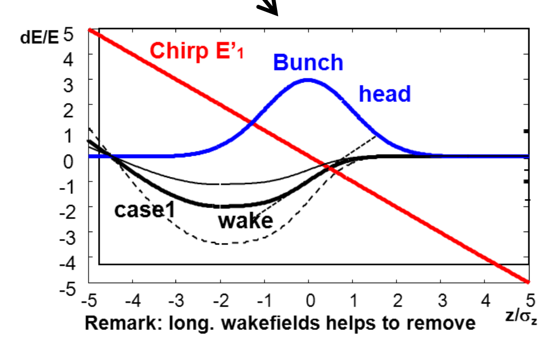


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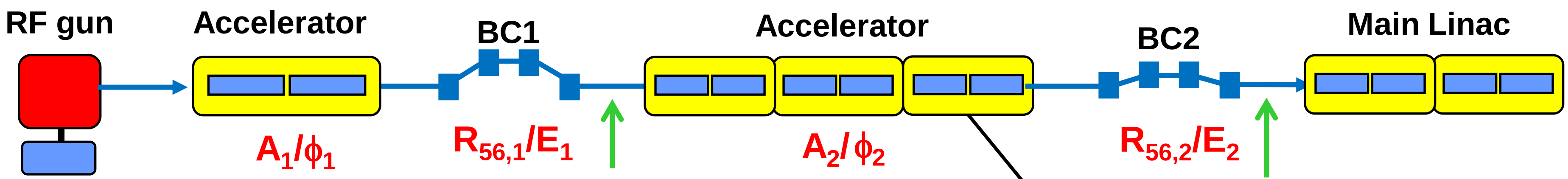


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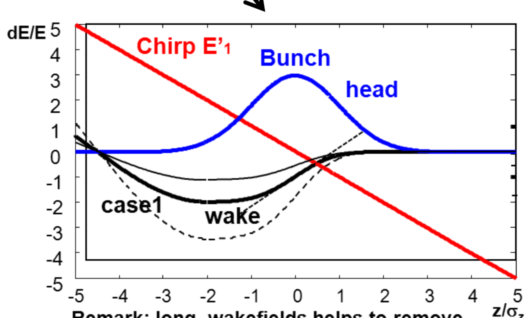


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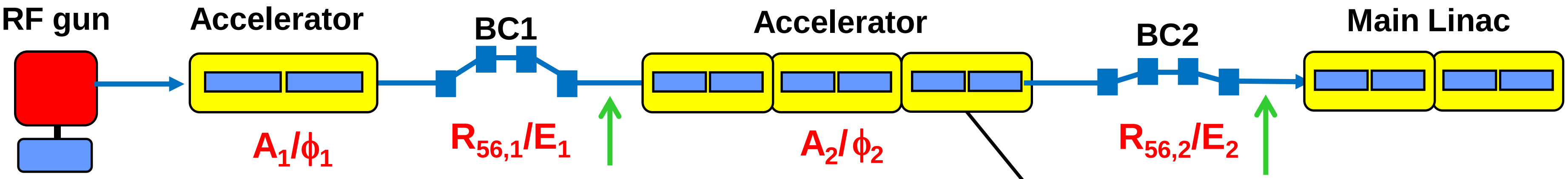


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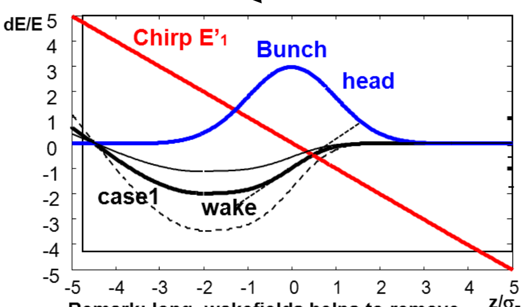


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# Synchronization schemes …

Various approaches:

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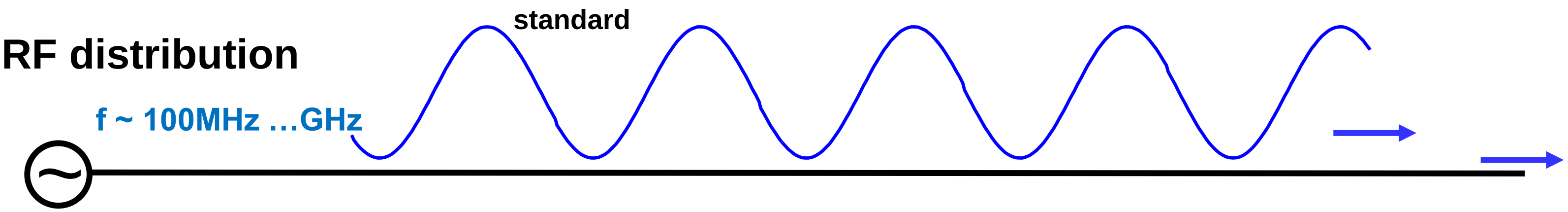

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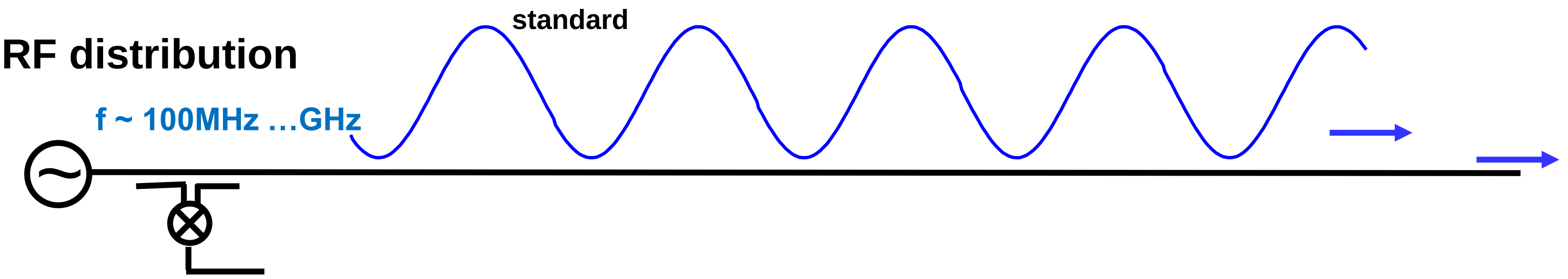

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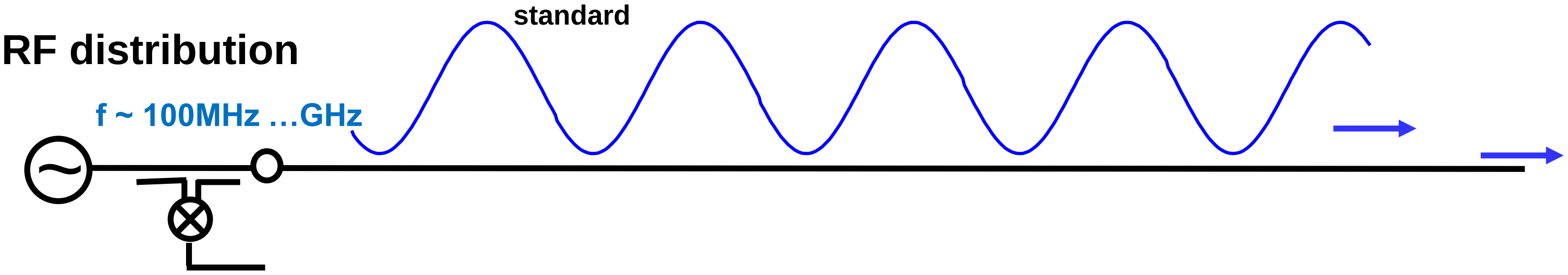

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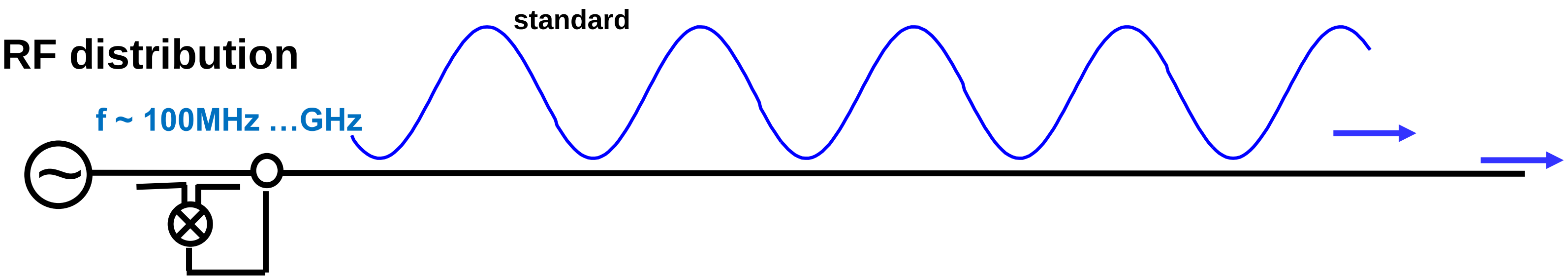
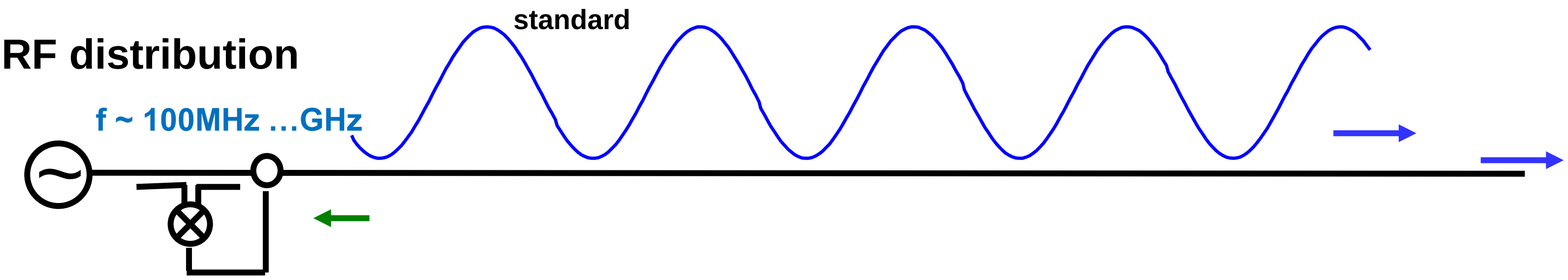


# Synchronization schemes …

Various approaches:

**1) RF distribution**



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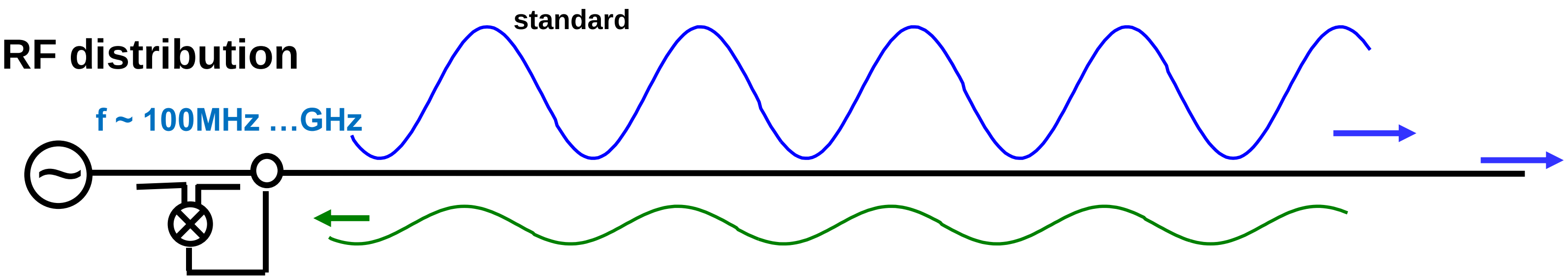

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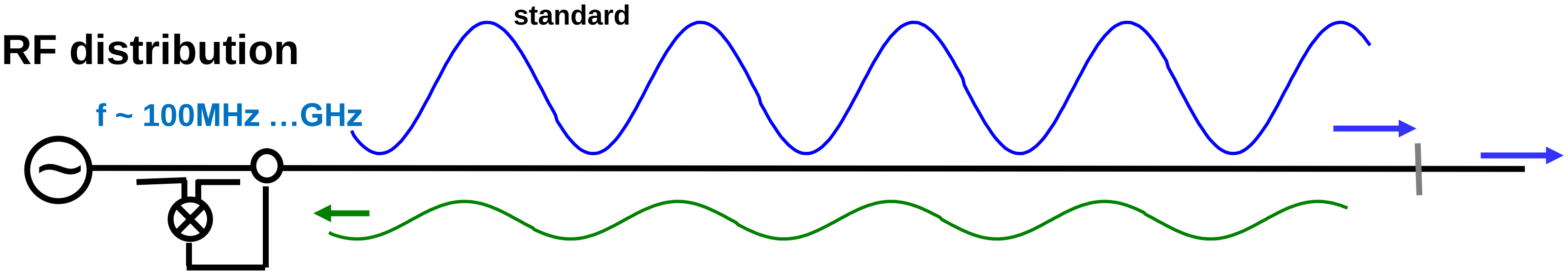

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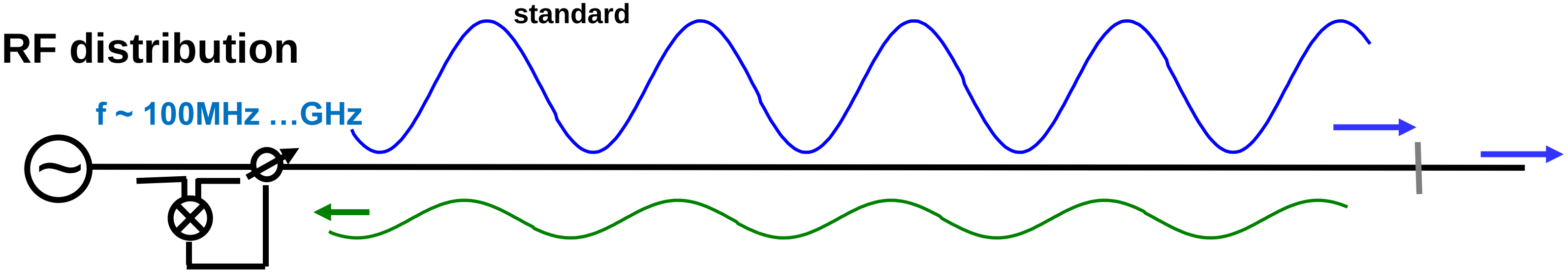

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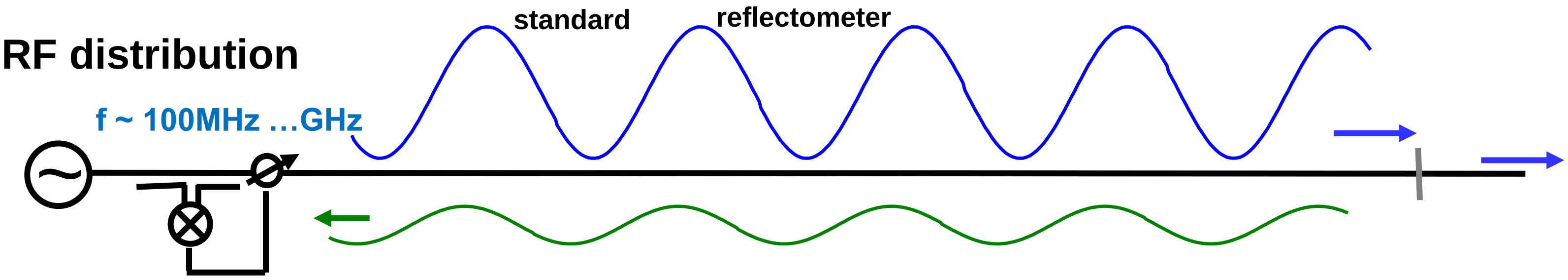

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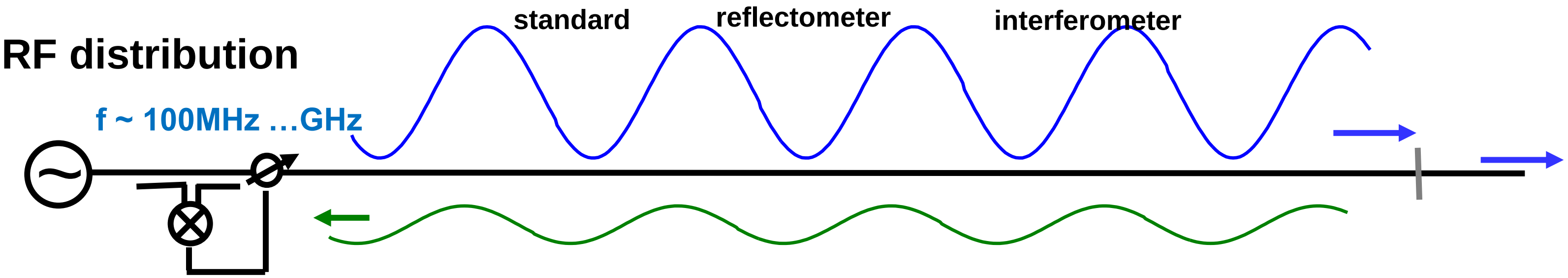

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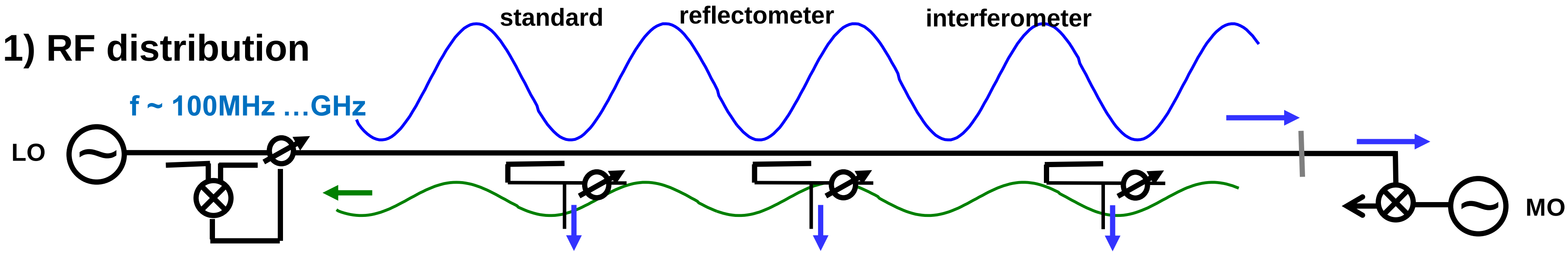

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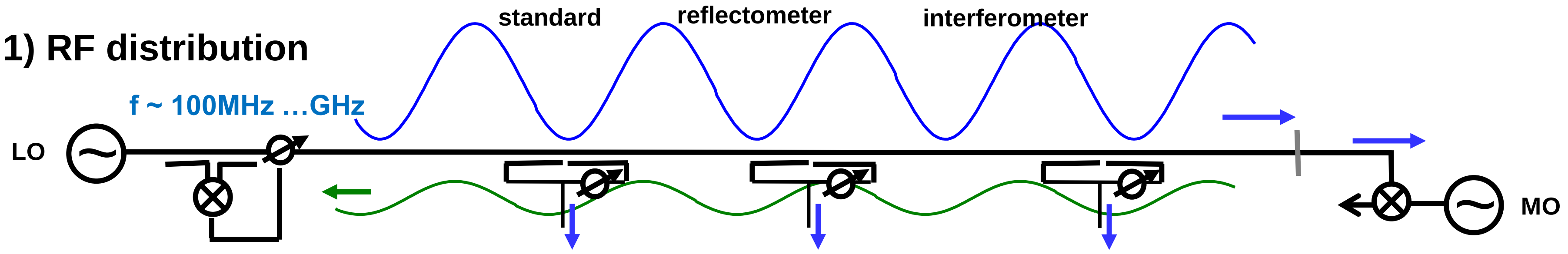

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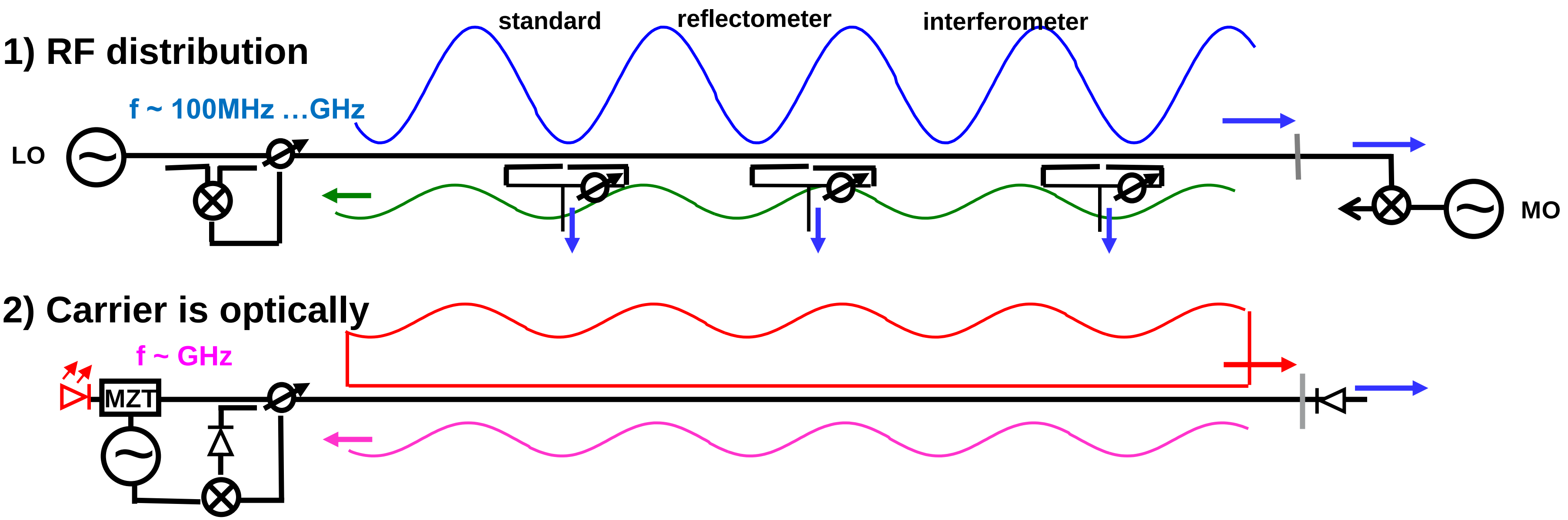

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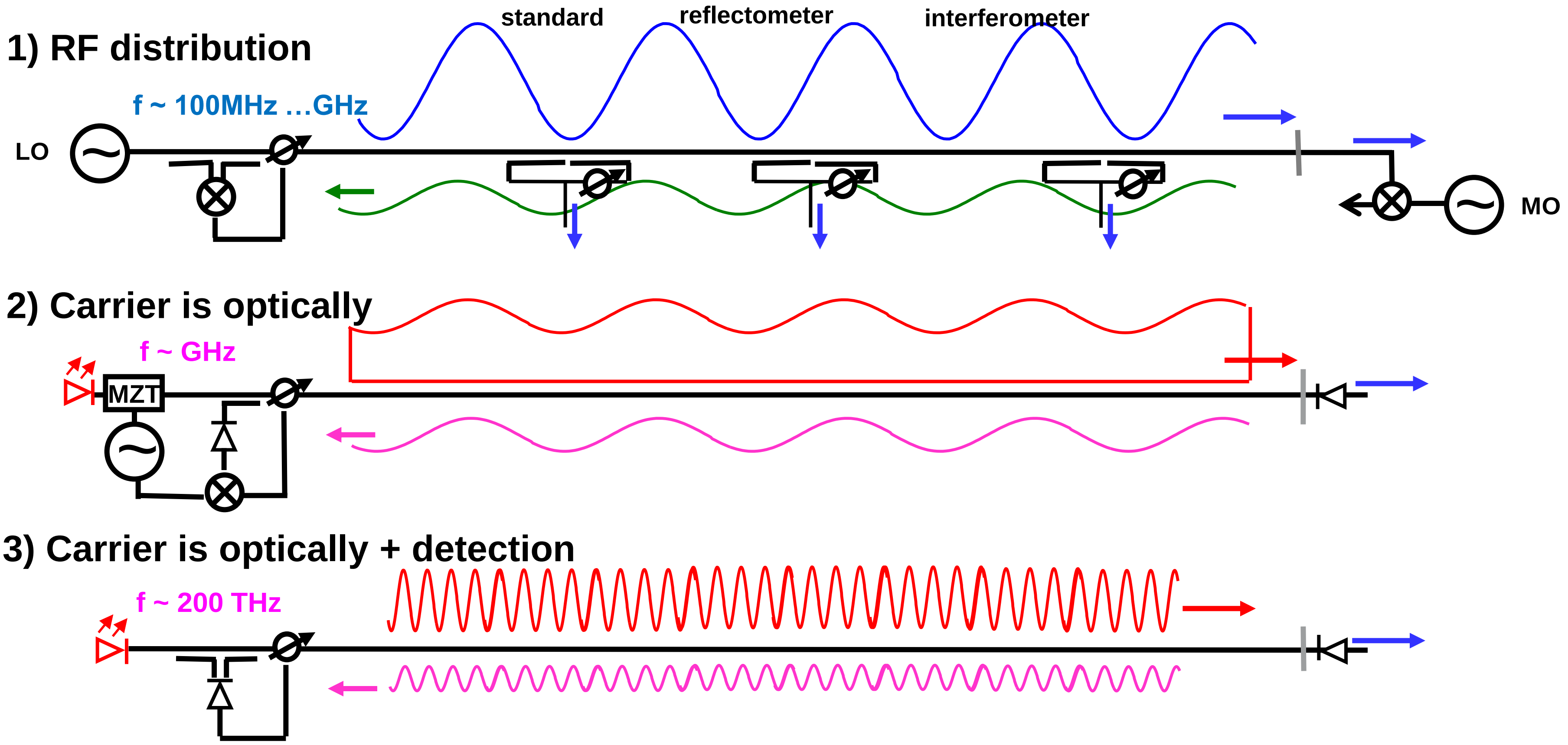

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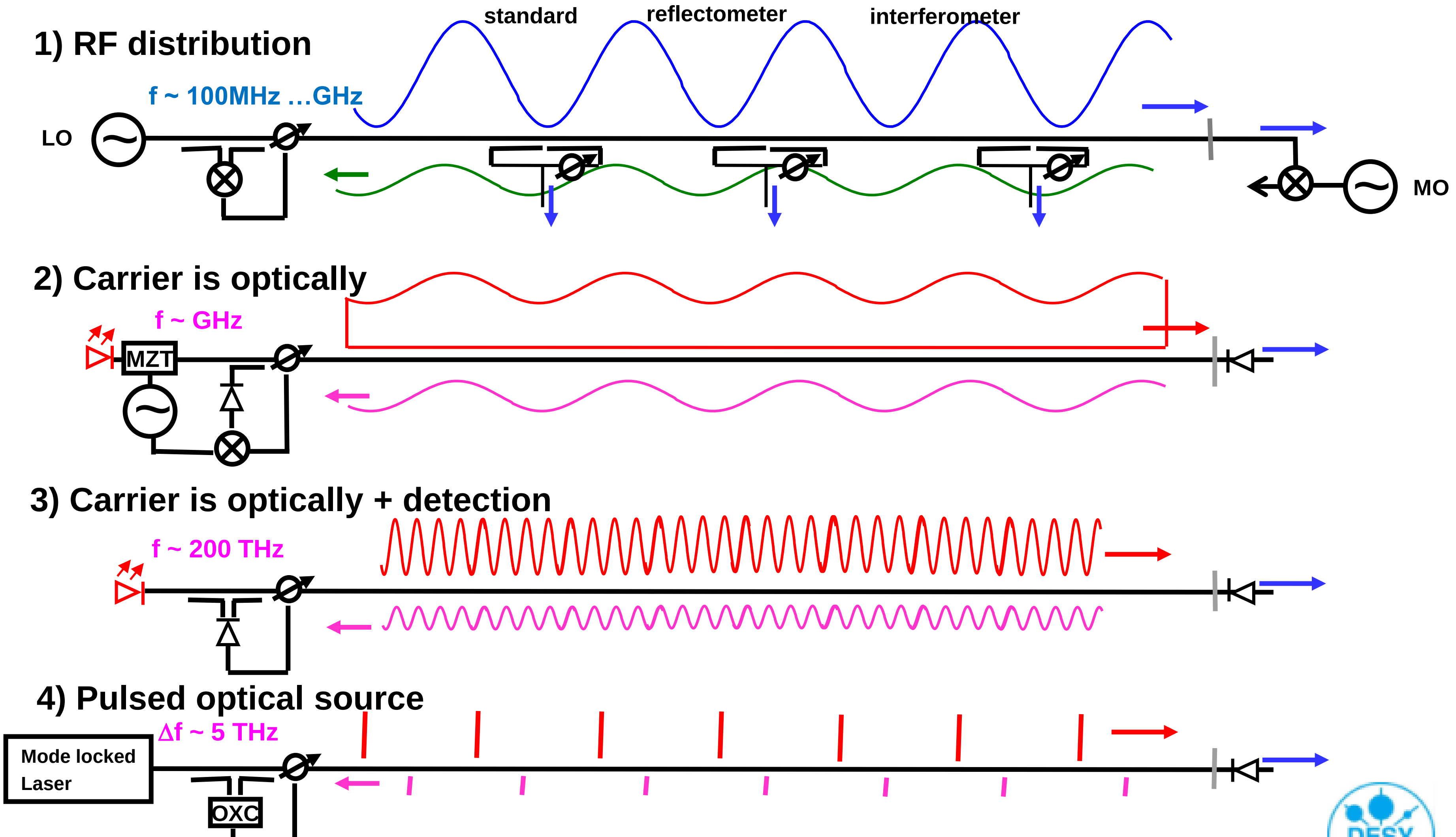
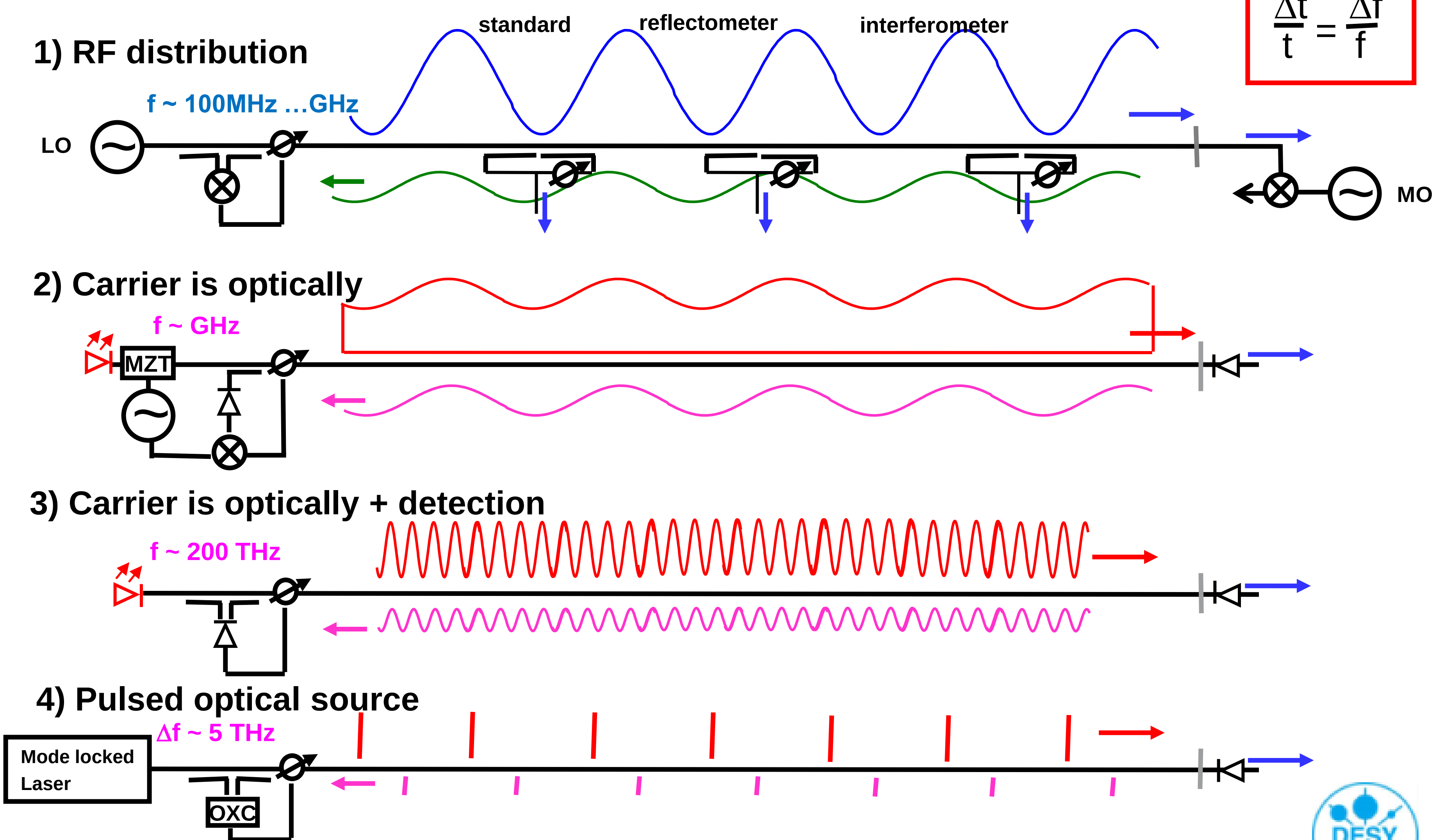


# Synchronization schemes …

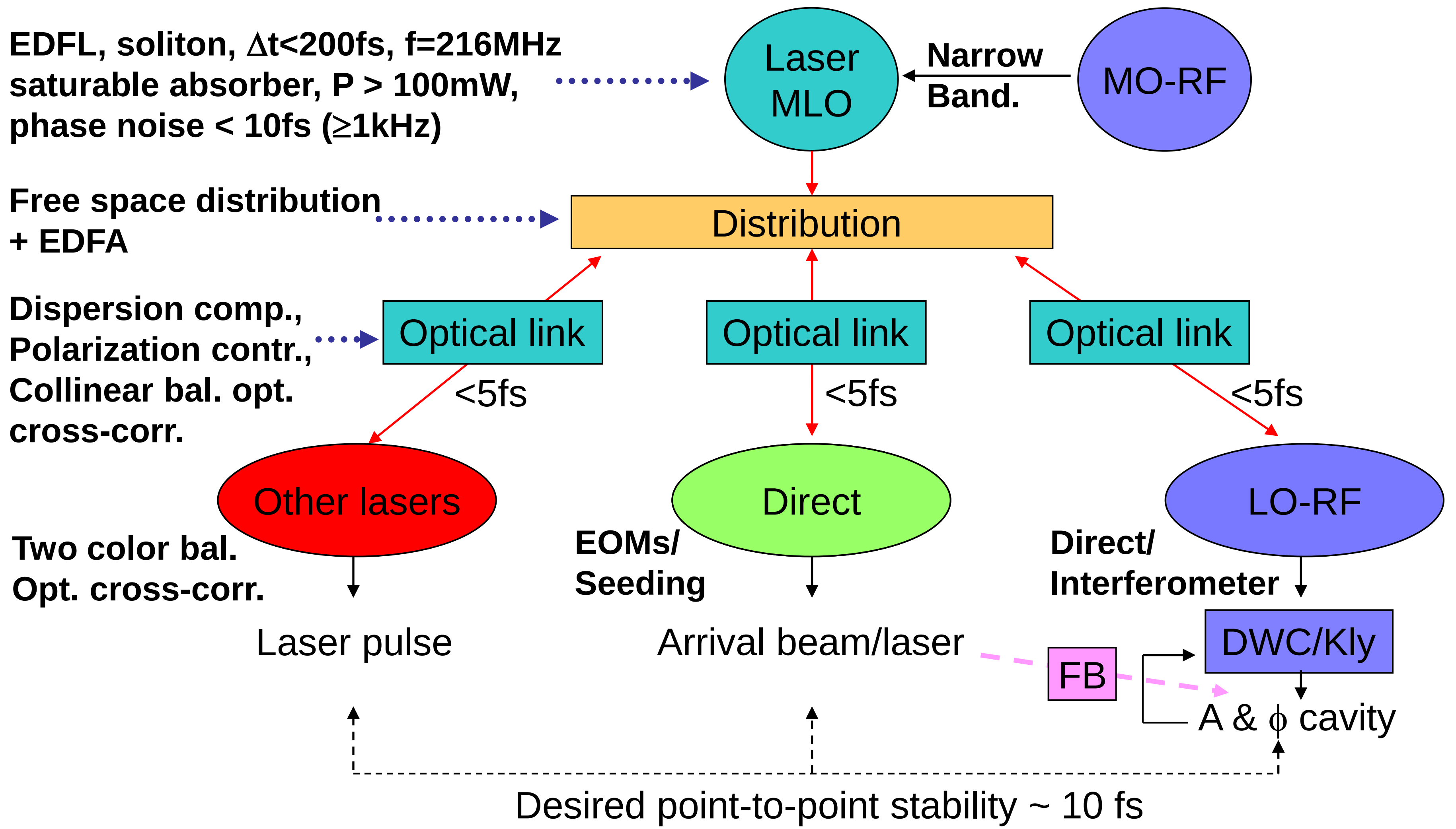
## Various approaches:

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



# Pulsed optical synchronization system

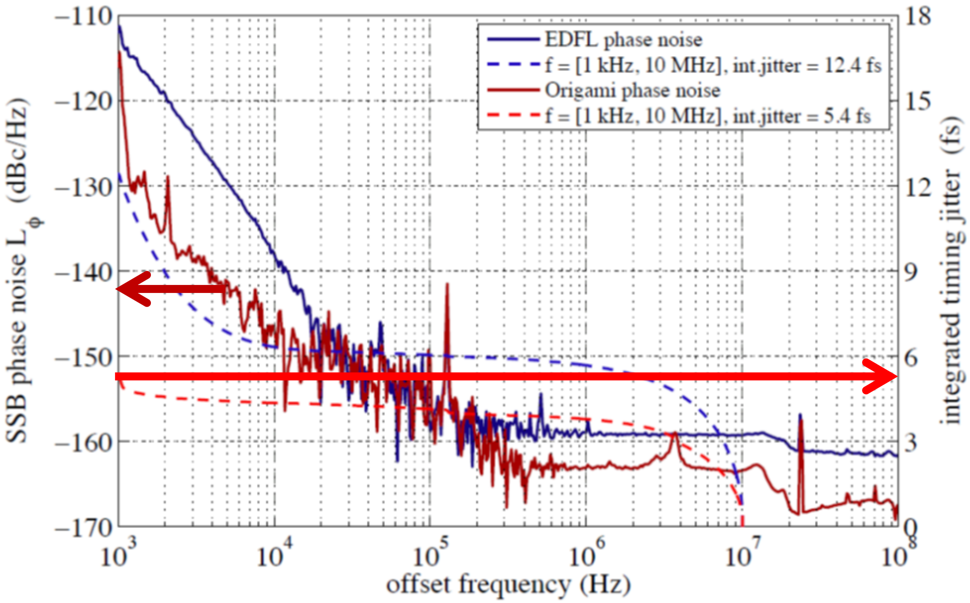


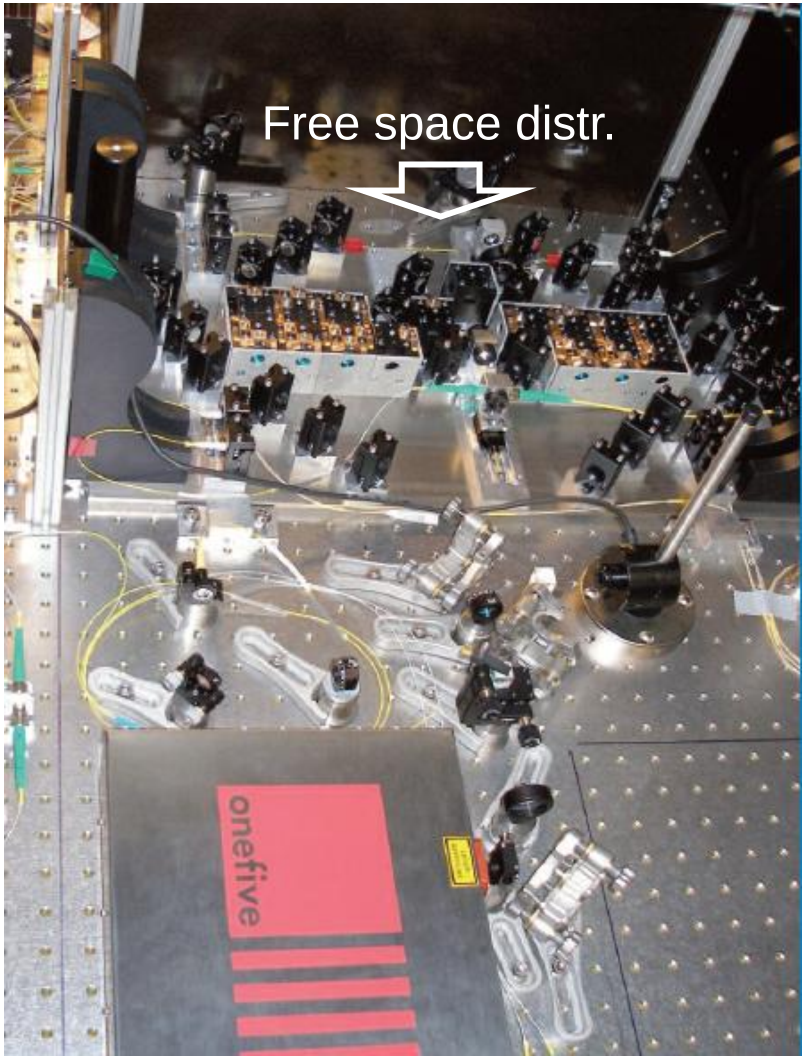



Main issue: robustness, stability and maintainability ⇒ Prototype at FLASH

# Master Laser Oscillator (MLO)

- Commercial: OneFive ORIGAMI-15
- Repetition rate: 216,66MHz
- Average power: > 100mW
- Pulse duration: < 200 fs
- Mechanically robust, easy to maintain
- **Phase noise ~ 5fs rms [1kHz-10MHz]**

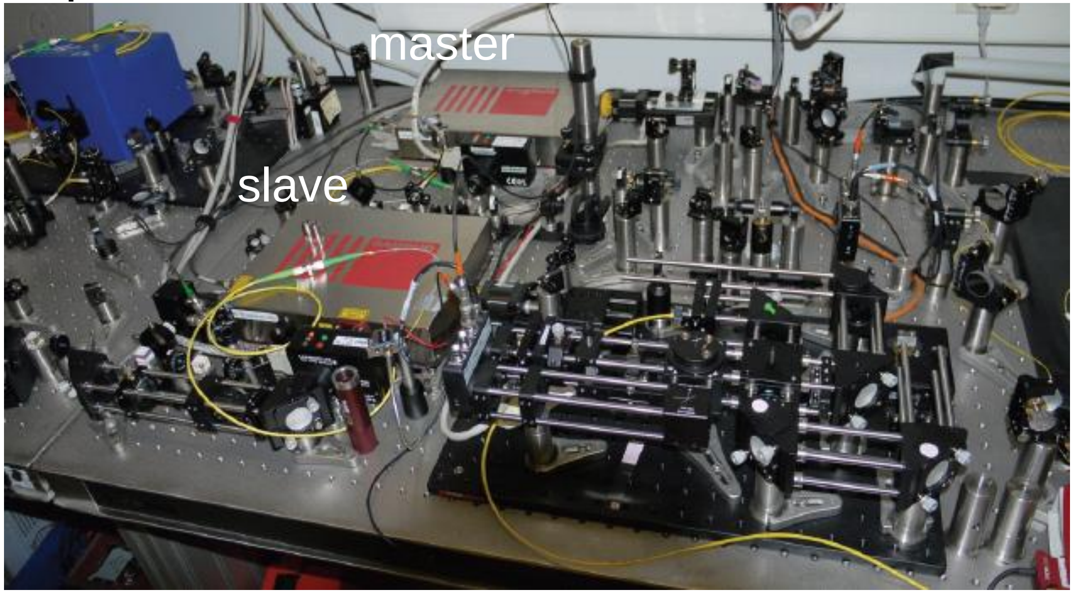


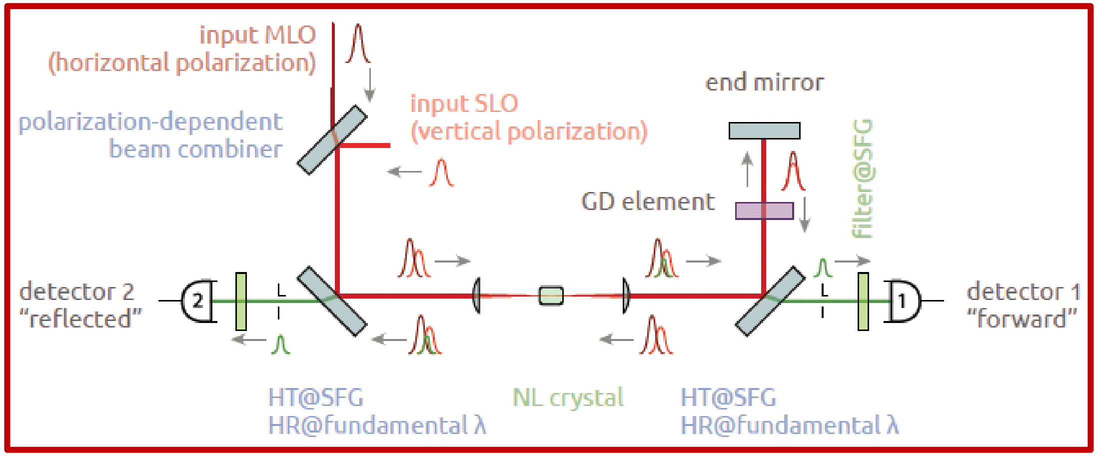

Courtesy: S. Schulz

# Master Laser Oscillator (MLO)

Optical lock of two laser oscillators




Balance, background free detection

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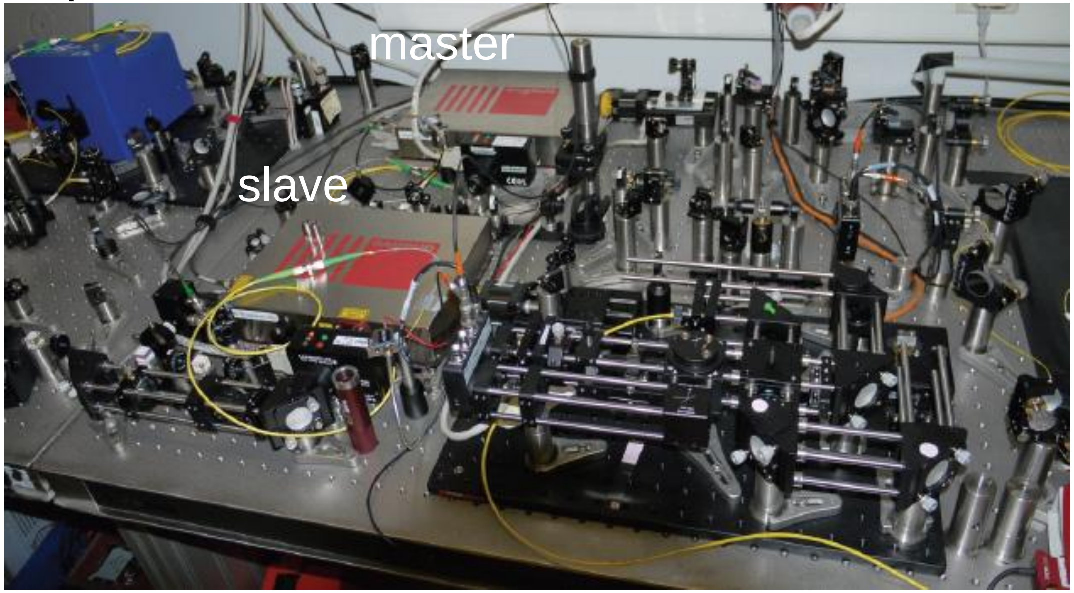


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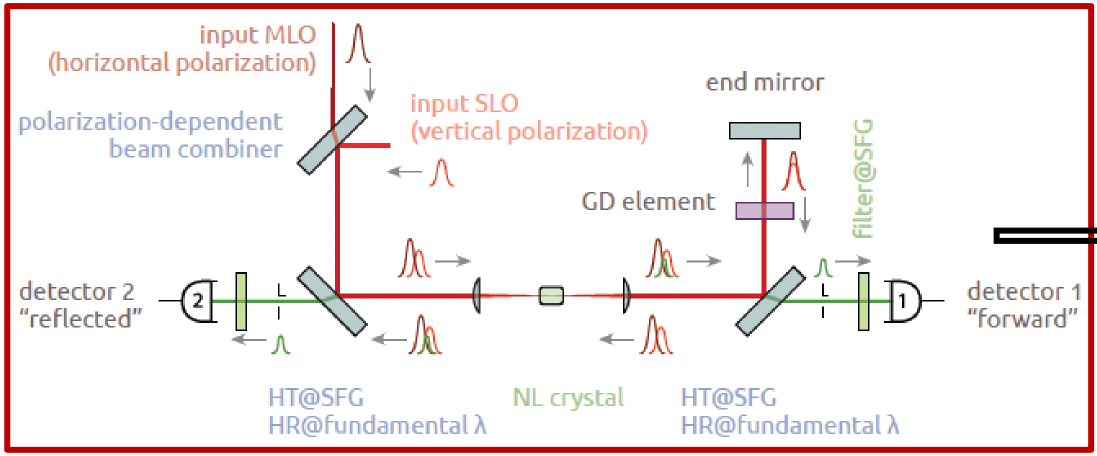
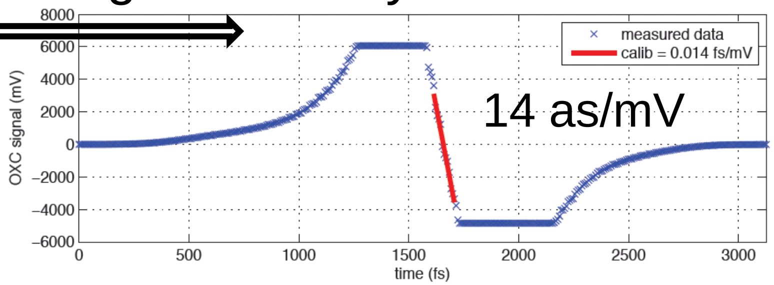



High sensitivity at low noise

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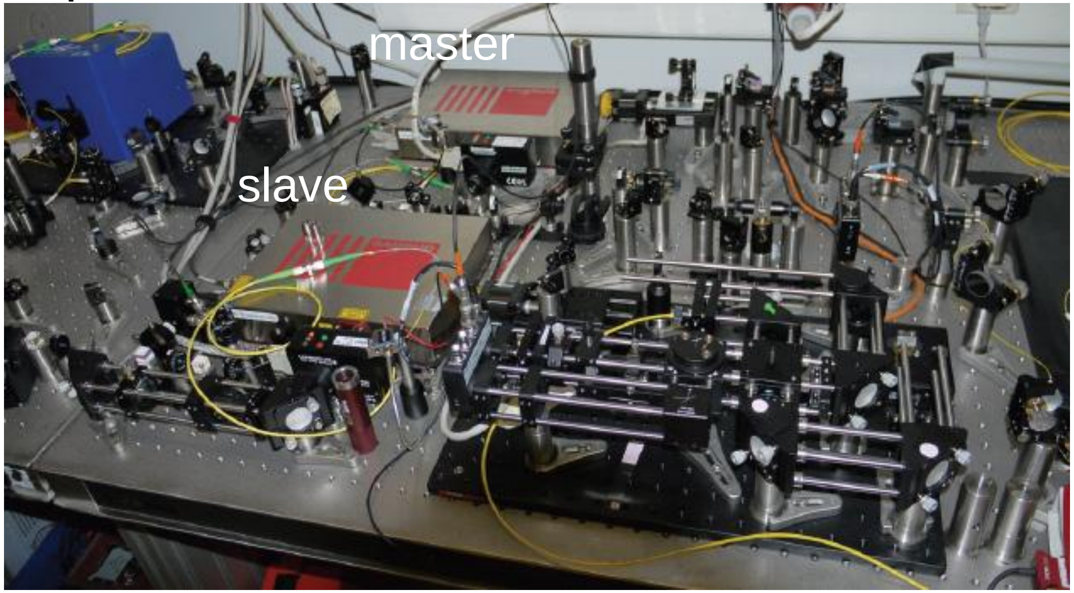


Needs:
- Low noise laser osc.
- High sensitive detection
- Fast actuator (PZT/driver)

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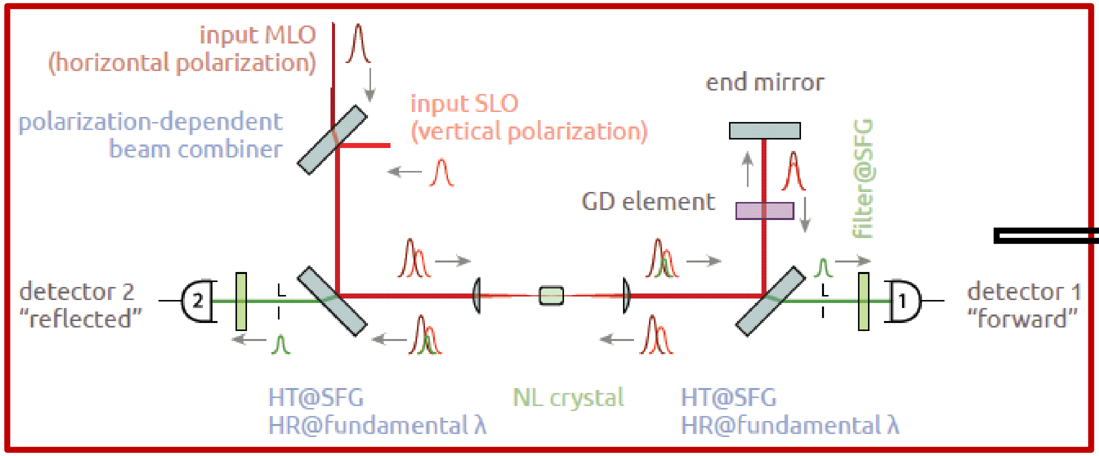


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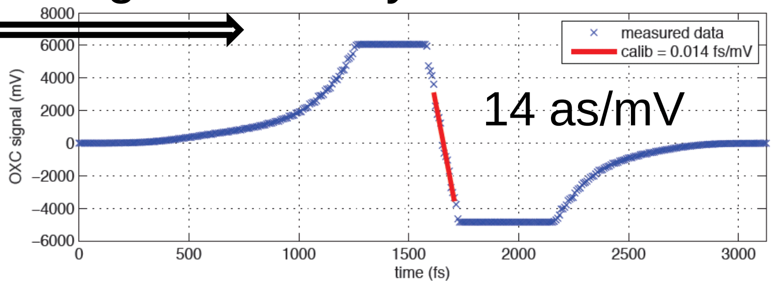


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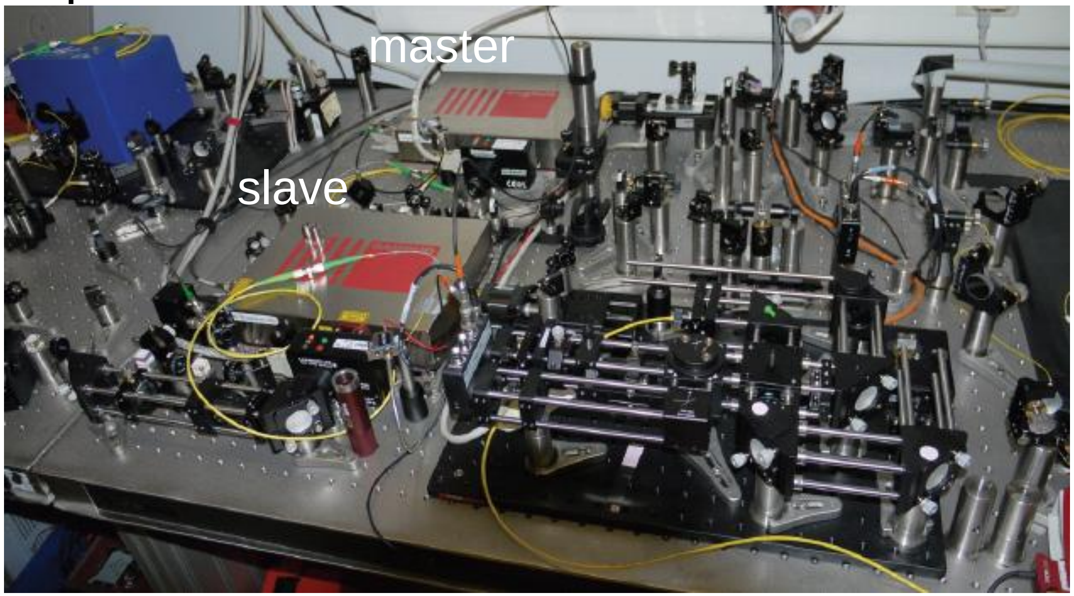


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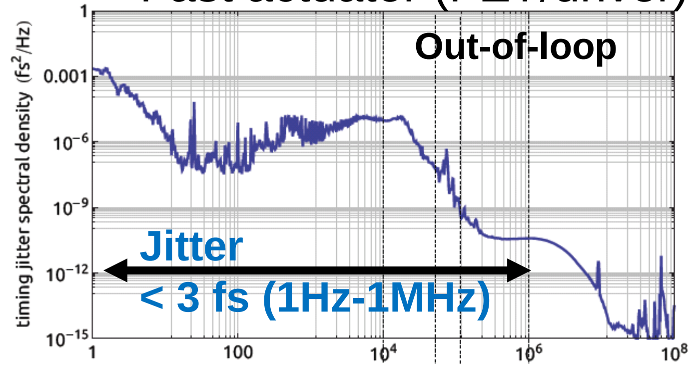


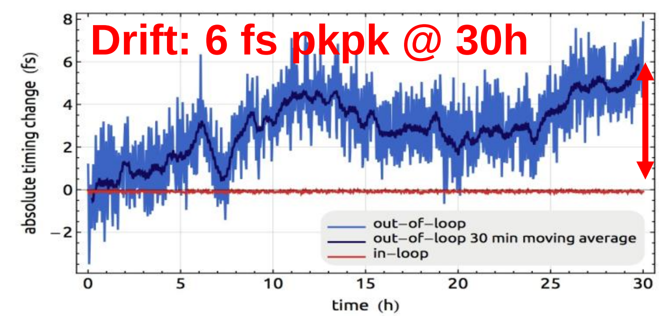


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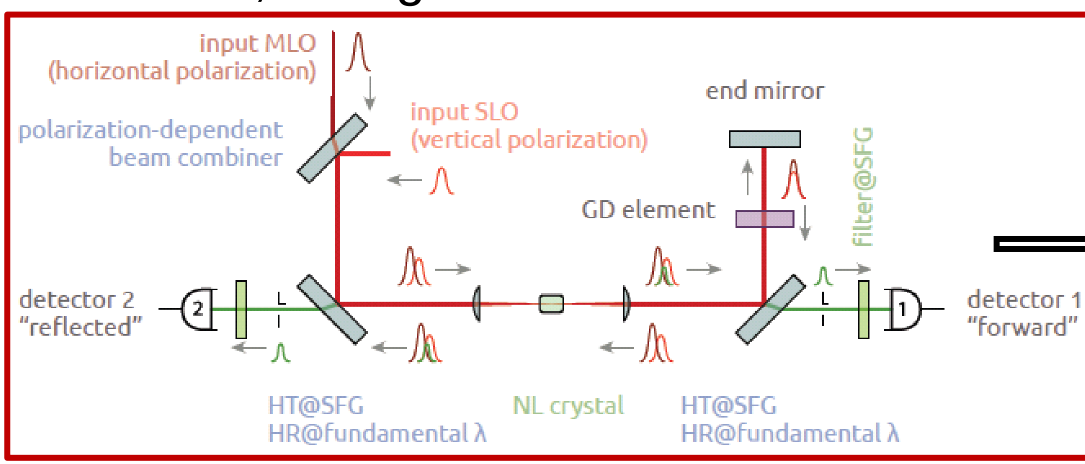


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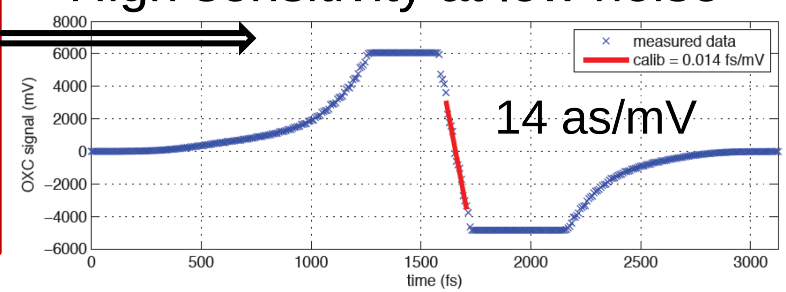
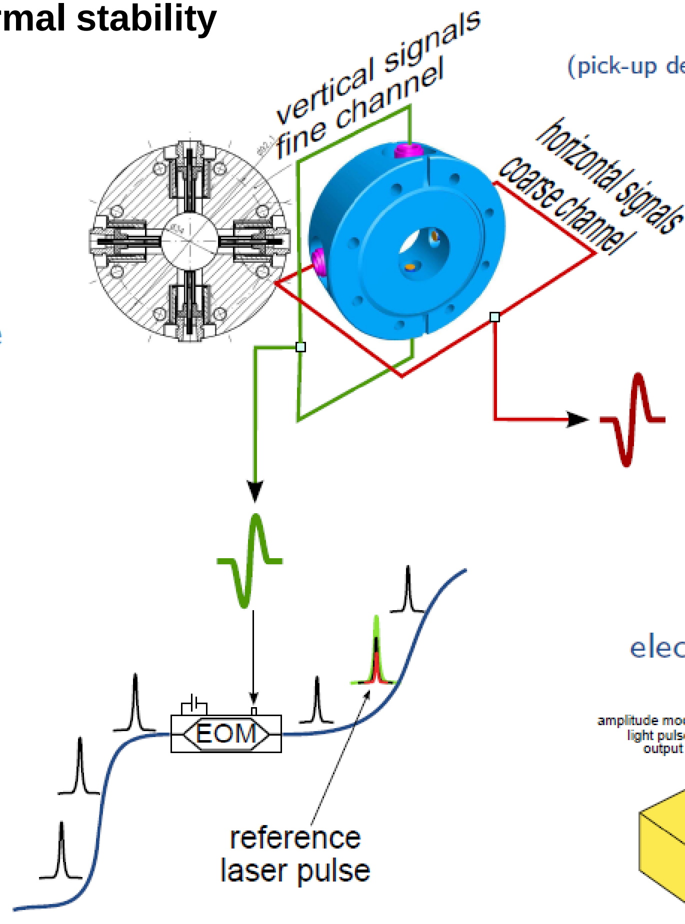



**Courtesy: S. Schulz**

# Bunch Arrival Monitor

**meanwhile rather reliable operation (still babysitting required)**
**switch from 10GHz -> 40GHz bandwidth for low charge operation**
**new front-end with improved thermal stability**

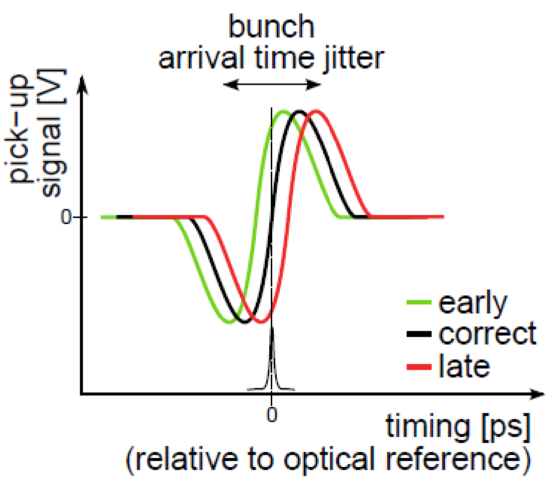
(pick-up design drawing, courtesy: K. Hacker)



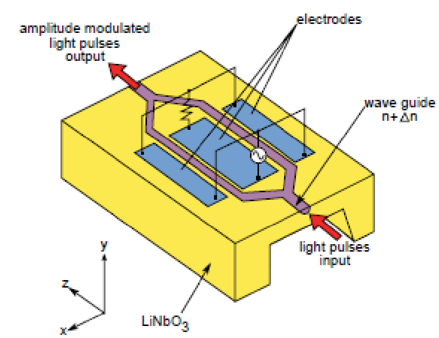

reduced dependency on beam orbit

reduced dependency on bunch charge

sensitivity in terms of
% modulation per fs timing change




electro-optical modulator



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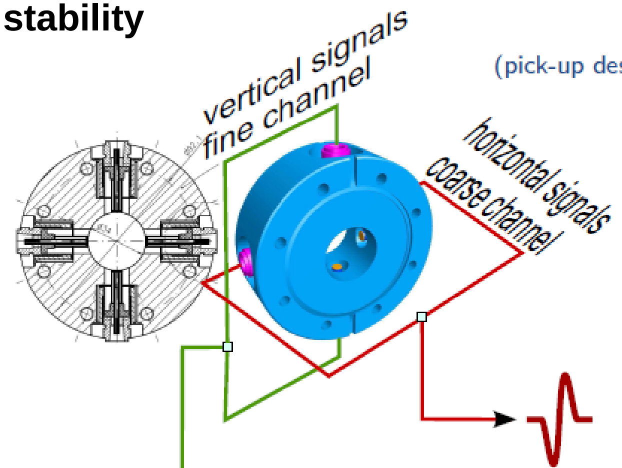


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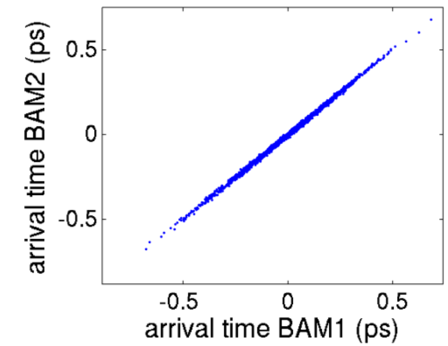


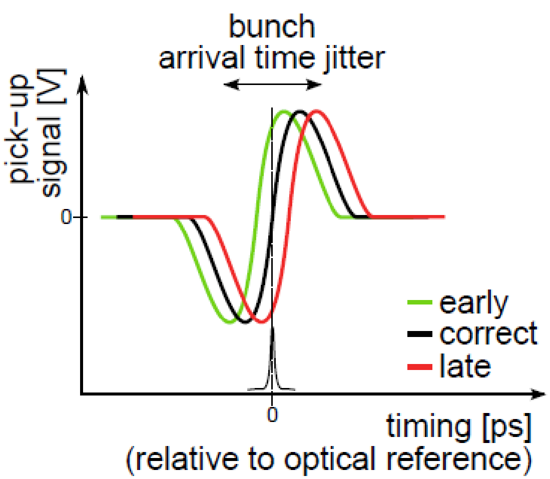


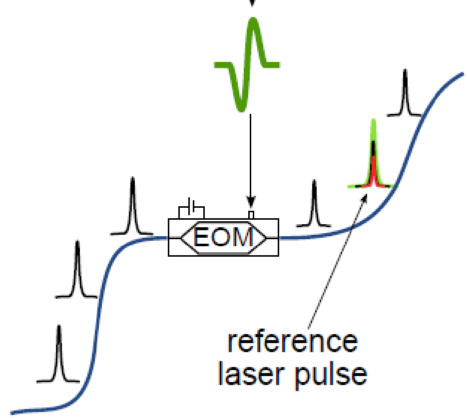


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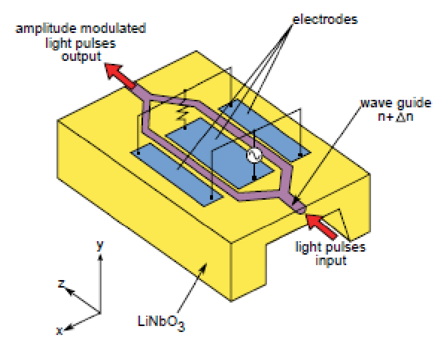

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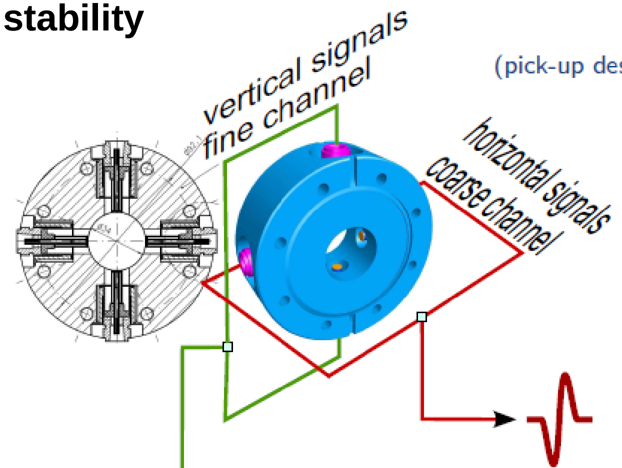


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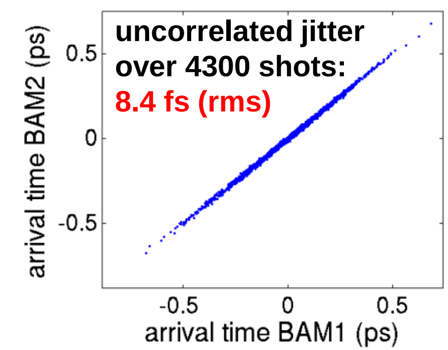


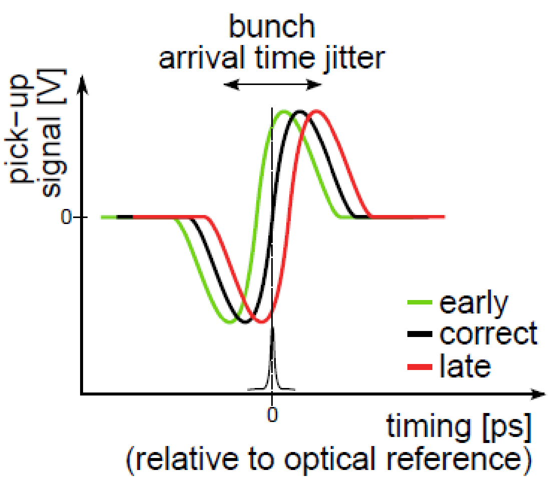


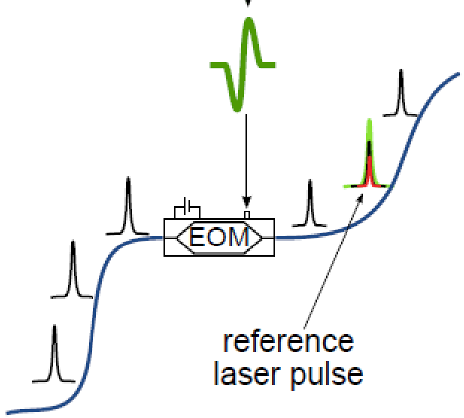


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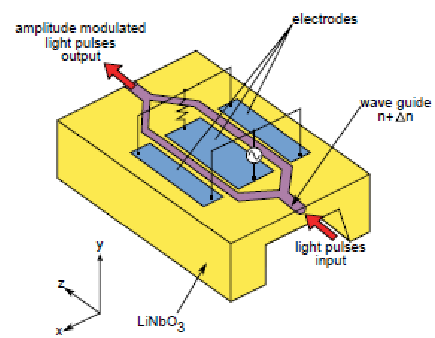


# Arrival time measurements


**Typically values**

**60-100fs rms from injector**

**50-60fs rms behind BC2**

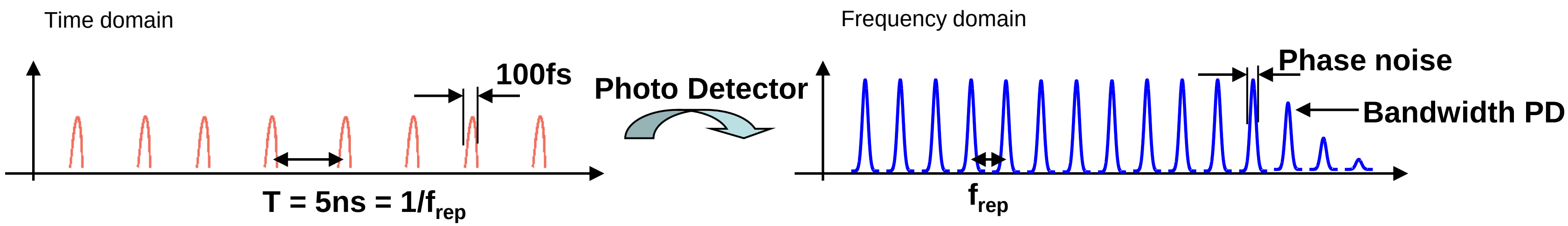
**40-50fs rms exit LINAC**

**Global slow feedback Implemented**

**Intra-train repetitive error correction implemented**

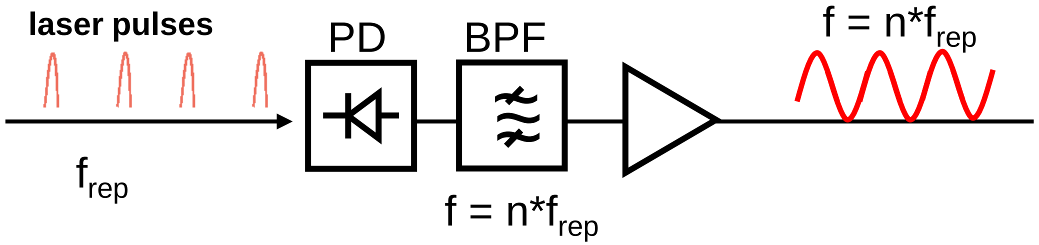
**Fast feedback reduce Bunch-to-bunch jitter ~ 20 fs**

# RF generation from optical pulses




**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)



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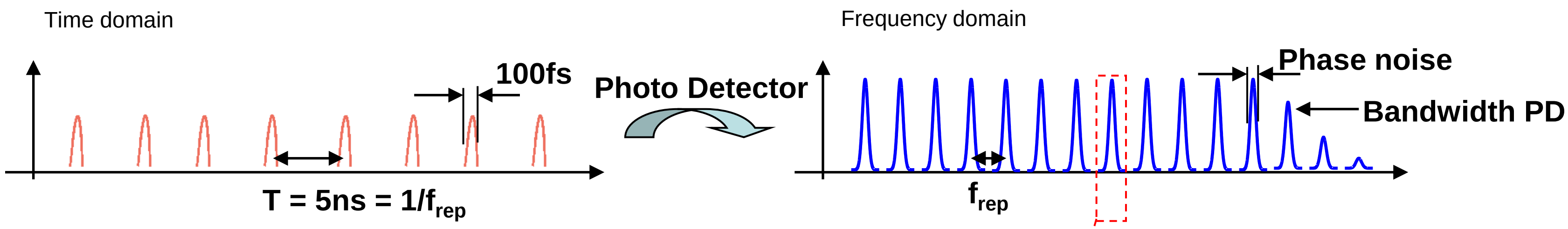


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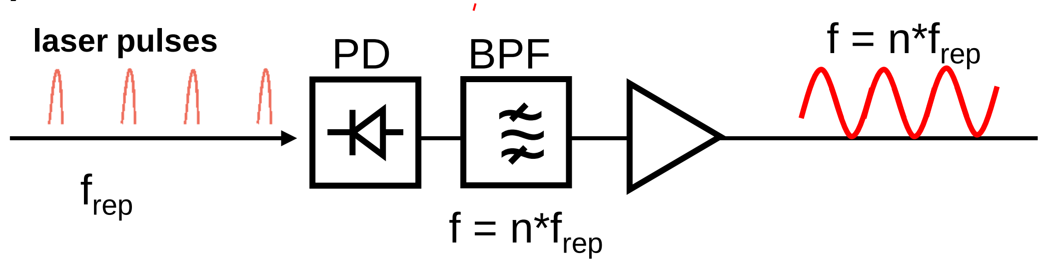

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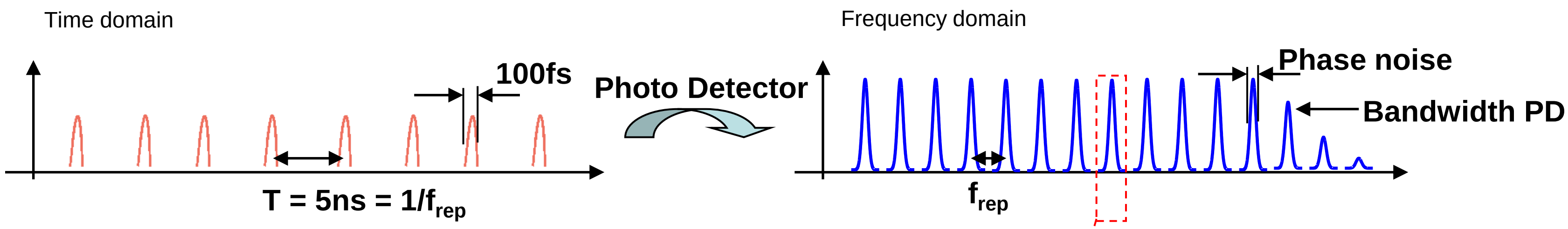


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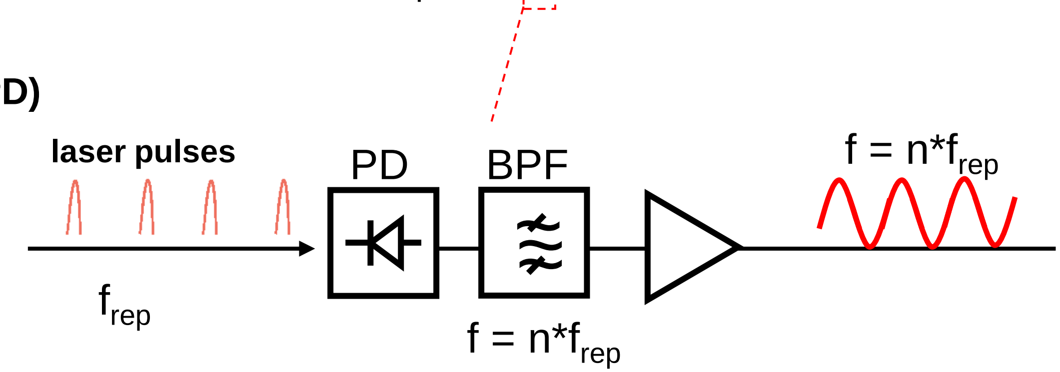


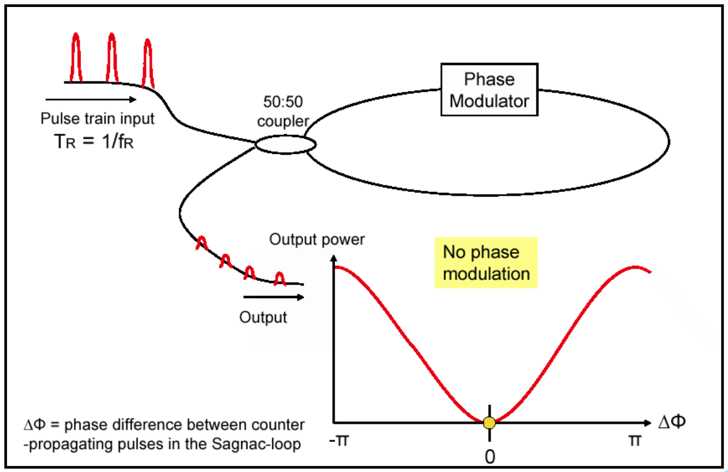

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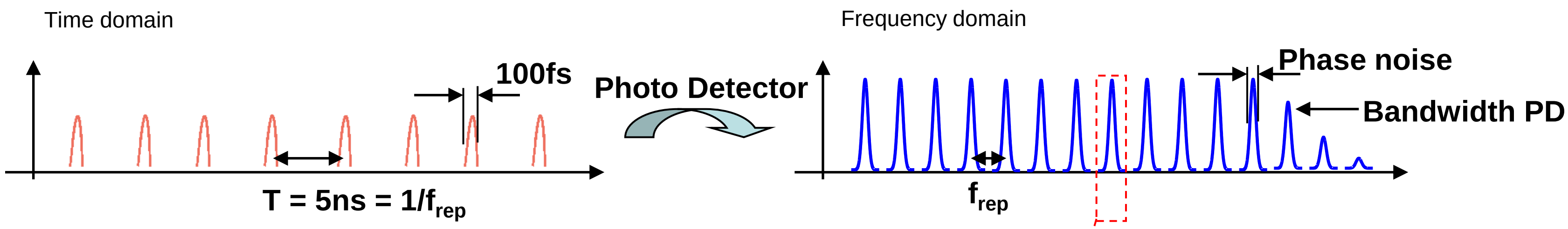


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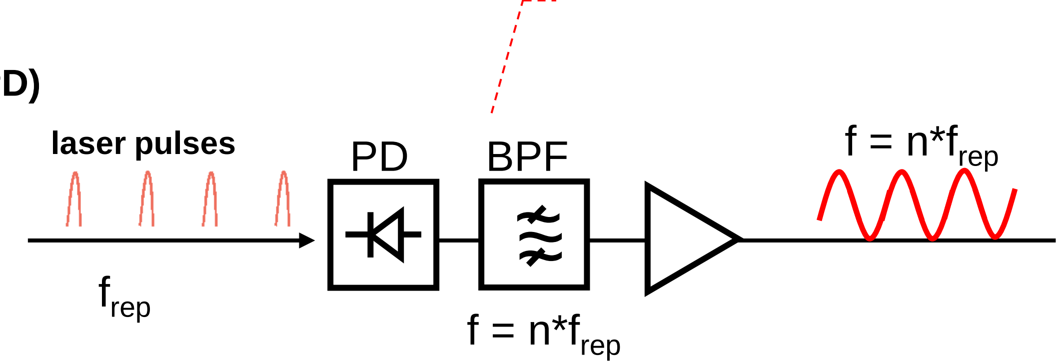
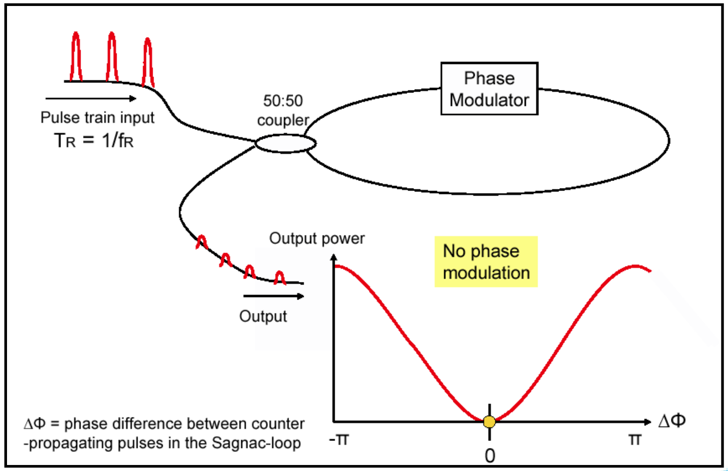



## Sagnac loop interferometer

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

f=1.3GHz jitter & drift < 10 fs rms limited by detection
Remark: much easier at higher frequencies …



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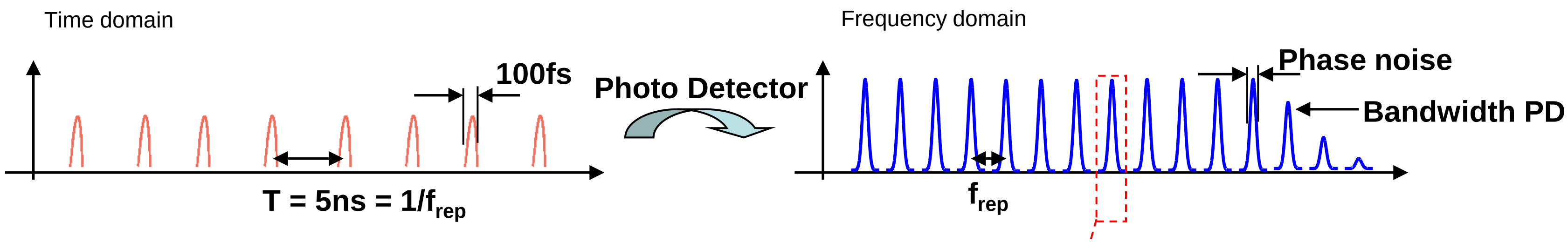


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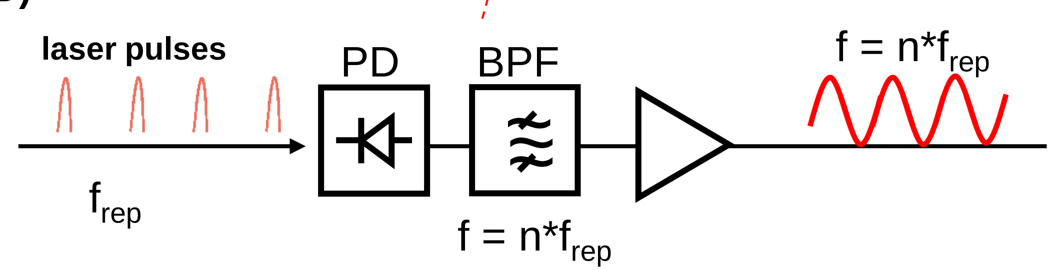


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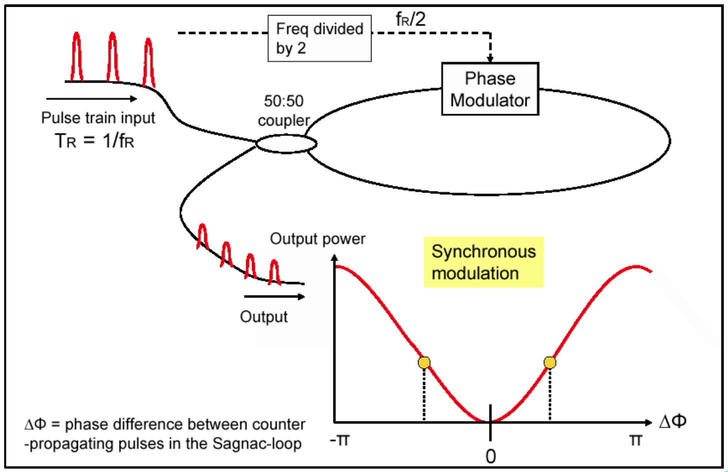


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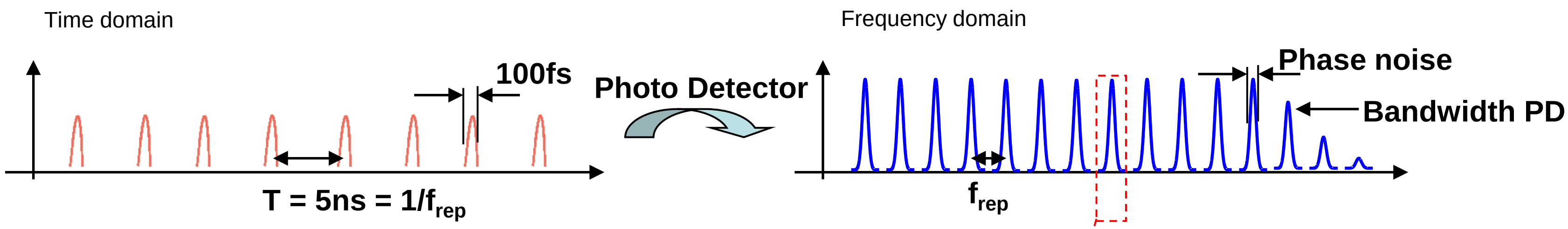


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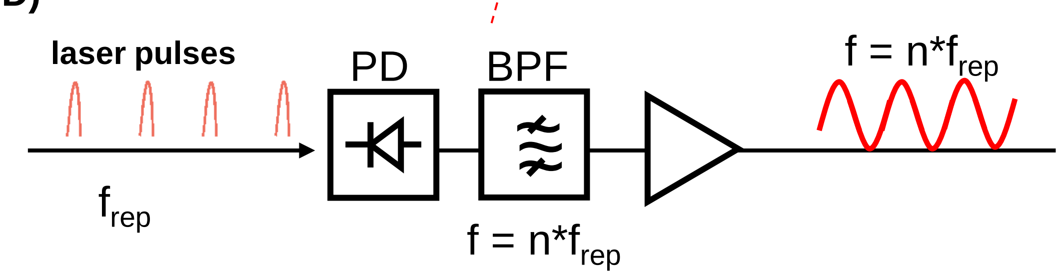


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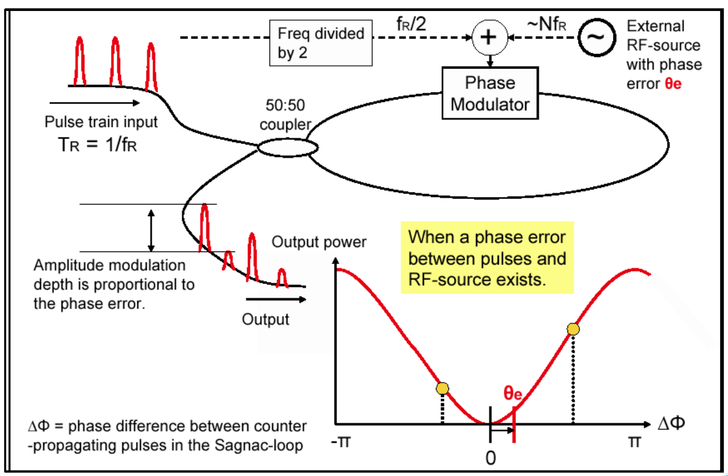

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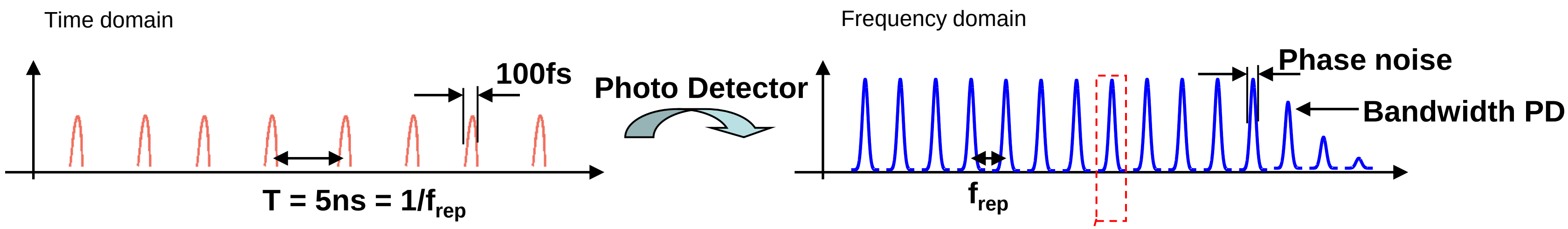


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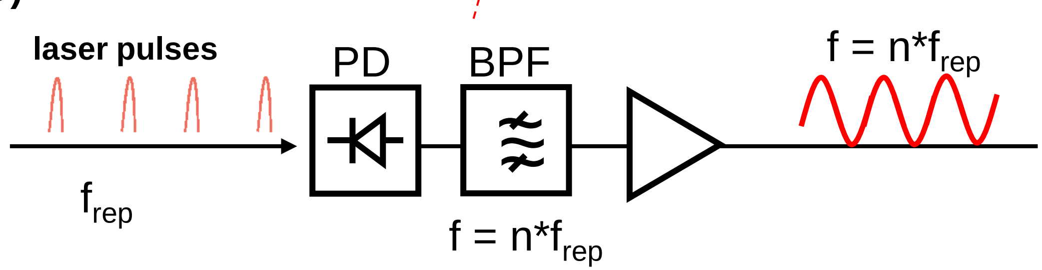


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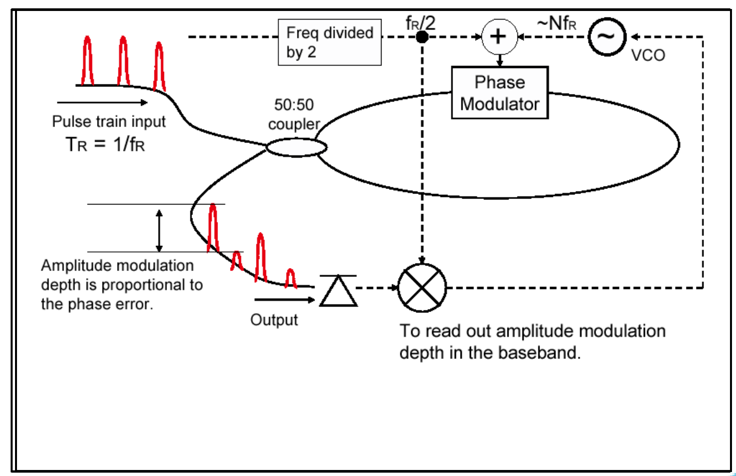


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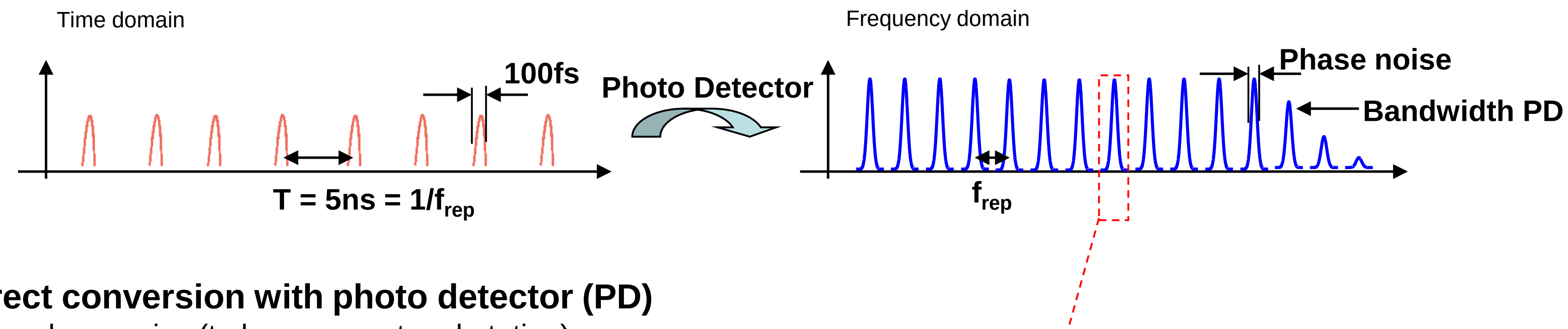
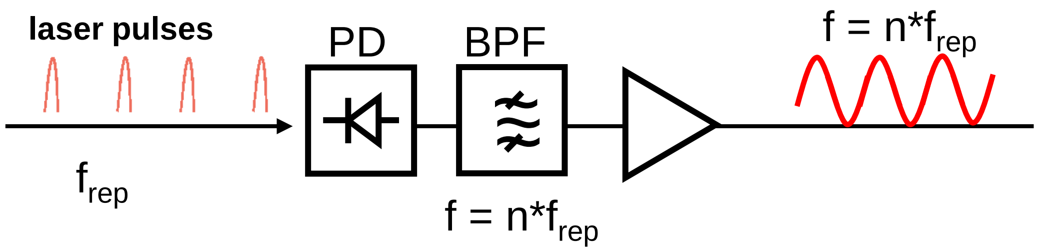
# RF generation from optical pulses




## Direct conversion with photo detector (PD)

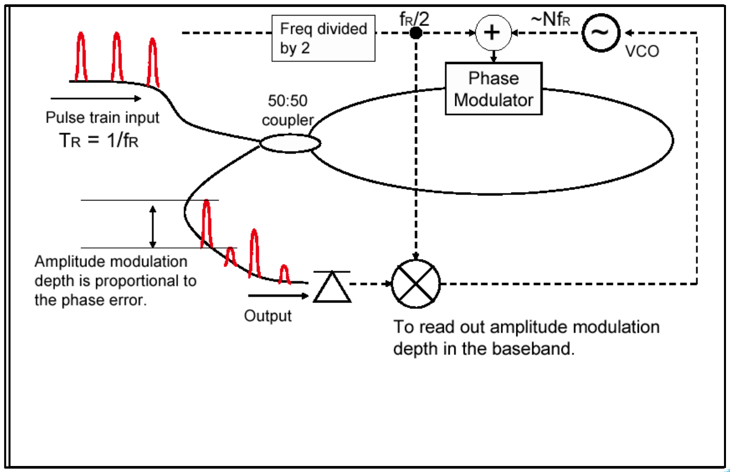
– Low phase noise (to be proven at end-station)
– Temperature drifts (0.4ps/C°)
– AM to PM conversion (0.5-4ps/W)
– Potential for improvement (corporation with PSI)




## Sagnac loop interferometer

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

f=1.3GHz jitter & drift < 10 fs rms limited by detection
Remark: much easier at higher frequencies …



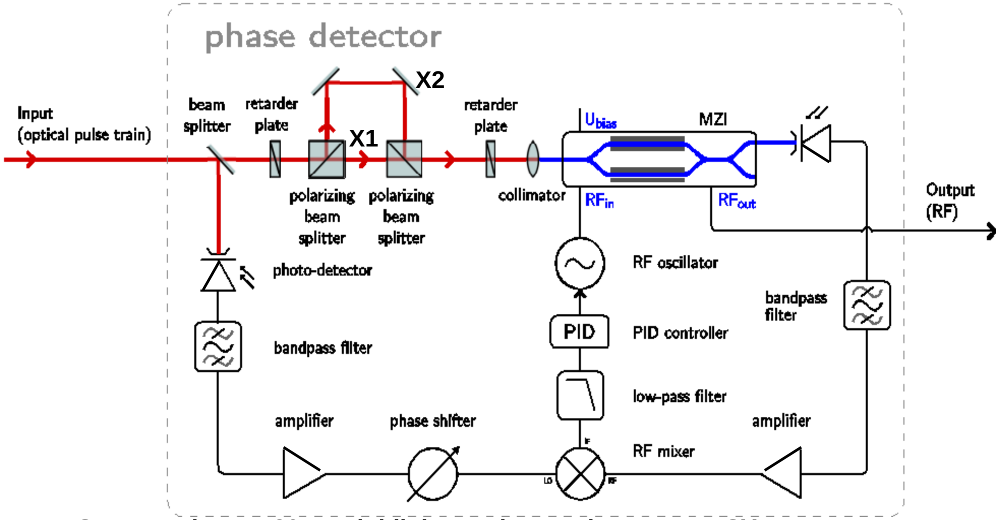

## MZI based balanced RF lock

– new scheme, under investigation

# MZI based balanced laser-to-RF phase detector

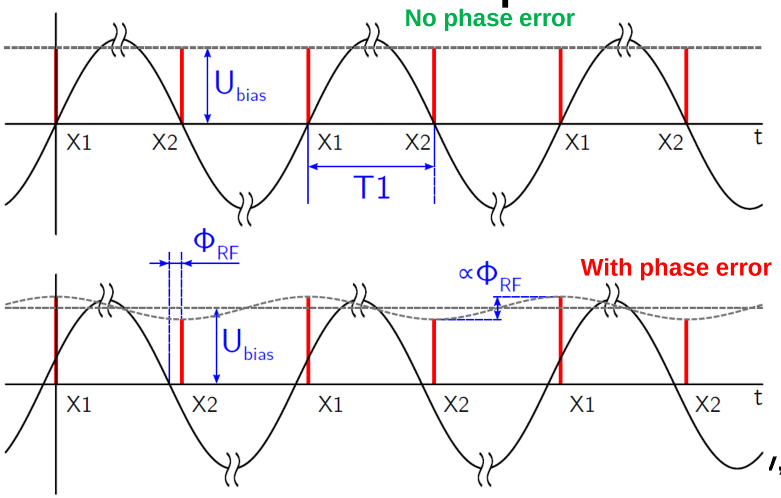
## Locking low-noise microwave oscillator to laser (or visa versa)

**RF Oscillator $f_{VCO} = n\ f_r$, split and delayed**




**See: Accelerator 2011, Highlights and Annual Report, DESY**
**http://www.desy.de/ueber_desy/jahresberichte/index_ger.html**

## Sketch of effect due to VCO phase shift



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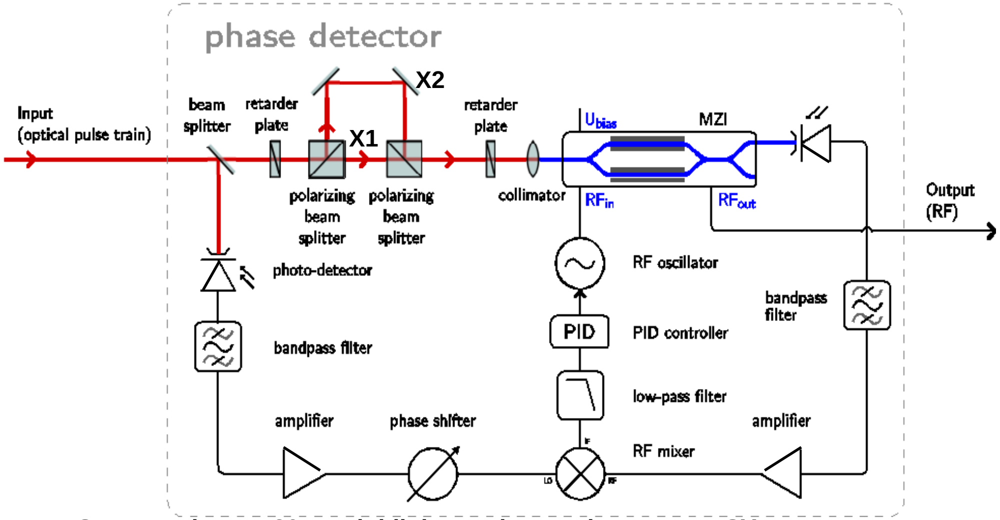
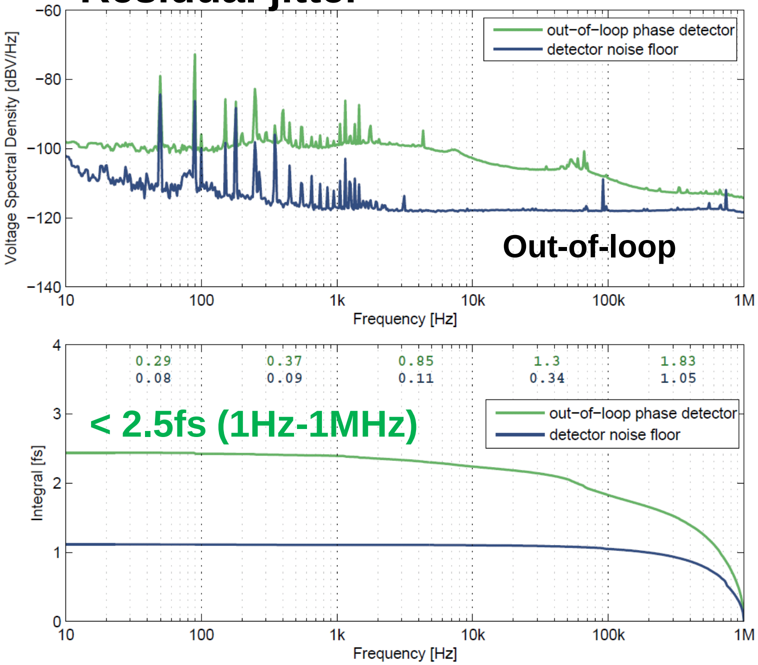
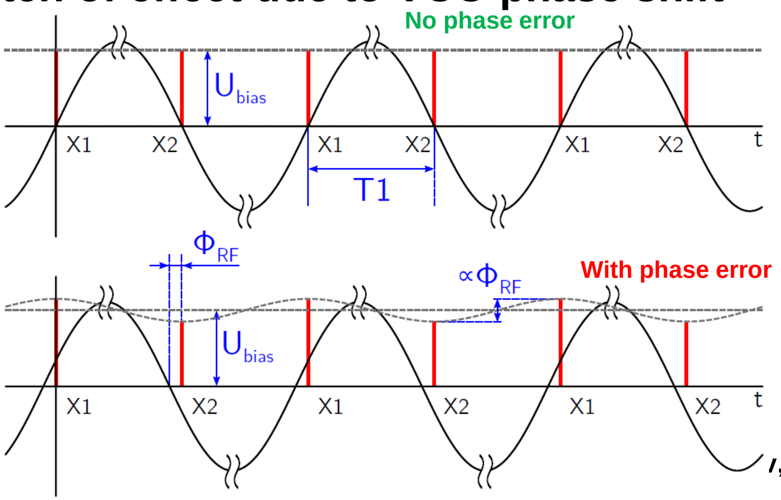



See: Accelerator 2011, Highlights and Annual Report, DESY
http://www.desy.de/ueber_desy/jahresberichte/index_ger.html

### Residual jitter

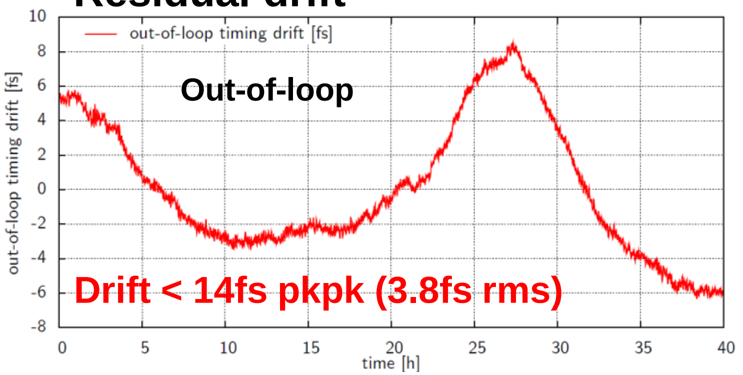



### Sketch of effect due to VCO phase shift




/, Israel,

### Residual drift

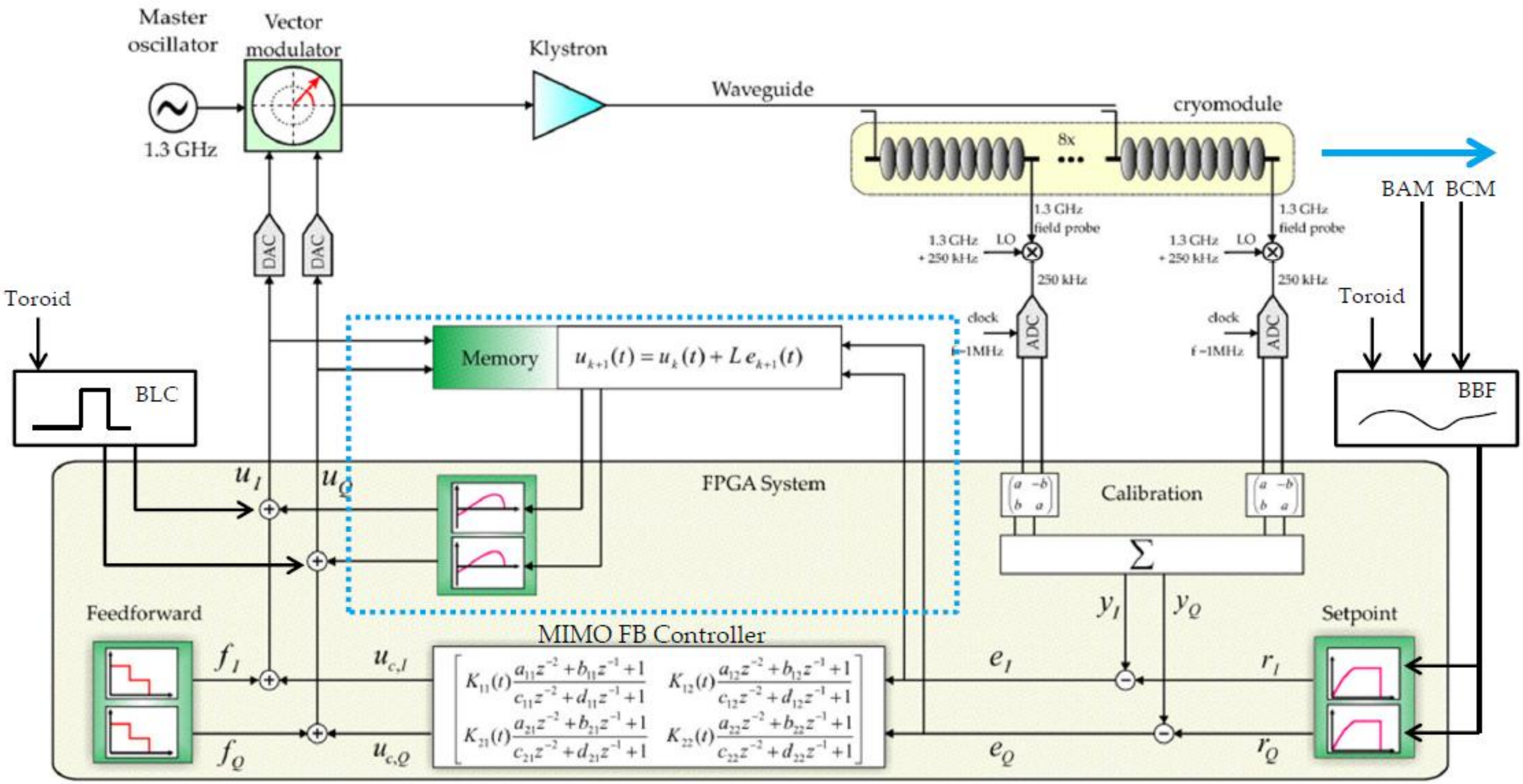



Courtesy: T. Lamb, DESY

# RF accelerator field control system

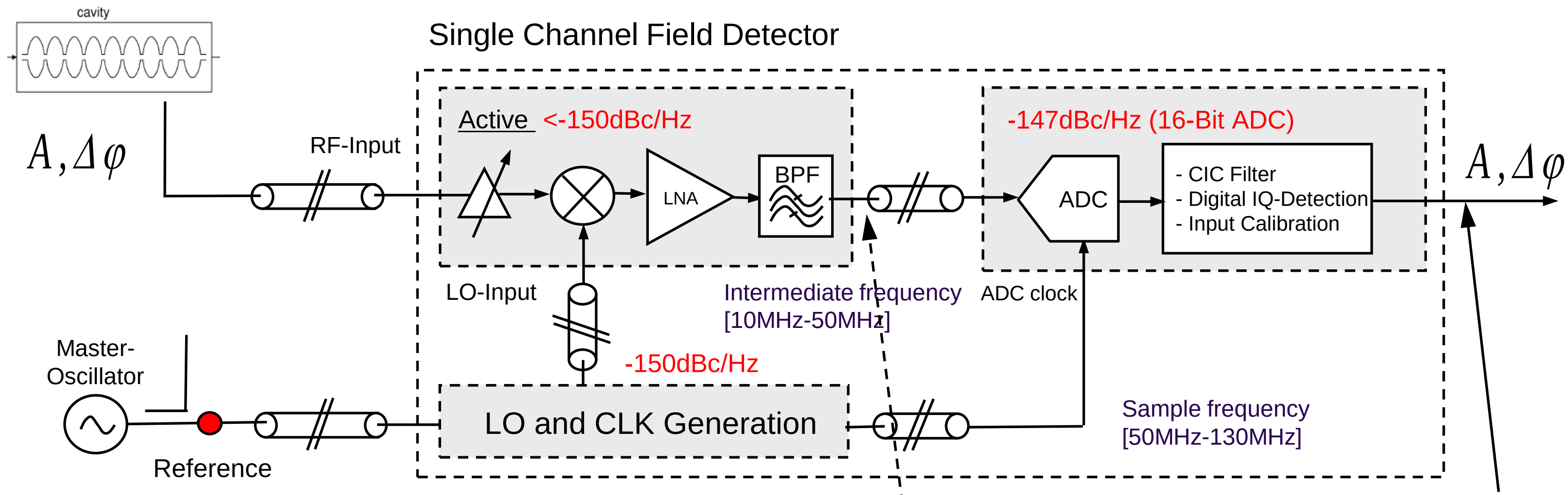
## Sketch of the controller structure

- Real-time FPGA processing of 8/16 RF channels and microsecond latency
- Generator driven Multiple-in-Multiple-out feedback controller, with adaptive feed forward drive
- Super-conducting RF cavities with ~ 300 Hz bandwidth




Courtesy: Ch. Schmidt, DESY

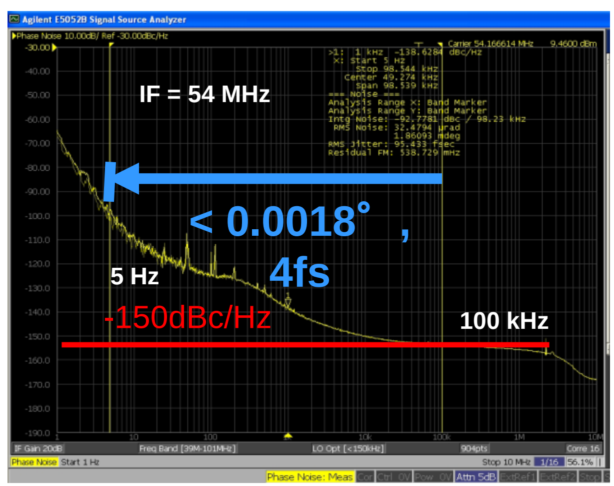
# Precision RF field detection (noise limitation)



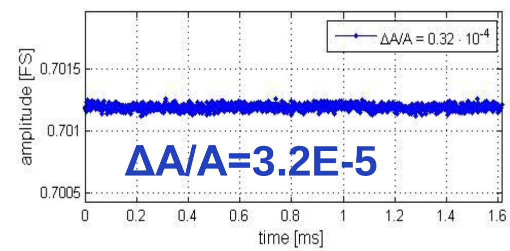

## Non-IQ sampling field detection limited by:

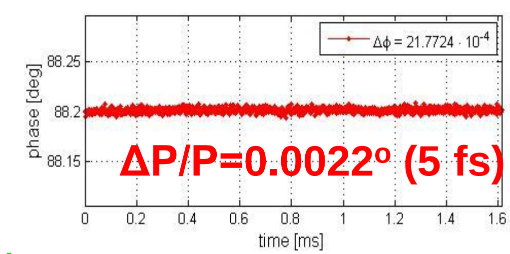
- Receiver active (< 4 fs)
- Receiver passive (< 2fs)
- LO-Generation (< 2 fs)
- ADC (limitation) (~5 fs)

at 1.3 GHz. Can be better at high frequencies.




## Measurement with ADC




Courtesy: F. Ludwig, DESY

# Drift compensation of microwave components

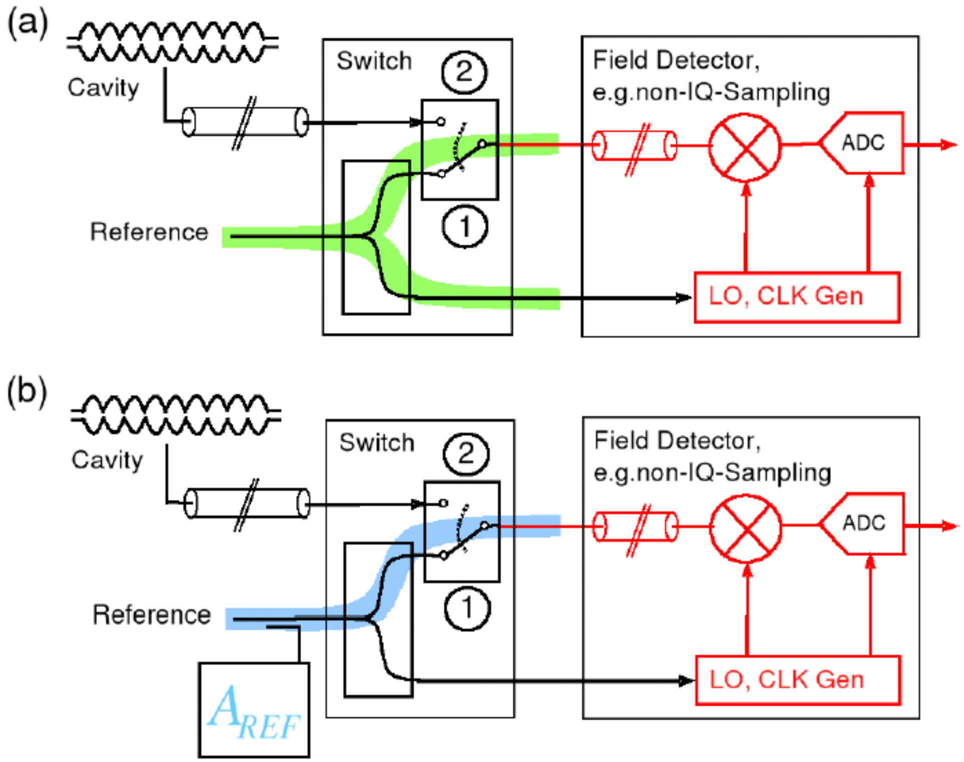
## Problem:

- **Mixer phase drifts ~ 0.2°/K**
- **Mixer amplitude drifts ~ 0.2%/K**

**+ dependence also on humidity**

**+ mixer drift not equal (one PCB)**

**⇒ Reference tracking for mixer drift removal**



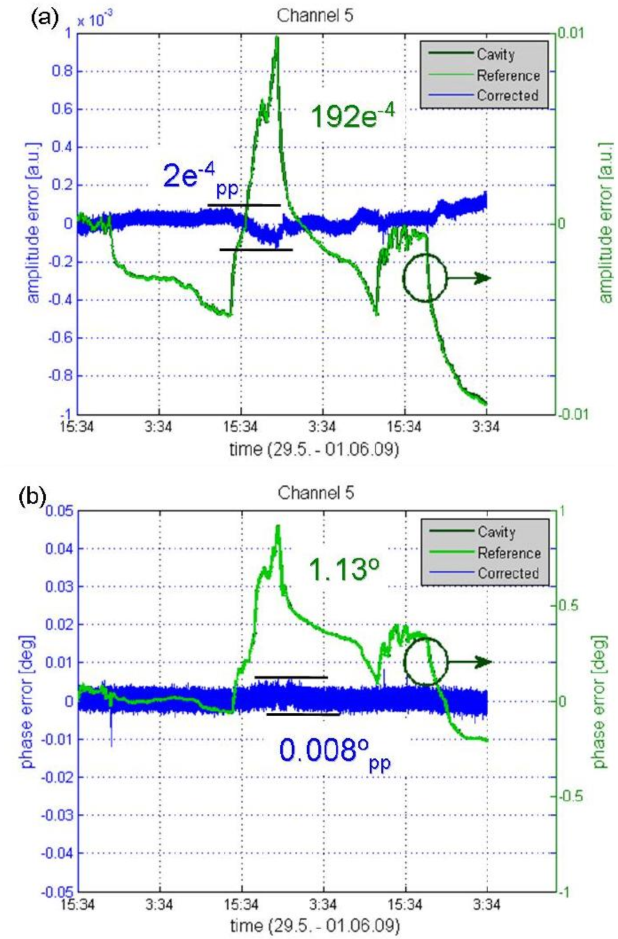
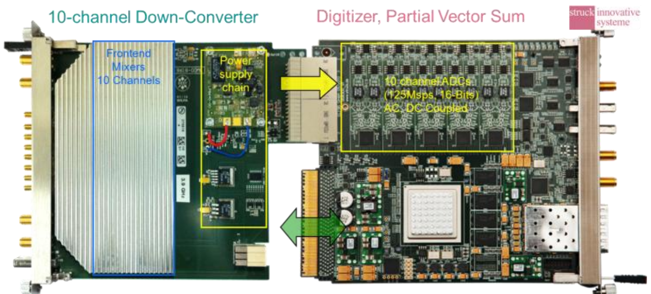




Figure 3: Measured (a) amplitude and (b) phase deviation for the injected corrected signal (blue marked) and uncorrected (green marked) over 60 hours.

Courtesy: F. Ludwig, DESY

# MTCA.4 crate system used as LLRF hardware platform

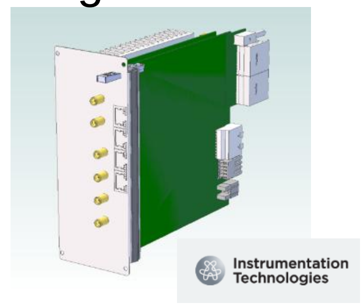
## fs Field detectors




- 10 channel field detection (1.3GHz, 3.0GHz, 3.9GHz)

- 10 channel ADCs (125Msps, 16-Bits)
- FPGA partial cavity vector sum
- Low latency links via uTCA-backplane

## LO generation

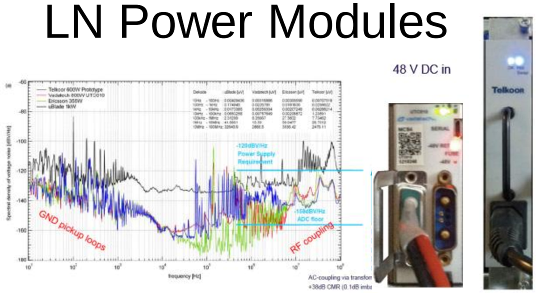



## Controller

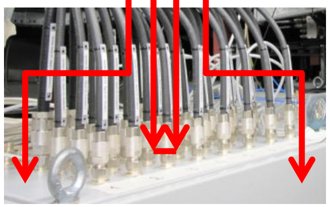

- 2 channel vector modulator (108MHz, 216MHz, 1.3GHz…3.9GHz)
- 16-bit

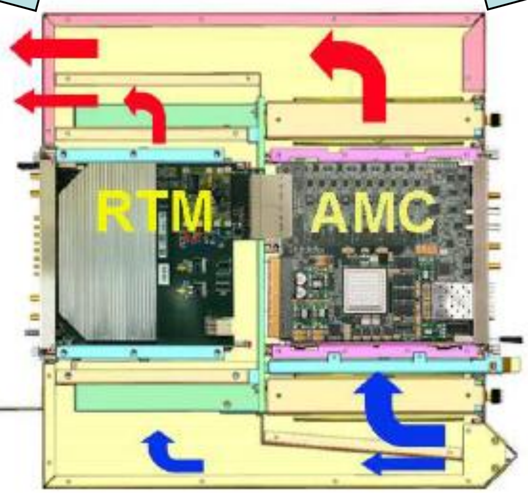
- LLRF Controller, 6 Fiber-Ports, 2 GB-Links
- FPGA(V5), DSP

## LN Power Modules

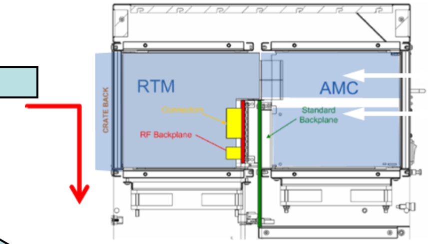



## Grounding!

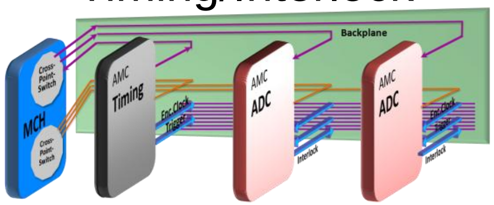





## EMC/EMI

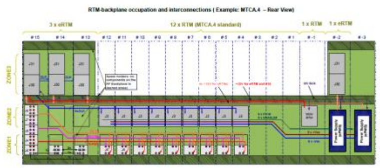



## Timing/Interlock




PICMG

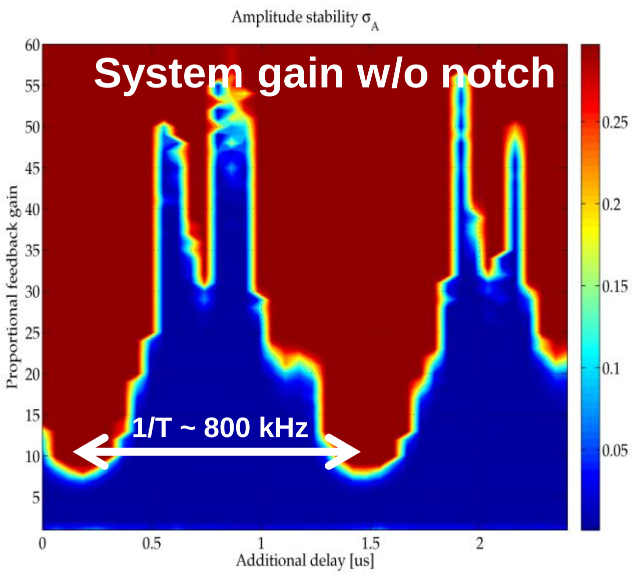
## RF Backplane



**Integration to low-noise, high processing power environment**

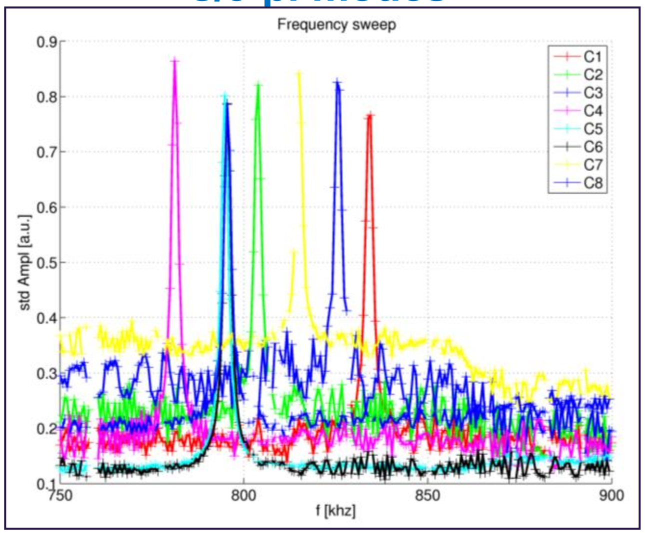
# MTCA.4 crate system used as LLRF hardware platform

Calibrated controller gain



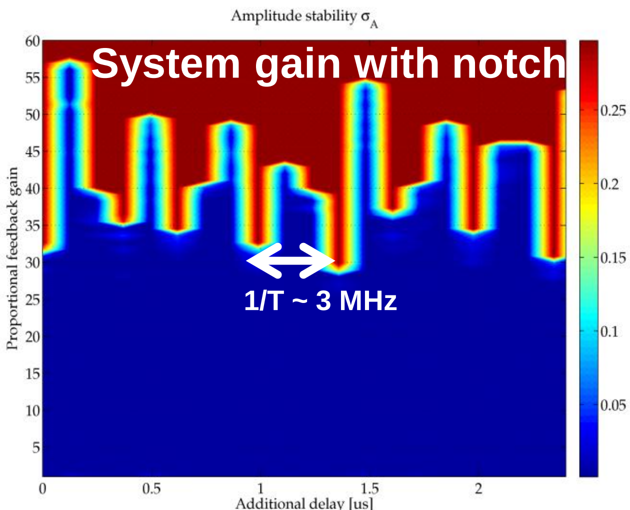

No impact on beam ⟷ but causes instabilities of regulation

## 8/9 pi modes



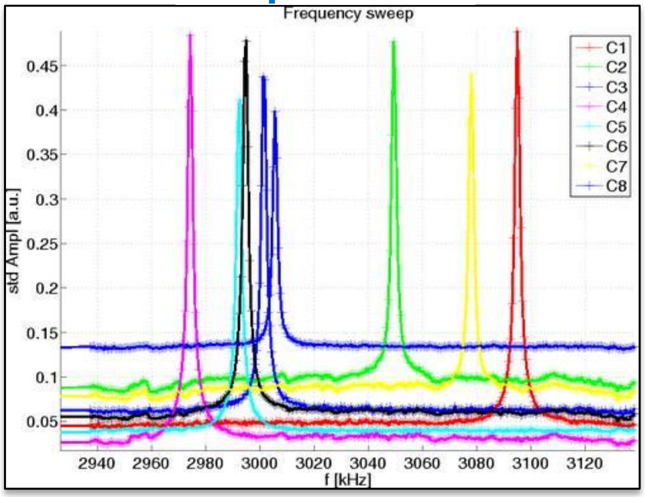

## Digital notch filter

Calibrated controller gain



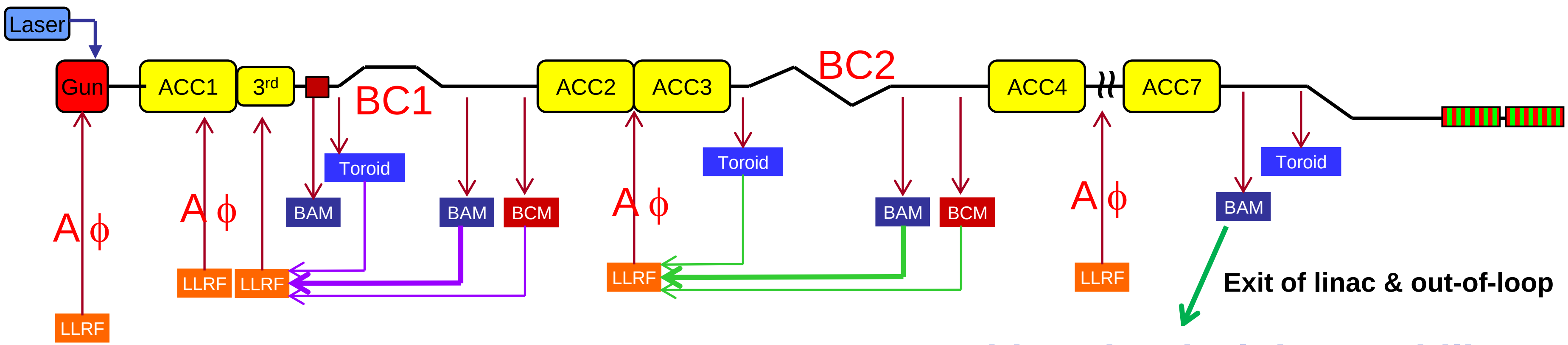

Has impact on beam ⟷ and causes instabilities of regulation

## 7/9 pi modes

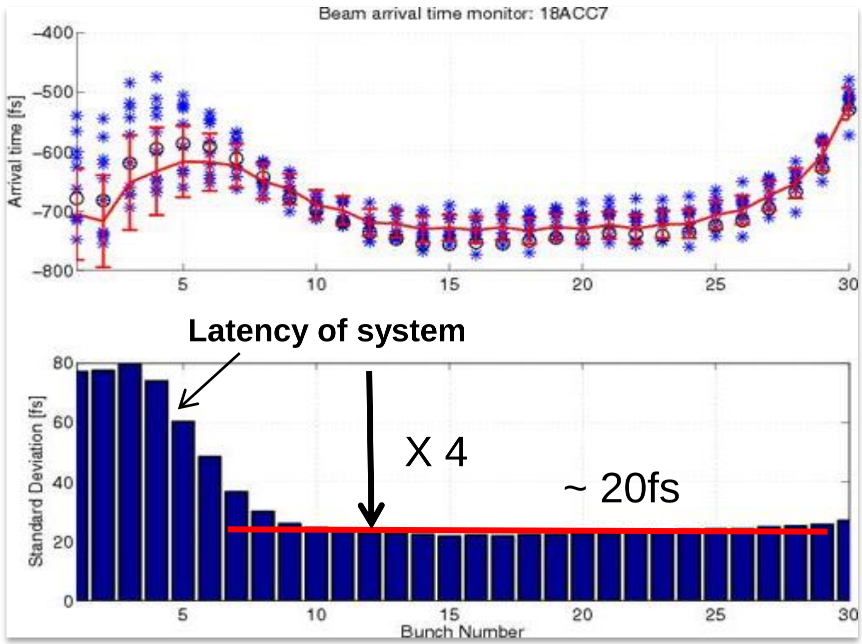



⇒ THPM086

# Intra-train beam based feedbacks (FLASH)




## Achieved arrival time stability




## New Beam Based Feedbacks algorithm

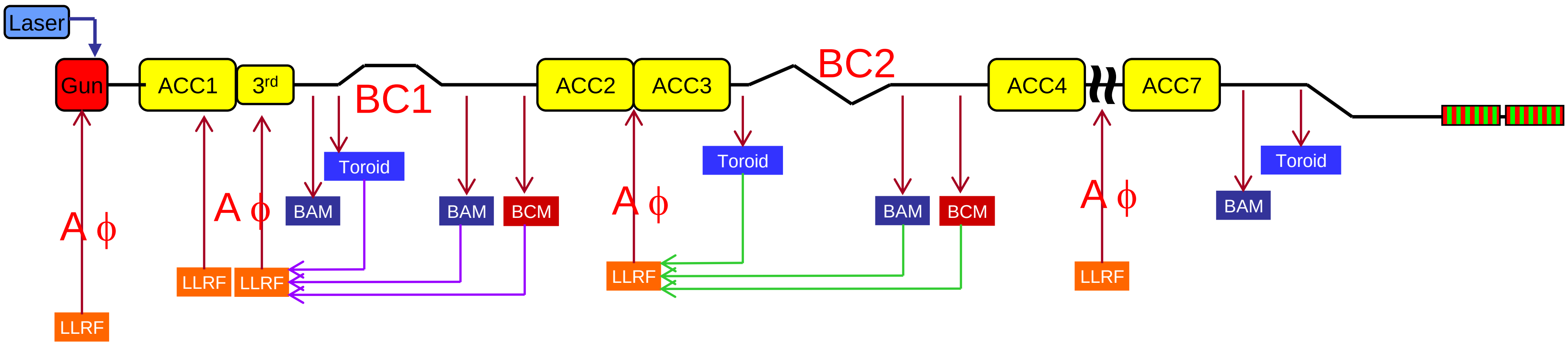
- Arrival FB on ACC1 only using monitors after BC1 ⇒ **~ 20 fs routine**
- Arrival FB on ACC2 (was not active) Test this week ⇒ **~ 10-15 fs expected**
- Ultimate: broadband NRF cavity & ultra-low latency digital feedback system From simulations ⇒ **~ 5 fs expected**

**Courtesy: Ch. Schmidt, S. Pfeiffer, DESY**

Thanks you for attention

# Intra-train beam based feedbacks (FLASH)





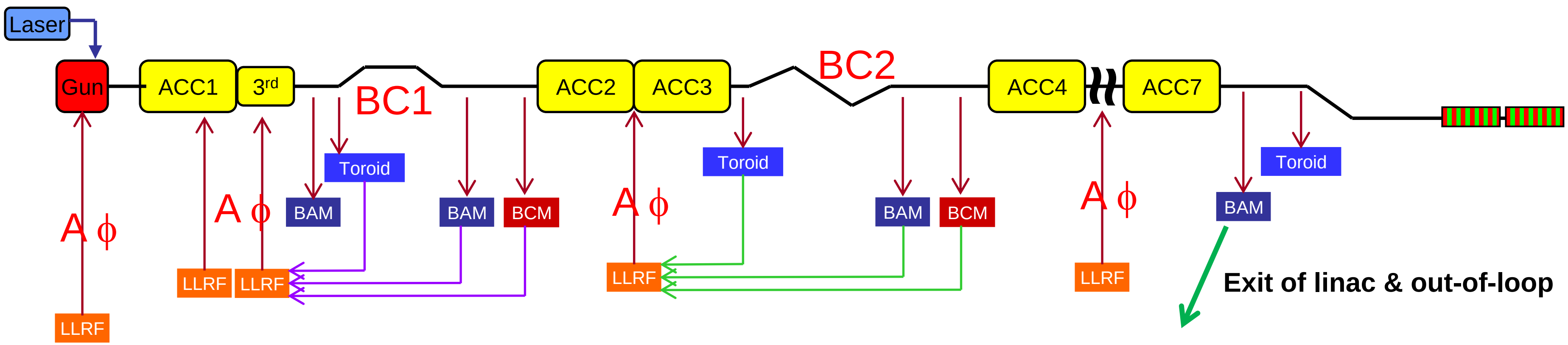

Beam Based Feedbacks:

- Arrival time (BAM) and bunch compression (BCM) after chicane BC1 are simultaneously correct amplitude and phase in ACC1 /39
- BAM and BCM after BC2 correct amplitude and phase in ACC23
- Charge measurement used for beam loading compensation

**Courtesy: Ch. Schmidt, S. Pfeiffer, DESY**

# Intra-train beam based feedbacks (FLASH)



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**Courtesy: Ch. Schmidt, S. Pfeiffer, DESY**

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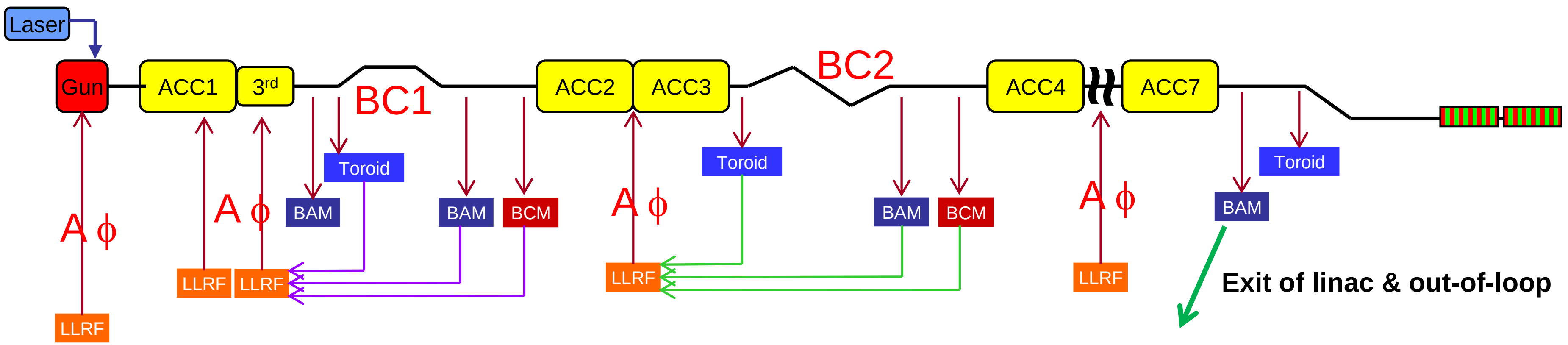


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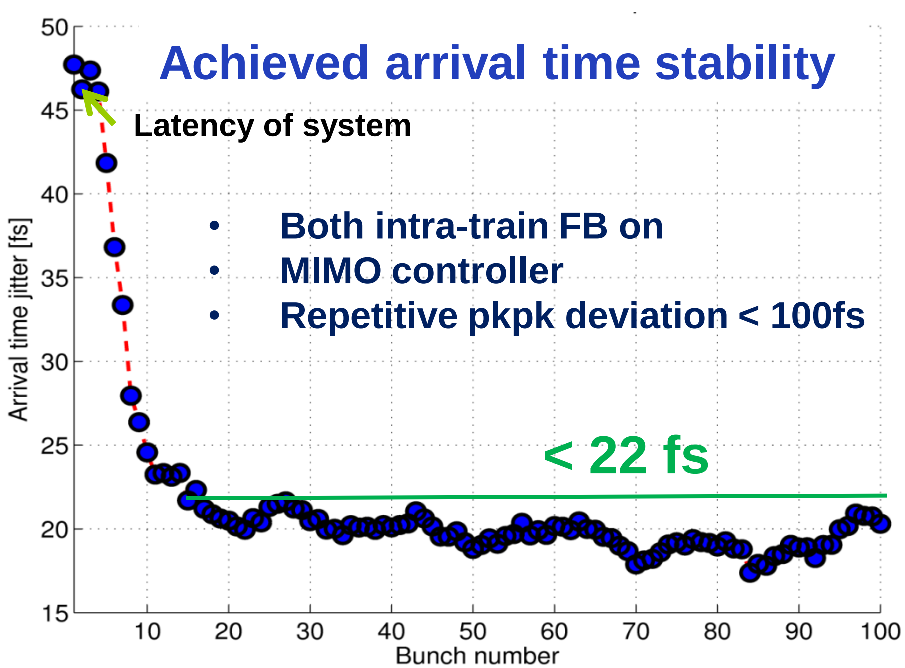
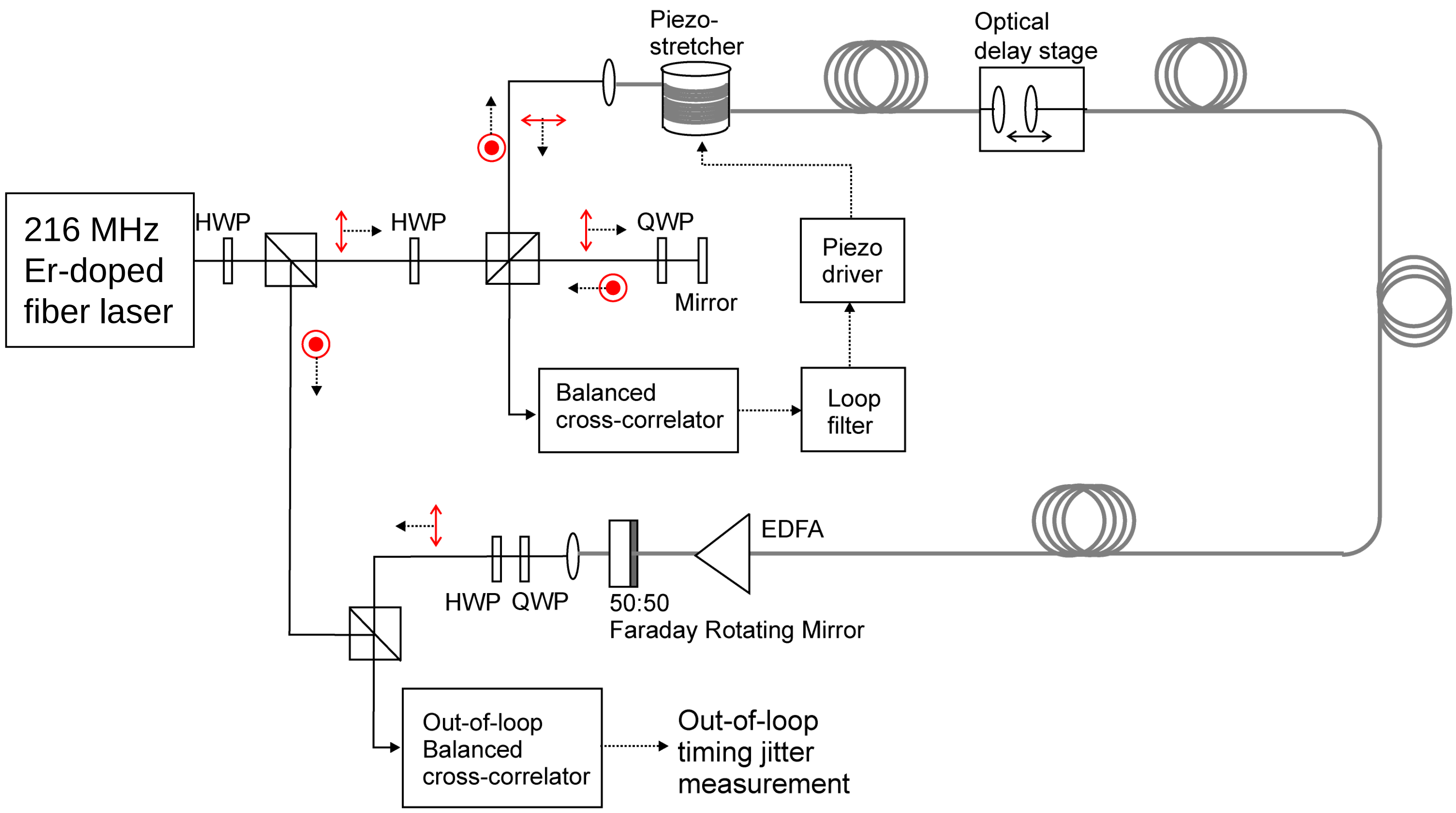


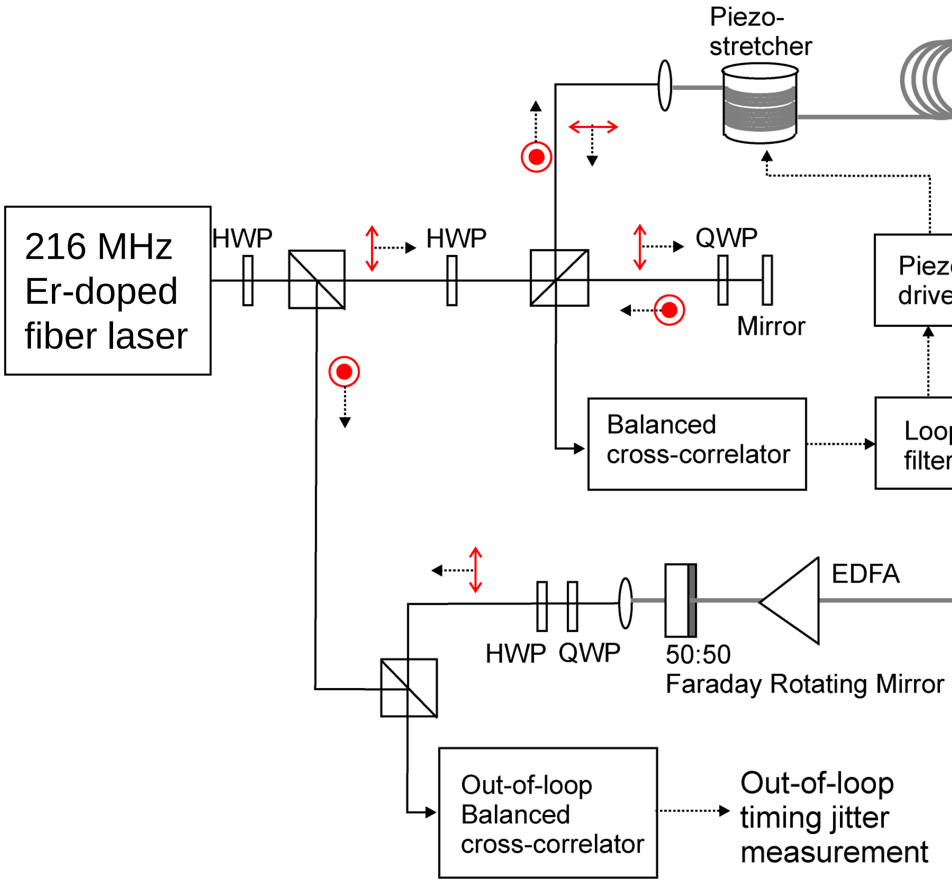

**Courtesy: Ch. Schmidt, S. Pfeiffer, DESY**

# Fiber Link Stabilization (optically)

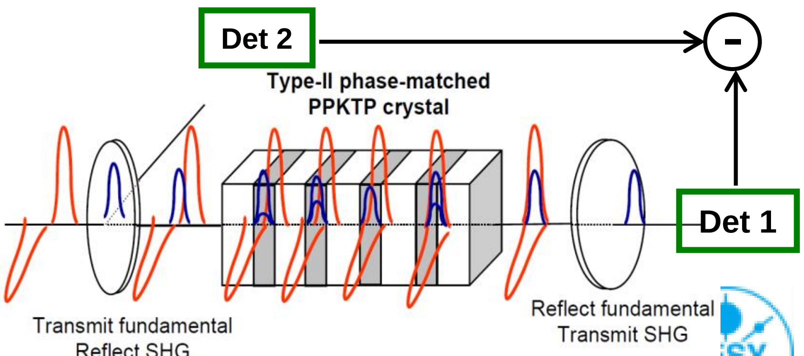



J. Kim et al., Opt. Lett. **32**, 1044-1046 (2007)

# Fiber Link Stabilization (optically)

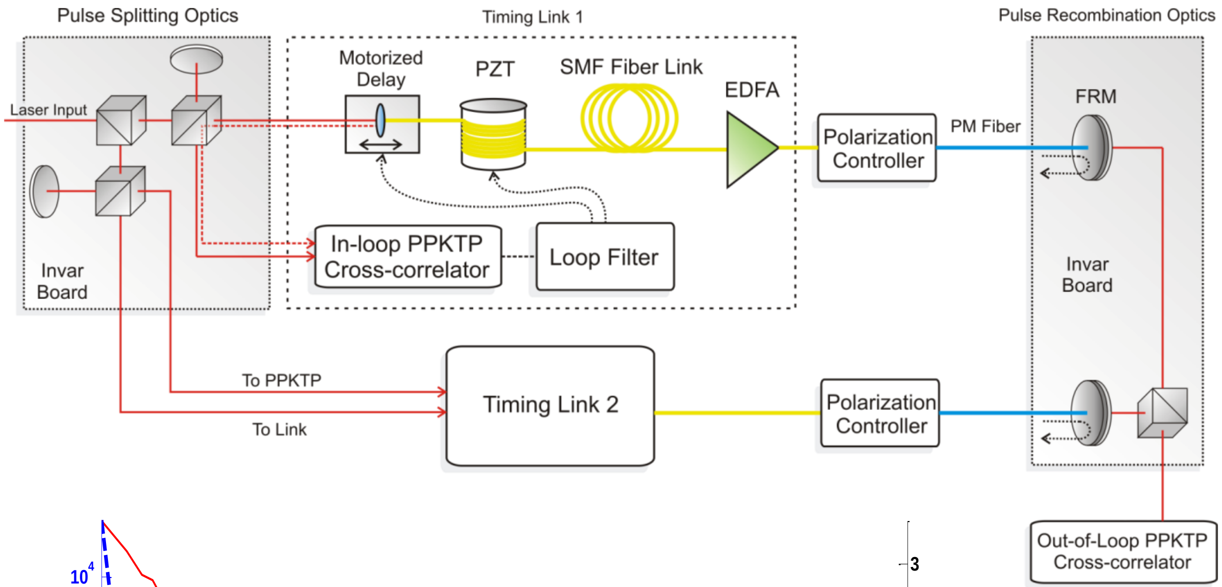


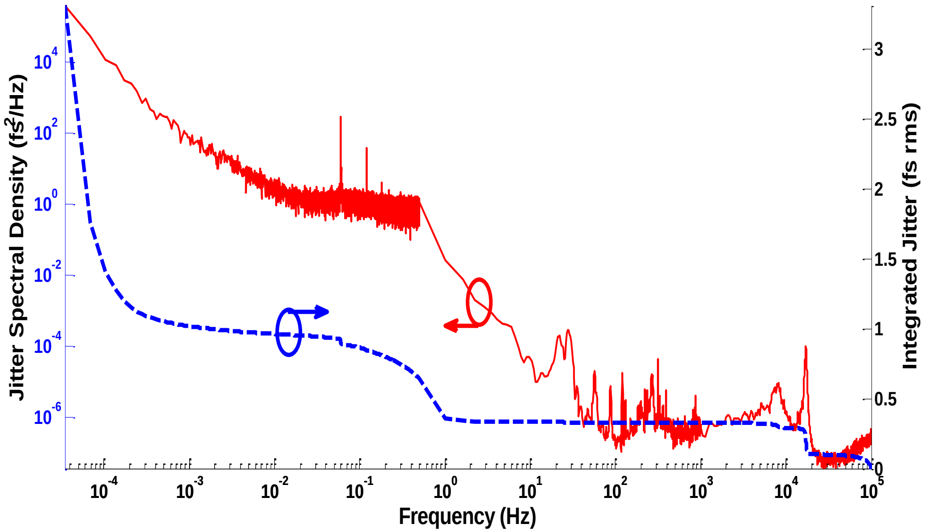

Balanced optical cross-correlator




J. Kim et al., Opt. Lett. **32**, 1044-1046 (2007)

# Fiber Link Stabilization (out-of-loop)



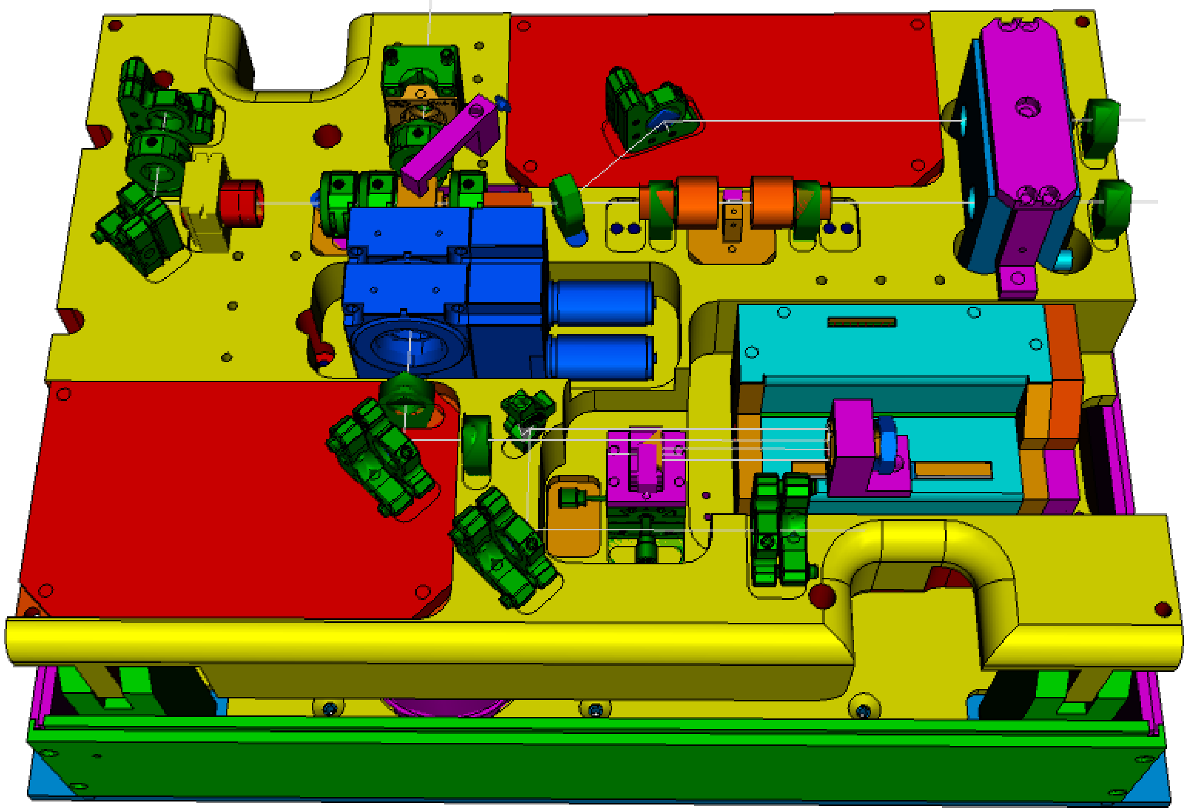

360 as (rms) timing jitter from 1 Hz to 100 kHz
3.3 fs (rms) timing jitter from 35 µHz to 100 kHz

**For 400m link !!!**
**3.5 km will be considerably more difficult!**
- ⇒ **Dispersion management**
- ⇒ **Accumulated delays**
- ⇒ **PMD/spurious SPM**
- ⇒ **Polarization control**

Courtesy: F. Kaertner

# Fiber Link Stabilization (optically)

3rd generation of opto-mechanics
typical in loop jitter ~ 1-2 fs rms (also smaller)



Courtesy: Bock/Schultz/Lamb

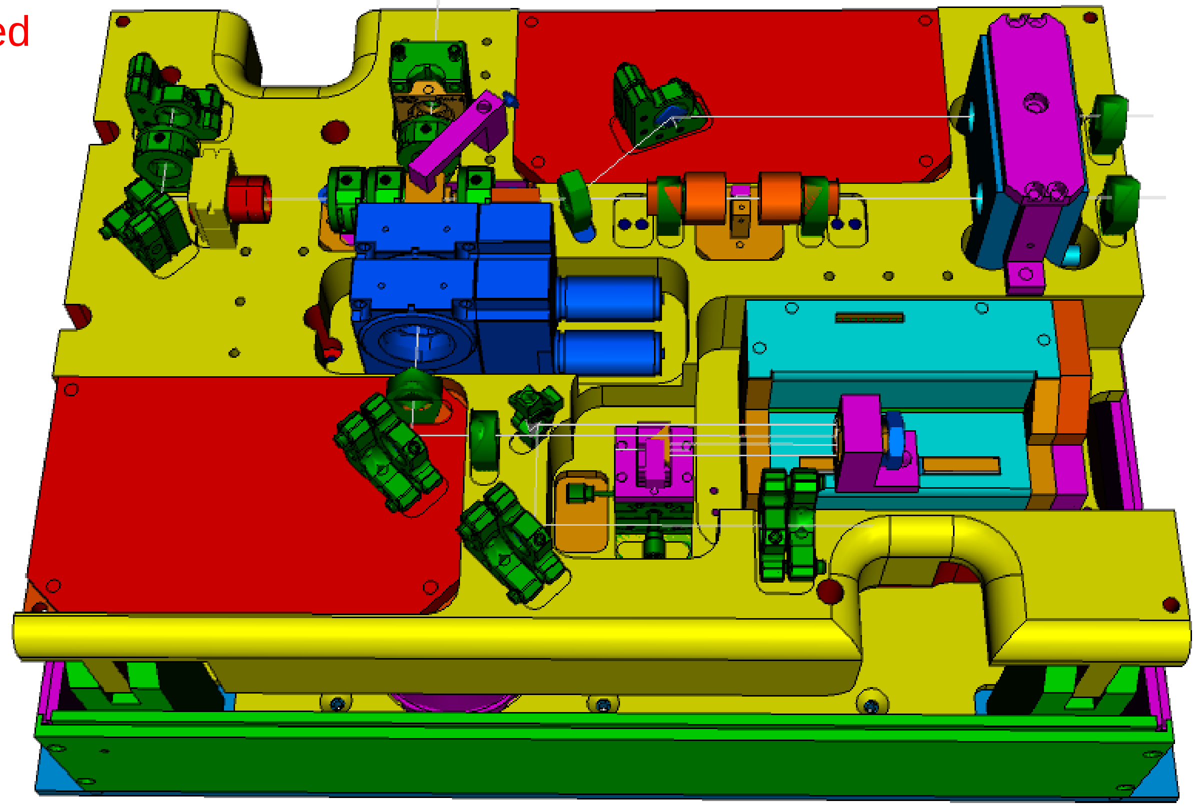
# Fiber Link Stabilization (optically)

3rd generation of opto-mechanics
typical in loop jitter ~ 1-2 fs rms (also smaller)

Experience:
Operate reliably
Some links fast AM noise observed

Recent developments:
Matching optics
Retro-reflector delay line with
precision stepper motor
Isolation to FSD
Link layout changed

Current developments 2011/12:
PCB for readout electronics
Low noise balanced detector
Ultra-low noise LDD driver
uTCA based digital FB controller



XFEL:
Dispersion management need to be improved (2 test links in 26a for 3.5km)
Delay stage too short  for long links and large temp. changes (PSOF fibers)

Courtesy: Bock/Schultz/Lamb