Timing and Synchronization

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Lecture outline

1. General overview
2. Introduction to phase noise
3. Synchronization in linear injectors
4. Timing in linear injectors
5. References

1.

General overview

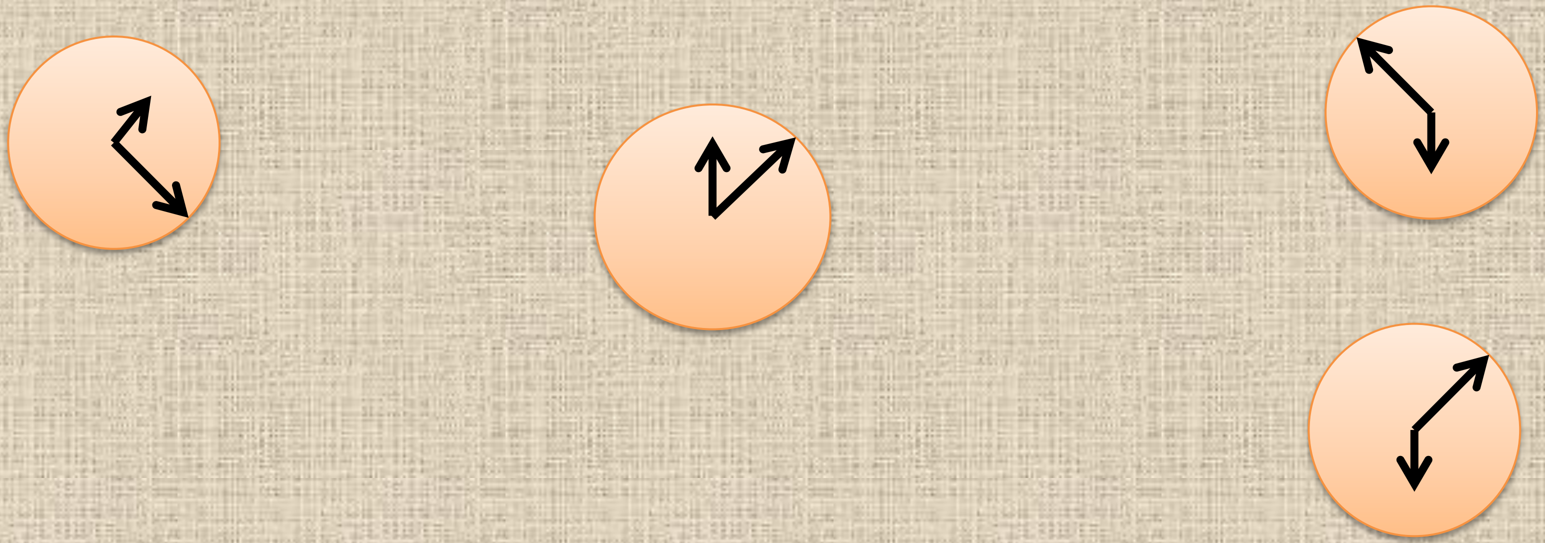
1. Definitions
2. Synchronization
3. Timing

1.1. General Overview - Definitions

- **Synchronization:** A fine temporal alignment among all the relevant sub-system oscillators that guarantees temporal coherence of their outputs (precision 10ps÷10fs)
  - Example: coherence between RF accelerating phase – laser oscillators frequency – ADC/DAC clocks
- **Timing:** digital delayed signals that define the temporization of events (precision 10ns÷10ps)
  - Example: RF pulse generation, lasers amplification temporal gate, BPM triggers, injection/extraction kickers, event tagging, …

1.2. General overview - Synchronization

- The aim of a **synchronization system** is to closely relate the timing information (frequency) of all the clocks (oscillators) present in a desired environment



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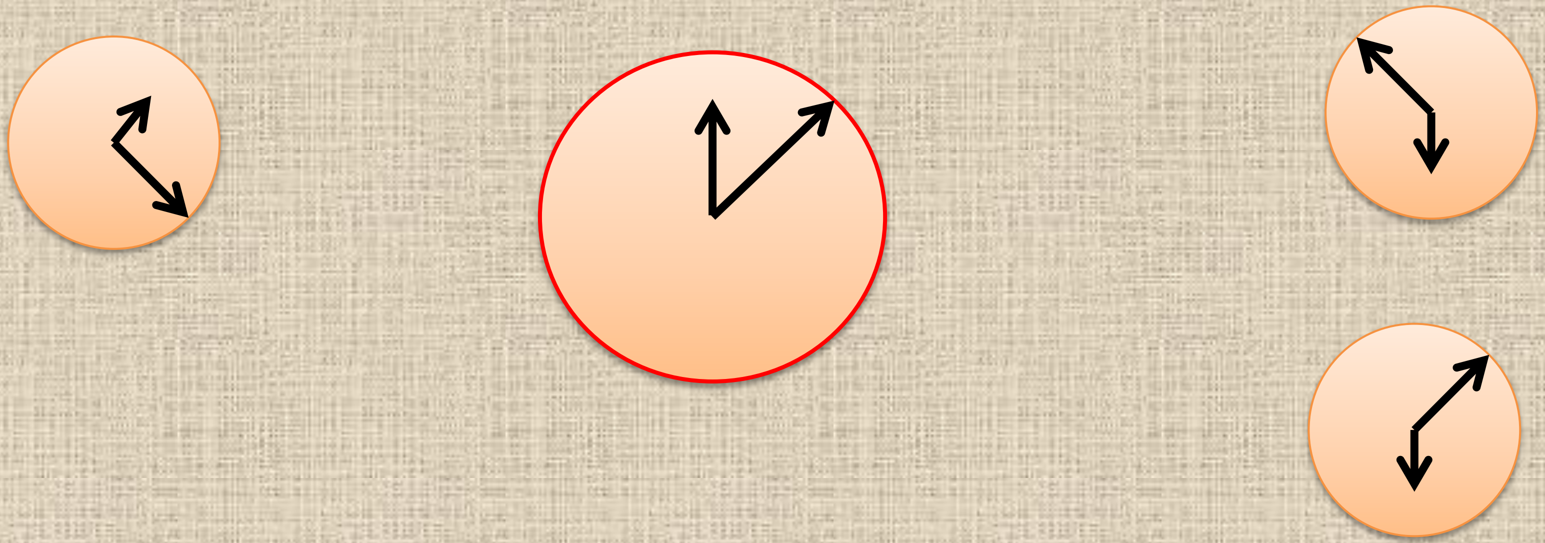
- Usually one stable oscillator is used as master reference



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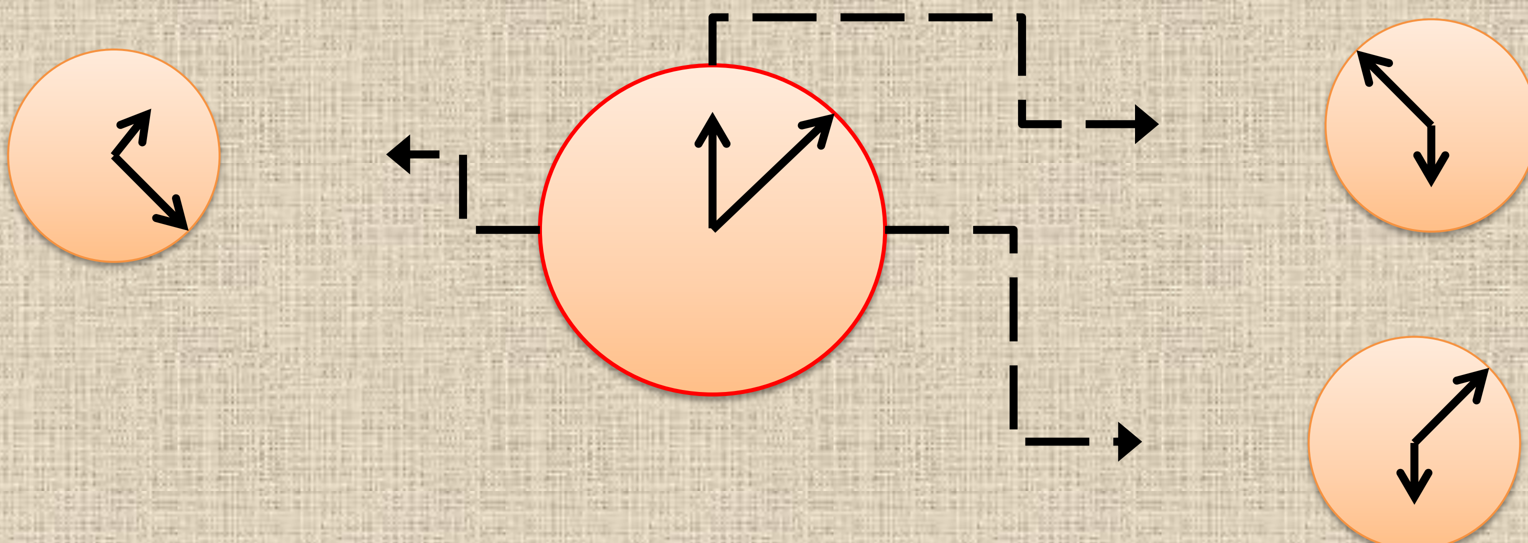
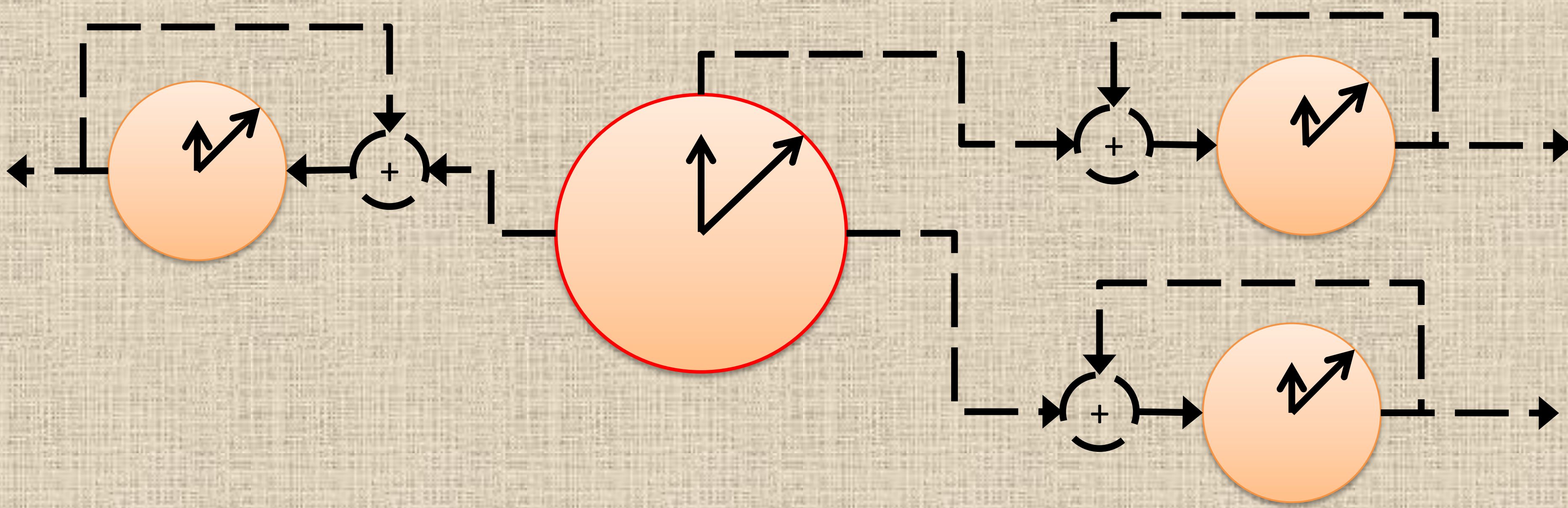
- Thus, the synchronization system tasks are:
  - distribute the reference signal



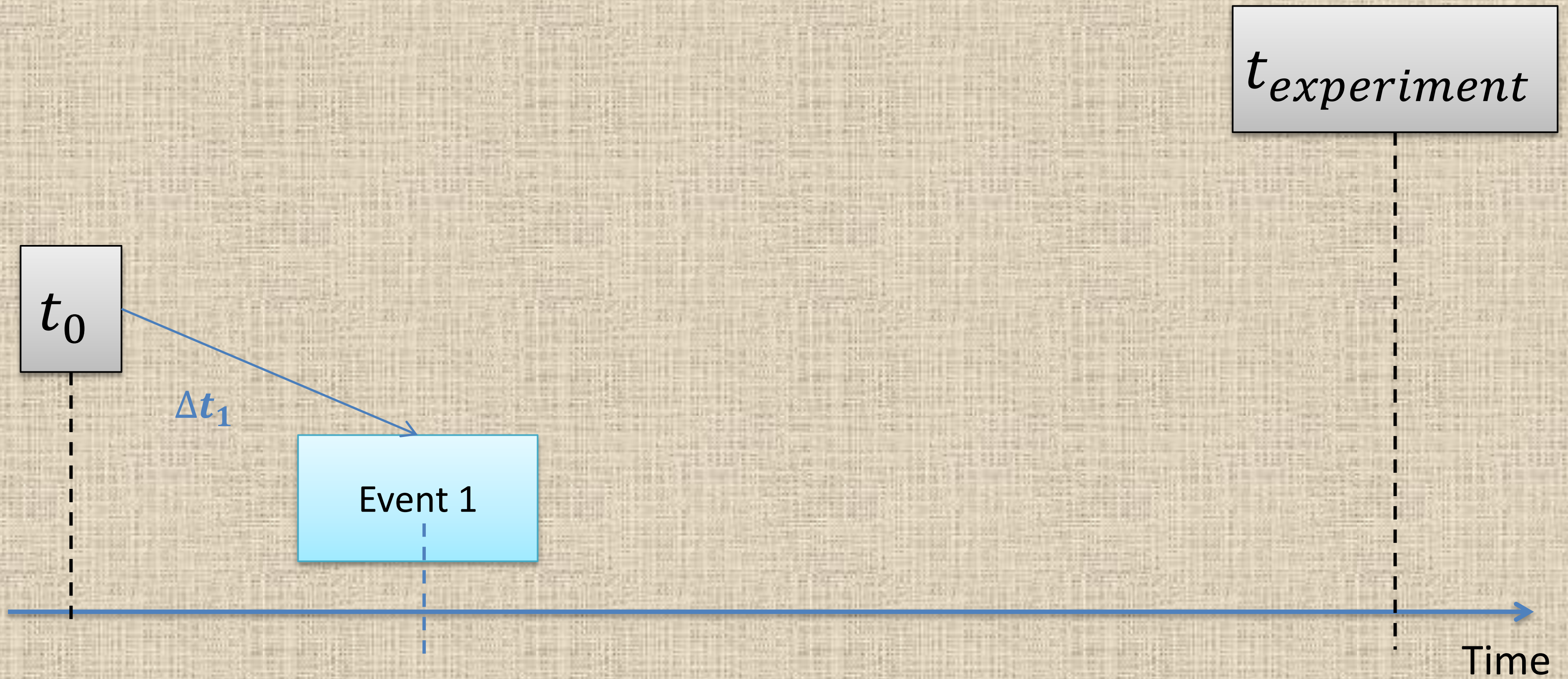
1.2. General overview - Synchronization

- The aim of a **synchronization system** is to closely relate the timing information (frequency) of all the clocks (oscillators) present in a desired environment
- Usually one stable oscillator is used as master reference
- Thus, the synchronization system tasks are:
  - distribute the reference signal
  - uniform the slave oscillations to those of the reference



1.3. General Overview - Timing

Once all the physical outputs of sub-systems are coherent, the **timing system** decides the chain of events that are necessary to realize an experiment.



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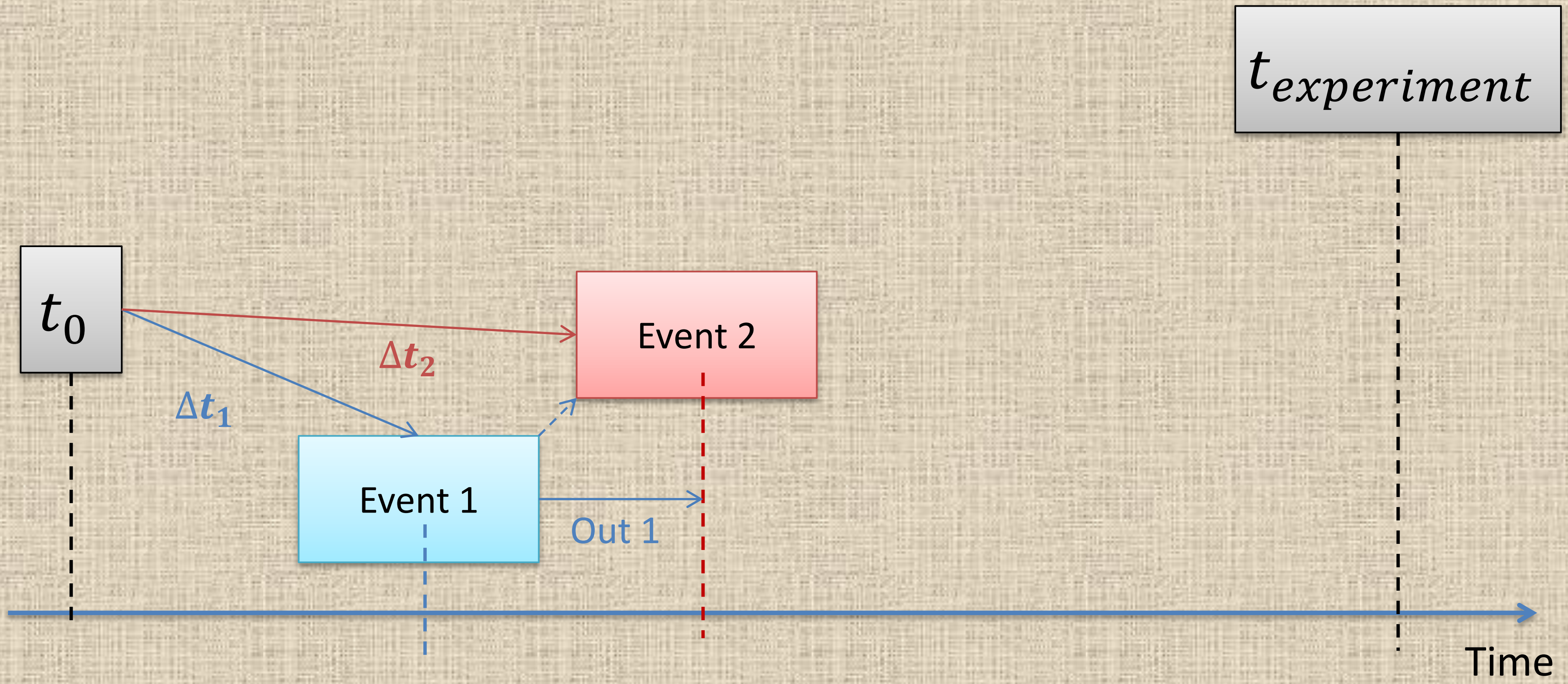

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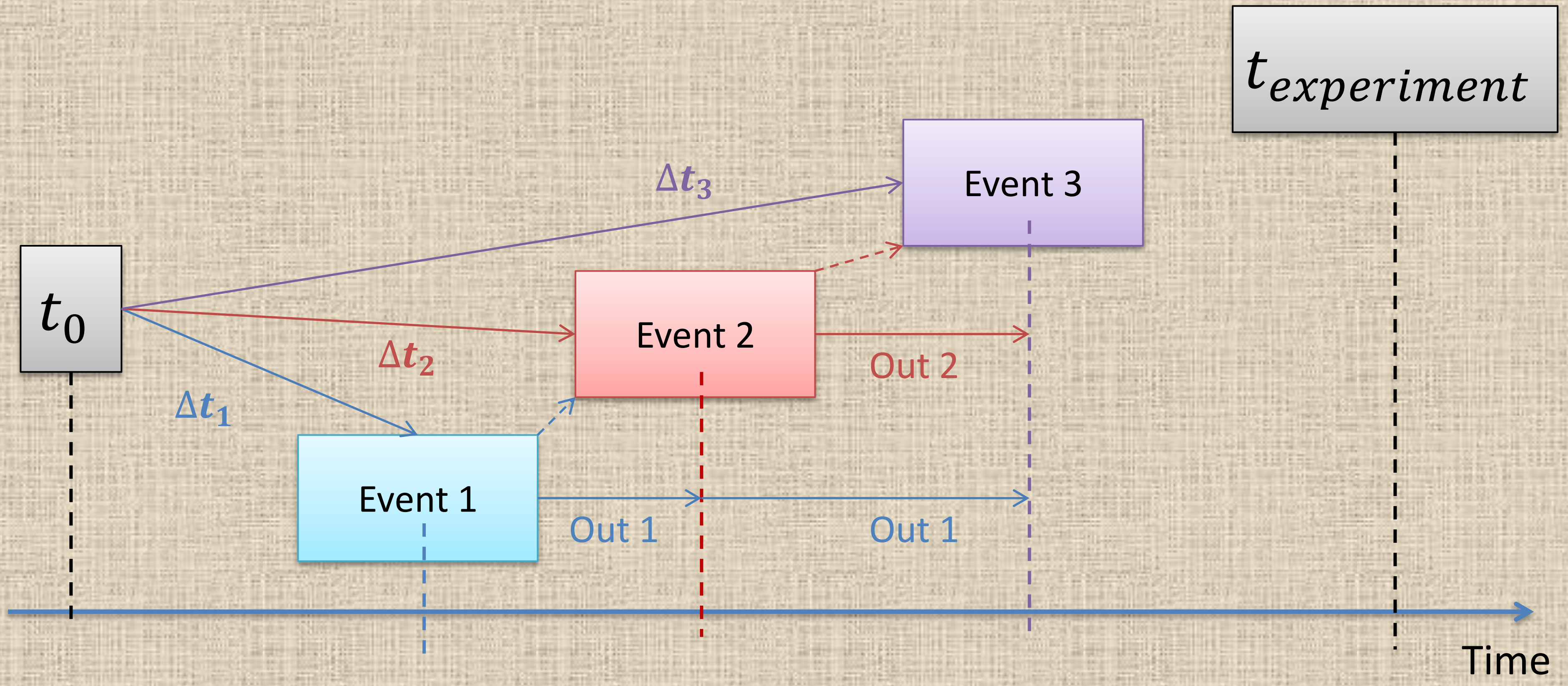

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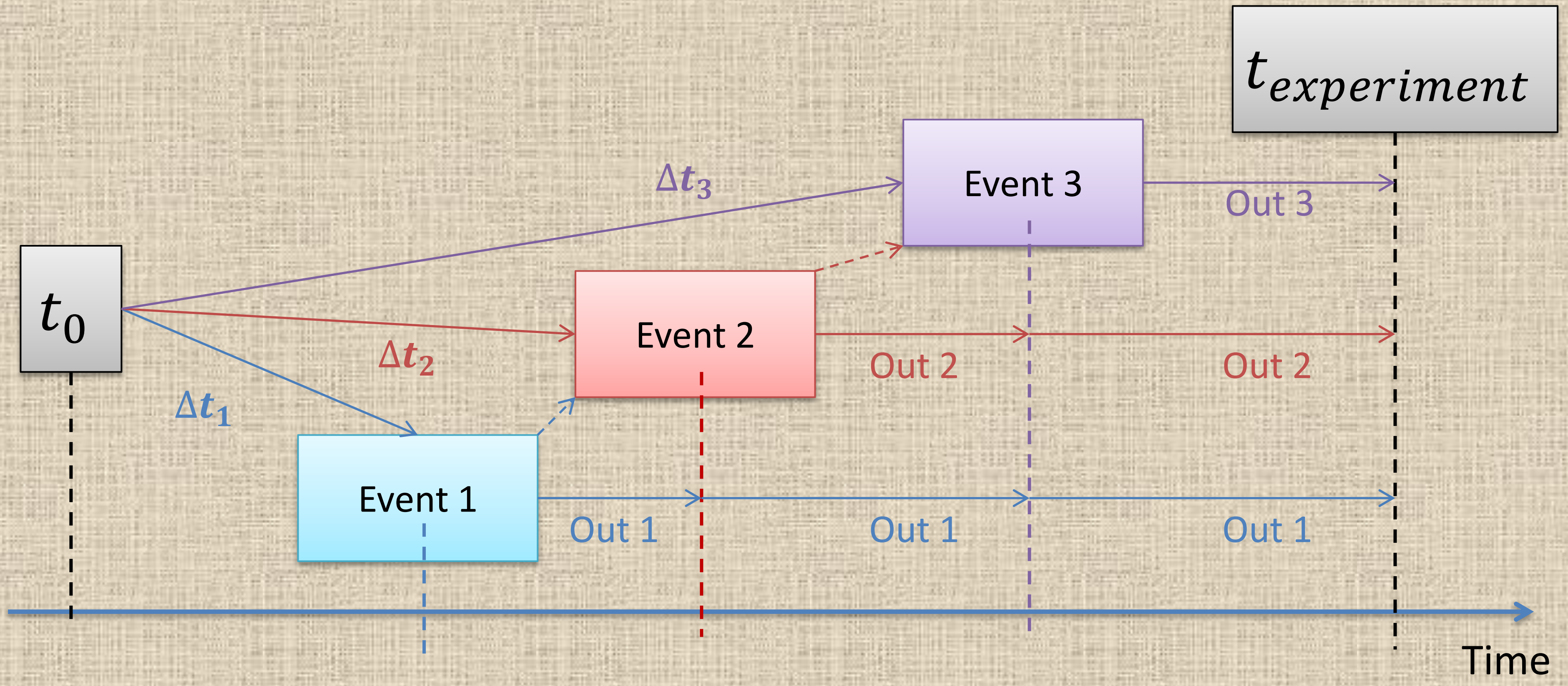


2.

Introduction to phase noise

1. Phase noise in oscillators
2. Noise sources
3. Measuring phase noise

2.1. Phase noise in oscillators [1]

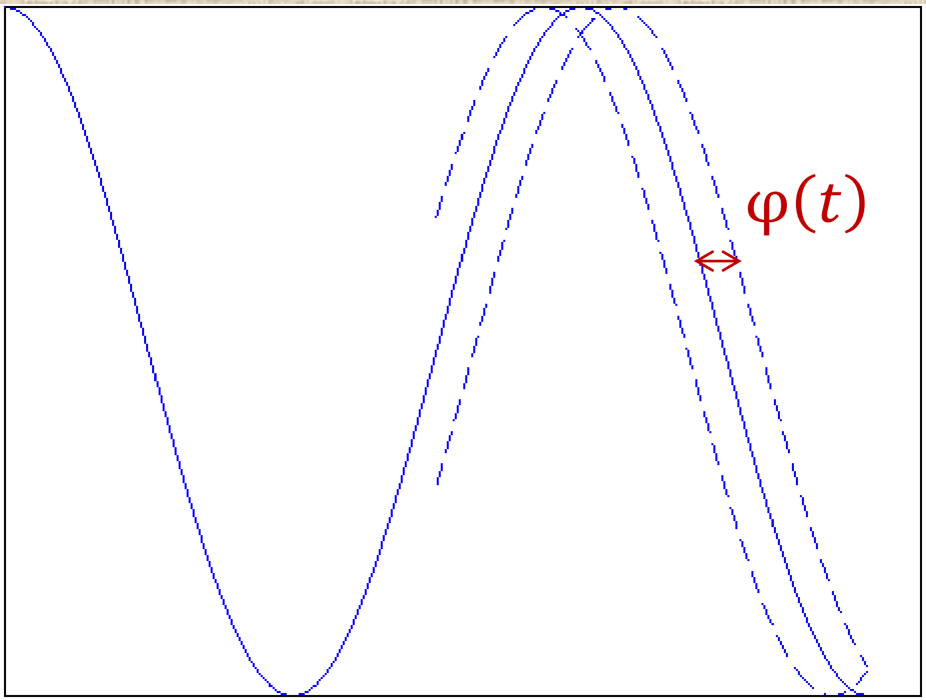
Oscillator output signal (time domain)

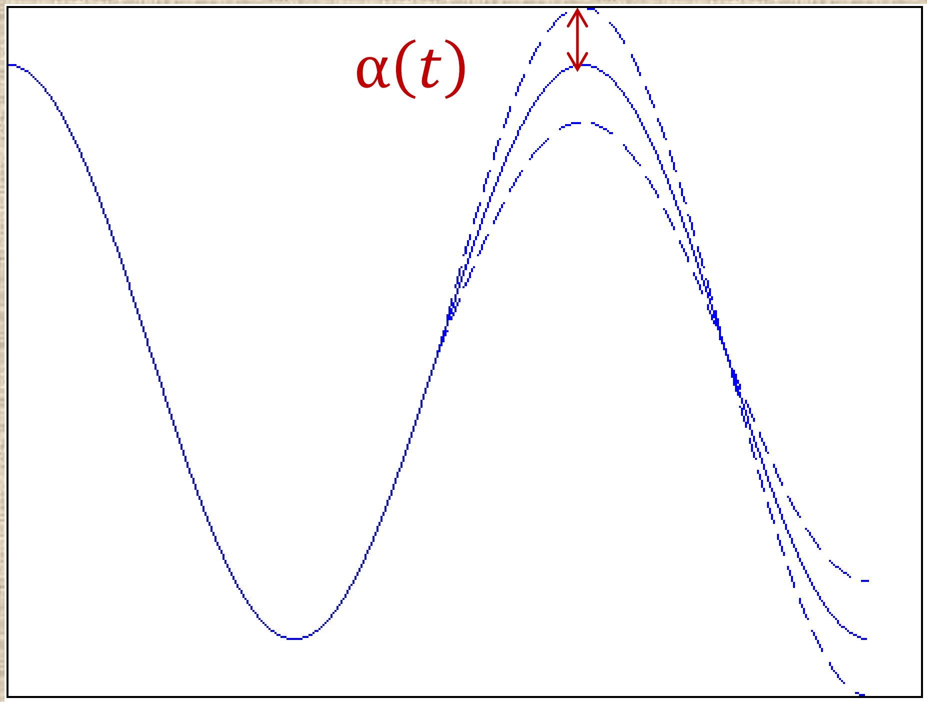
IDEAL

$$v(t) = V_0 \cos(\omega_0 t)$$

REAL

$$v(t) = V_0[1 + \alpha(t)]\cos[\omega_0 t + \varphi(t)]$$

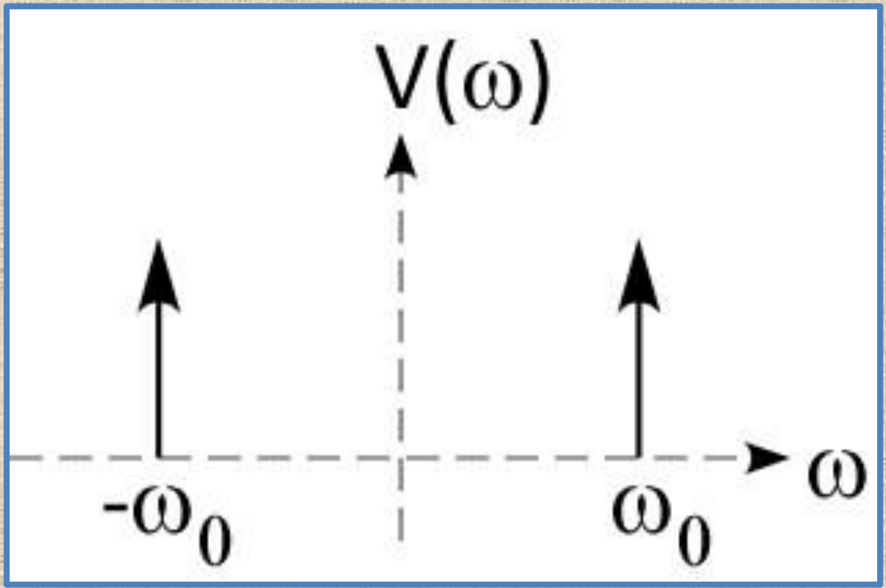




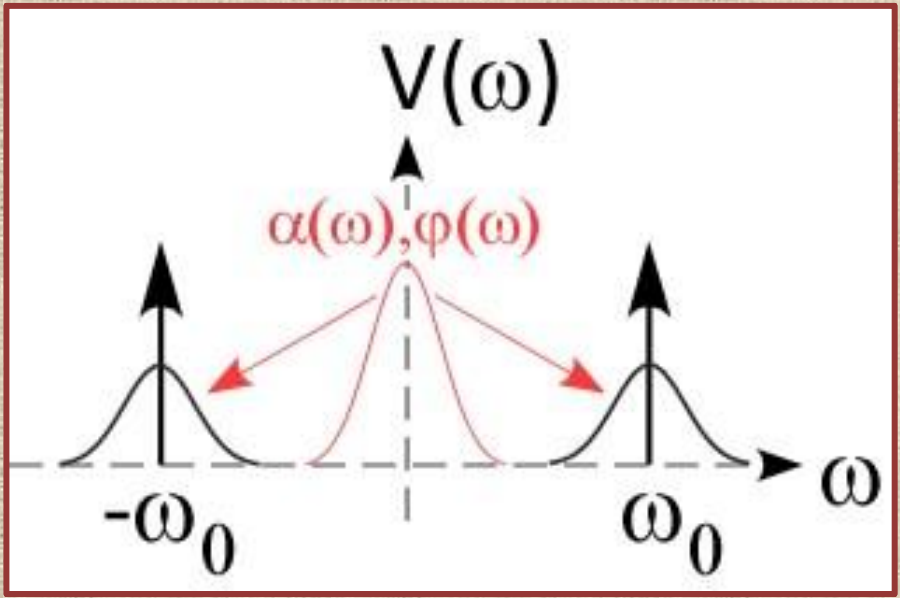
2.1. Phase noise in oscillators

Frequency domain

IDEAL (pure sinusoidal tone)



REAL (sideband broadening)



2.1. Phase noise in oscillators

Assumptions:

- $|\alpha(t)| \ll 1$ (negligible amplitude noise)
- $\left|\frac{d\varphi}{dt}\right| \ll \omega_0$ (phase variations much slower than carrier frequency)
- $\varphi(t)$ ergodic and stationary random process
- $\varphi(t) = 0$, for $t < -\frac{\Delta T}{2}$ *and* $t > \frac{\Delta T}{2}$, being ΔT the observation time
- $\overline{\varphi(t)} = 0$

The variance of the random process (Single Side Band Power Spectral Density definition) is then:

$$\sigma_{\varphi}{}^2 = \lim_{T\to\infty} \frac{1}{T} \int_{-\frac{T}{2}}^{\frac{T}{2}} \left|\varphi(t) - \overline{\varphi(t)}\right|^2 dt = \lim_{T\to\infty} \frac{1}{T} \int_{-\infty}^{+\infty} |\varphi(t)|^2 dt =$$

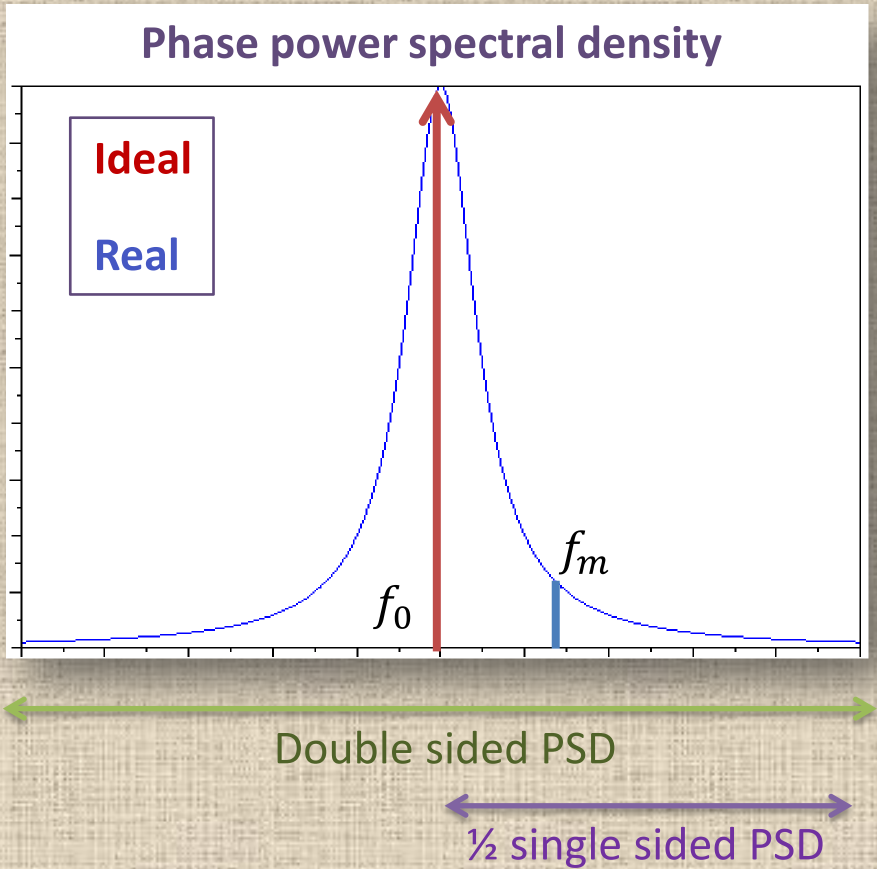
Parseval

$$= \lim_{\Delta T\to\infty} \frac{1}{\Delta T} \int_{-\infty}^{+\infty} |X_{\Delta T}(f)|^2 \, df \overset{\text{def}}{=} \int_{0}^{+\infty} S_{\varphi}(f) \, df$$

2.1. Phase noise in oscillators

For convenient display of SSB PSD we define the "script el" function:

$$\mathscr{L}(f_m) = 10\, log_{10}\left(\frac{1}{2}S_\varphi(f_0 + f_m)\right), \quad \mathrm{f} > 0, \quad \mathrm{dBc/Hz}$$

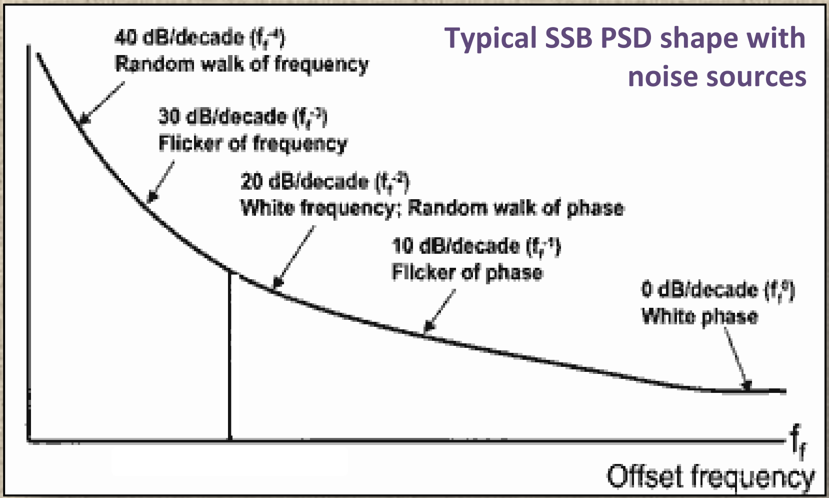


And one can calculate (and measure) the contribution to the RMS time jitter of a source, in a certain frequency region, as follows:

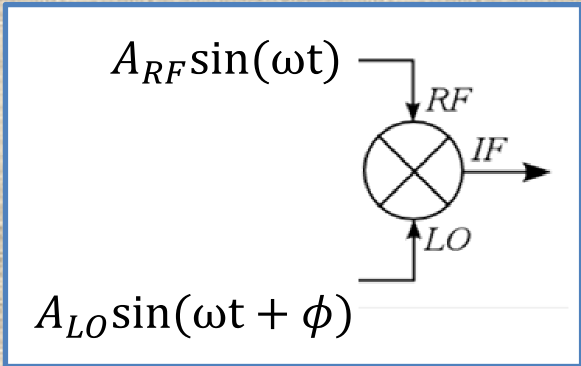
$$\Delta t_{RMS} = \frac{1}{2\pi f_0}\sqrt{2\int_{f_1}^{f_2} 10^{\frac{\mathscr{L}(f_m)}{10}}\, df}$$

2.2. Noise sources

- AM/PM noise
  - parametric (DC)
    - Environmental
      - Temperature
      - 50 Hz B field
      - Power supply
      - Acoustic
      - Radiation
    - Internal
      - Flicker (f^{-1})
      - Random walk (f^{-2})
      - Drift
  - additive (f_0)
    - Environmental
      - RF leakage
    - Internal
      - White

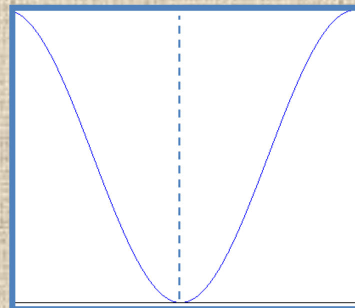


2.3. Measuring phase noise – RF mixers



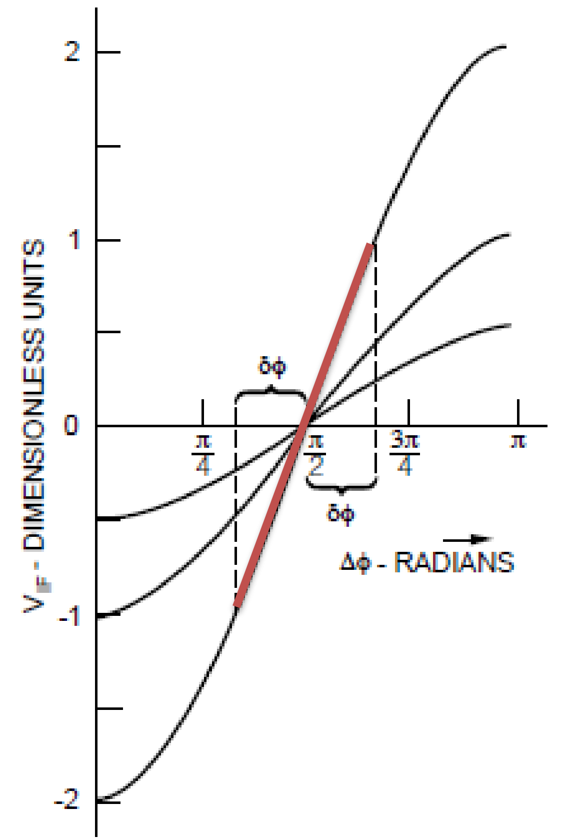
$$V_{IF} = V_{RF}(t)\cdot sgn[V_{LO}(t)] \approx -k\cos(\phi)$$

$A_{RF} \ll A_{LO}$

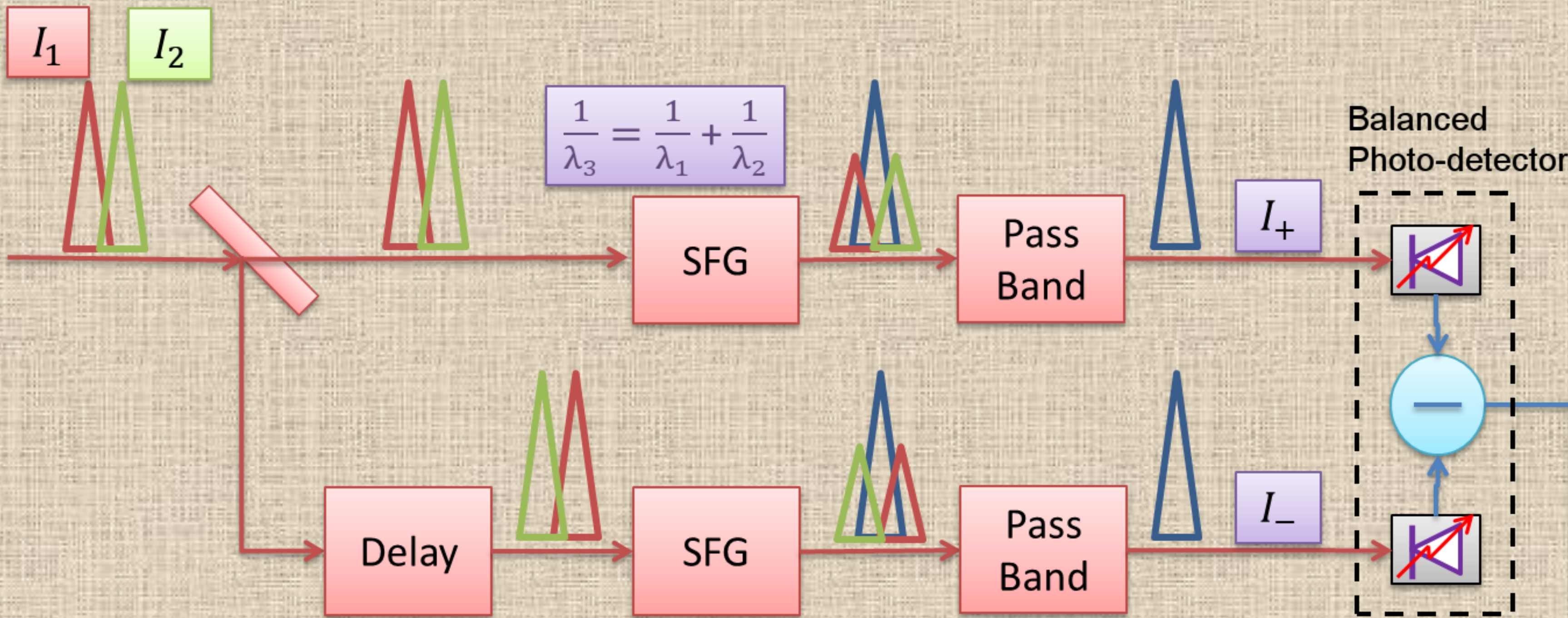


- RF and LO inputs have the same frequency (IF is baseband)
- For $\phi \approx \frac{\pi}{2} + \Delta\phi$, $\quad V_{IF} \approx k \cdot \Delta\phi$
- Detector sensitivity **k** measured in V/degrees (typically **20mV/ps**)
- Sensitivity depends on the input signals amplitude and frequency
- Cheap, wideband, passive
- AM/PM conversion

Mixer characteristics



2.3. Measuring phase noise – optical x-correlators

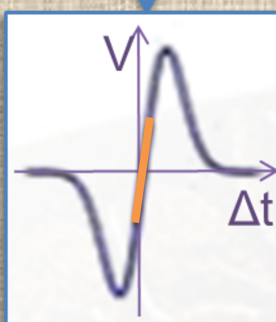


- Balanced detector [4, 13] insensitive to lasers amplitude jitter
- Short (< 100 fs) pulse rise time leads to a sensitivity up to **10mV/fs**
- Complex design, higher cost

$$I_{+,-} \propto \int_{-\infty}^{+\infty} I_1(\tau) I_2(t-\tau)\, d\tau =$$

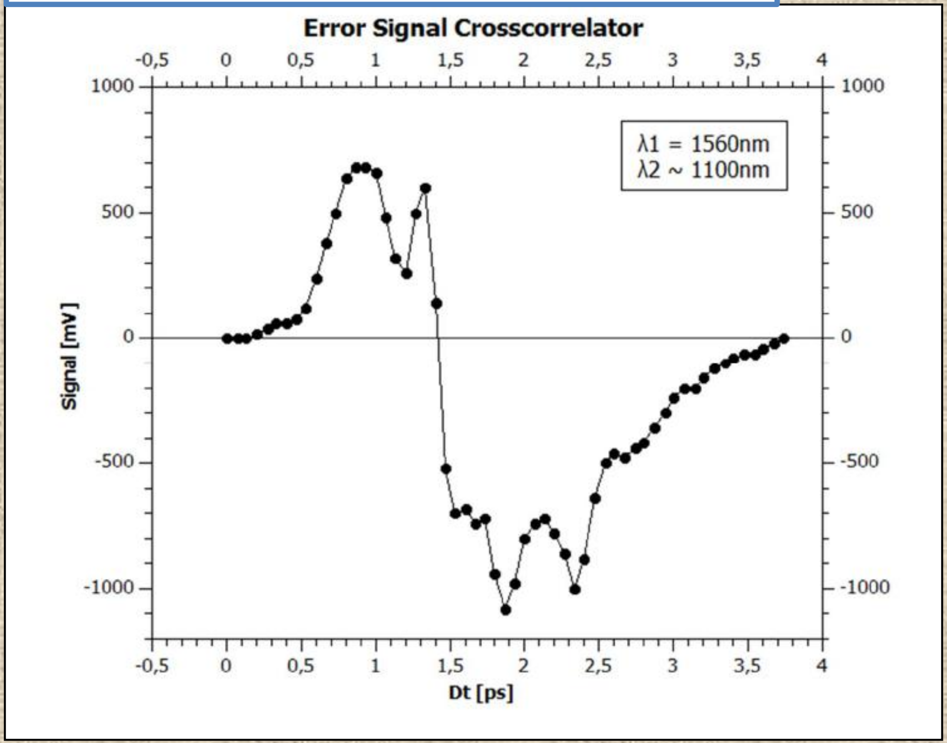
$$= \frac{1}{\sqrt{2\pi(\sigma_1^2 + \sigma_2^2)}} exp\left\{-\frac{(t-\Delta t)^2}{2(\sigma_1^2 + \sigma_2^2)}\right\}$$

Gaussian longitudinal profile

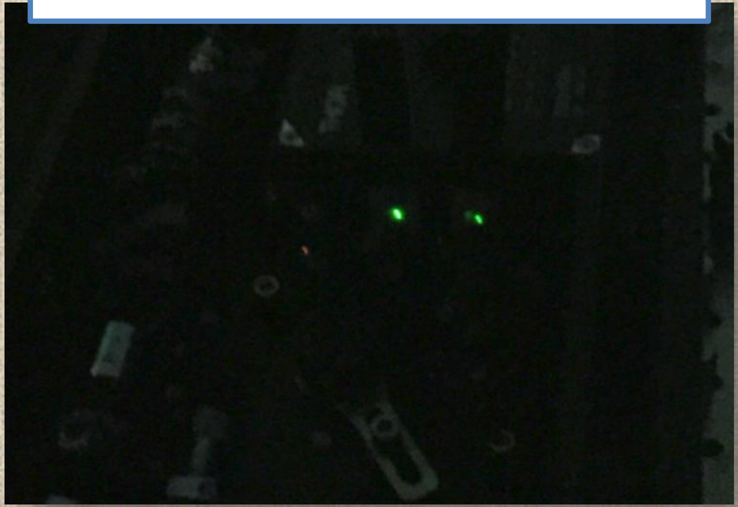


2.3. Measuring phase noise – optical x-correlators

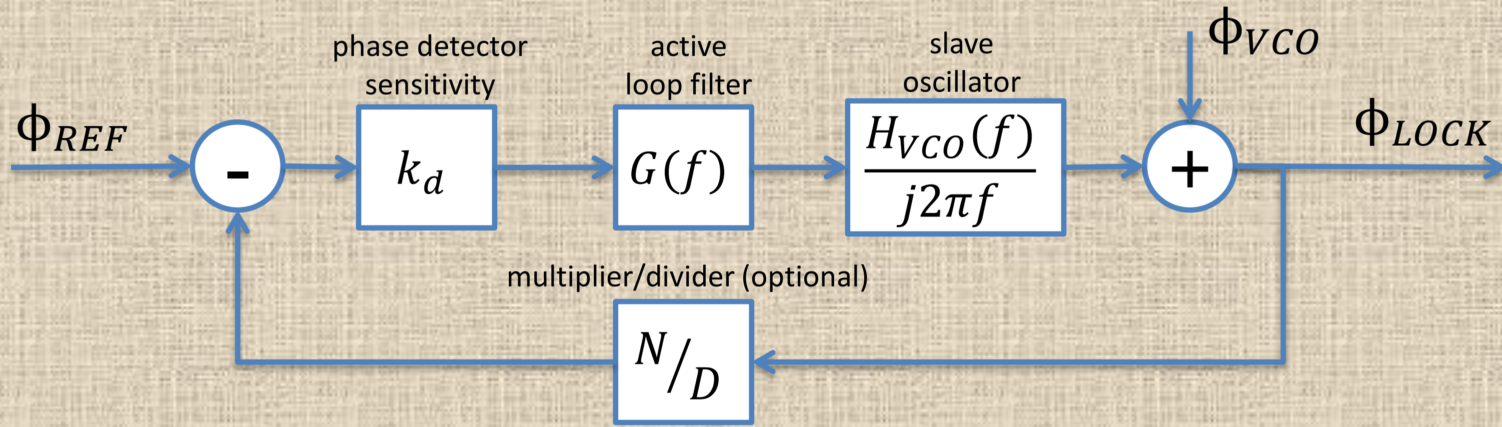
Measured x-correlator characteristics (at MENLO Systems GMBH [5])



Detected signal from one of the SPARC_LAB [10] x-correlators



2.3 Measuring phase noise – Phase Locked Loops



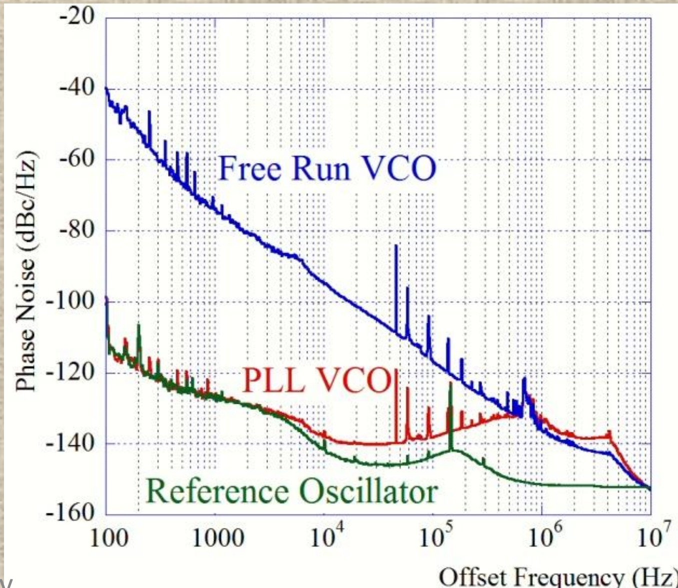
Open loop gain

$$H(f) \stackrel{\text{def}}{=} K_d \cdot G(f) \cdot \frac{H_{VCO}(f)}{j2\pi f}$$

Closed loop transfer function ($^N/_D = 1$)

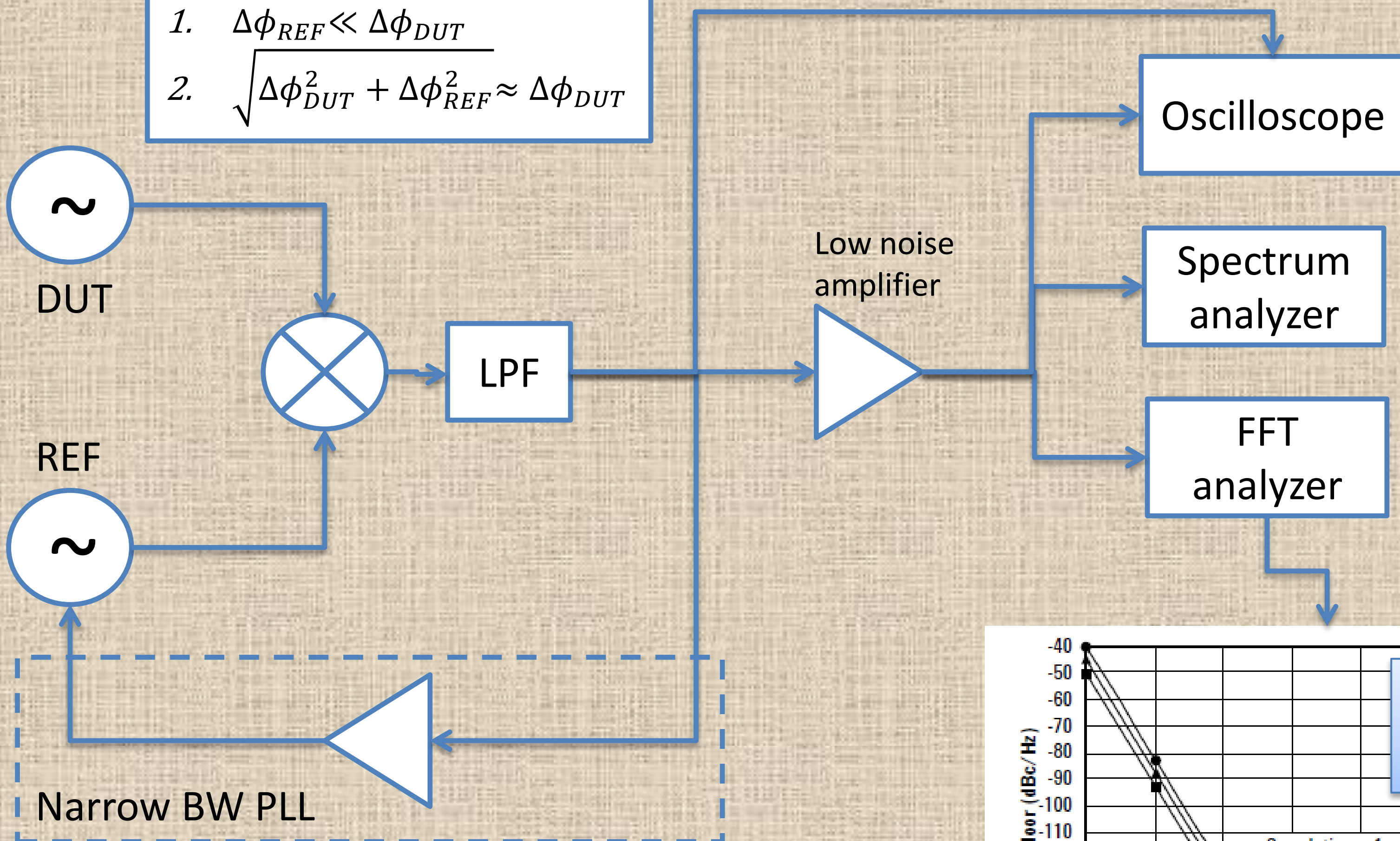
$$\phi_{LOCK} = \frac{H(f)}{1 + H(f)} \phi_{REF} + \frac{1}{1 + H(f)} \phi_{VCO}$$

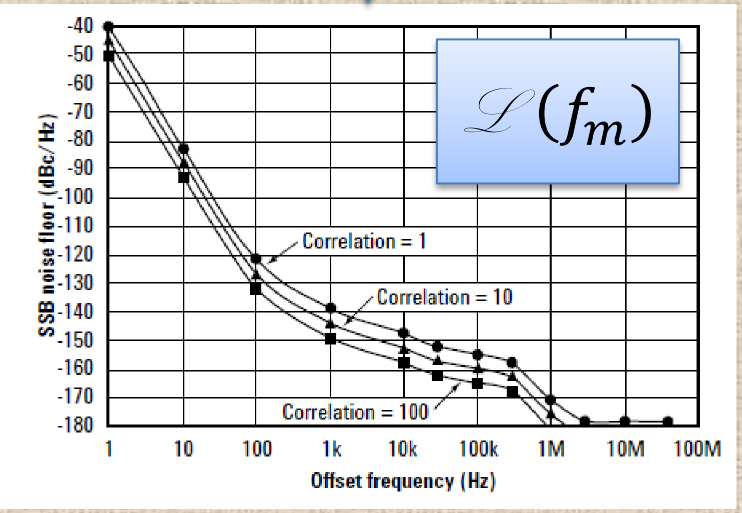
- The closed loop transfer function has a limited bandwidth ($H(f) \gg 1, for\ f < f_{BW}$)
- For low frequencies, the output phase is tightly linked to the reference phase
- For frequencies out of the loop bandwidth, the output phase progressively come back to that of the free running VCO



2.3 Measuring phase noise – Absolute Phase noise

1. $\Delta\phi_{REF} \ll \Delta\phi_{DUT}$
2. $\sqrt{\Delta\phi_{DUT}^2 + \Delta\phi_{REF}^2} \approx \Delta\phi_{DUT}$





- The PLL on REF is used to maintain its central frequency aligned to DUT

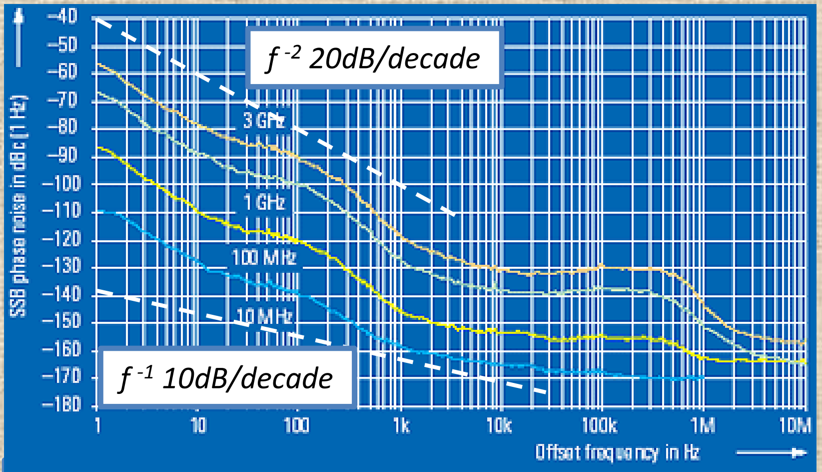
2.3 Measuring phase noise – Typical SSB PSDs

Time jitter can be computed according to:

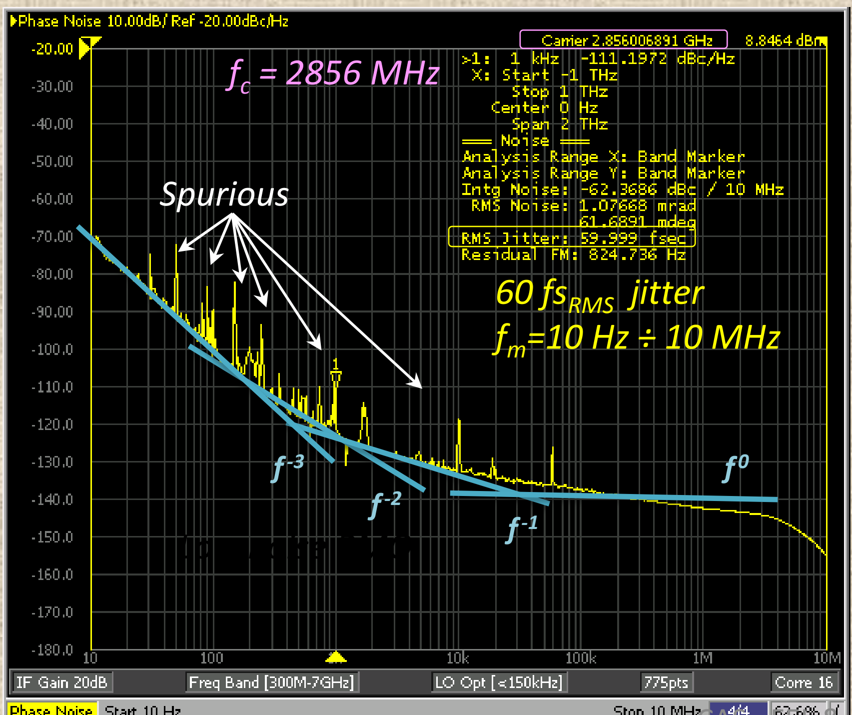
$$\sigma_t^2 = \frac{\varphi_{rms}^2}{\omega_c^2} = \frac{1}{\omega_c^2} \int_{f_{min}}^{f_{max}} S_\varphi(f)\, df$$

same time jitter $\rightarrow$ $S_\varphi(f) \div \omega_c^2$.

Phase noise spectral densities of different oscillators have to be compared at same carrier frequency ω_c or scaled as ω_c^{-2} before comparison.

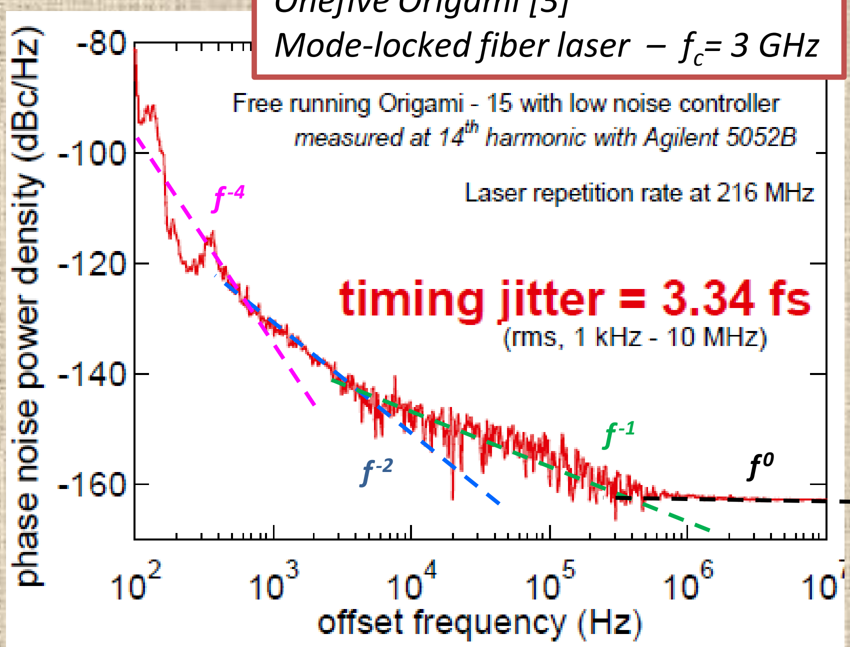


Commercial frequency synthesizer



Onefive Origami [3]

Mode-locked fiber laser – f_c= 3 GHz

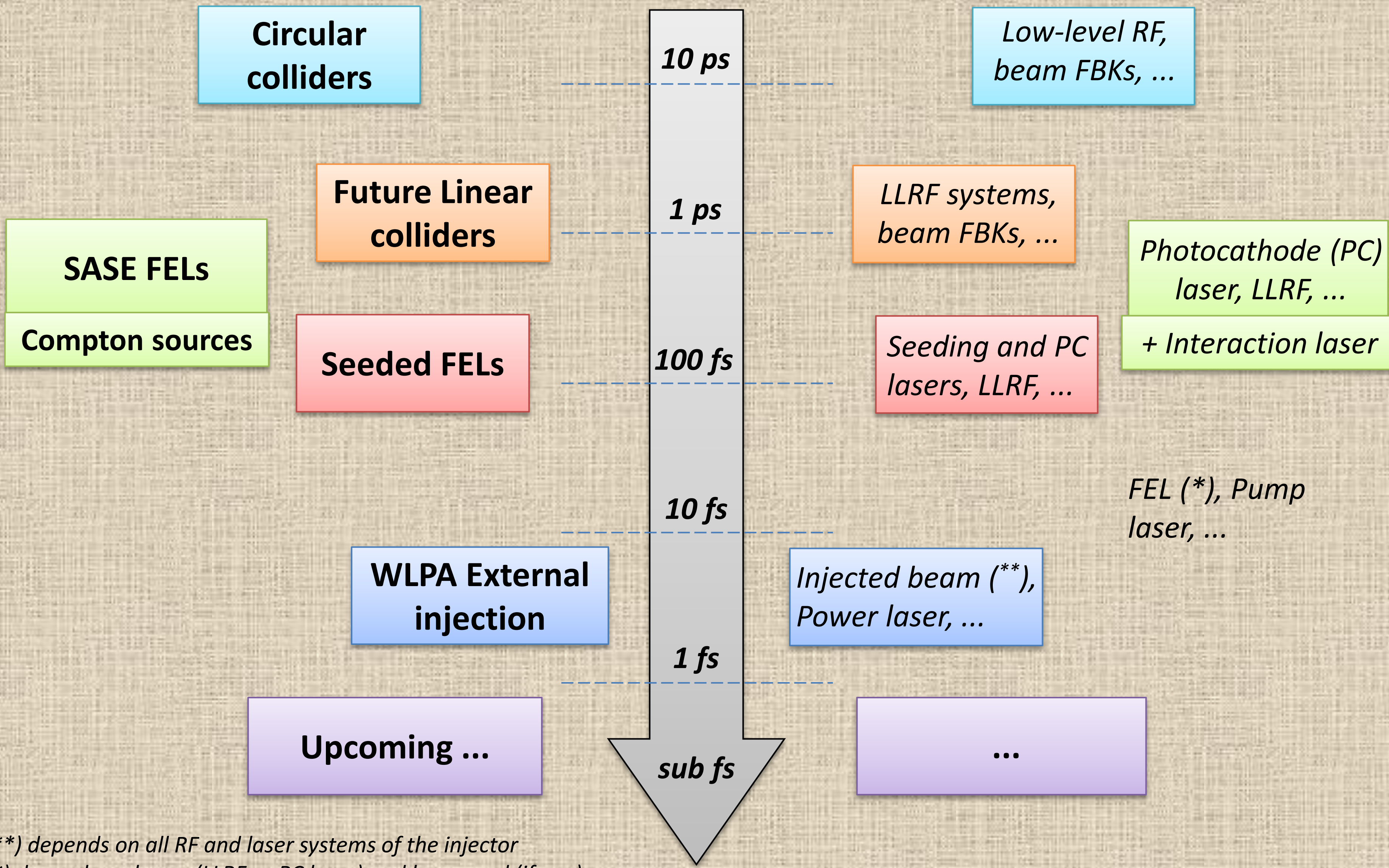


3.

Synchronization in linear injectors

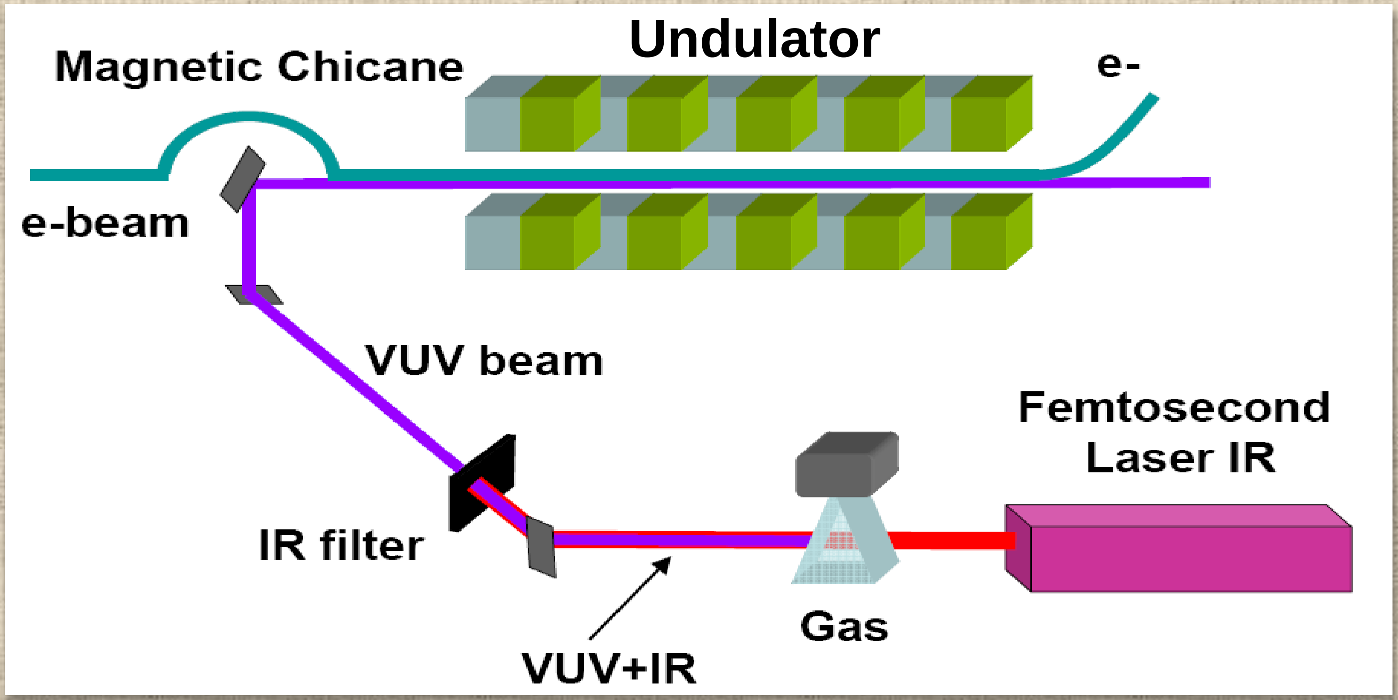
1. Experiment requirements
2. Overview
3. Reference generation
4. Reference distribution
5. Client locking
6. Beam timing jitter
7. Diagnostics

3.1 Experiment requirements - History



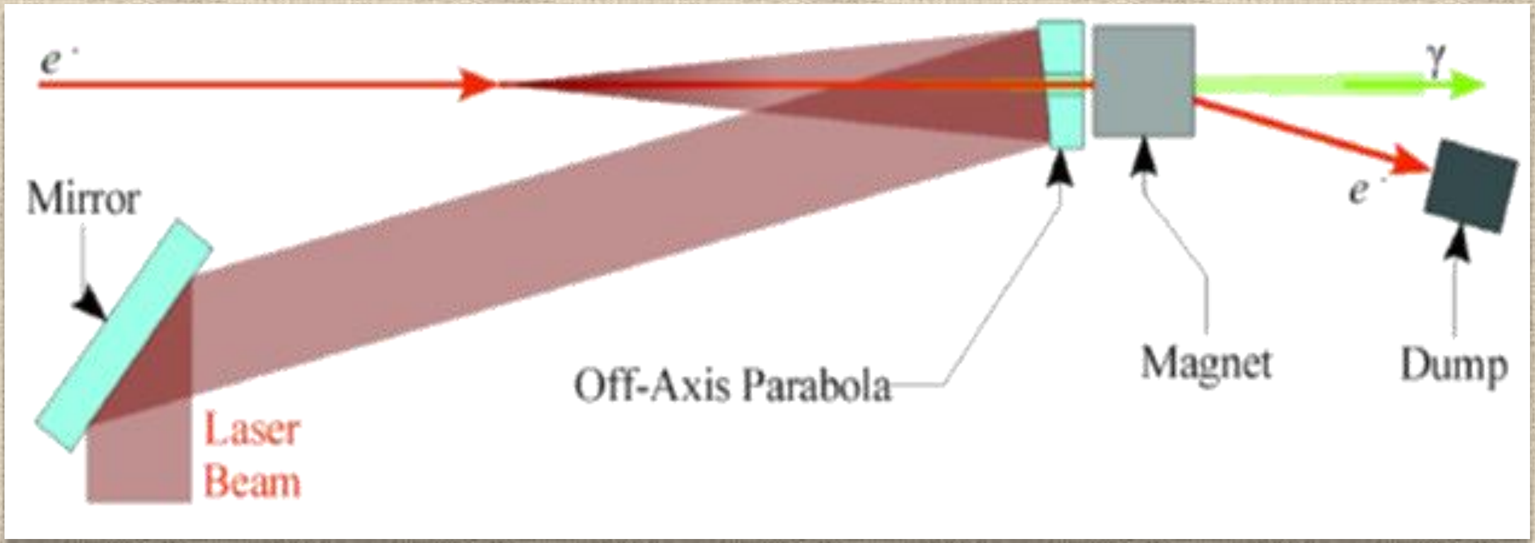
(**) depends on all RF and laser systems of the injector
(*) depends on beam (LLRFs + PC laser) and laser seed (if any)

3.1 Experiment requirements – Seeded FEL



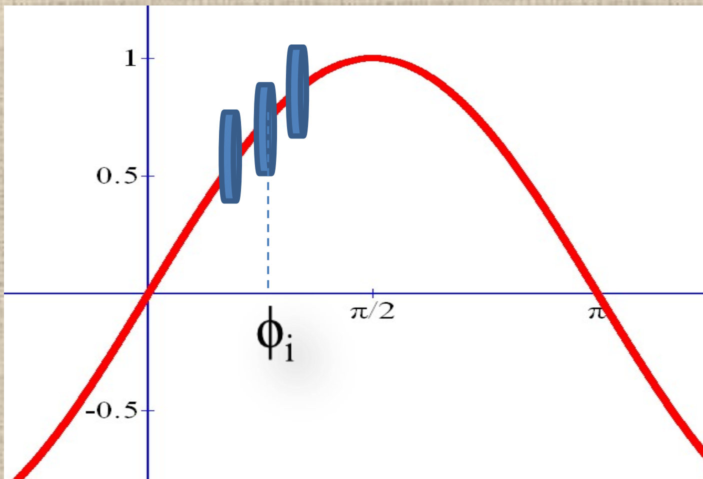
- Seed amplification in undulator sections
- e-bunch and seeding laser are co-propagating
- **Request: $\Delta t < 0.5\ ps_{RMS}$**

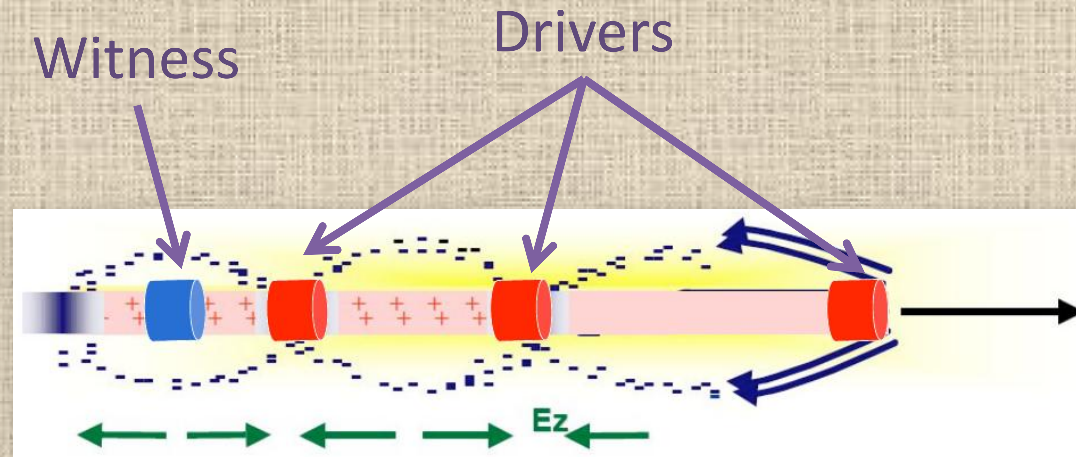
3.1 Experiment requirements – Thomson



- Thomson backscattering experiment
- Requires physical overlapping of SPARC and FLAME (TW class laser) beams within the depth of focus of the laser focusing optics.
- **Request: $\Delta t < 0.5\ ps_{RMS}$**

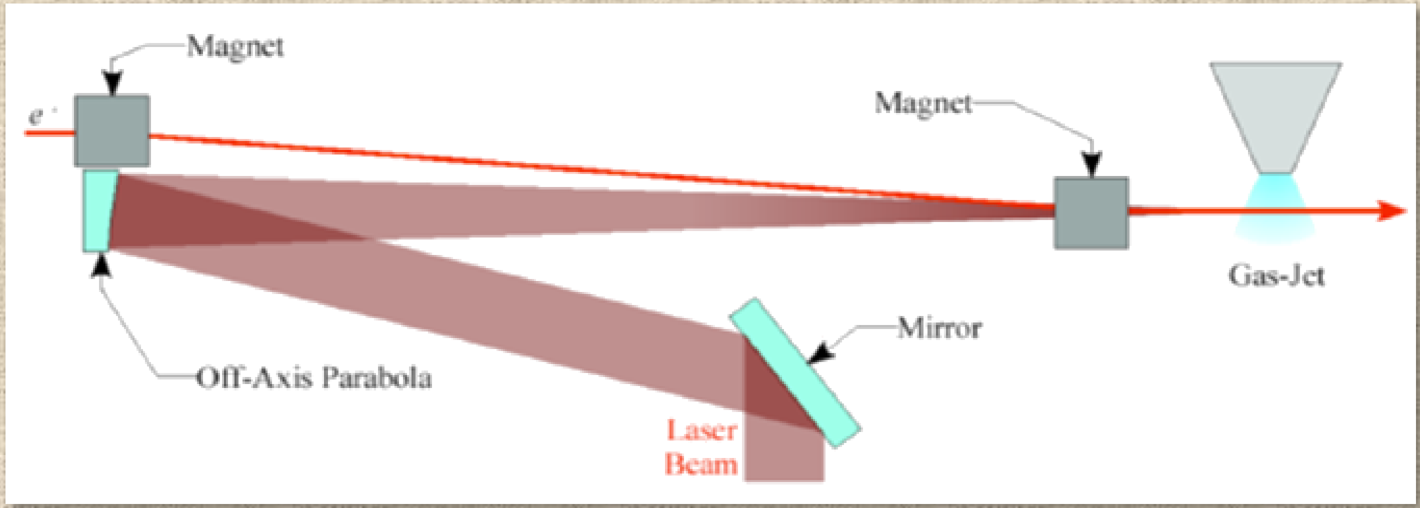
3.1 Experiment requirements - PWFA





- Particle driven PWFA experiment
- Multiple e-bunches injected in the same RF bucket
- Critical injection phase for RF compression
- **Request: $\Delta t < 100\ fs_{RMS}$**

3.1 Experiment requirements - LWFA

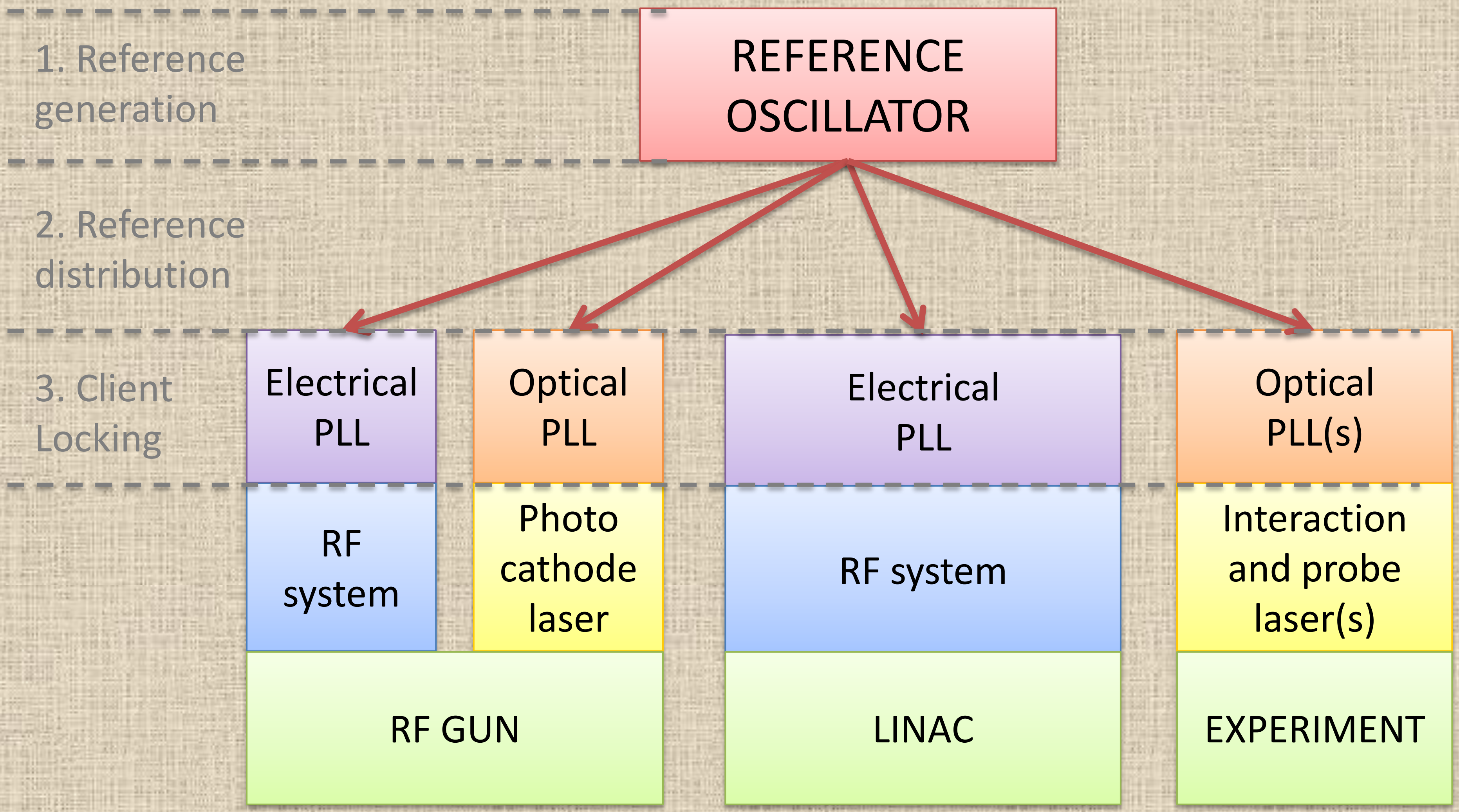


- LWFA experiment with external e-bunch injection
- SPARC and Flame short (< 100 fs) pulses injected in a plasma channel inside a gas-jet or a gas-filled capillar, requires synchronization at the level of the period of the plasma wave.
- **Request: $\Delta t < 10\ fs_{RMS}$**

3.2 Overview – General concepts

- Every accelerator is built to produce a ***specific physical process*** (shots of bullet particles, nuclear and sub-nuclear reactions, synchrotron radiation, FEL radiation, Compton photons, ...).
- A necessary condition for an efficient and reproducible experiment is the ***relative temporal alignment*** (i.e. the ***synchronization***) of
  - ***all the accelerator sub-systems***: this impacts on beam longitudinal phase-space and time-of-arrival (such as RF fields, PC laser system, ...)
  - ***beam bunches*** with ***any sub-system they have to interact with*** during and after the acceleration (such as seeding lasers, pump lasers, interaction lasers, ...).

3.2 Overview – General layout



3.2 Overview - Definitions

The synchronization error of a client with respect to the reference is identified as ***jitter*** or ***drift*** depending on the time scale of the involved phenomena.
The boundary btw these disturbances is somewhat arbitrary. For pulsed machines, the rep. rate f_{REP} it is commonly used as threshold.

Drift

- slow variations
  - mainly caused by modifications of the environment conditions
  - temperature (primarily) but also humidity fluctuations
  - materials and components aging
  - infra-sounds
  - can be corrected by the machine feedback system

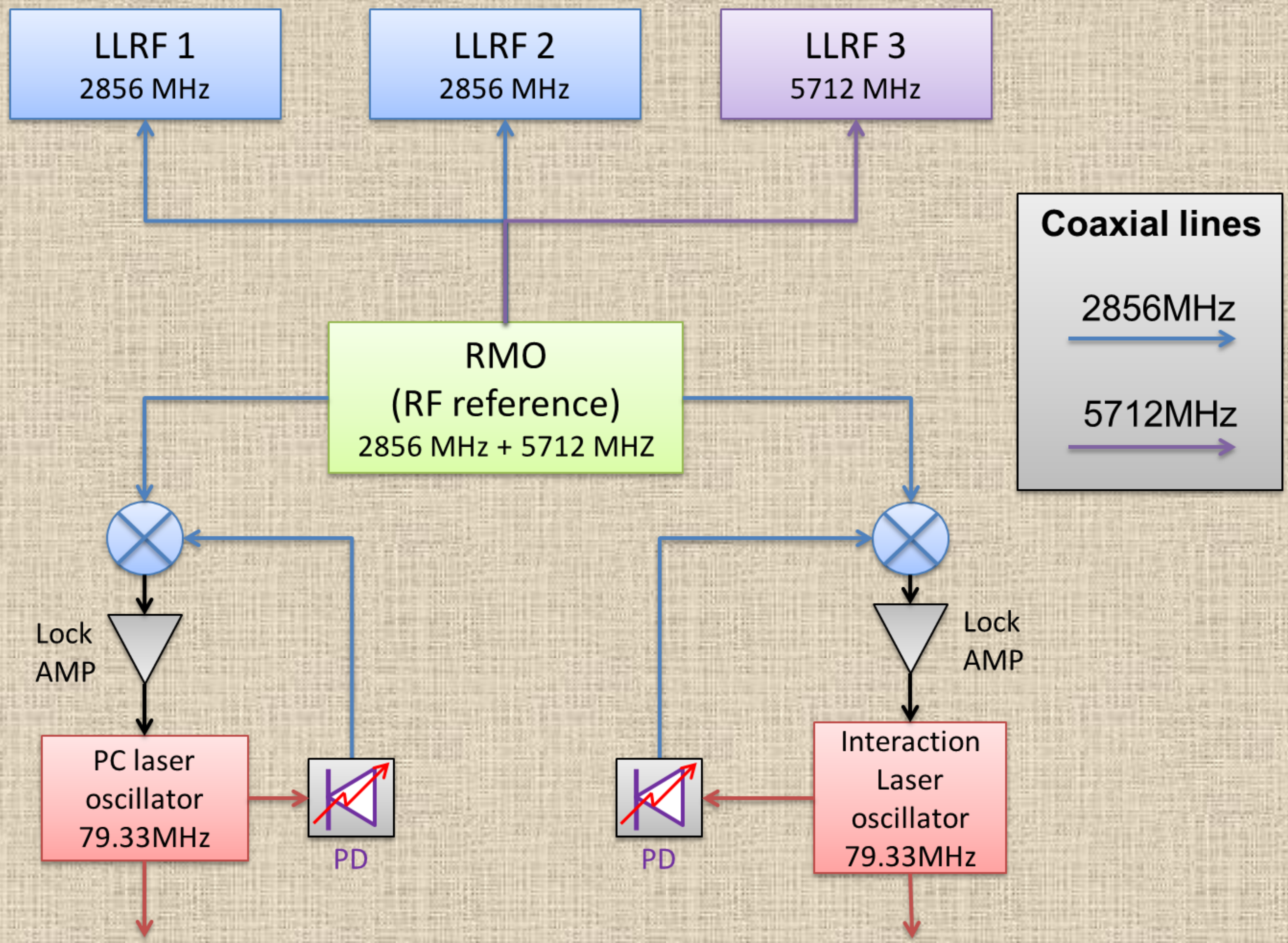
Jitter

- fast variations
  - residual lack of coherency between oscillators
  - acoustic waves
- it cause the pulse-to-pulse chaotic scatter of the beam characteristics
- can be minimized designing a good synchronization system
- can be measured, but cannot be corrected

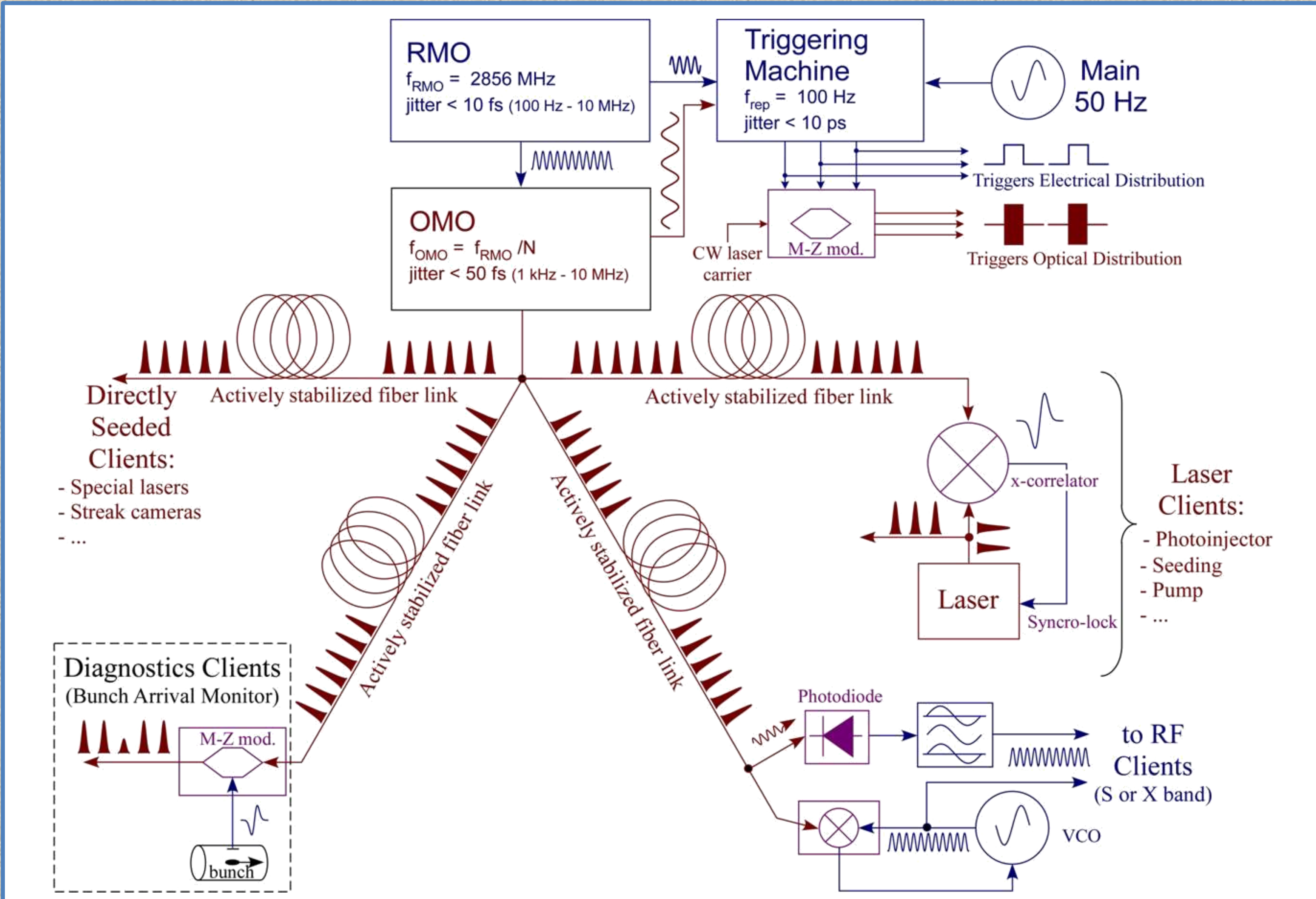
3.2 Overview – System architecture types

- The signal distribution could be achieved by:
  - Electrical signal distribution with coaxial cables
    - Electrical PD sensitivity ~20 mV/ps
    - Sub-system (LLRF, lasers) relative jitter < 50 fs_{RMS}
  - Optical signal distribution with fiber optics
    - Optical PD sensitivity ~10 mV/fs (opt. cross-correlation)
    - Sub-system relative jitter < 10 fs_{RMS}
- The locking PLL depends on the nature of clients and distributed signals. Options are: fully electrical, electro-optical, electro-opto-mechanical

3.2 Typical electrical architecture

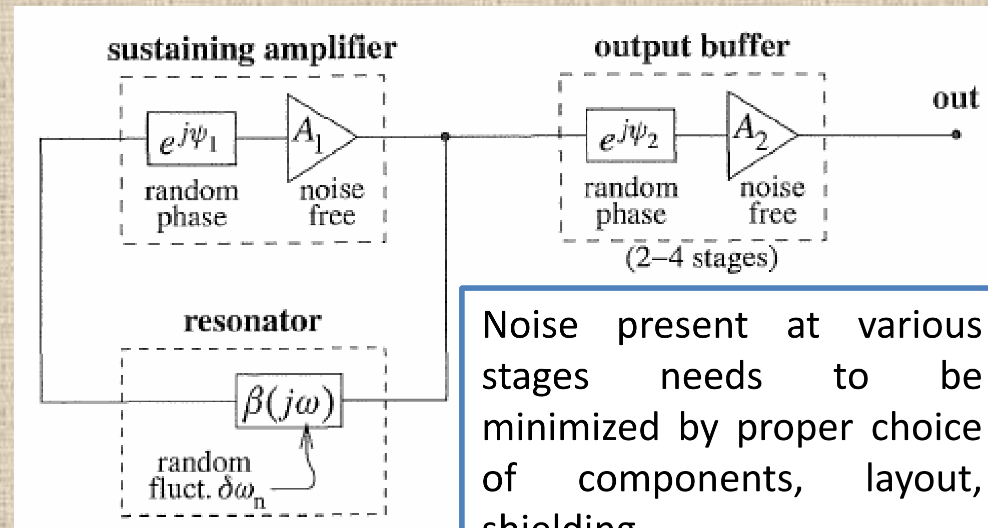


3.2 Typical optical architecture

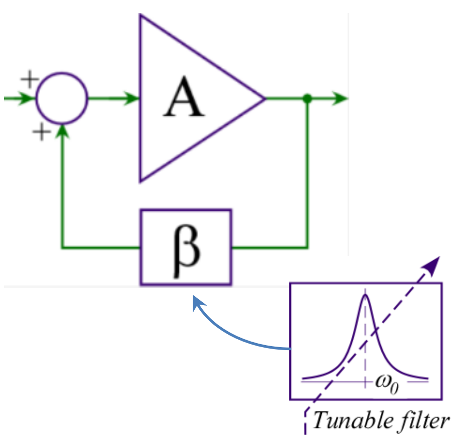


3.3 Reference generation – RMO

- Oven controlled RF crystal oscillators (OXCO) are commonly used as Reference Master Oscillators (RMO)
- low phase noise in the lower side of the spectrum ($f_m < 100kHz$)
- RF reference oscillators are typically based on positive-feedback network (Barkhausen's Criterion)



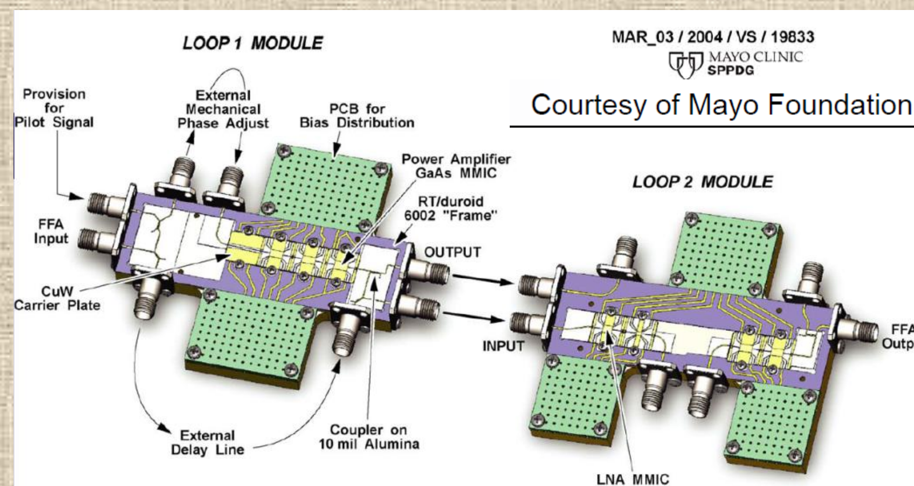
Noise present at various stages needs to be minimized by proper choice of components, layout, shielding, …



$$|H(j\omega)| = 1;$$

$$\angle H(j\omega) = 2n\pi$$

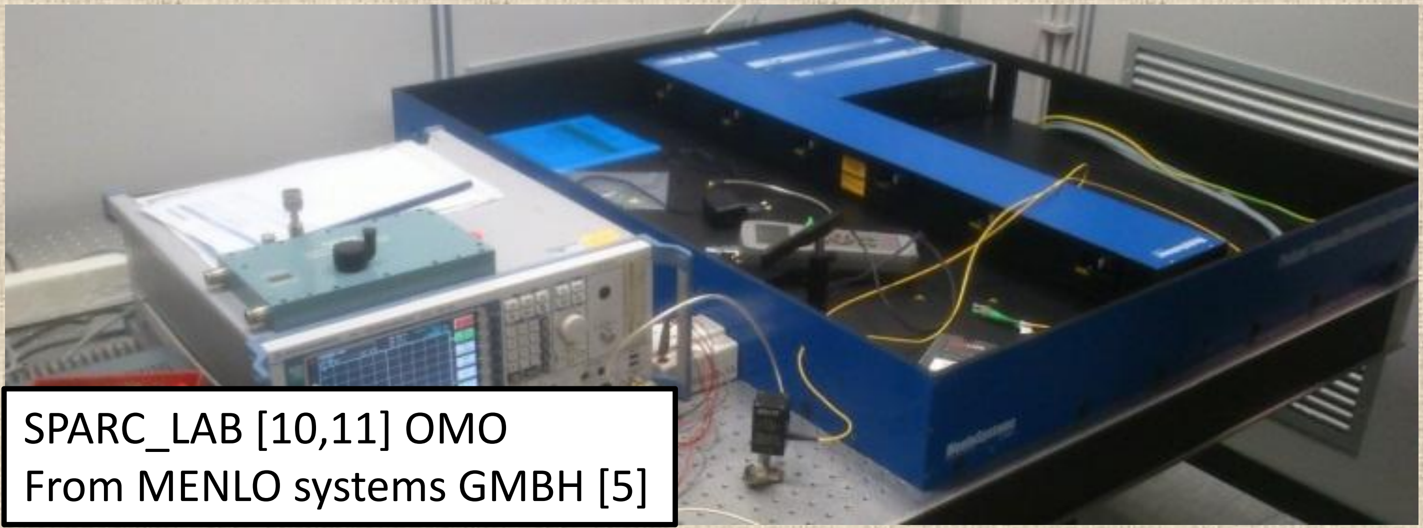
Barkhausen's Criterion



D. A. Howe and A. Hati
National Institute of Standards & Technology (NIST), Boulder, CO, USA

[7]

3.3 Reference generation - OMO



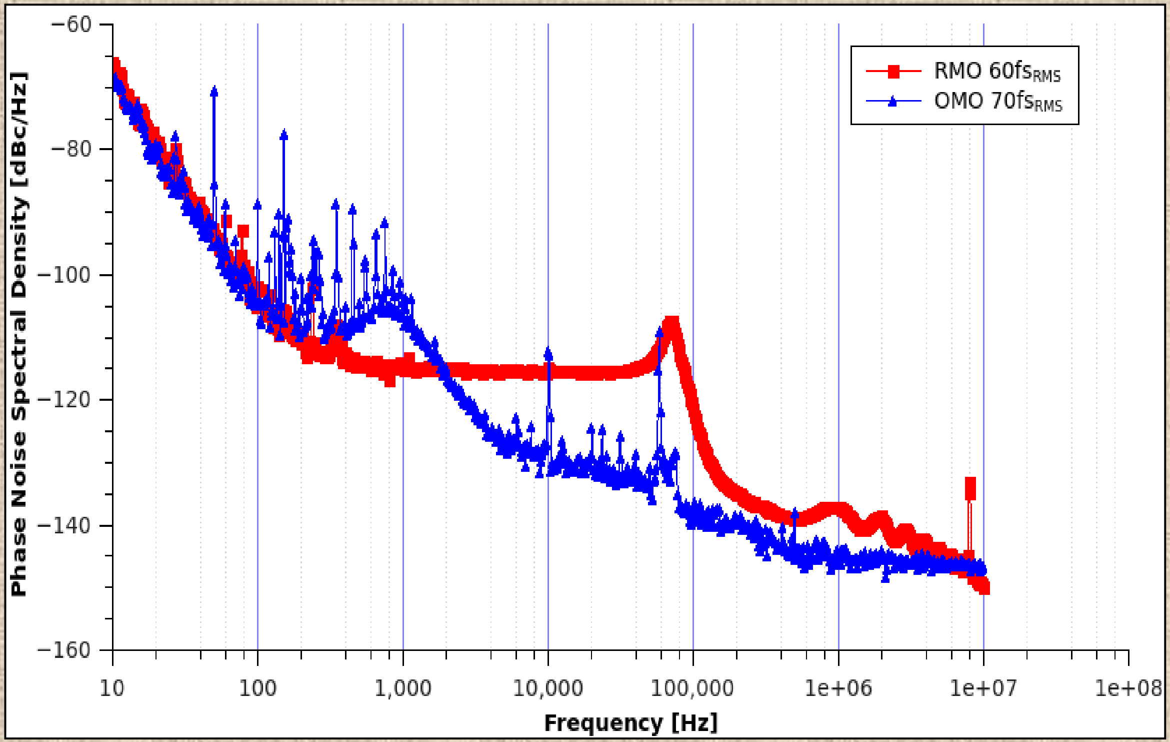
SPARC_LAB [10,11] OMO
From MENLO systems GMBH [5]

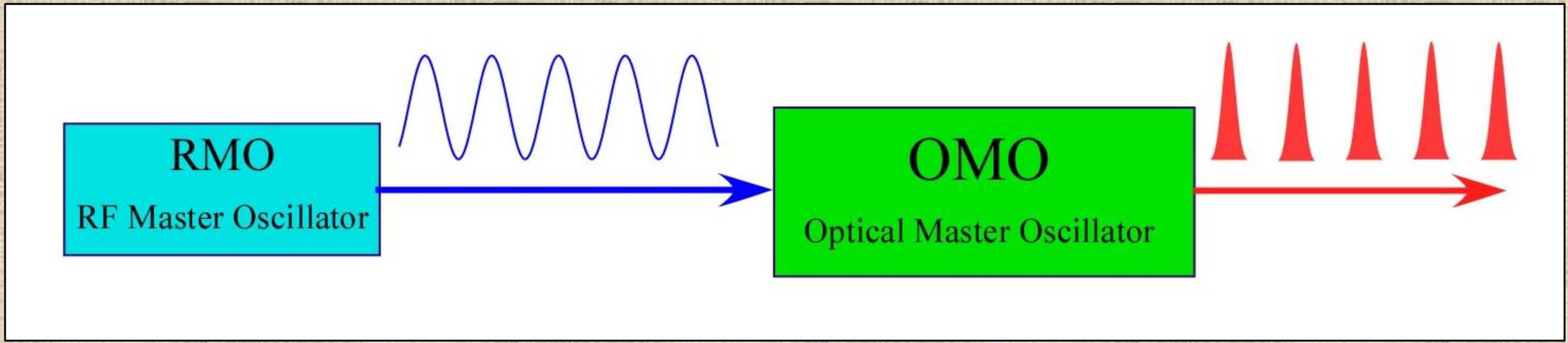
- Mode-locked fiber laser oscillator for pulsed reference distribution
- Typically standard telecommunication wavelength 1560nm (Er doped fiber)

Pulse width	*tpulse*	*< 200 fs*
Wavelength 1	*λ1*	*1560 nm*
Wavelength 2 (optional)	*λ2*	*780 nm*
Pulse rep rate	*f_rep*	*2856/N MHz*
Pulse energy	*E_pulse*	*> 2 nJ (~ 180 mW)*
Phase jitter	Δt	*< 10 fs rms* *(SSB Df > 1 kHz)*
Amplitude jitter	*(ΔA/A)rms*	*< 0.05 % rms*
Synchrolock BW	*f_cutoff*	*> 5 kHz*
Phase jitter relative to reference	Δt_{rel}	*< 10 fs rms* *(dc – 1 kHz)*

3.3 Reference generation – RMO and OMO

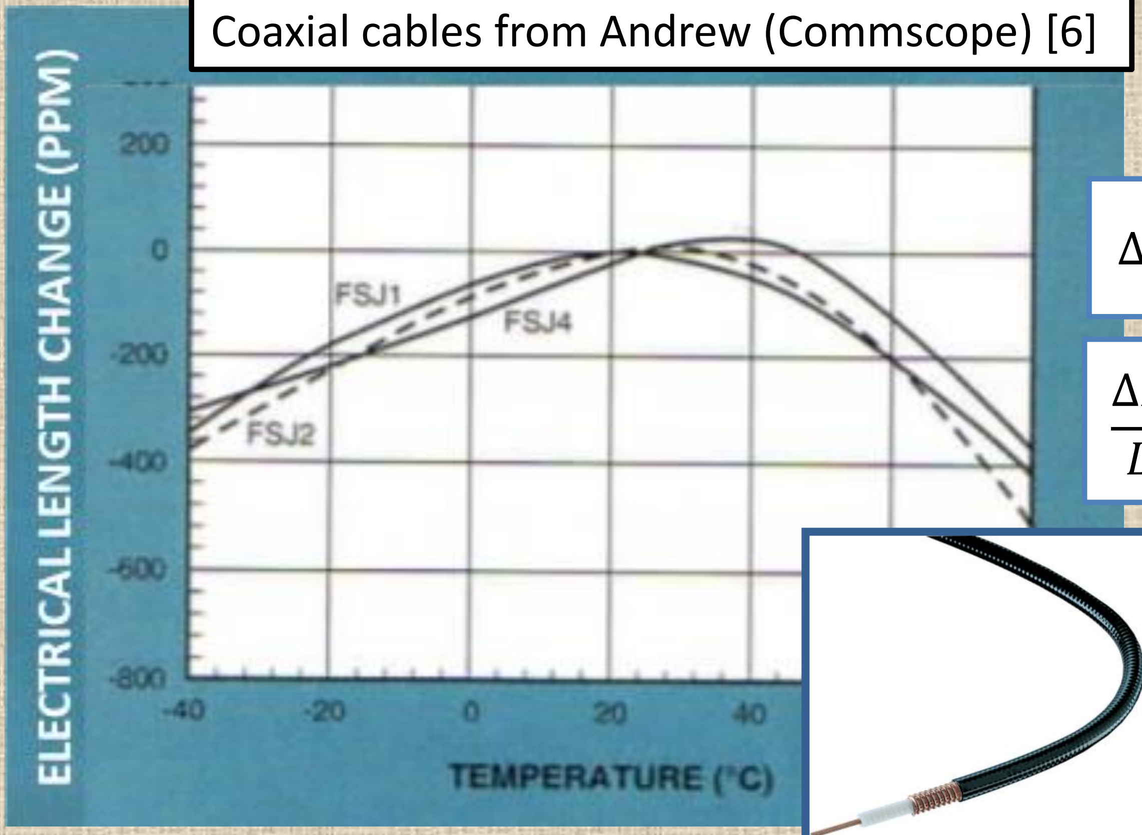
- RMO is used to minimize central frequency drift of the Optical Master Oscillator (OMO)
- Signal purity of RMO is important at low frequencies, since the OMO is locked to the RMO in the region f_m<10kHz





3.4 Reference distribution – Coaxial cables

Coaxial cables from Andrew (Commscope) [6]



cable length

carrier frequency in MHz

propagation velocity (relative to c)

$$\Delta\varphi \approx 3.66E-7 \cdot \left.\frac{\Delta L}{L}\right|_{PPM} \cdot L \cdot f_0/v$$

$$\left.\frac{\Delta L}{L}\right|_{PPM} = \left.\frac{\Delta\tau}{\tau}\right|_{PPM} \approx -\left(\frac{T-T_{opt}}{T_c}\right)^2$$

For a 3/8" cable (FSJ2):

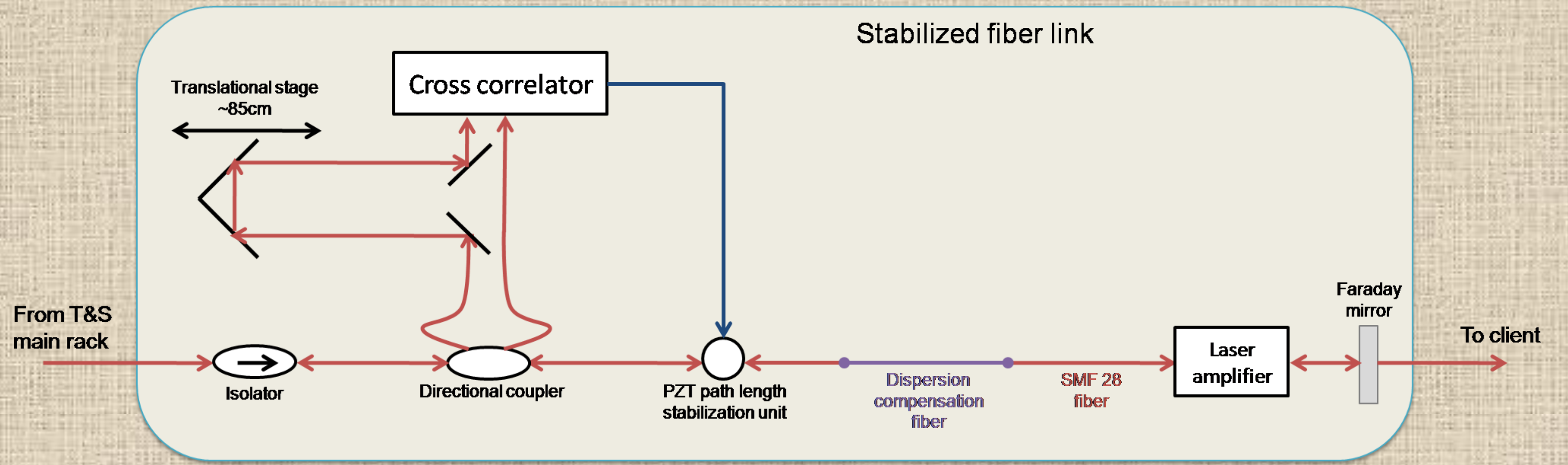
$T_{opt} \approx 24\,°C,\quad T = 24.5°C$

$T_c \approx 2\,°C, L \approx 1\,km, f_0 = 3GHz$

$\Delta t \approx 100fs$

- Special coaxial cables built to minimize the elongation VS temperature characteristics (using a suitable dielectric material)
- For long links an active stabilization is needed

3.4 Reference distribution – Fiber links

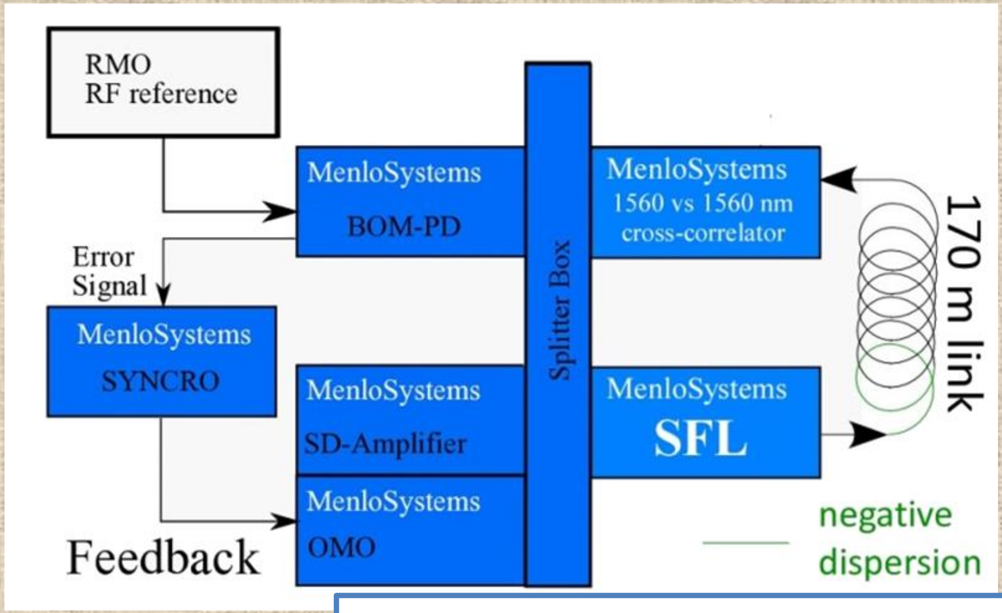


Active stabilized links are based on high resolution **round trip time measurements** and **path length correction** to stick at some stable reference value.
Pulsed optical distribution is especially suitable, because of low signal attenuation over long links and path length monitoring through very sensitive pulse cross-correlators. However, **dispersion compensation of the link is crucial** to keep the optical pulses very short (down to < 100 fs).

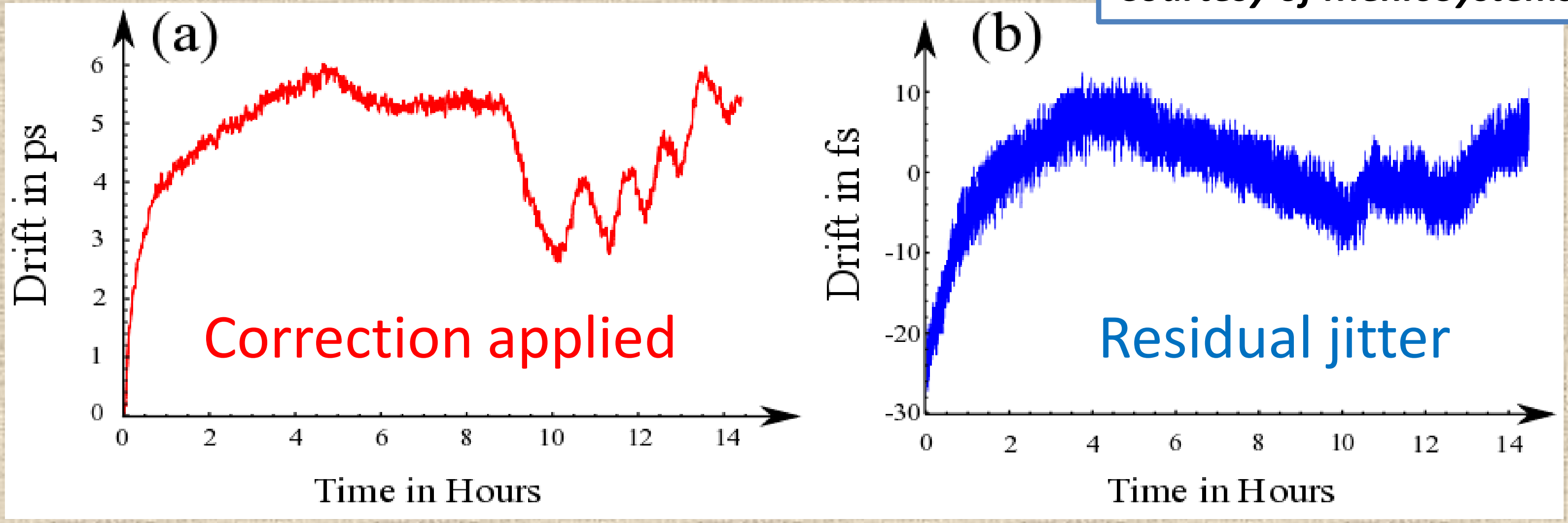
- All the noise in the DC÷10kHz band (thermal drifts, mechanical vibrations, mains disturbances, …) can be corrected.
- No major noise contributions outside the loop BW of the link stabilizers are expected
- Signal distributed up to km scale machines with added jitter **<10fs**

3.4 Reference distribution – Fiber links

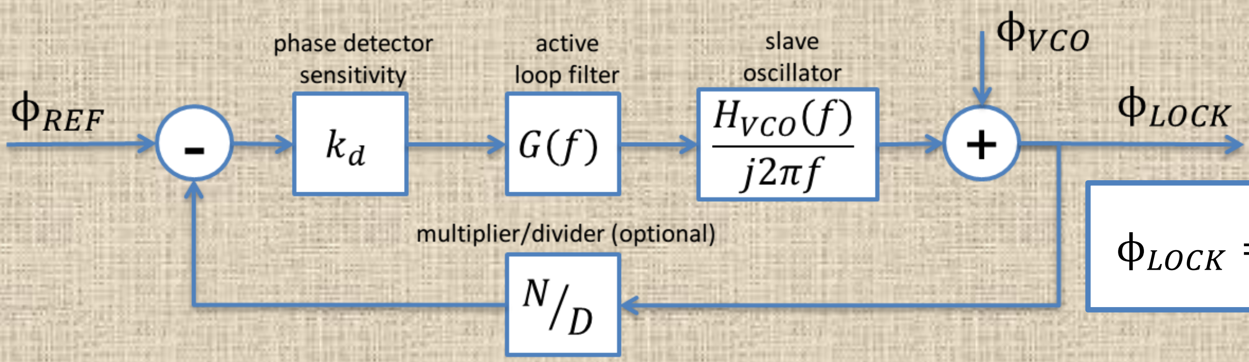
- **length correction** applied to the link *≈1 ps RMS over 14 hours*
- **residual link drift** *≈6 fs RMS over 14 hours*



Courtesy of MenloSystems GmbH [5]



3.4 Client locking – Jitter wrt RMO



$$H(f) \stackrel{\text{def}}{=} K_d \cdot G(f) \cdot \frac{H_{VCO}(f)}{j2\pi f}$$

$$H(f) \gg 1, for\ f < f_{BW}$$

$$\phi_{LOCK} = \frac{H(f)}{1+H(f)}\phi_{REF} + \frac{1}{1+H(f)}\phi_{VCO}$$

We can estimate the residual noise between clients and reference $\varphi_{i-r} = \varphi_i - \varphi_{ref}$:

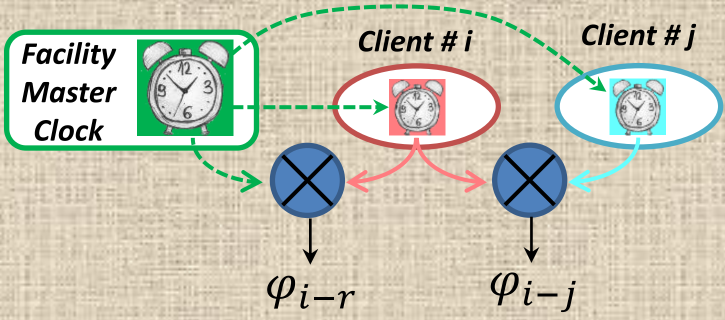
$$\varphi_{i-r} = \frac{\varphi_{i_0} - \varphi_{ref}}{1+H_i(f)} \rightarrow S_{i-r}(f) = \frac{S_{i_0}(f) + S_{ref}(f)}{|1+H_i(f)|^2}$$

And integrating the PSD we obtain the relative timing jitter RMS:

$$\sigma_{t_{i-r}} = \sqrt{\frac{1}{\omega_{ref}^2}\int_{f_{min}}^{+\infty} \frac{S_{ref}(f) + S_{i_0}(f)}{|1+H_i(f)|^2} df}$$

3.5 Client locking – Jitter btw clients

The same calculations can be made to obtain the phase noise among different clients $\varphi_{i-j} = \varphi_i - \varphi_j$

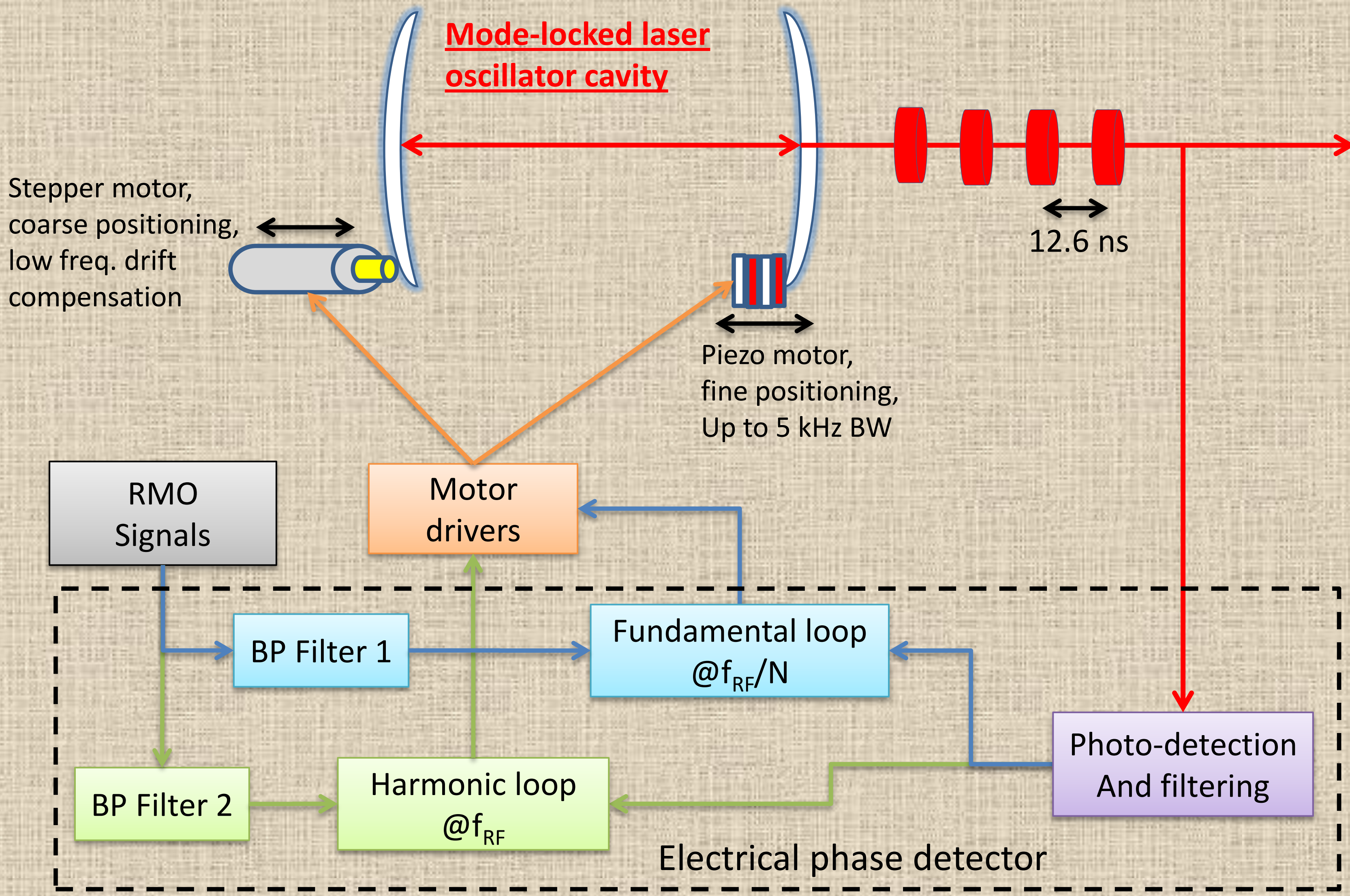


$$\varphi_{i-j} = \varphi_{i-r} - \varphi_{j-r} = \frac{\varphi_{i_0} - \varphi_{ref}}{1 + H_i(f)} - \frac{\varphi_{j_0} - \varphi_{ref}}{1 + H_j(f)}$$

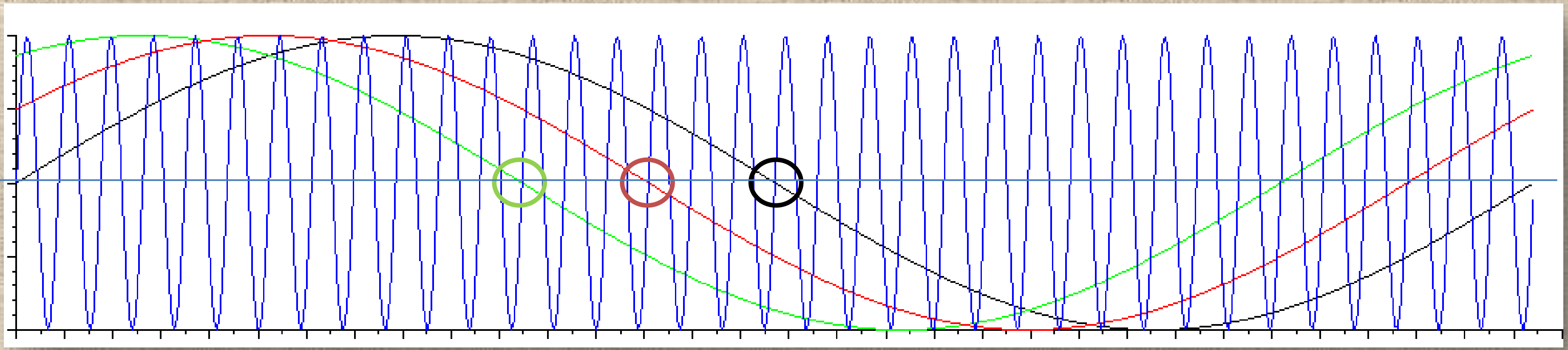
$$S_{i-j}(f) = \frac{S_{i_0}(f)}{|1 + H_i(f)|^2} + \frac{S_{j_0}(f)}{|1 + H_j(f)|^2} + \left|\frac{H_i(f) - H_j(f)}{[1 + H_i(f)][1 + H_j(f)]}\right|^2 S_{ref}(f)$$

- In general two different PLL have different t.f. $H_i(f) \neq H_j(f)$
- And in particular they have two different BWs $f_{BW1} \neq f_{BW2}$
- There is a direct contribution of the master clock phase noise $S_{ref}(f)$ to the relative jitter between clients *i* and *j* in the region $f_{BW1} < f < f_{BW2}$
- In this frequency region (typically 100 Hz ÷ 100 kHz), a very low RMO phase noise is needed

3.5 Client locking – Lasers (electrical architecture)



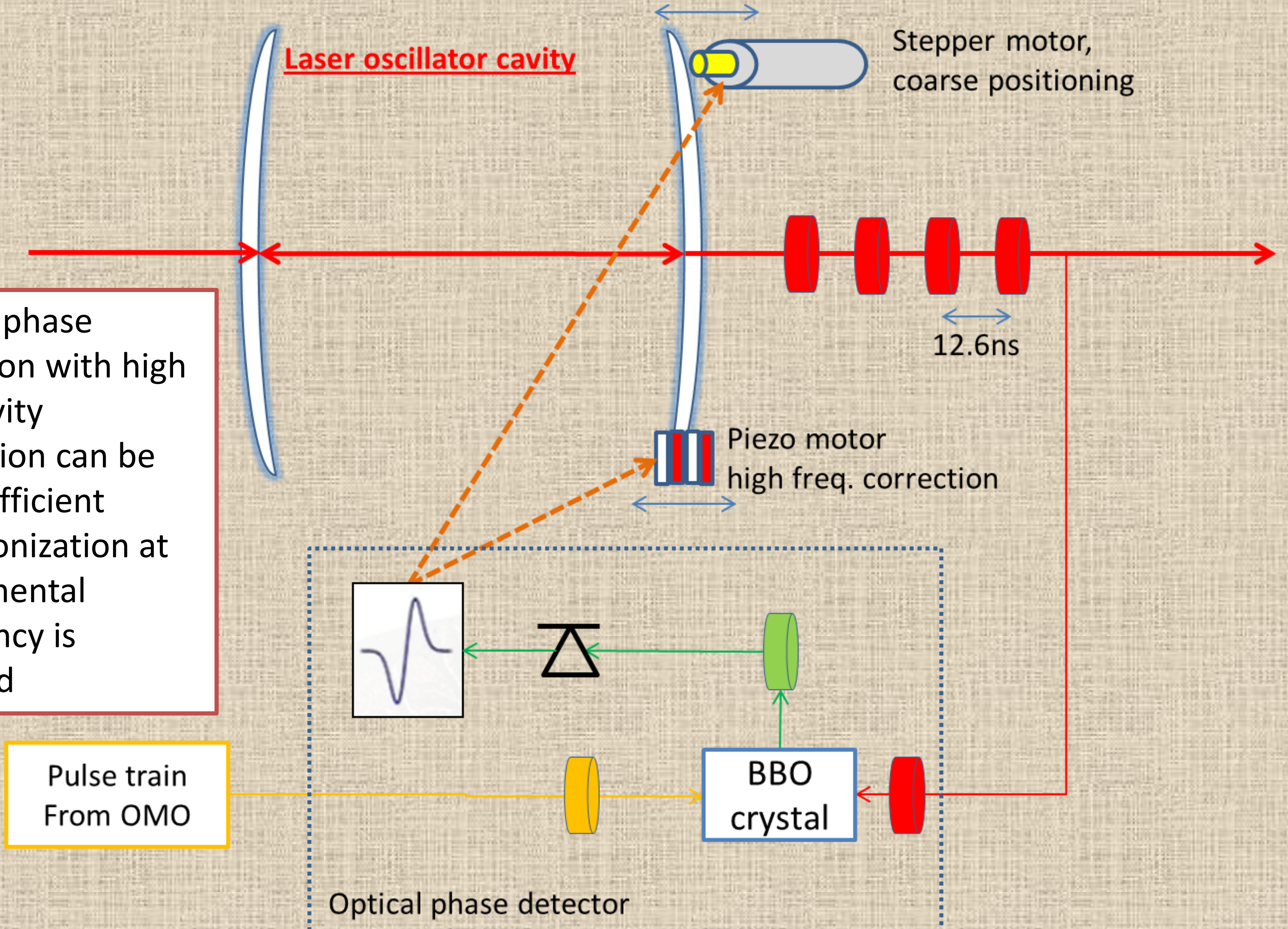
3.5 Client locking - Lasers



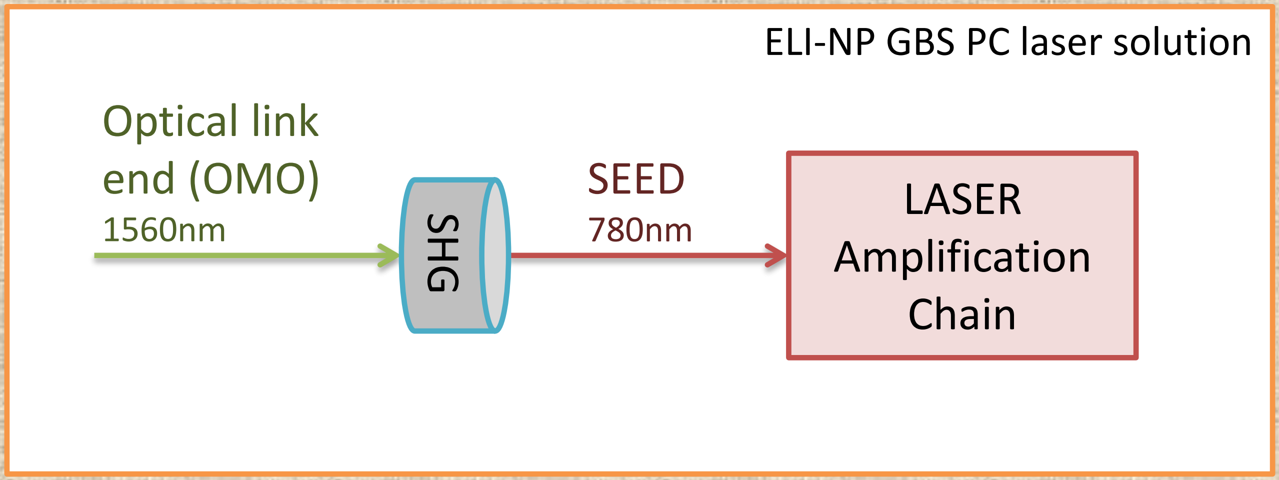
- **Blue curve:** locking frequency (f_{REF}), typically the RF frequency (Nth harmonic of laser repetition rate) to increase the phase detection sensitivity
- **Other colors:** laser oscillator frequency $\left({}^{f_{REF}}\!/_{N}\right)$
- **N possible time delays between different lasers locked at f_{REF} (every time locking is performed)**
- **Locking methods must take it into account**

3.5 Client locking - Lasers (optical architecture)

- optical phase detection with high sensitivity
- correction can be more efficient
- synchronization at fundamental frequency is ensured

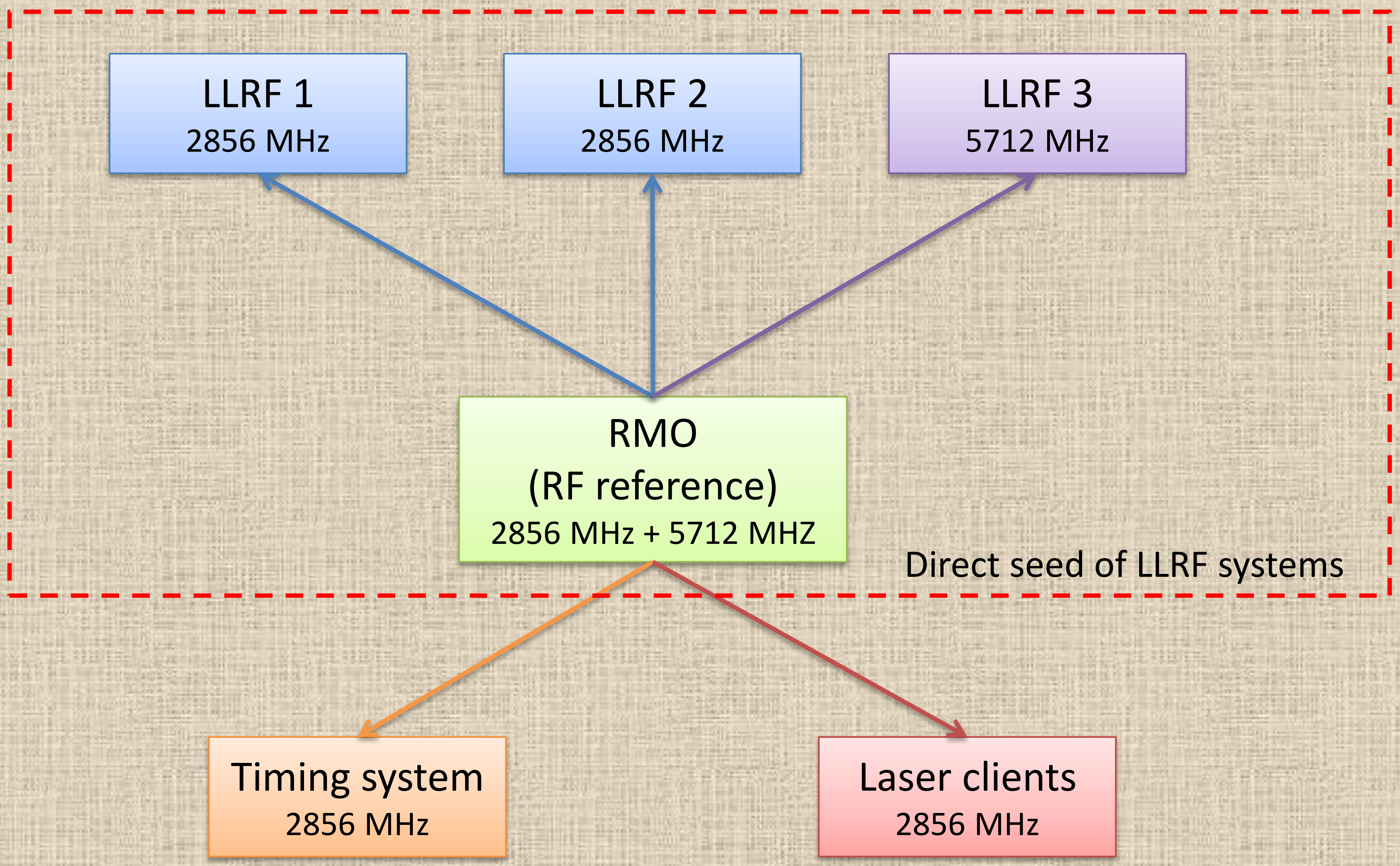


3.5 Client locking – Lasers (direct seeding)

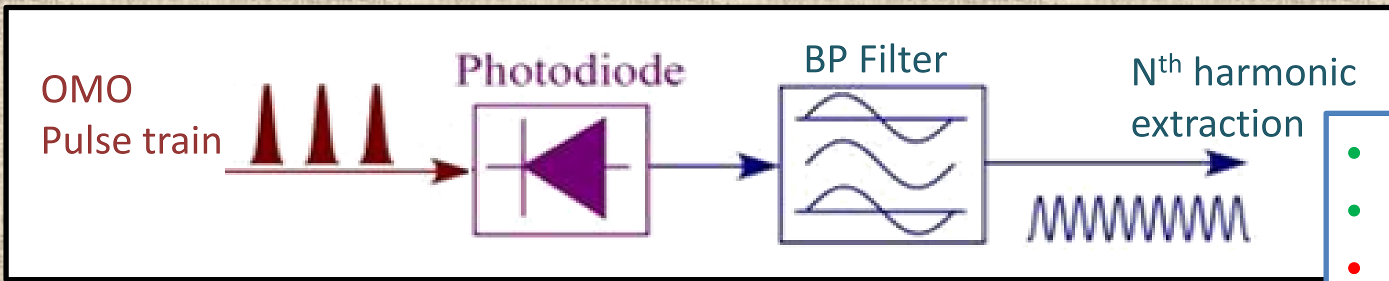


- Simplest and (relatively) low cost solution, if technically doable
- Client directly synchronized to the reference (only distribution residual noise is present)
- OMO and client lasers have to be wavelength "compatible"
- OMO has to be suitable parameters for amplification (i.e. power, spectral bandwidth, …)

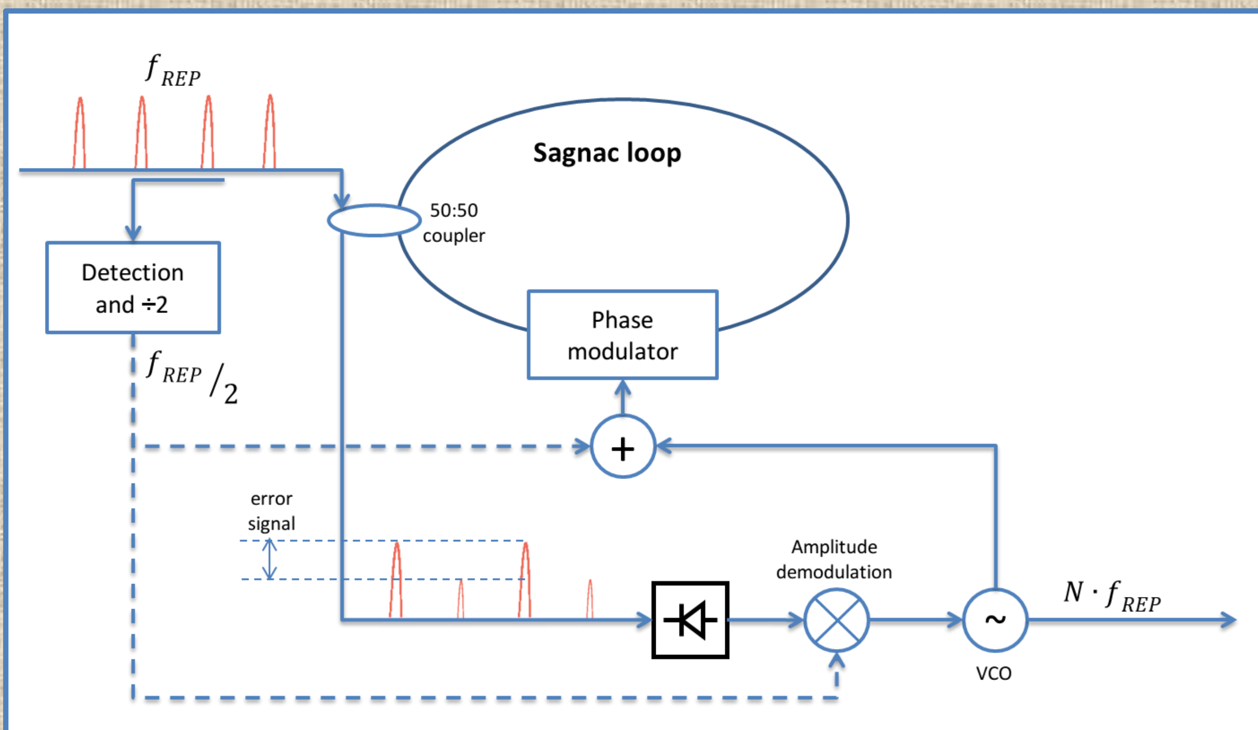
3.5 Client locking – RF (electrical architecture)



3.5 Client locking – RF (optical architecture)

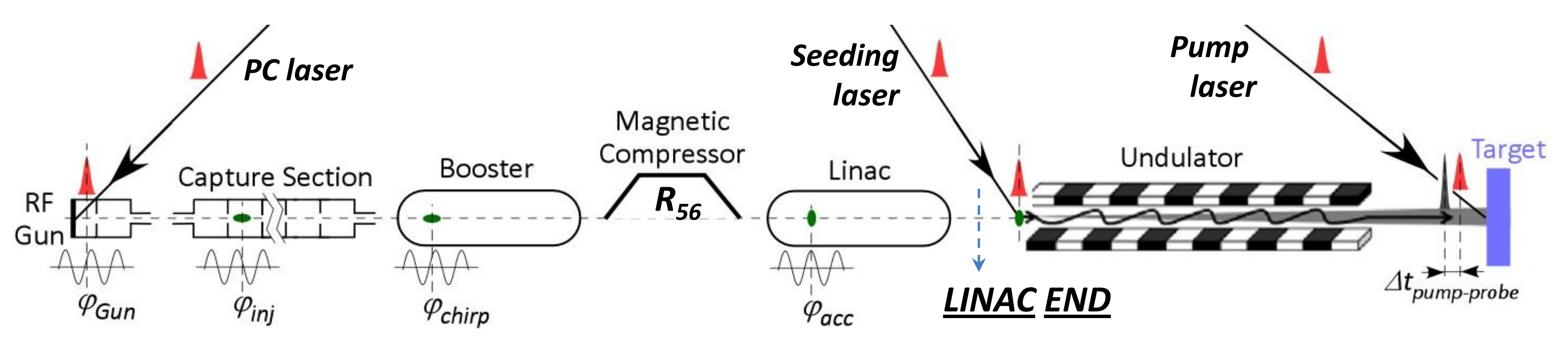


- Simple layout
- Low cost
- AM-to-PM conversion in photo-detector (1÷10ps/mW)
- <10fs added jitter



- No AM-to-PM conversion
- Negligible added jitter
- Higher cost and complexity

3.6 Beam timing jitter - Sources



- The time T_i of all sub-systems is properly set to provide required beam characteristics at the linac end, where the bunch centroid arrives at time T_b.
- Time fluctuation Δt_i in each subsystem will produce a change Δt_b of the beam arrival time.

$$\Delta t_b = \sum_i a_i \, \Delta t_i = \sum_i \frac{\Delta t_i}{c_i} \qquad with \qquad \sum_i a_i = 1$$

Compression coefficients

Values of a_i can be computed analytically, by simulations or even measured experimentally. They very much depends on the machine working point.

3.6 Beam timing jitter - Sources

- No compression: Beam captured by the GUN and accelerated on-crest

$$a_{PC} \approx 0.65; a_{RF_{GUN}} \approx 0.35; others\ a_i \approx 0$$

- Magnetic compression: Energy-time chirp imprinted by off-crest acceleration in the booster and exploited in magnetic chicane to compress the bunch

$$a_{RF_{boost}} \approx 1; |a_{PC}| \ll 1;\ others\ a_i \approx 0$$

  - Bunch can be over-compressed (head and tail reversed, $a_{PC} < 0$).

- RF compression: a non fully relativistic bunch ($E_0 \approx few\ MeV$ at Gun exit) injected ahead the crest in an RF capture section slips back toward an equilibrium phase closer to the crest during acceleration, being also compressed in this process

$$a_{RF_{CS}} \approx 1; |a_{PC}|, |a_{RF_{GUN}}| \ll 1;\ others\ a_i \approx 0$$

  - In this case the bunch gains also an Energy-time chirp, thus RF and magnetic compressions can be combined.

3.6 Beam timing jitter – Relative jitter

- If we consider uncorrelated residual jitter Δt_i (measured wrt the facility reference clock), the bunch arrival time jitter σ_{t_b} is given by:

$$\sigma_{t_b}^2 = \sum_i a_i^2 \, \sigma_{t_i}^2$$

- while the jitter of the beam respect to a specific facility sub-system (such as the PC laser or the RF accelerating voltage of a certain group of cavities) $\sigma_{t_{b-j}}$ is:

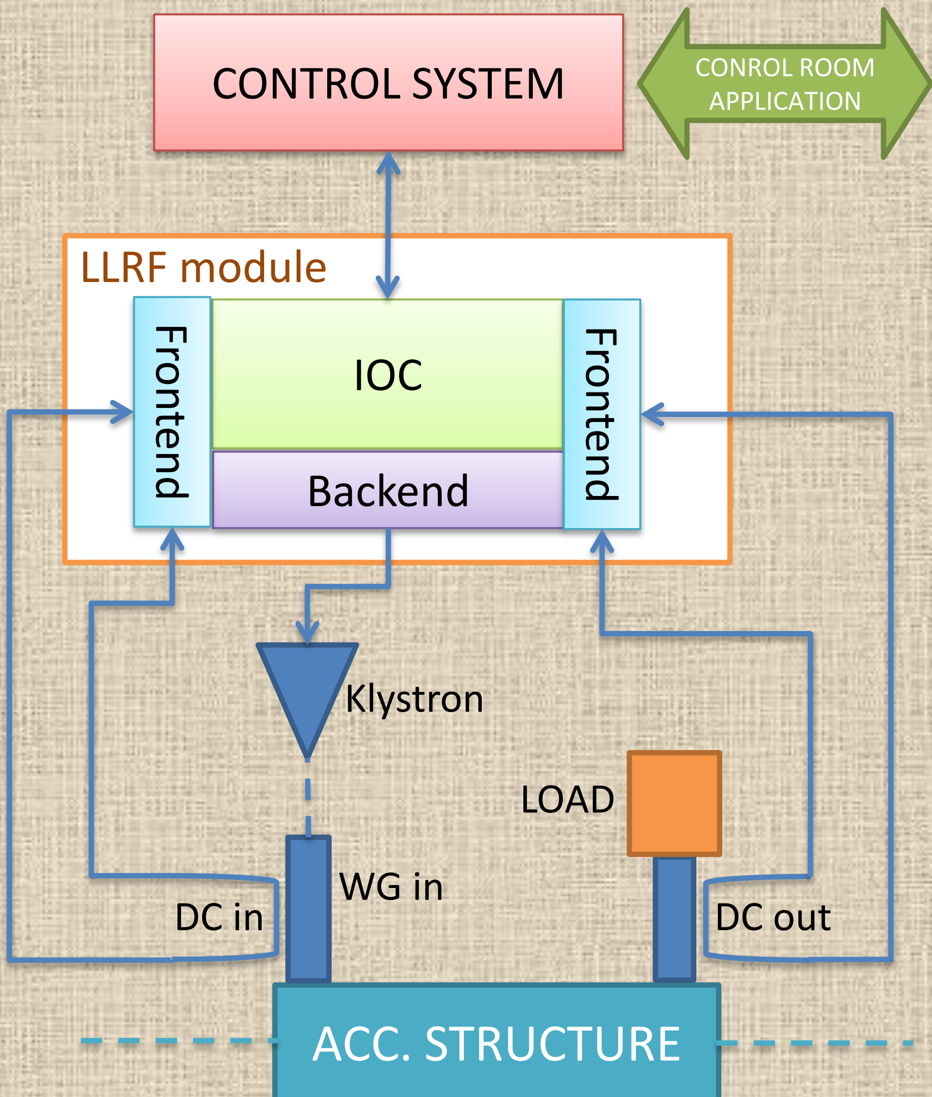
$$\sigma_{t_{b-j}}^2 = \left(a_j - 1\right)^2 \sigma_{t_j}^2 + \sum_{i \neq j} a_i^2 \, \sigma_{t_i}^2$$

EXAMPLE: PC laser jitter $\sigma_{t_{PC}} \approx 70\ fs$, RF jitter $\sigma_{t_{RF}} \approx 30\ fs$ (<u>uncorrelated</u>)

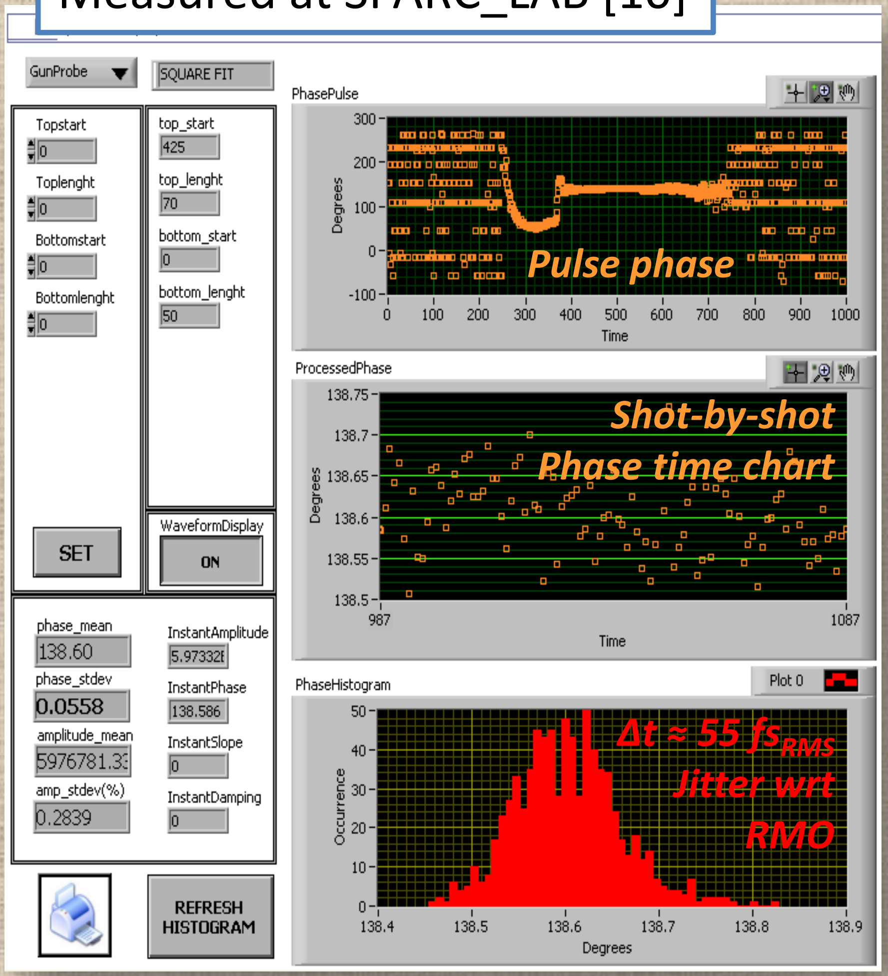
No Compression: $a_{PC} \approx 0.65,\ a_{RF_{GUN}} \approx 0.35$ → $\sigma_{t_b} \approx 47\ fs$; $\sigma_{t_{b-PC}} \approx 27\ fs$; $\sigma_{t_{b-RF}} \approx 50 fs$

Magnetic Compression: $a_{PC} \approx 0.2,\ a_{RF_{boost}} \approx 0.8$ → $\sigma_{t_b} \approx 28\ fs$; $\sigma_{t_{b-PC}} \approx 61\ fs$; $\sigma_{t_{b-RF}} \approx 15 fs$

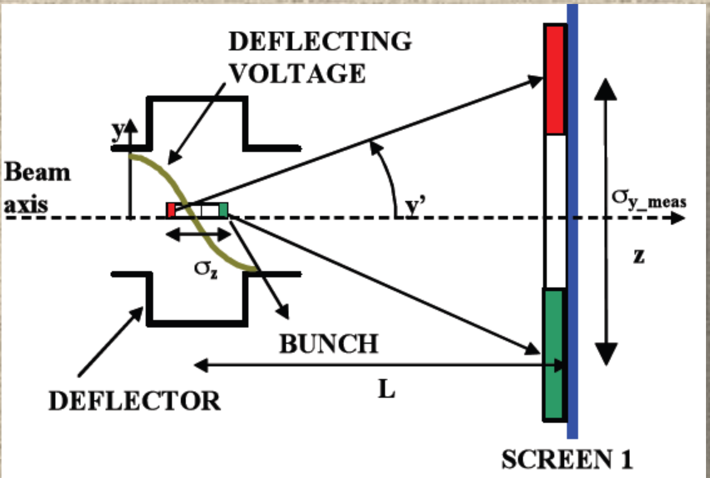
3.7 Diagnostics – LLRF phase noise detection



Measured at SPARC_LAB [10]



3.7 Diagnostics – RF deflector

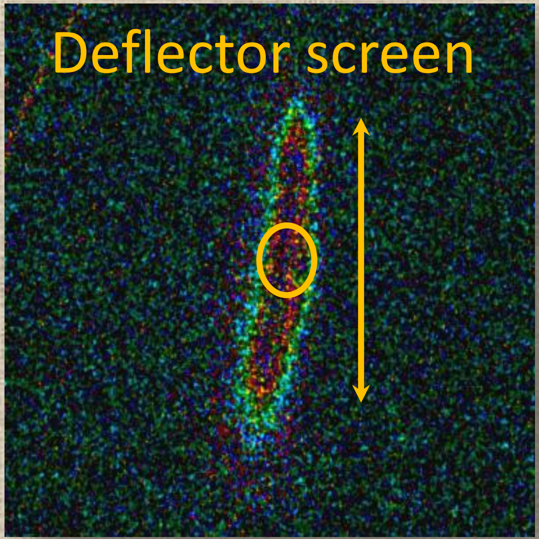


The beam is ***streaked*** by a ***transverse RF cavity*** on a ***screen***. The image is captured by a camera. Longitudinal charge distribution and centroid position can be measured.

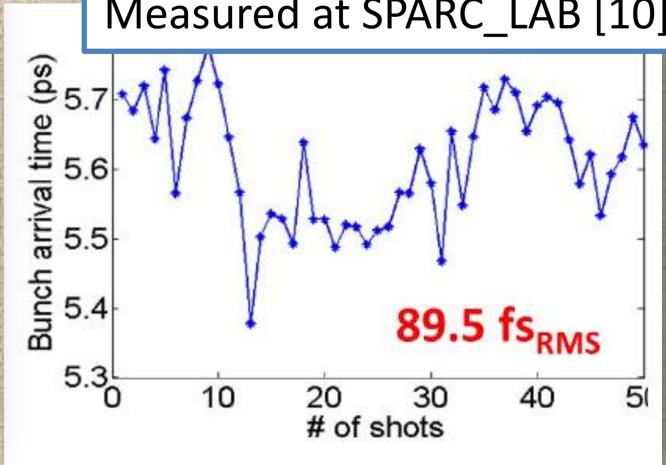
- ✓ Works typically on single bunch. Bunch trains can be eventually resolved with fast gated cameras;
- ✓ Destructive (needs a screen ...)
- ✓ Measure bunch wrt to RF (relative measurement)

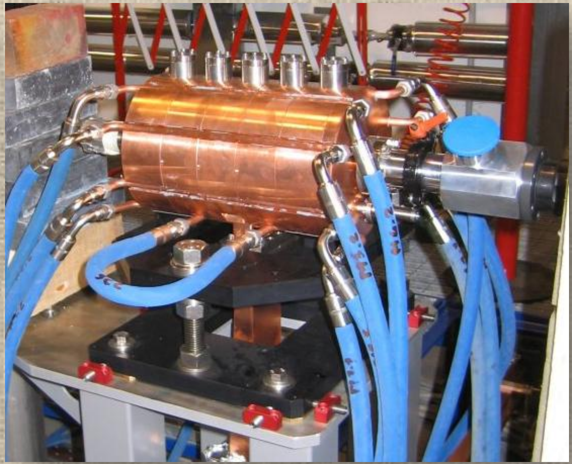
resolution

$$\tau_{res} = \frac{E/e}{\omega_{RF} V_\perp} \sqrt{\frac{\varepsilon_\perp}{\beta_\perp^{defl}}}$$



Measured at SPARC_LAB [10]

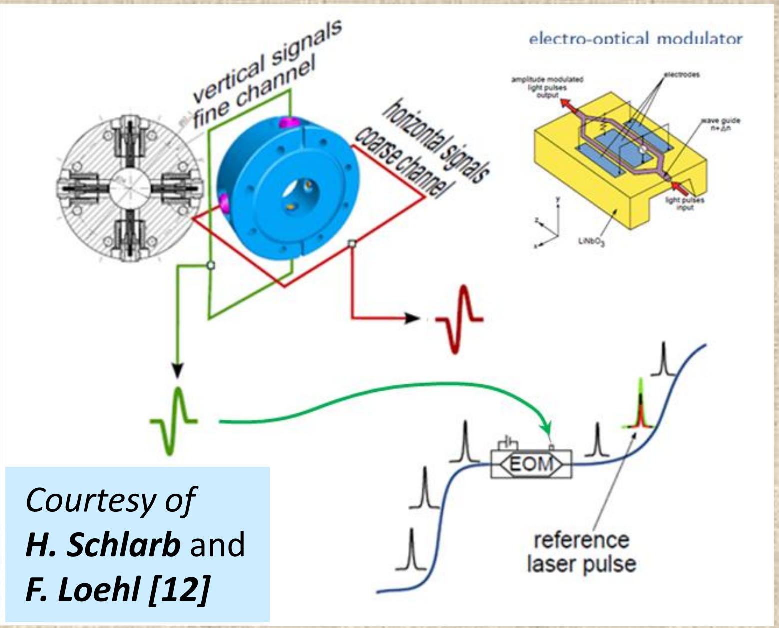




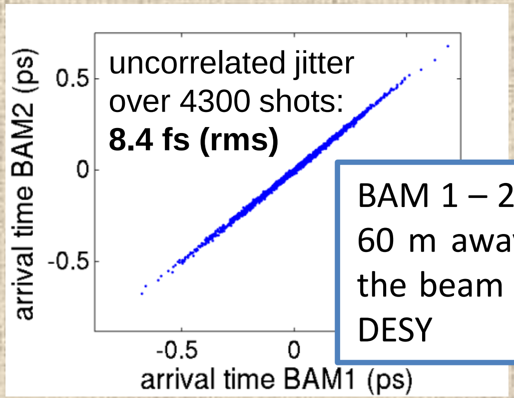
3.7 Diagnostics – BAM with EOM

A ***reference laser pulse train*** (typically taken from the facility OMO) is connected to the optical input of a ***Mach-Zehnder interferometric modulator*** (***EOM***). The short laser pulses are ***amplitude-modulated*** by a bipolar signal taken from a ***button BPM*** placed along the beam path and synchronized near to the voltage zero-crossing. ***The bunch arrival time jitter*** and ***drift*** is converted in ***amplitude modulation*** of the laser pulses and measured.

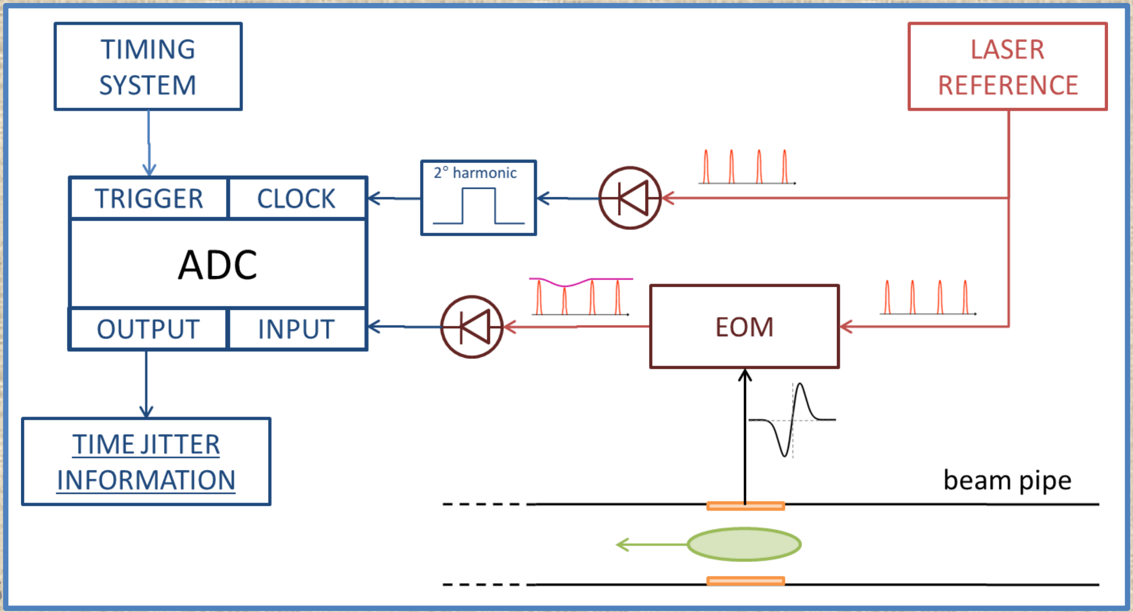
- ✓ Works very well on bunch trains;
- ✓ Non-intercepting;
- ✓ Measure bunch wrt to OMO
- ✓ Demonstrated high resolution



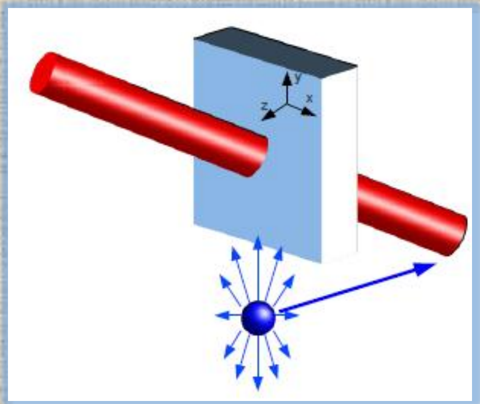
Courtesy of ***H. Schlarb*** and ***F. Loehl [12]***

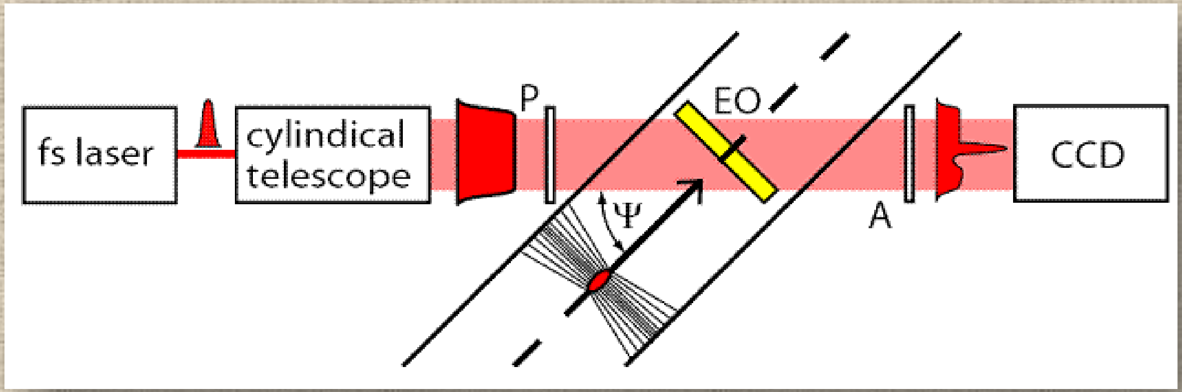


BAM 1 – 2 placed 60 m away along the beam path at DESY



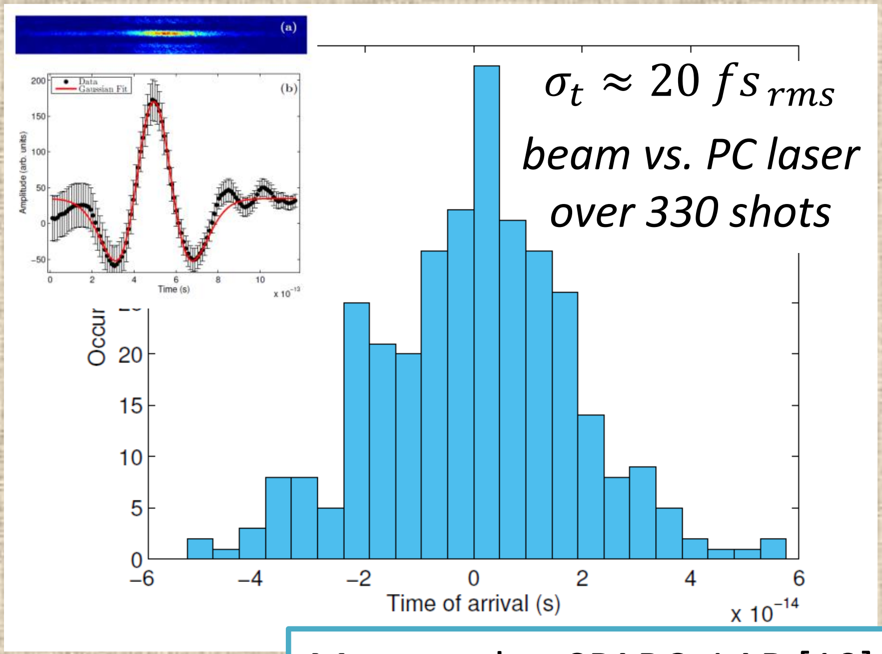
3.7 Electro-optic sampling





An ***electro-optic crystal*** is placed near the beam trajectory. In correspondence to the beam passage the crystal is illuminated with a ***short reference laser pulse*** transversally enlarged and ***linearly polarized***. The bunch electric field induces ***bi-rifrengence*** in the crystal, so that while propagating the laser gains ***elliptical polarization***. A polarized output filter delivers a signal proportional to the ***polarization rotation***, i.e. to the ***beam longitudinal charge distribution***.

- ✓ Single shot, non-intercepting;
- ✓ Provides charge distribution and centroid position;
- ✓ Resolution $\approx 50\ fs$ for the bunch duration, higher for centroid arrival time (*1 pixel ≈ 10 fs*).



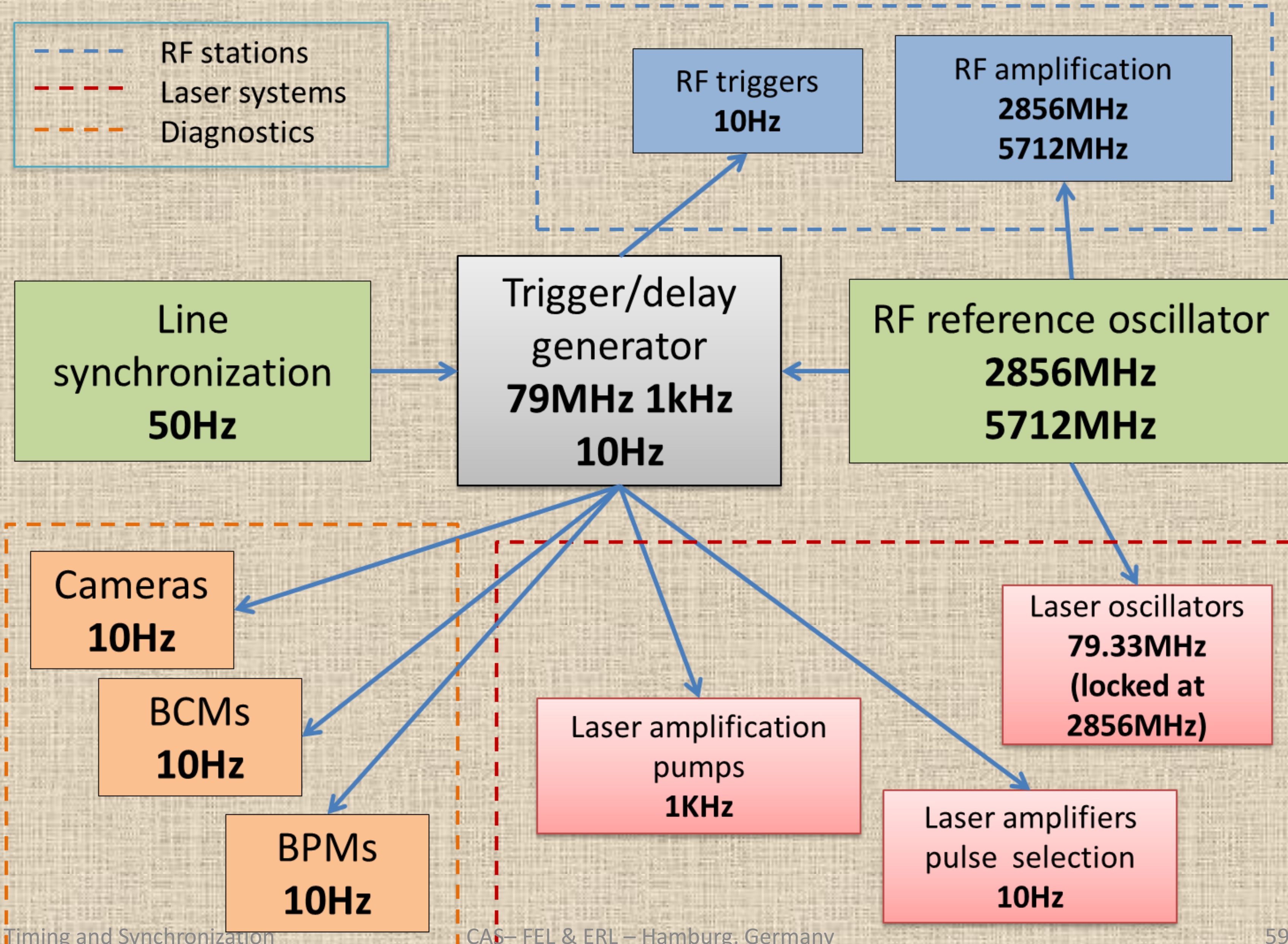
Measured at SPARC_LAB [10]

4.

Timing in linear injectors

1. Overview
2. Timing signals generation
3. Timing signals distribution
4. Timing example - Typical event sequence

4.1 Typical injector timing system layout



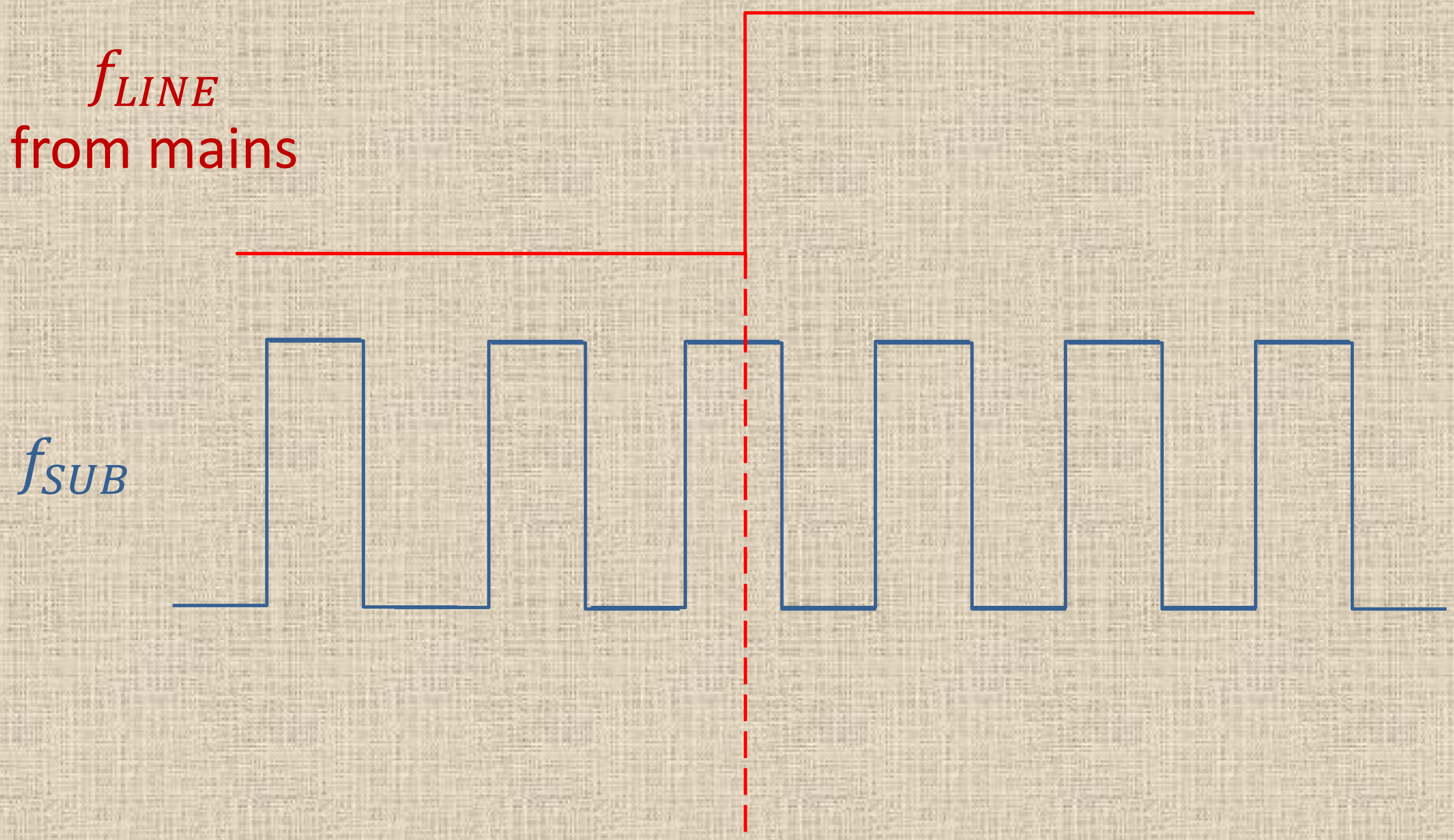
4.2 Timing signals generation

- The machine trigger generator is mainly a frequency divider
- Typically it divides one output of the RMO (f_{RMO}) at different stages to generate all the desired sub-harmonics, down to the machine rep. rate (f_{REP})
- The resulting jitter is 10ps ÷10ns depending of the divider stage
- It also take the 50Hz mains input and generate from it a signal at f_{REP} (either dividing or multiplying). We call it f_{LINE}
- The final machine clock is generated selecting the first logic front of one f_{RMO} sub-harmonic (f_{SUB}) following a f_{LINE} front (reducing magnet power supply current ripple)
- f_{SUB} must be coherent with all the system clocks (lasers rep. rate, ADC and DAC sample clocks, …) to avoid trigger edge slippage/jumps

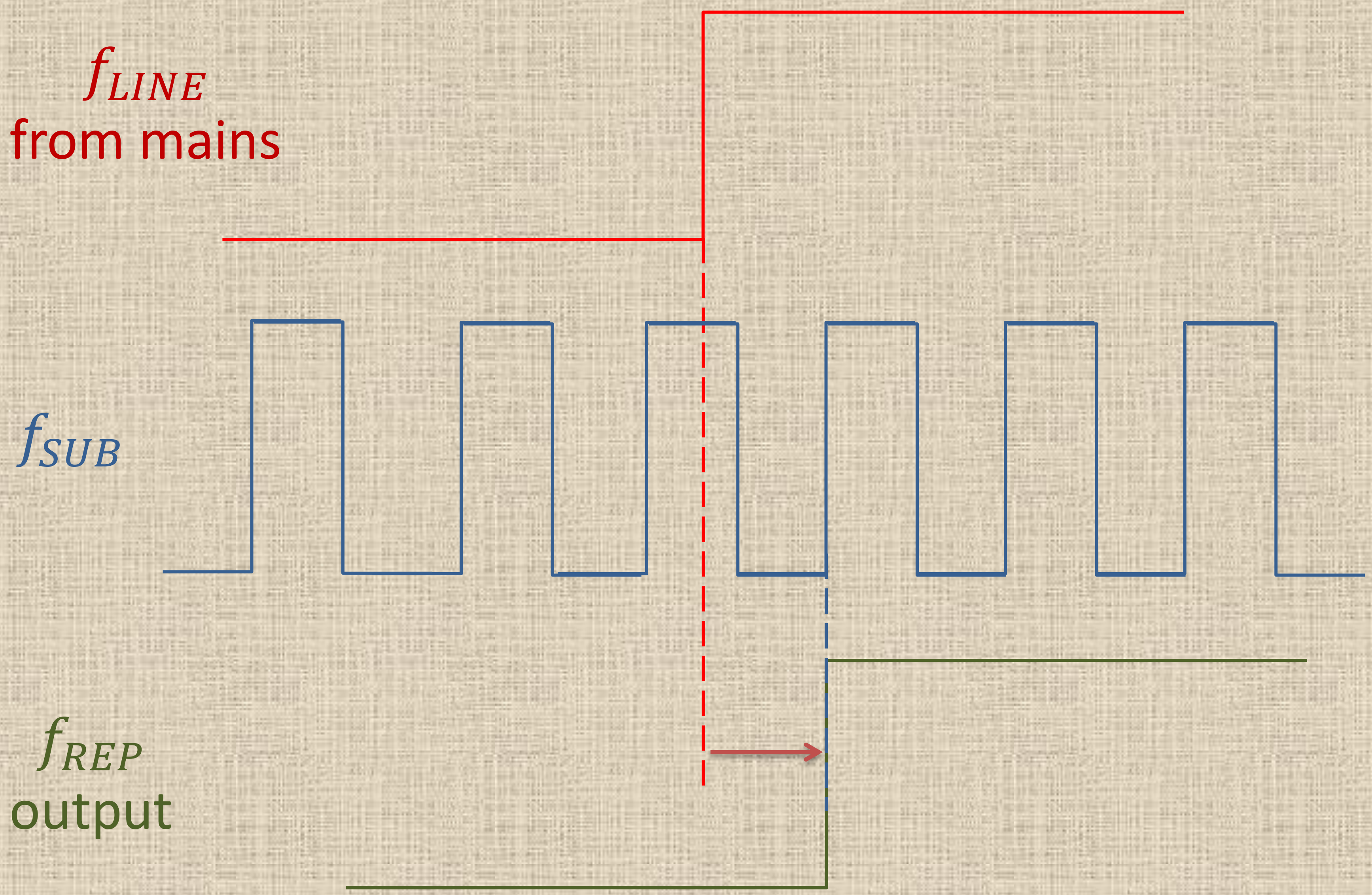
4.2 Timing signals generation

f_{LINE}
from mains

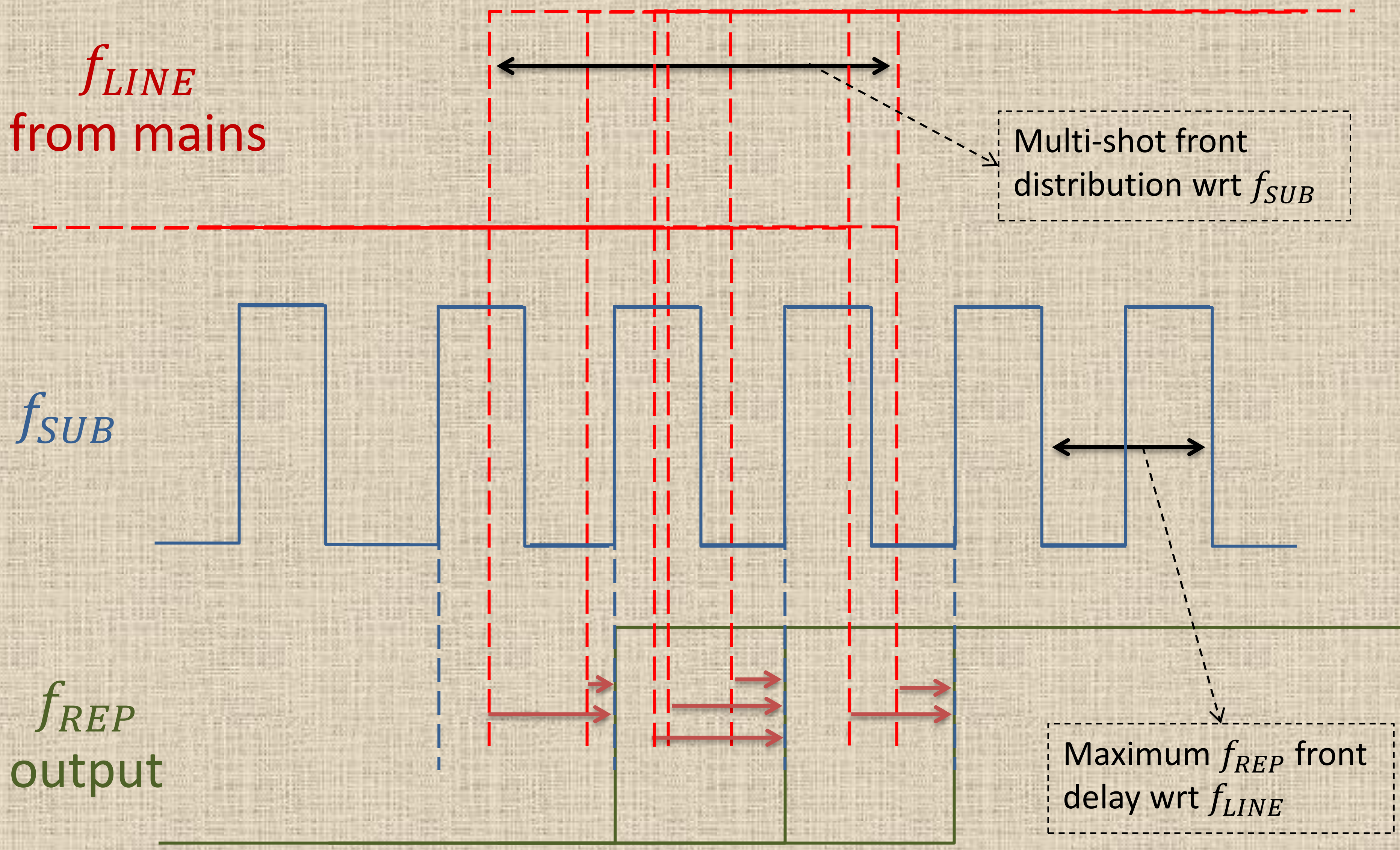
4.2 Timing signals generation



4.2 Timing signals generation



4.2 Timing signals generation



4.3 Timing signals distribution

- The main f_{REP} trigger is then split, delayed and distributed towards each subsystem
- Digital logic standards are commonly used (TTL, ECL, NIM, …)
- The signal distribution can be analogue or digital

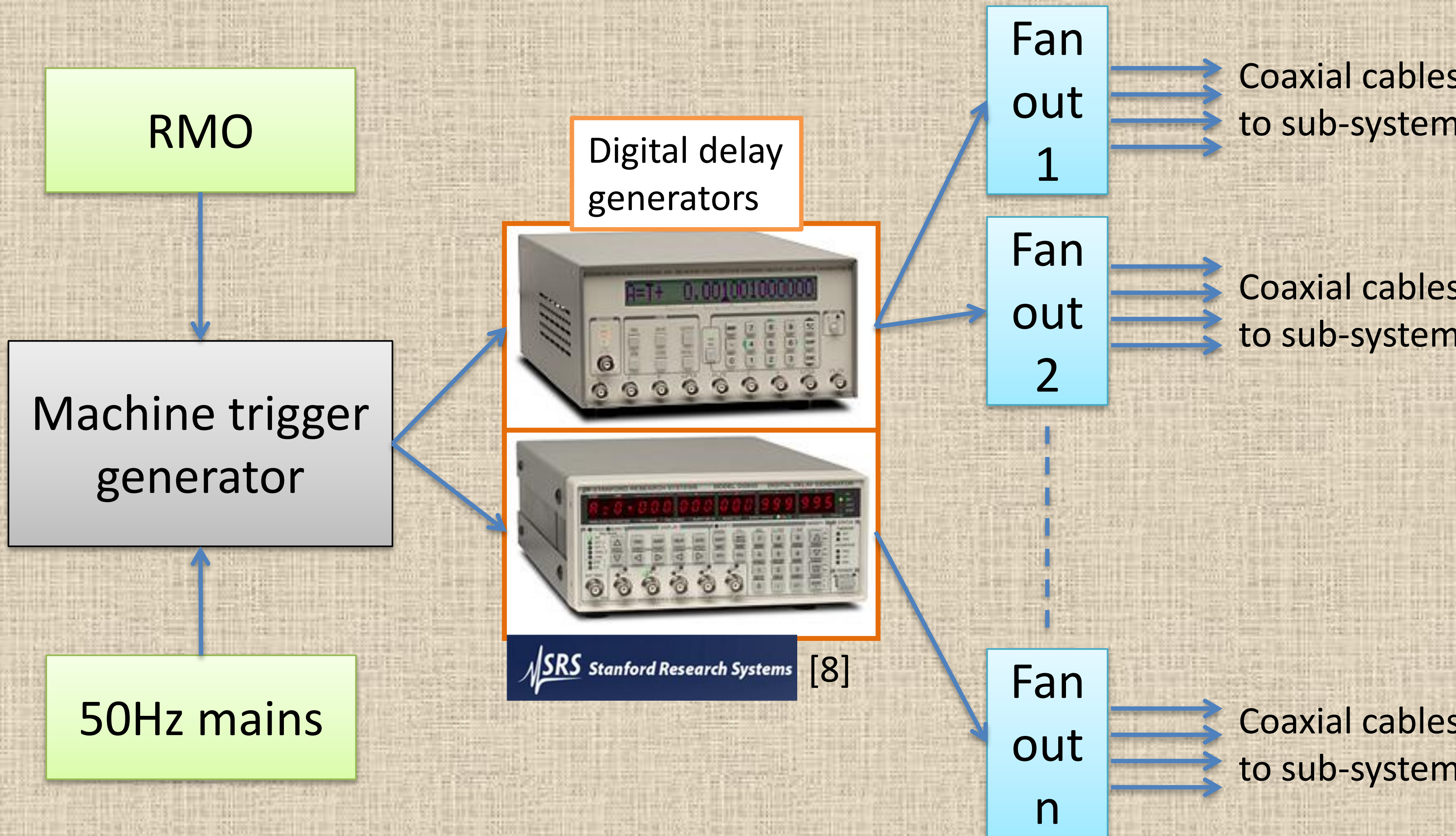
Analogue distribution

- Signal is distributed through coaxial cables (~100m range)
- Commercial digital delay generators are used
- No advanced features can be implemented
- Simple design and control
- Low cost
- Limited length of cables

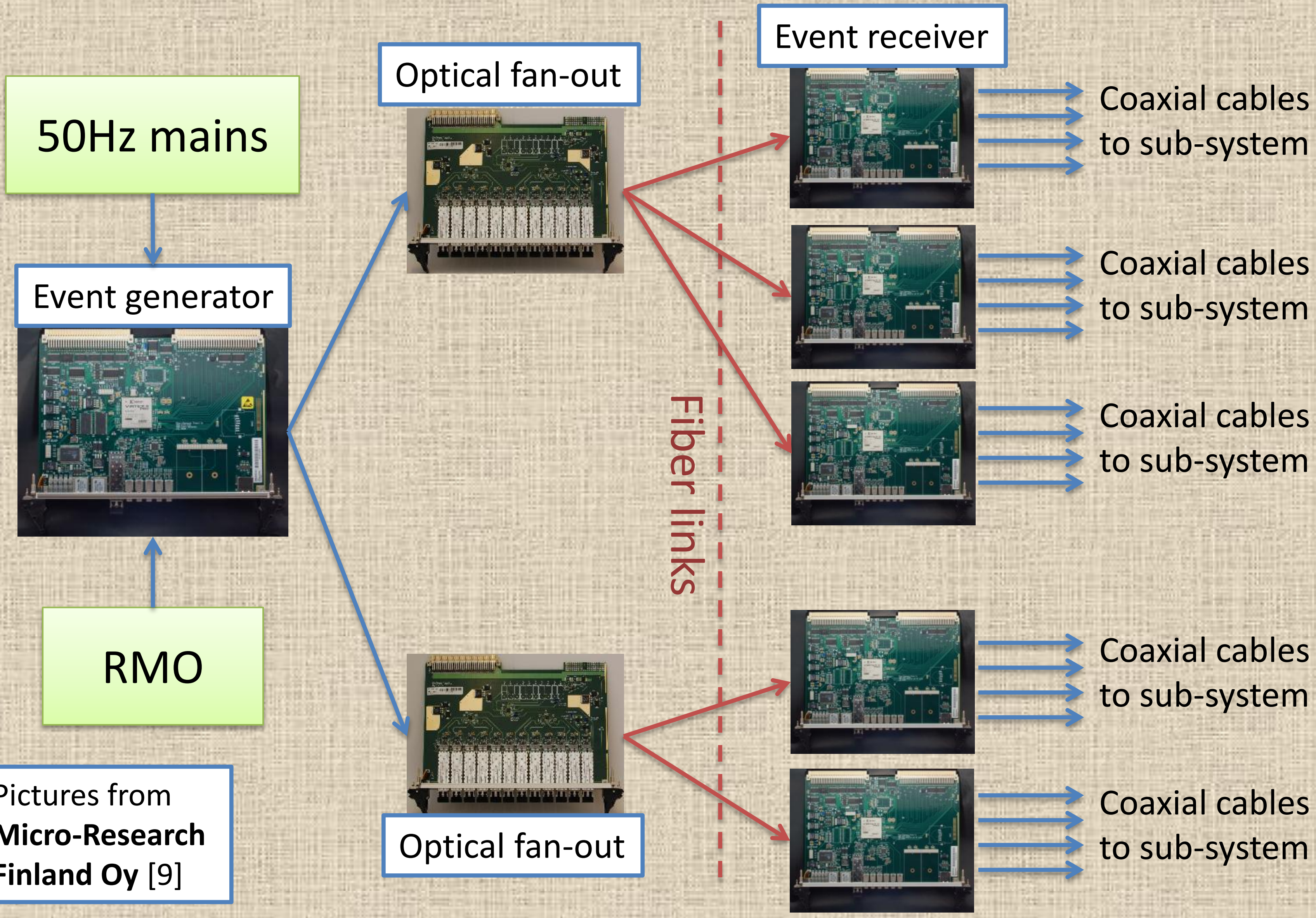
Digital distribution

- Signal is distributed through fiber links (km range)
- Information packed according to a proper communication protocol
- Programmable event generator/receivers are used
- More flexible (locally delayed triggers, status word, diagnostics on system, …)
- Higher cost, complex design
- Standard commercially available systems for accelerators

4.3 Analogue distribution layout

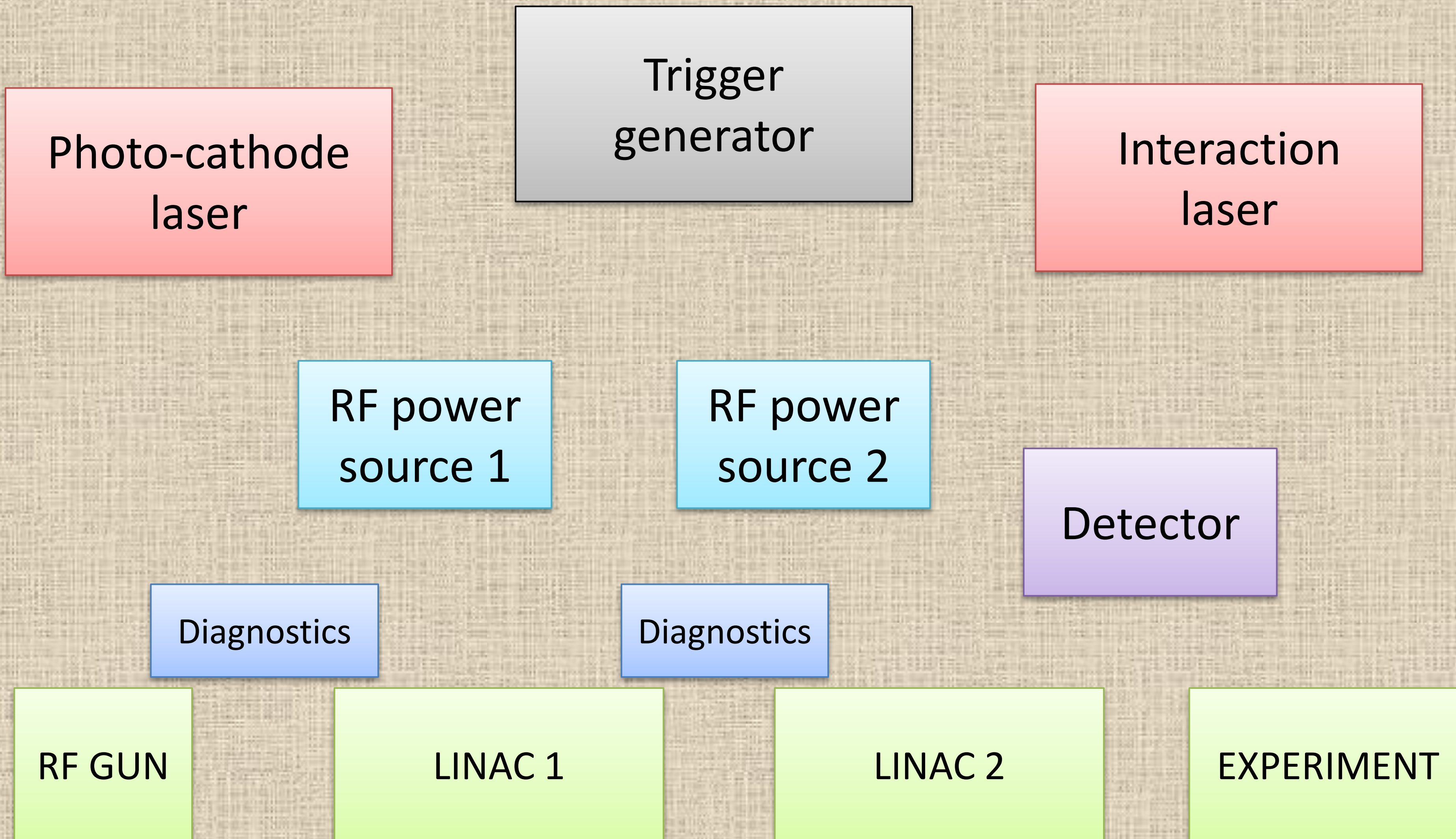


4.3 Digital distribution layout

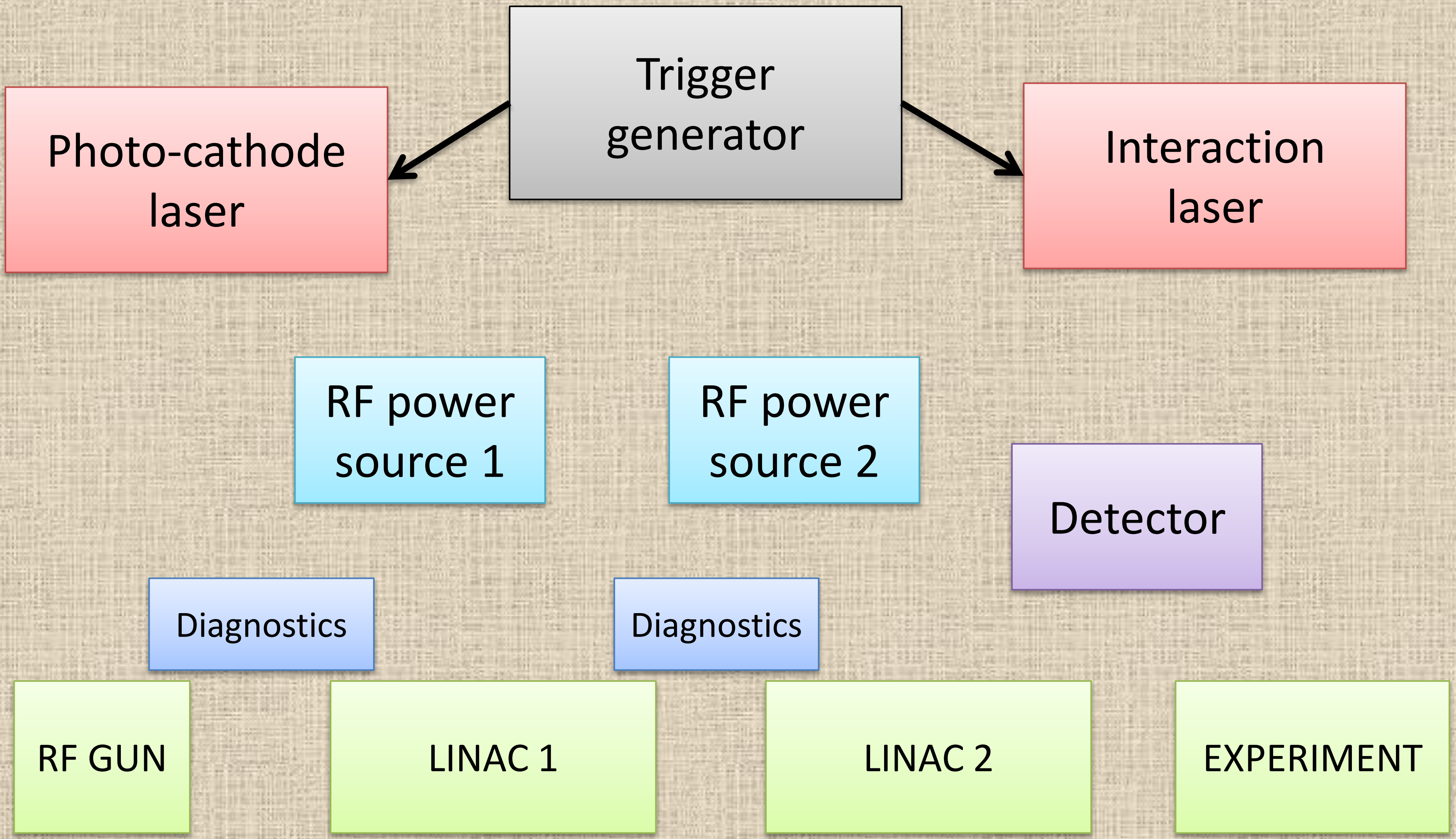


Pictures from **Micro-Research Finland Oy** [9]

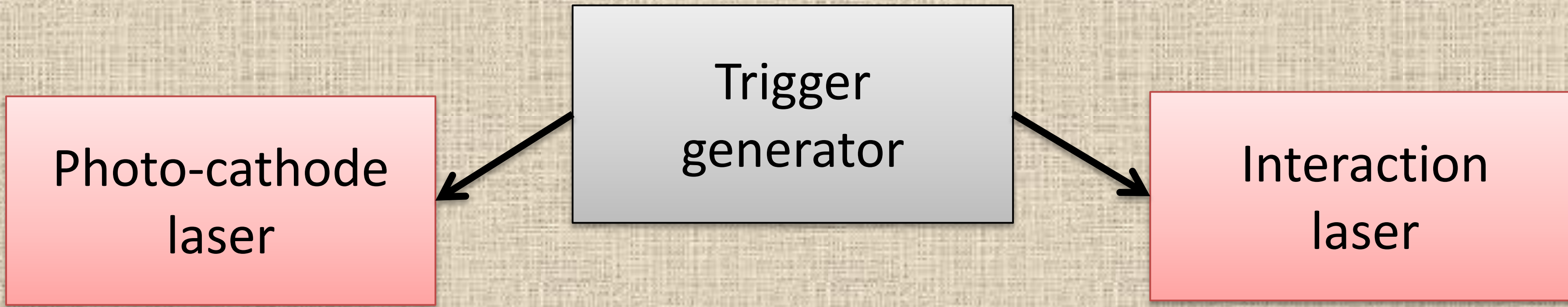
Timing example – Typical event sequence



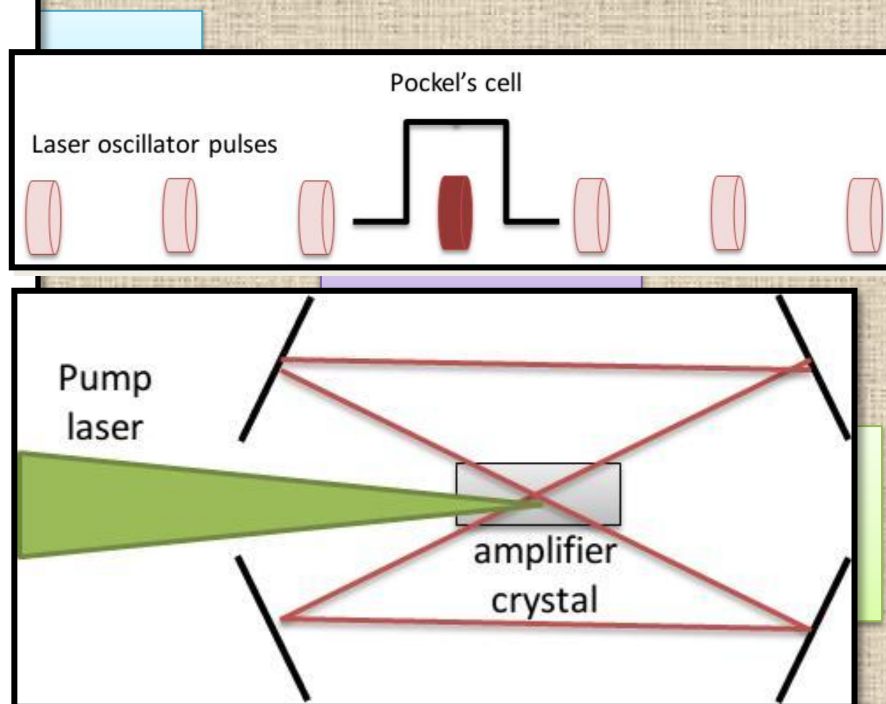
Timing example – Typical event sequence



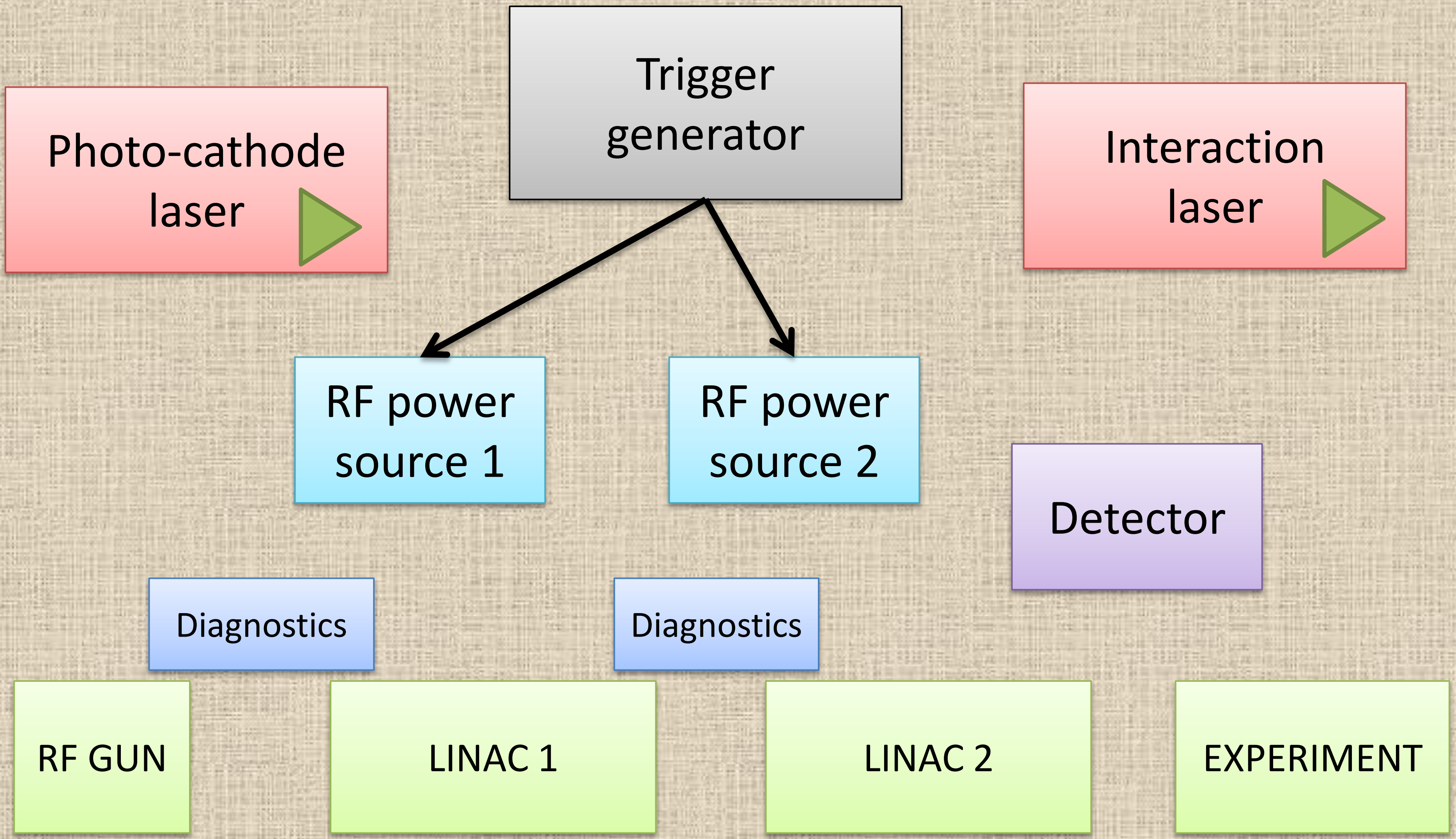
Timing example – Typical event sequence



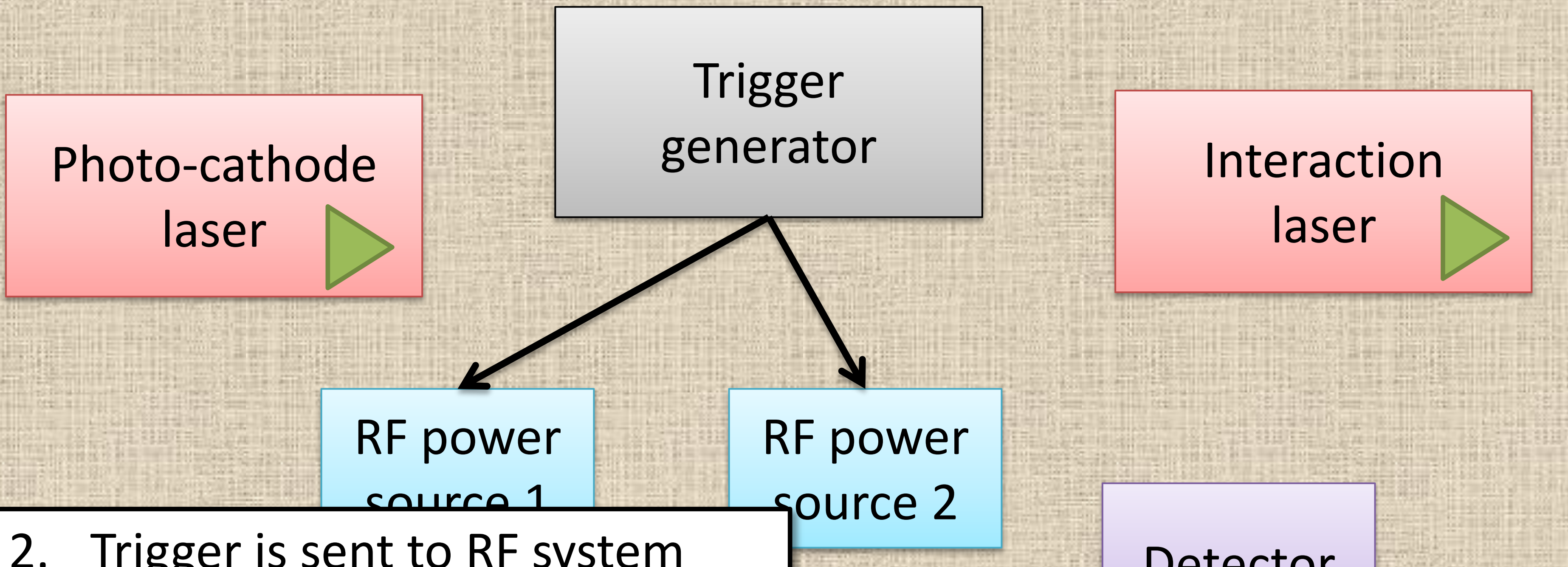
1. Trigger is sent to the laser systems
    1. Amplification chain starts
    2. Triggers are used for pulse pickers and optical amplifier pumps
    3. Typically a multi-pass optical amplifier with a large delay is used
    4. Thus this has to be the first event in the sequence



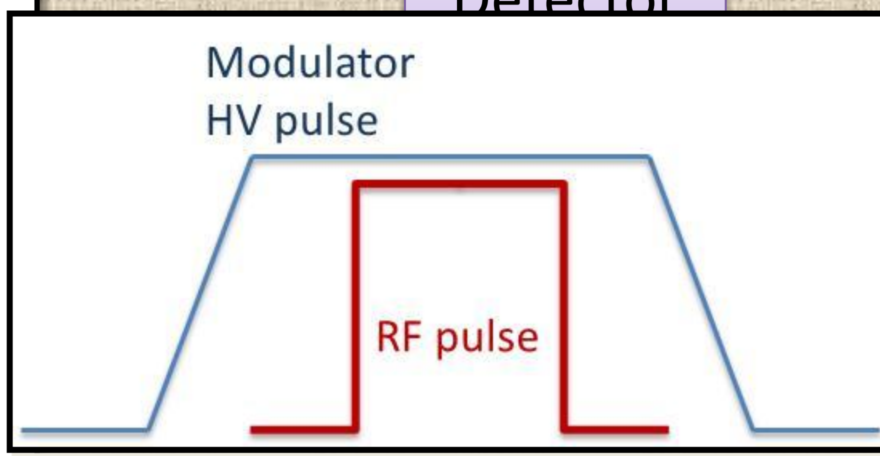
Timing example – Typical event sequence



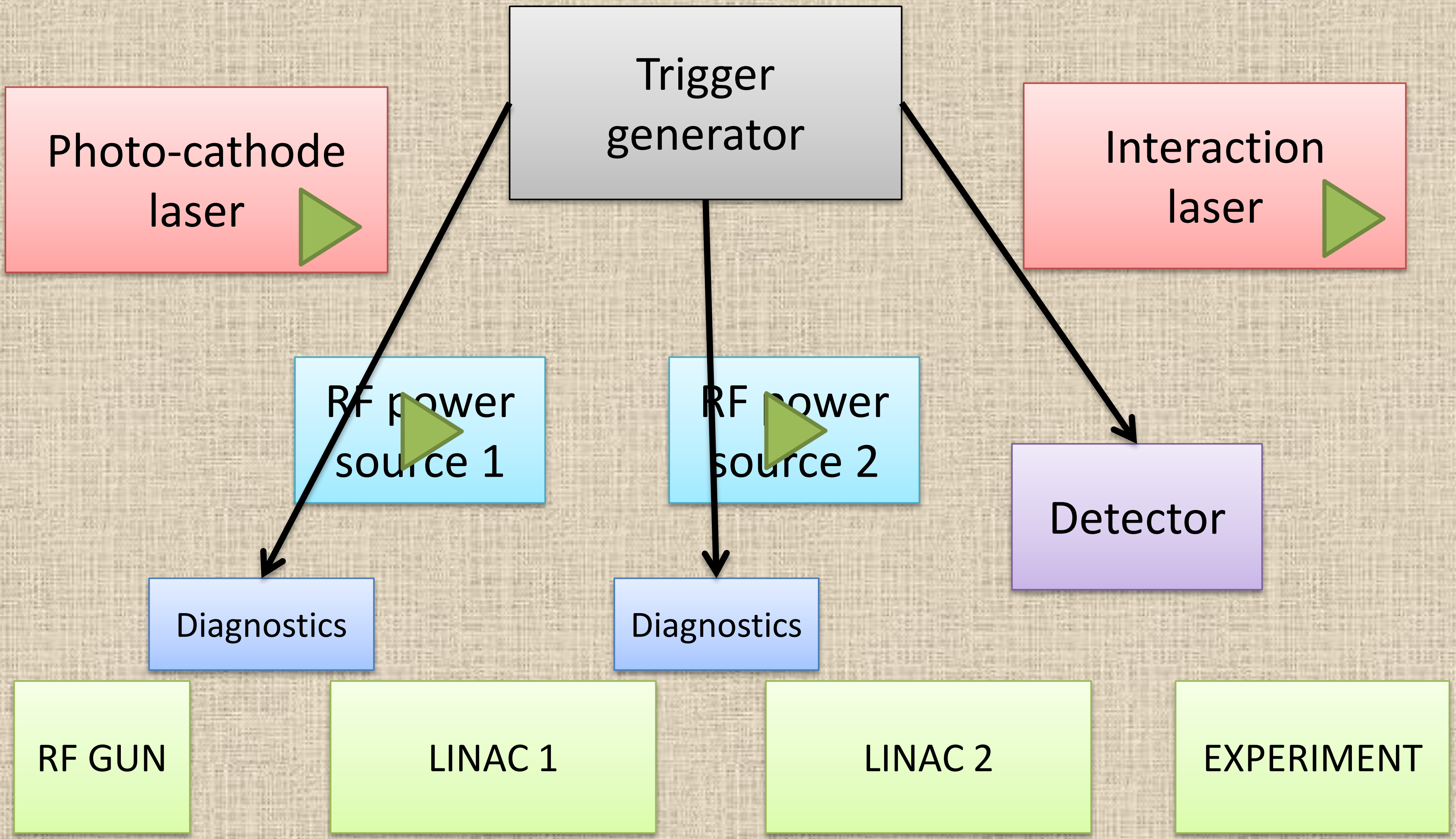
Timing example – Typical event sequence



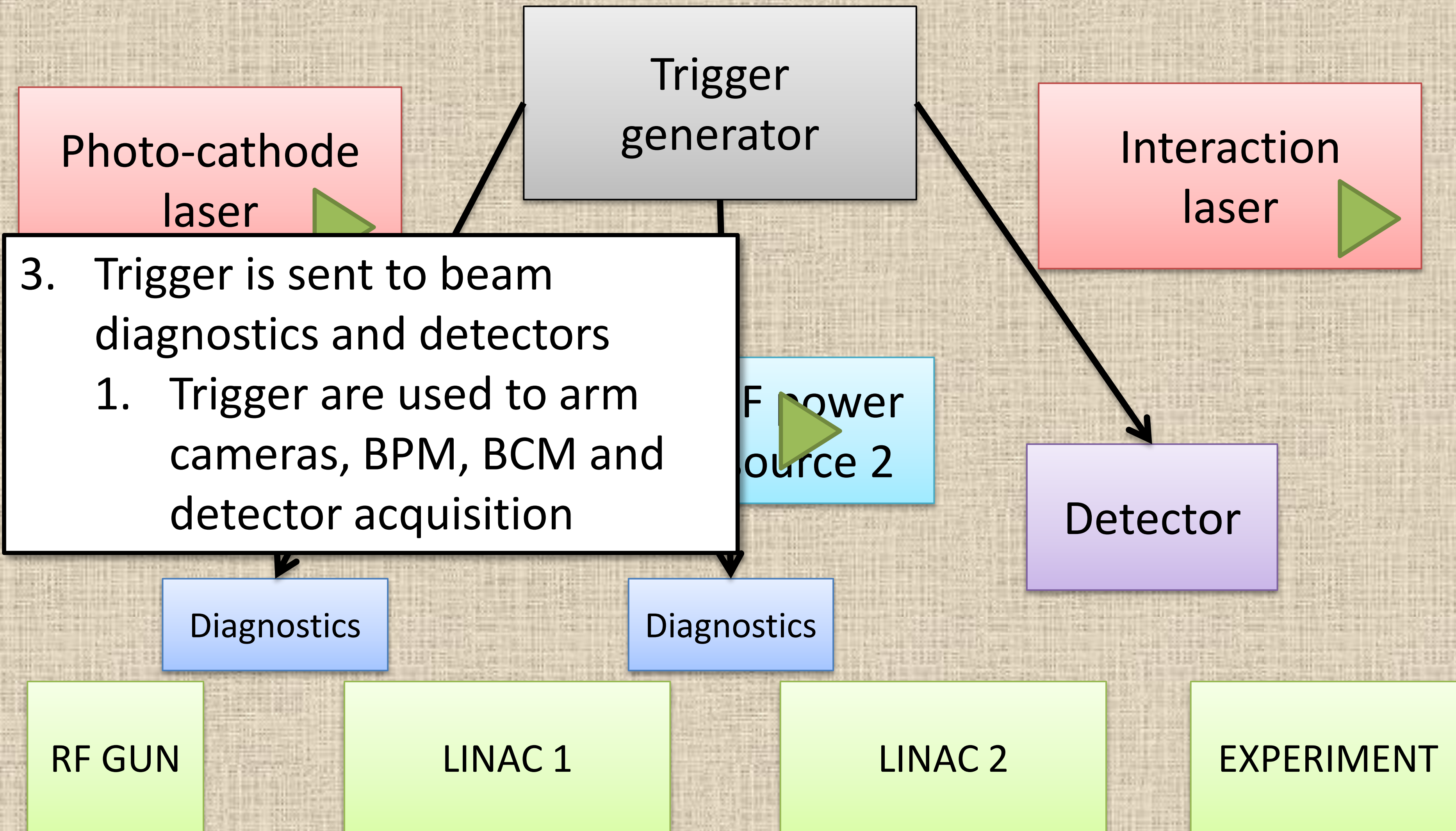
2. Trigger is sent to RF system
    1. Lasers are still running to prepare their outputs
    2. Trigger are used to start the modulator HV pulse forming and to trigger the LLRF systems



Timing example – Typical event sequence

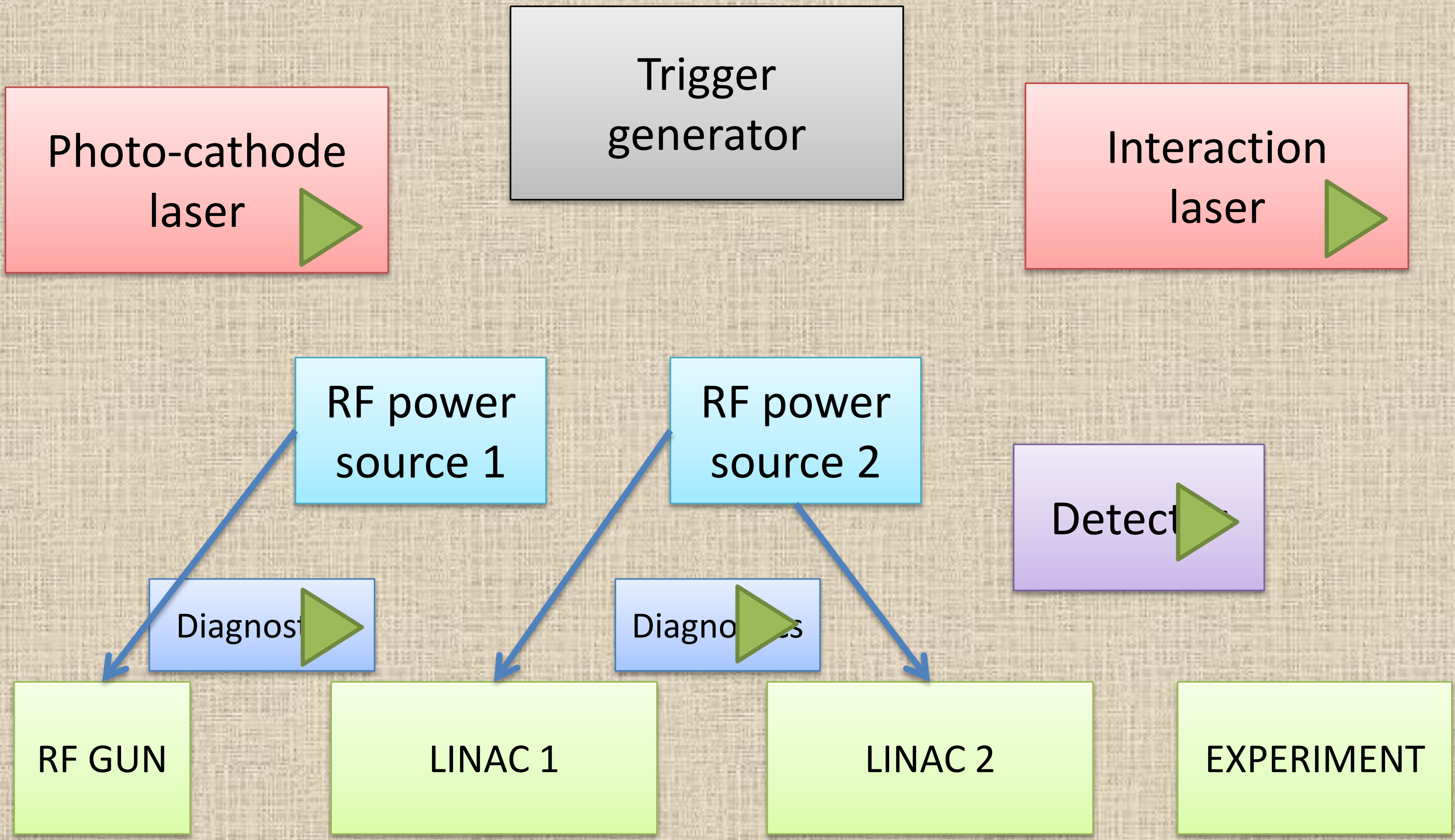


Timing example – Typical event sequence



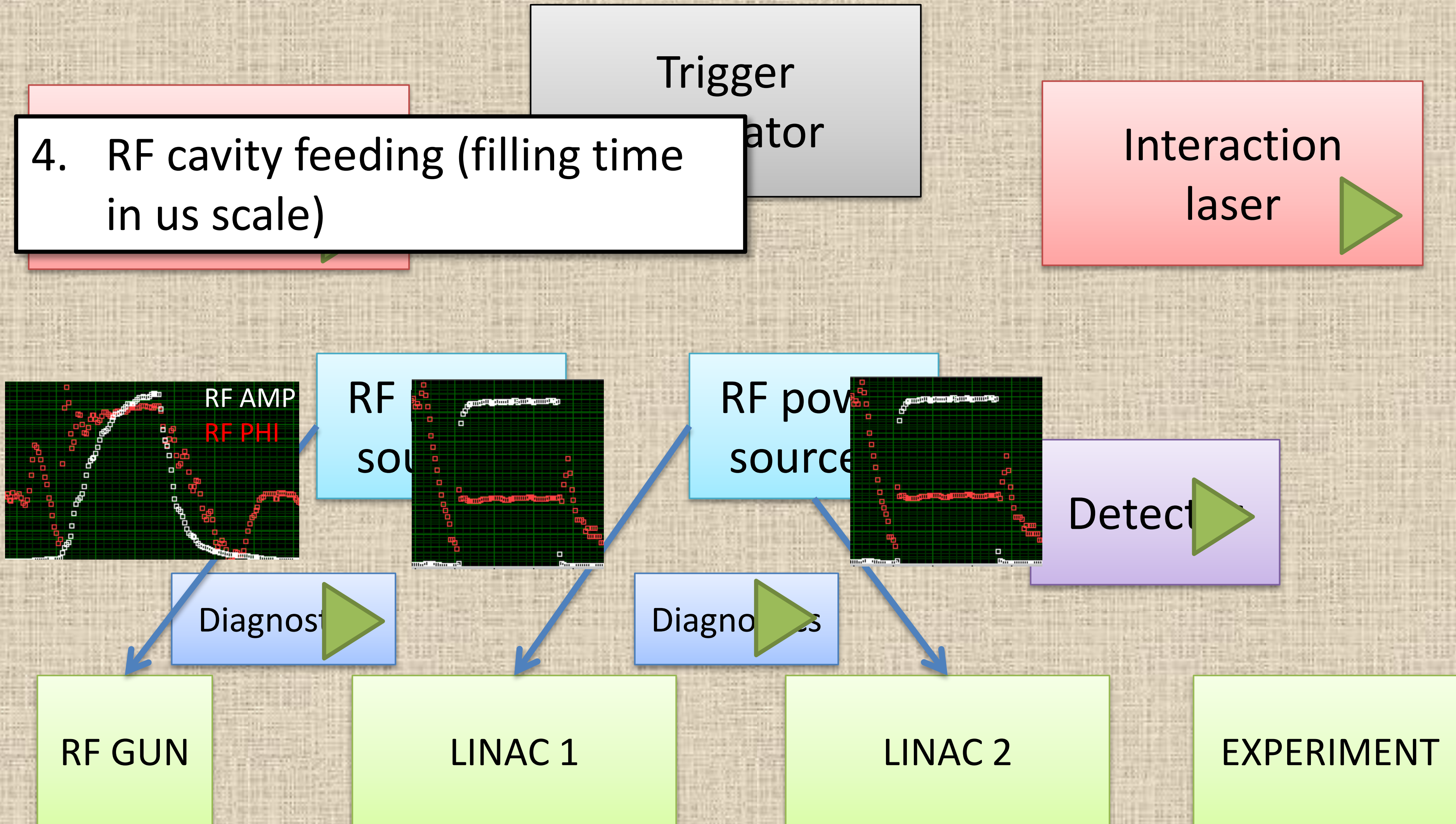
3. Trigger is sent to beam diagnostics and detectors
    1. Trigger are used to arm cameras, BPM, BCM and detector acquisition

Timing example – Typical event sequence

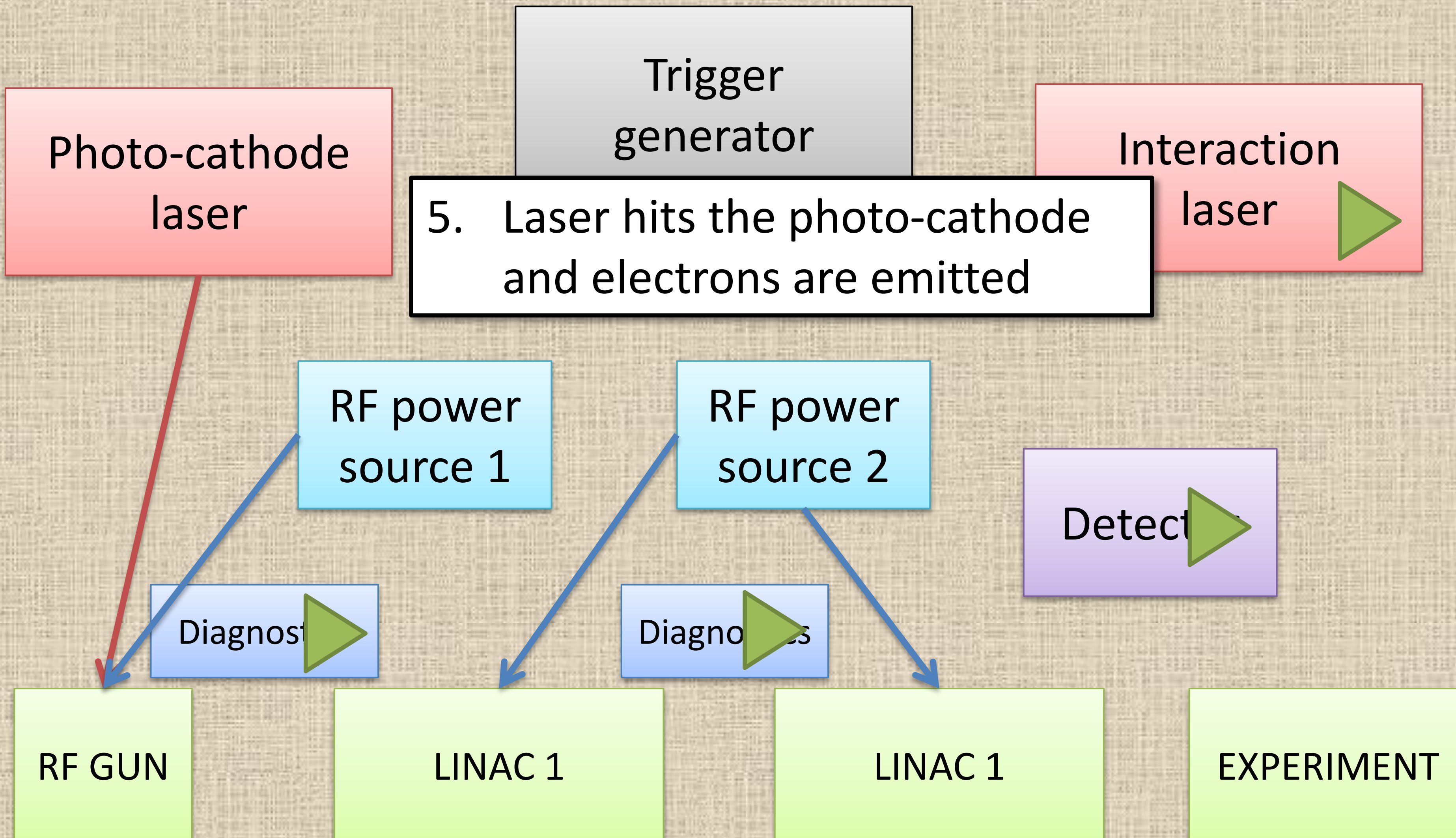


Timing example – Typical event sequence

4. RF cavity feeding (filling time in us scale)

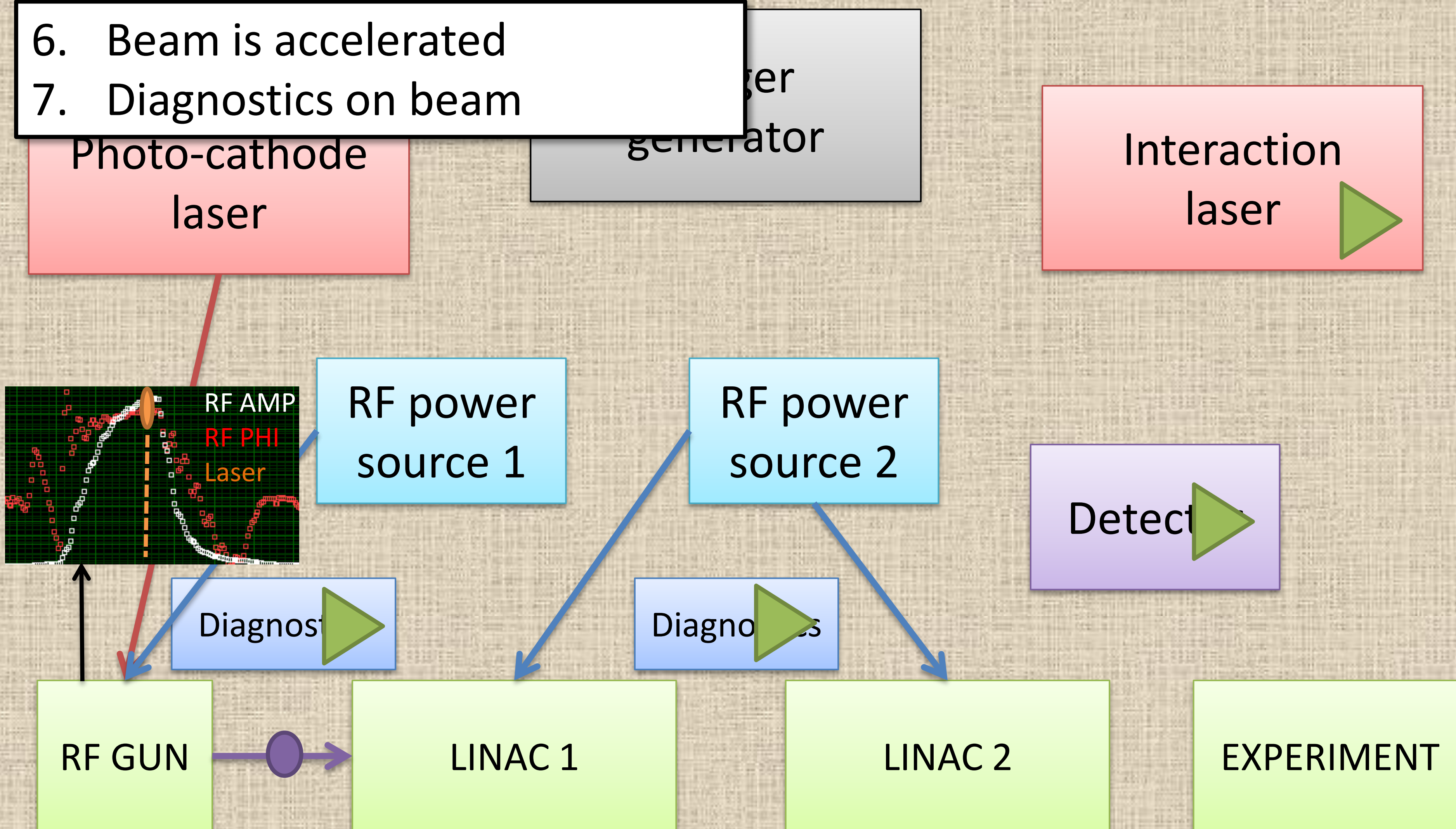


Timing example – Typical event sequence



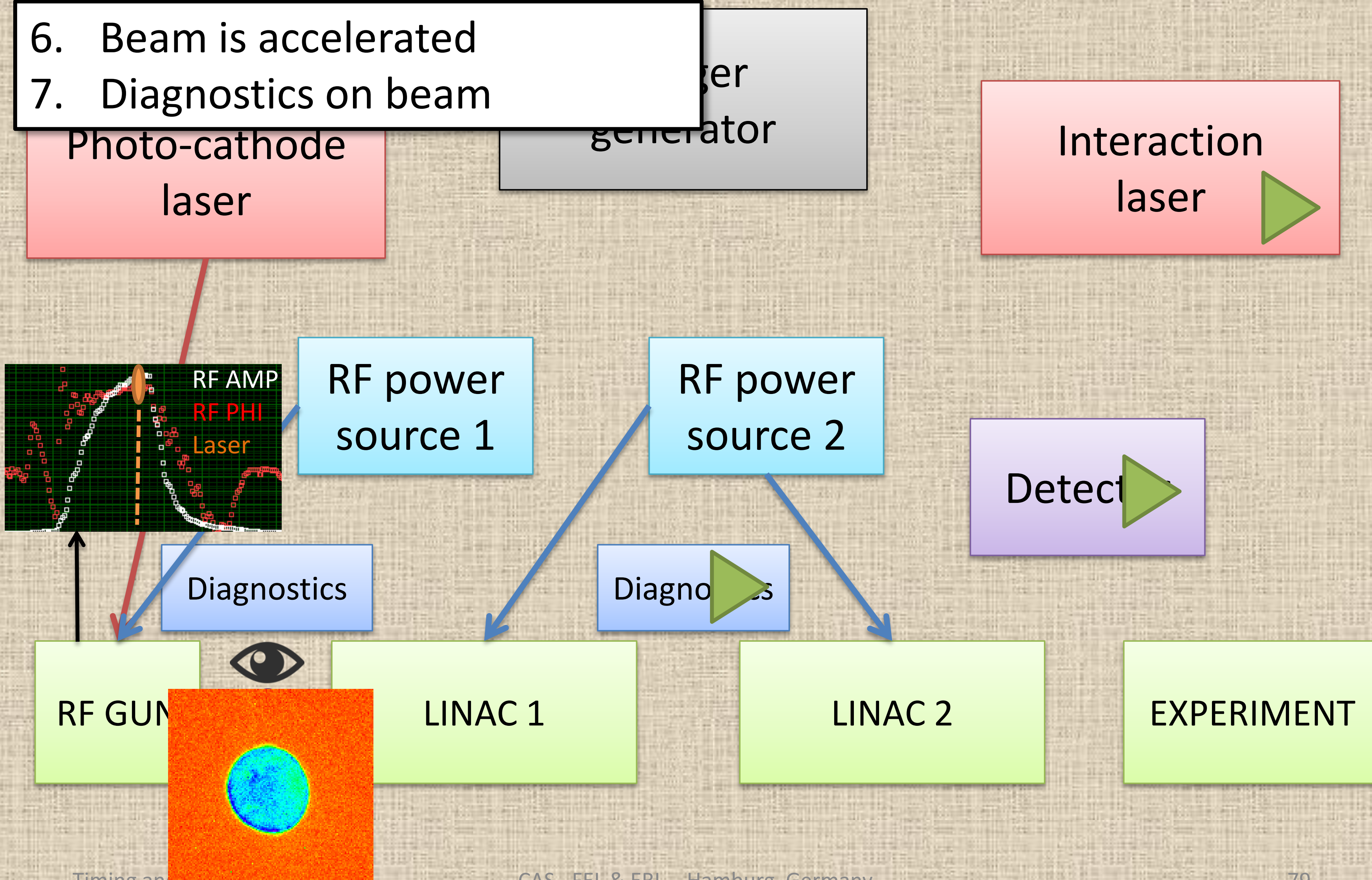
Timing example – Typical event sequence

6. Beam is accelerated
7. Diagnostics on beam



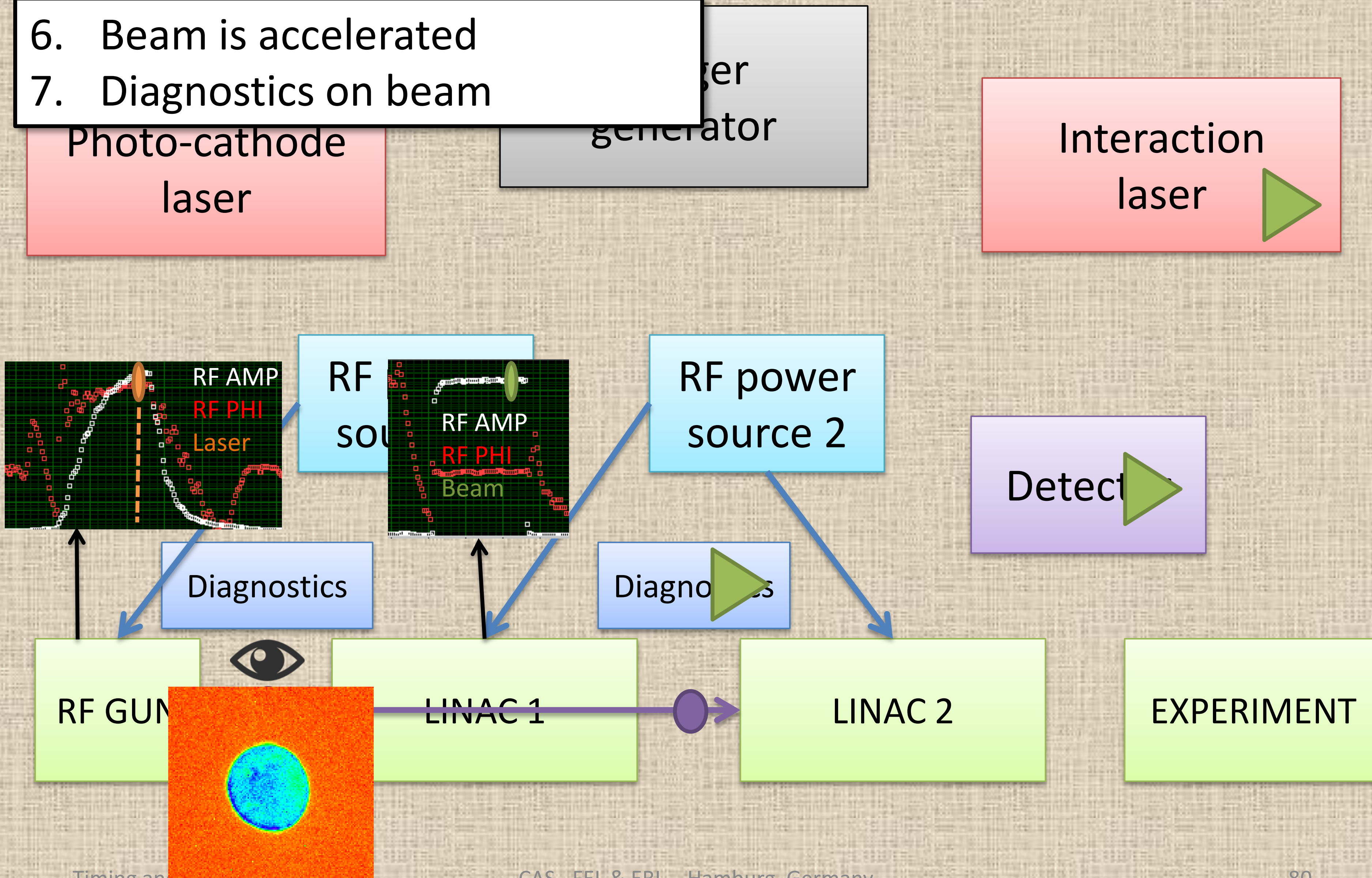
Timing example – Typical event sequence

6. Beam is accelerated
7. Diagnostics on beam



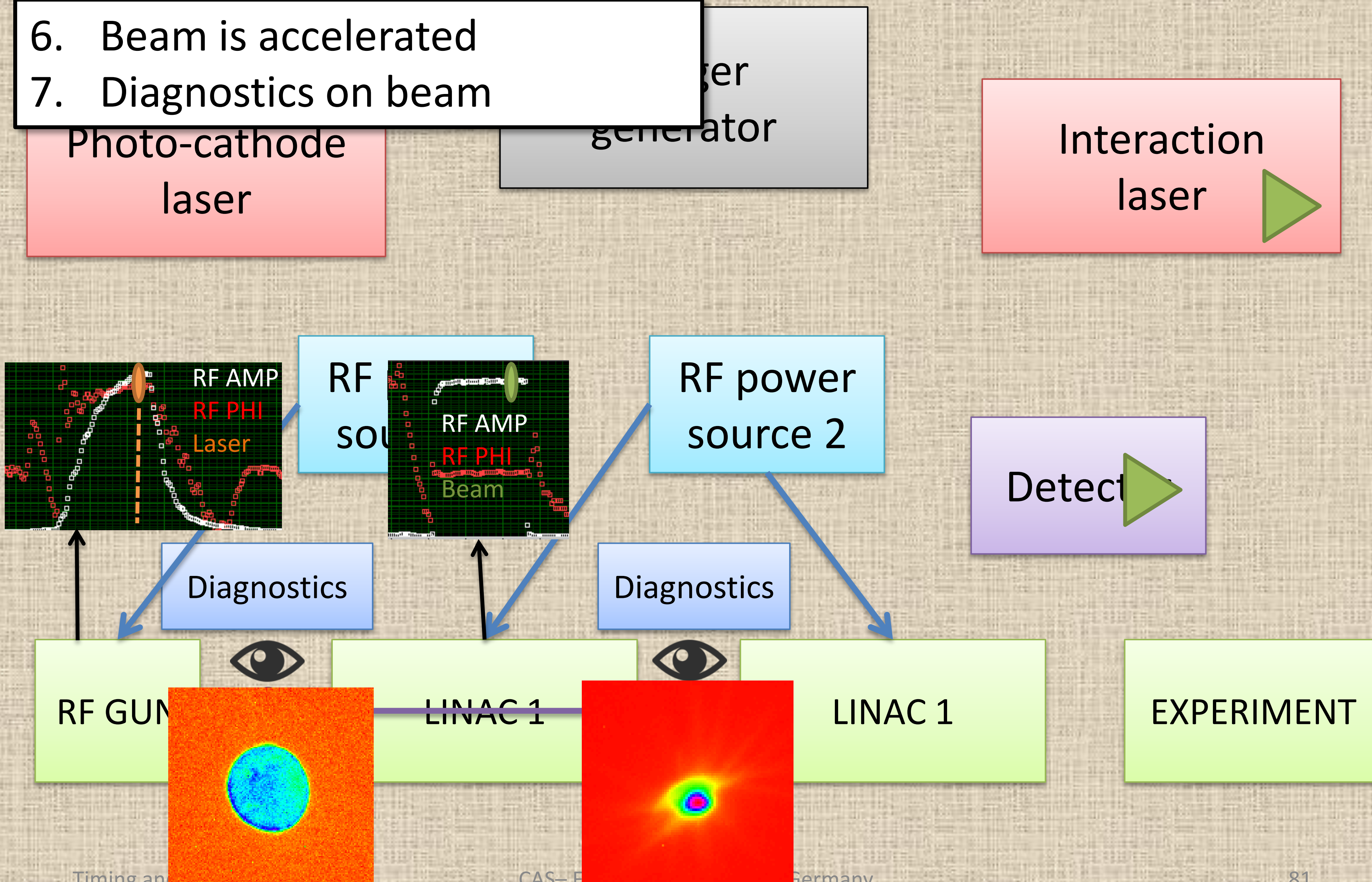
Timing example – Typical event sequence

6. Beam is accelerated
7. Diagnostics on beam

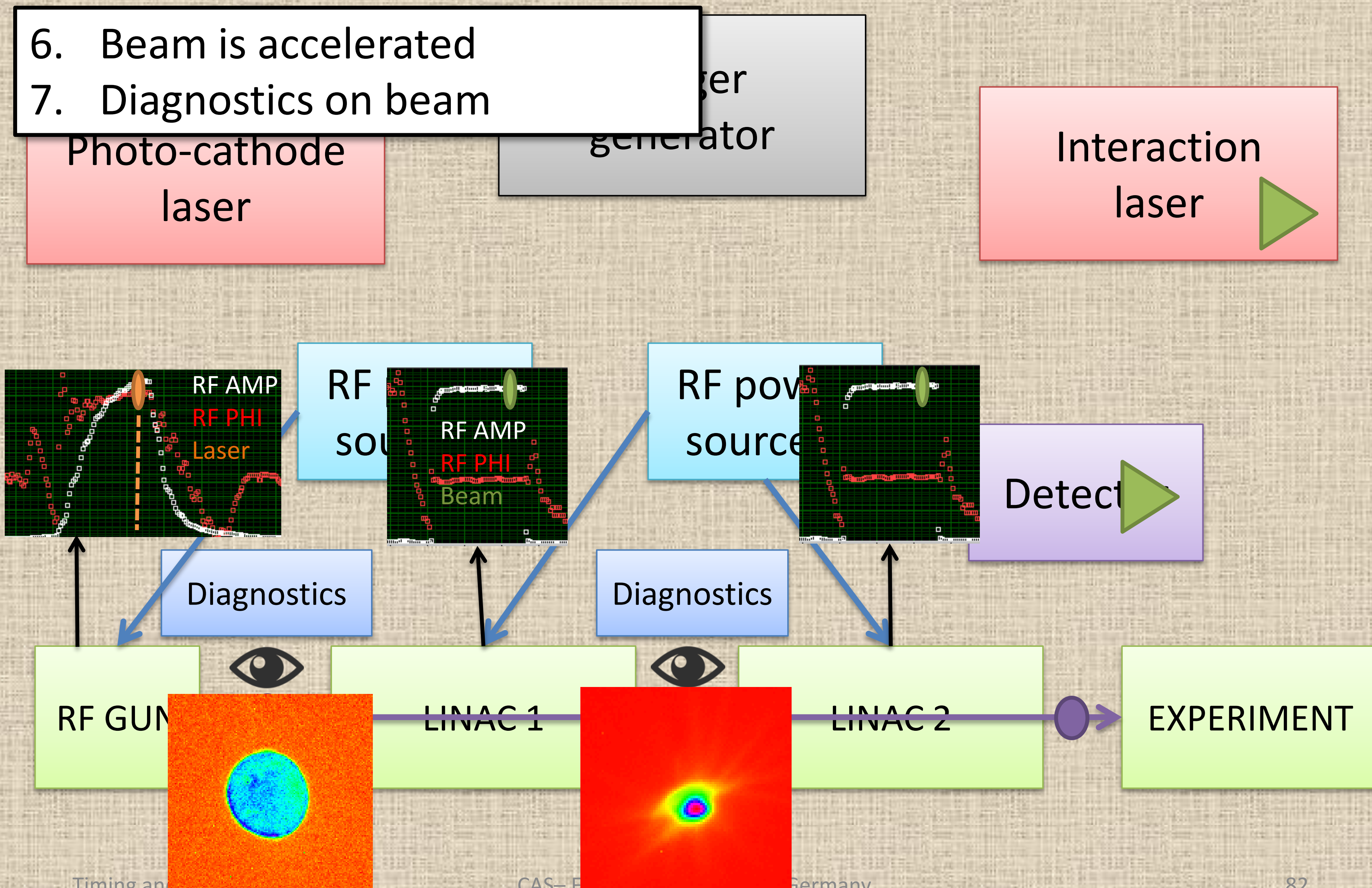


Timing example – Typical event sequence

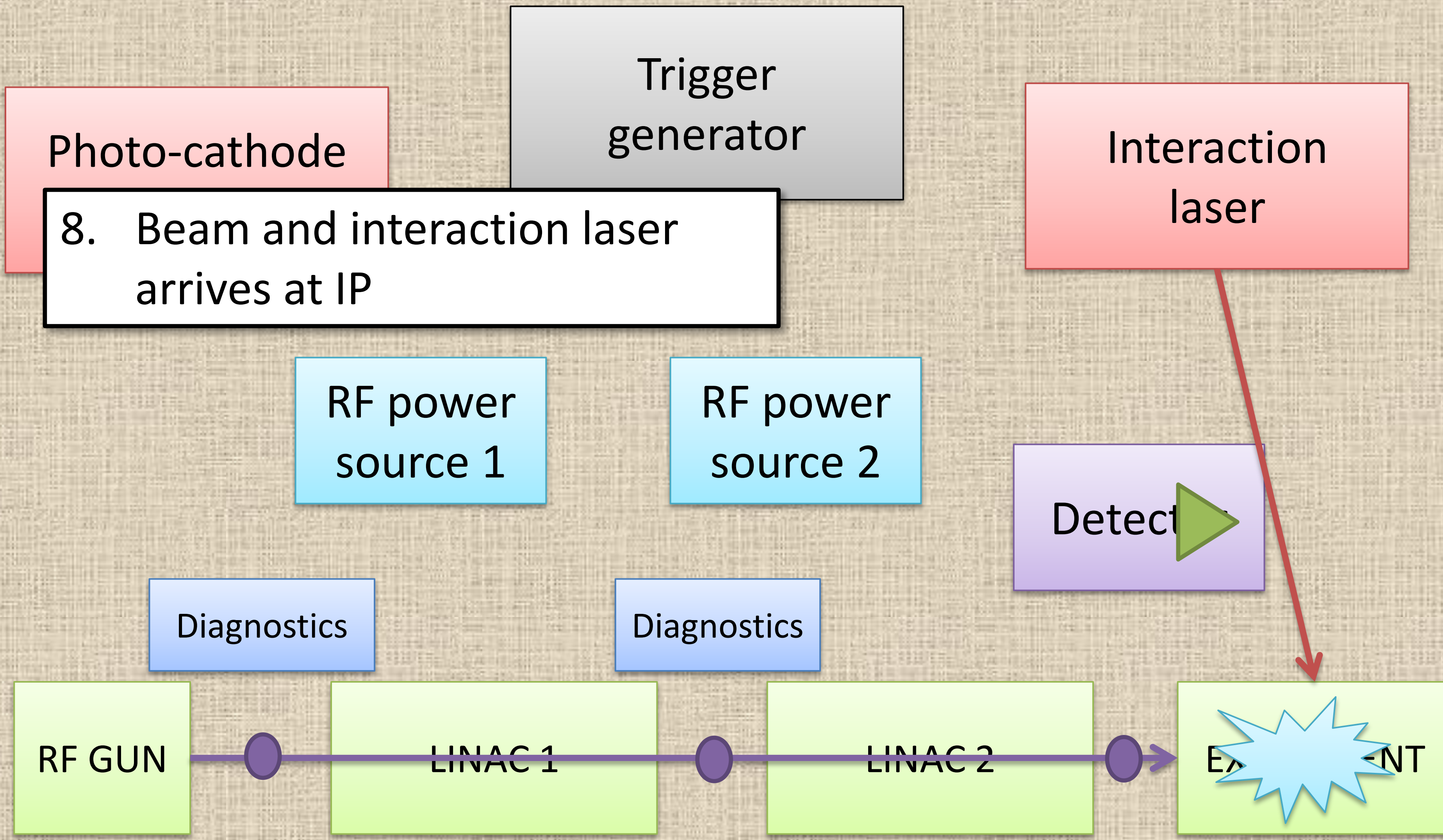
6. Beam is accelerated
7. Diagnostics on beam



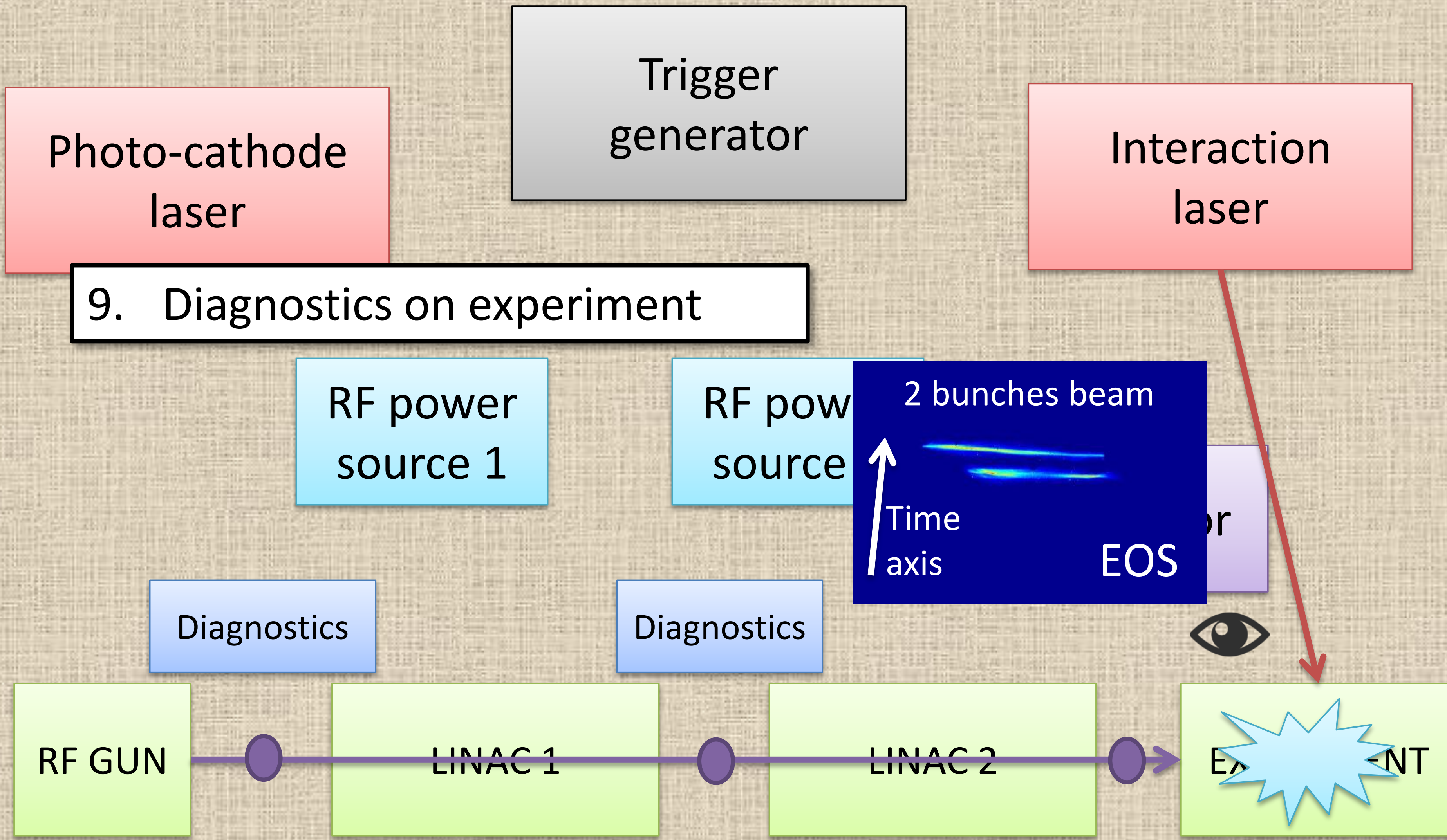
Timing example – Typical event sequence



Timing example – Typical event sequence



Timing example – Typical event sequence



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