Timing and Synchronization

A. Gallo

Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati
via Enrico Fermi 40 - 00044 Frascati(RM) - Italy

INFN Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati

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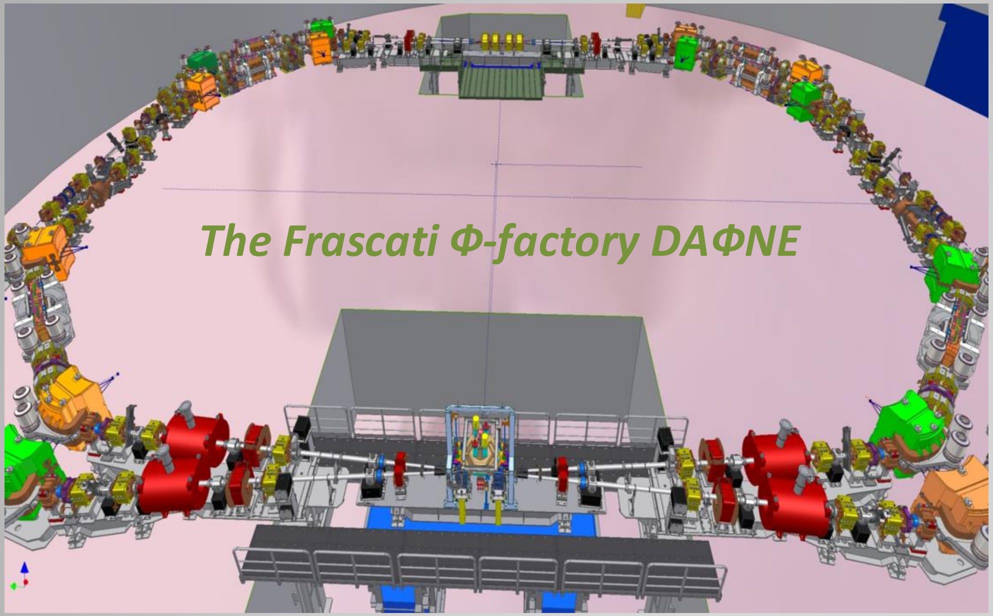
Lecture Outline

- **MOTIVATIONS**
  - ✓ Why accelerators need synchronization, and at what precision level
- **DEFINITIONS AND BASICS**
  - ✓ Synchronization, Synchronization vs. Timing, Drift vs. Jitter, Master Oscillator
  - ✓ Fourier and Laplace Transforms, Random processes, Phase noise in Oscillators
  - ✓ Phase detectors, Phase Locked Loops
- **SYNCRONIZATION ARCHITECTURE AND PERFORMANCES**
  - ✓ Phase lock of synchronization clients (RF systems, Lasers, Diagnostics, ...)
  - ✓ Residual absolute and relative phase jitter
  - ✓ Reference distribution – actively stabilized links
- **BEAM ARRIVAL TIME FLUCTUATIONS**
  - ✓ Beam synchronization
  - ✓ Bunch arrival time measurement techniques
- **CONCLUSIONS**

MOTIVATIONS: FLAT BEAM COLLIDERS

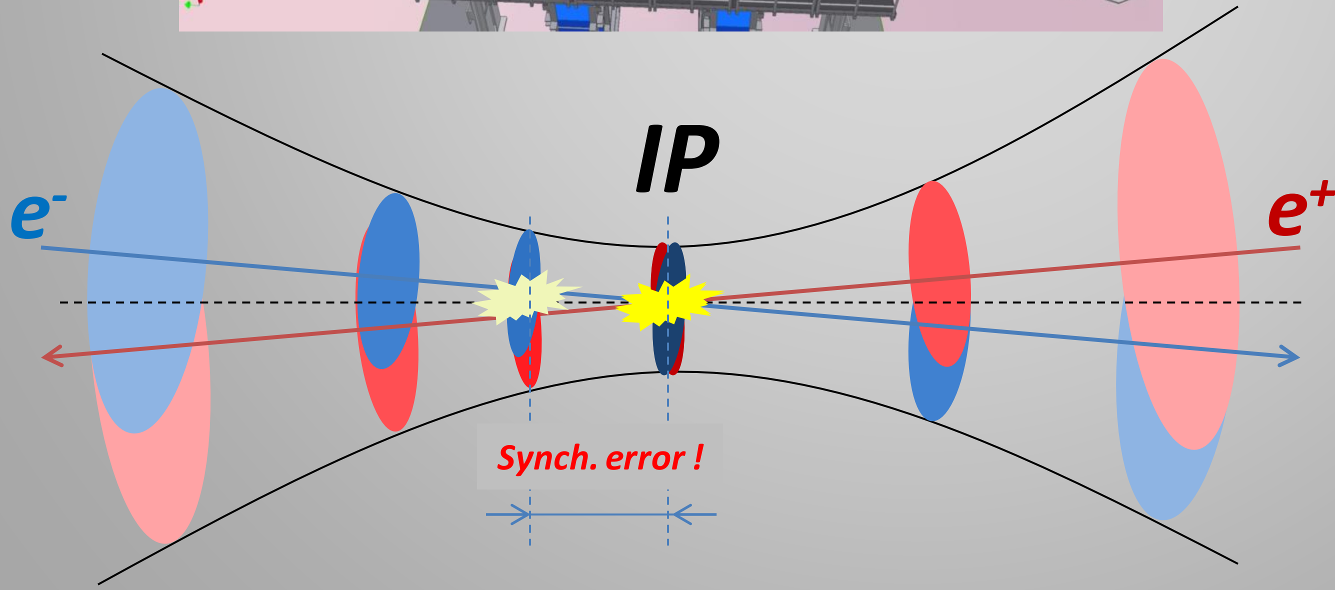


Bunches of the 2 colliding beams need to ***arrive*** at the ***Interaction Point*** (max vertical focalization) at the same time.

Waist length $\approx \beta_y \approx \sigma_z$ *(hourglass effect)*

Synchronization requirement:

$$\Delta t \ll \sigma_{t\,bunch} = \frac{1}{c} \cdot \sigma_{z\,bunch}$$



CIRCULAR COLLIDERS:

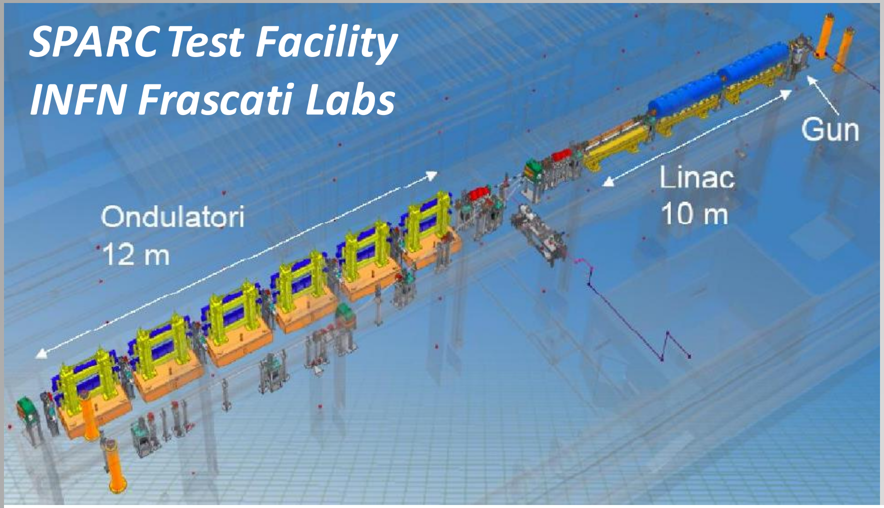
$\sigma_z \approx 1\,cm \rightarrow \Delta t < 10\,ps$

LINEAR COLLIDER (ILC):

$\sigma_z < 1\,mm \rightarrow \Delta t < 1\,ps$

RF Stability spec

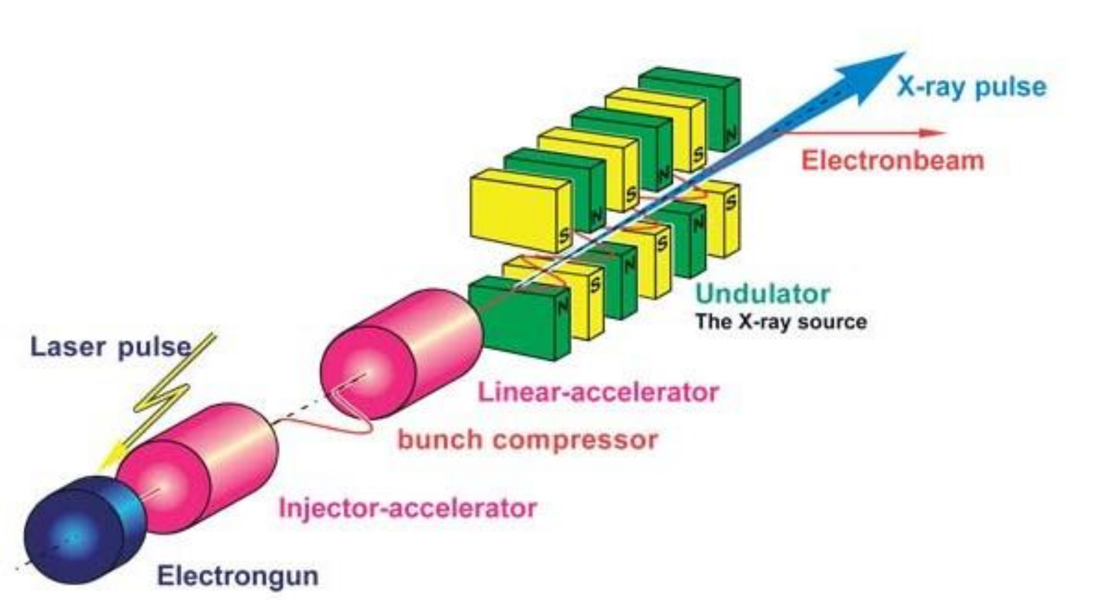
MOTIVATIONS: SASE FELs



Free Electro Laser machines had a crucial role in pushing the accelerator synchronization requirements and techniques to a new frontier in the last ≈15 years.

The simplest FEL regime, the ***SASE*** (***Self-Amplified Spontaneous Emission)***, requires high-brightness bunches, being:

$$B \div \frac{I_{bunch}}{\epsilon_{\perp}^{2}}$$



Large peak currents I_{bunch} are typically obtained by ***short laser pulses*** illuminating a ***photo-cathode*** embedded in an RF Gun accelerating structure, and furtherly increased with ***bunch compression*** techniques.

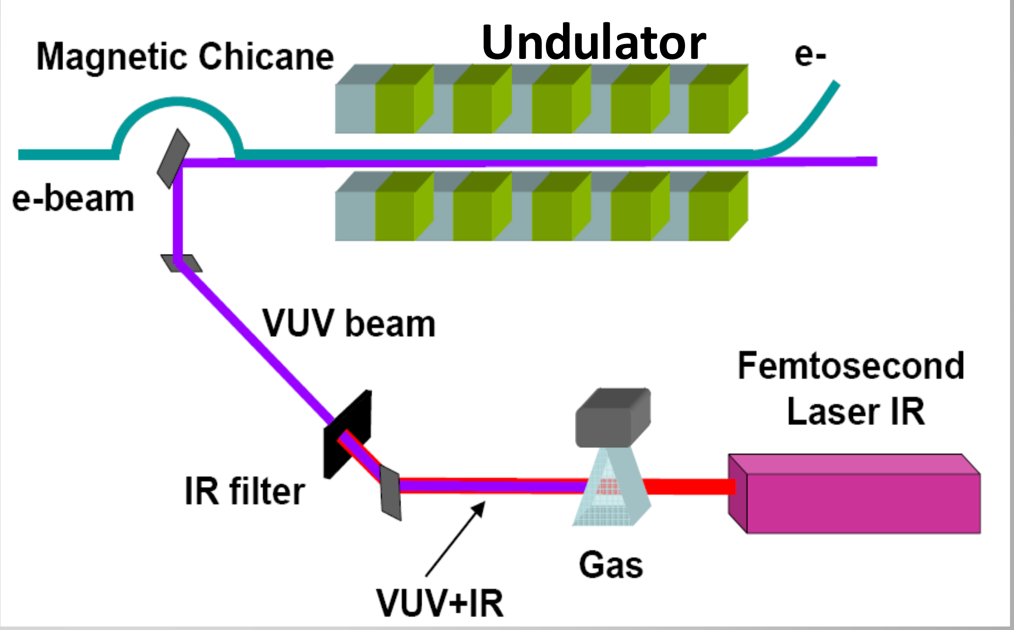
Small transverse emittances $\epsilon_{\perp}$ can be obtained with ***tight control*** of the global machine WP, including amplitude and phase of the RF fields, magnetic focusing, laser arrival time, …

Global Synchronization requirements: < 500 fs rms

MOTIVATIONS: Seeded FELs

In a simple SASE configuration the ***micro-bunching process***, which is the base of the FEL radiation production, starts from ***noise***. Characteristics such as radiation intensity and envelope profile can vary considerably from shot to shot.

A better control of the radiation properties resulting in more ***uniform*** and ***reproducible*** shot to shot pulse characteristics can be achieved in the "***seeded***" FEL configuration.



To "trigger" and guide the avalanche process generating the exponentially-growing radiation intensity, the ***high brightness bunch*** is made to interact with a ***VUV*** short and intense ***pulse*** obtained by HHG (High Harmonic Generation) in gas driven by an IR pulse generated by a dedicated high power laser system (typically TiSa). The presence of the external radiation since the beginning of the micro-bunching process inside the magnetic undulators seeds and drives the FEL radiation growth in a steady, repeatable configuration. The ***electron bunch*** and the ***VUV pulse***, both ***very short***, must constantly ***overlap*** in ***space*** and ***time*** shot to shot.

Synchronization requirements (e- bunch vs TiSa IR pulse): < 100 fs rms

MOTIVATIONS: Pump-probe with FELs

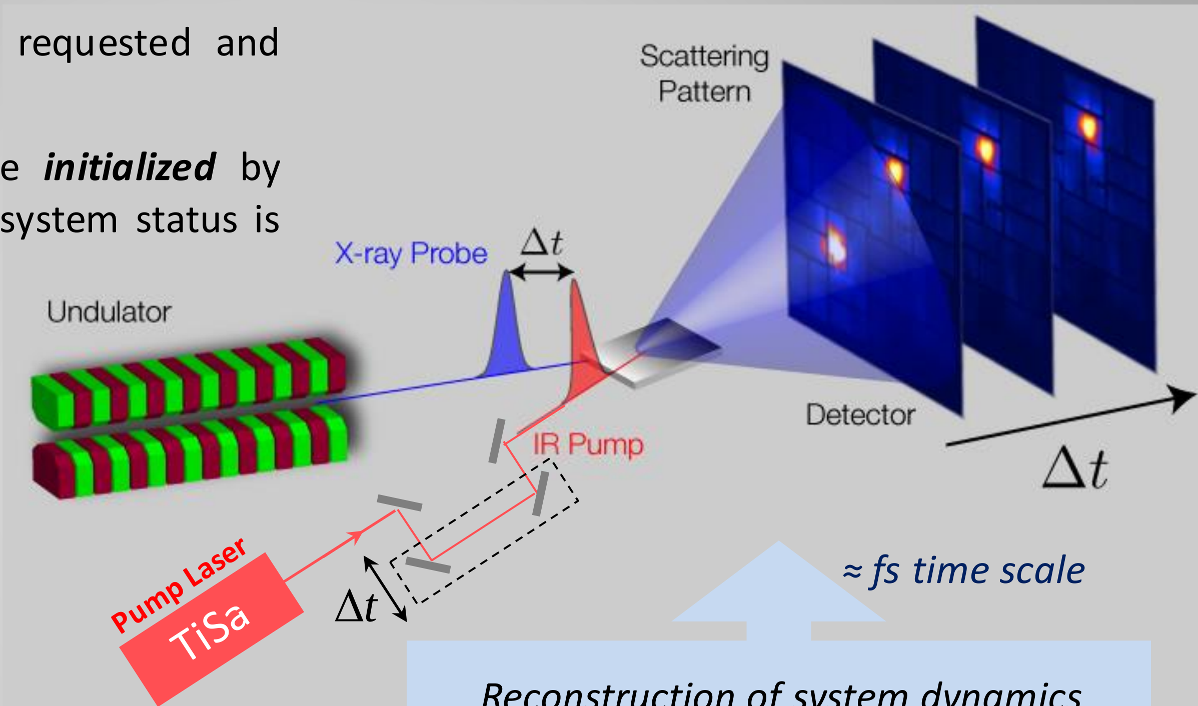
Pump-probe technique is widely requested and applied by user experimentalists.

Physical / chemical processes are ***initialized*** by ultra-short ***laser pulses***, then the system status is ***probed*** by ***FEL radiation***.

The dynamics of the process under study is captured and stored in a "snapshots" record.

Pump laser and FEL pulses need to be ***synchronized*** at level of the ***time-resolution*** required by the experiments (down to ≈ ***10 fs***).

The relative delay between pump and probe pulses needs to be finely and precisely scanned with proper time-resolution.



≈ fs time scale

Reconstruction of system dynamics

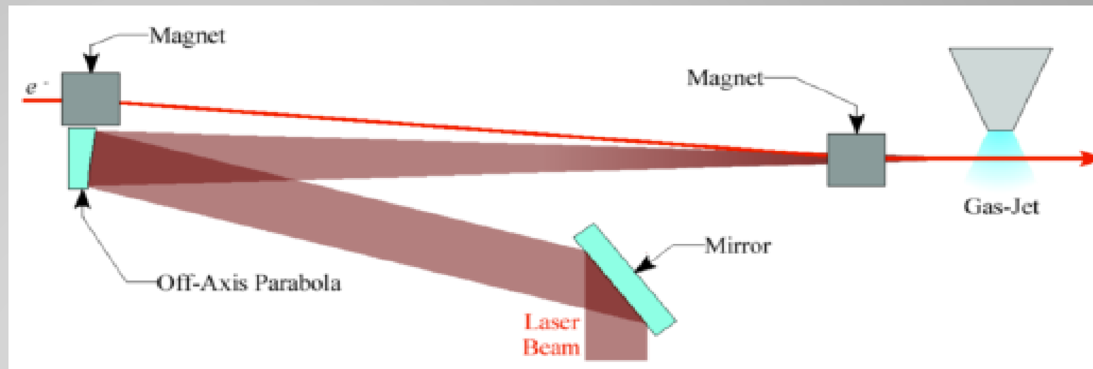
≈ ms time scale

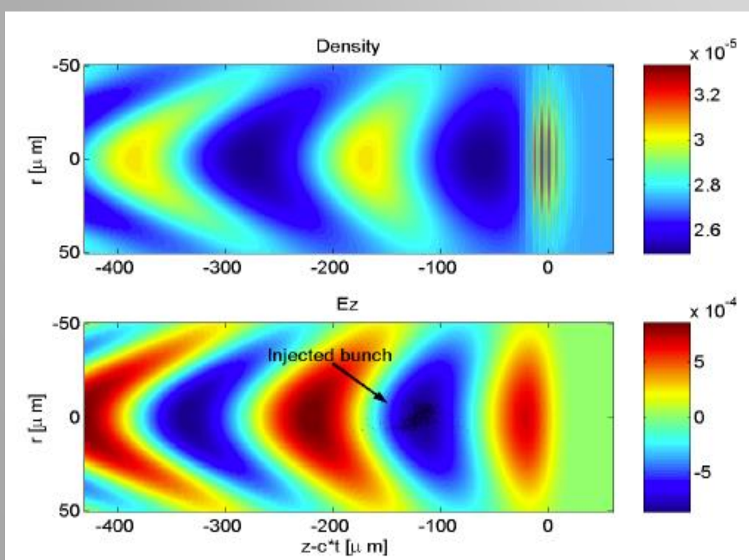
Synchronization requirements (FEL vs Pump Laser pulses): ≈ 10 fs rms

MOTIVATIONS: WLPA of injected bunches

Plasma acceleration is the new frontier in accelerator physics, to overcome the gradient limits of the RF technology in the way to compact, high energy machines.

Wakefield Laser-Plasma Acceleration (WLPA) is a technique using an extremely intense laser pulse on a gas jet to generate a plasma wave with large accelerating gradients (many GV/m).





To produce good quality beams external bunches have to be injected in the plasma wave. The "accelerating buckets" in the plasma wave are typically few 100 μm long.

The injected bunches have to be very short to limit the energy spread after acceleration, and ideally need to be injected constantly in the same position of the plasma wave to avoid shot-to-shot energy fluctuations.

This requires synchronization at the level of a small fraction of the plasma wave period.

Synchronization requirements (external bunch vs laser pulse): < 10 fs rms

MOTIVATIONS: SUMMARY

Application	Timescale	Requirement
Circular colliders	*10 ps*	*Low-level RF, beam FBKs, …*
Future Linear colliders	*1 ps*	*LLRF systems, beam FBKs, …*
SASE FELs / **Compton sources**		*Photocathode (PC) laser, LLRF, …* / *+ Interaction laser*
Seeded FELs	*100 fs*	*Seeding and PC lasers, LLRF, …*
FELs Pump-Probe	*10 fs*	*FEL (*), Pump laser, …*
WLPA External injection		*Injected beam (#), Power laser, …*
	1 fs	
Upcoming …	*sub fs*	**…**

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

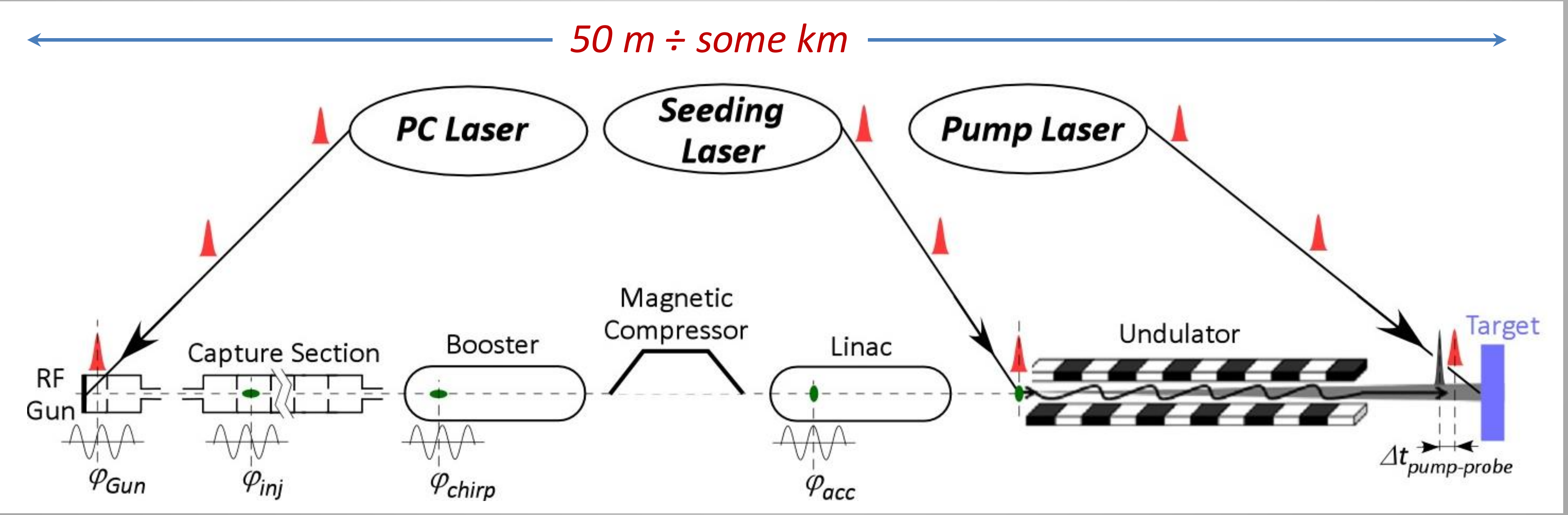
DEFINITIONS

DEFINITIONS: Synchronization

According to the previous examples, the synchronization of a facility based on a particle accelerator is a ***time domain concept***.

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, ...).

It turns out that a ***necessary condition*** for an efficient and reproducible event production is the ***relative temporal alignment*** (i.e. the ***synchronization***) of ***all the accelerator sub-systems*** impacting the beam longitudinal phase-space and time-of-arrival (such as RF fields, PC laser system, ...), and of the ***beam bunches*** with ***any other system they have to interact with*** during and after the acceleration (such as seeding lasers, pump lasers, interaction lasers, ...).



DEFINITIONS: Timing vs. Synchronization

In general the sub systems of an accelerator based facility need temporal alignments over different time scales:

A. A fine temporal alignment, down to the fs scale, among all the relevant sub-systems presenting fundamental time structures in their internal mechanisms and in their physical outputs (main topic discussed so far).

Synchronization

B. A set of digital signals – triggers - with proper relative delays to start (or enable, gate, etc. …) a number of processes such as: firing injection/extraction kickers, RF pulse forming, switch on RF klystron HV, open/close Pockels cells in laser system, start acquisition in digitizer boards, start image acquisition with gated cameras, … Time resolution and stability of the trigger signals is way more relaxed (< 1 ns often sufficient, ≈10 ps more than adequate)

Timing

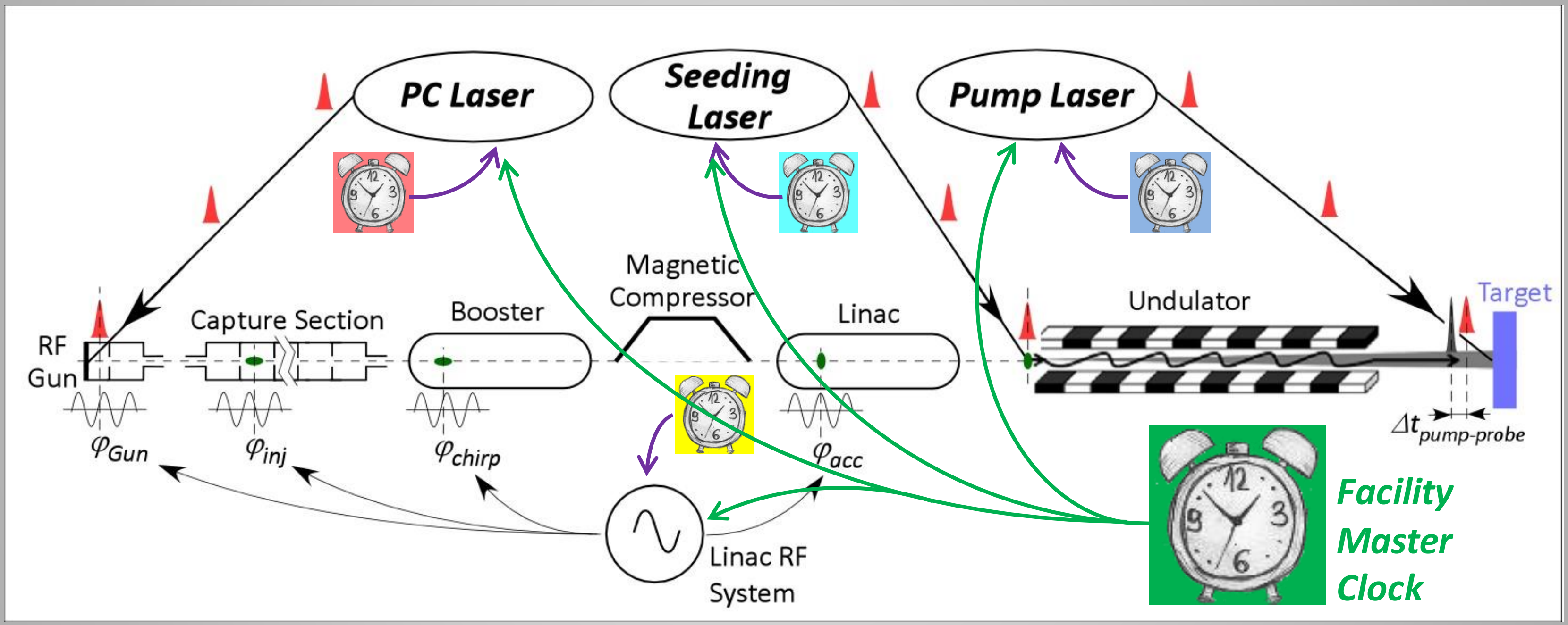
The task A is accomplished by the machine "***Synchronization system***". It deals with ***transporting*** the ***reference signal*** all over the facility with constant delay and ***minimal drifts***, and ***locking*** all the ***clients*** (i.e. the relevant sub-systems) to it with the ***lowest residual jitter***. The object of the present lecture is the introduction to this kind of systems.

The task B is accomplished by the machine "***Timing system***" or "***Trigger managing system***". Although this is an interesting topic impacting the machine performances, it will not be covered in this lecture.

However, sometimes the words "Timing" and "Synchronization" are taken as synonyms, or used together - "Timing and Synchronization" – to indicate activities related to task A.

DEFINITIONS: Master Clock

Naive approach: can each sub-system be synchronized to a local high-stability clock to have a global good synchronization of the whole facility ?



Best optical clocks → $\Delta\omega/\omega \approx 10^{-18}$ → $\Delta T/T \approx 10^{-18}$ → $T \approx 10\ fs/10^{-18} \approx$ ***3 hours !!!***

It is impossible to preserve a tight phase relation over long time scales even with the state-of-the-art technology.

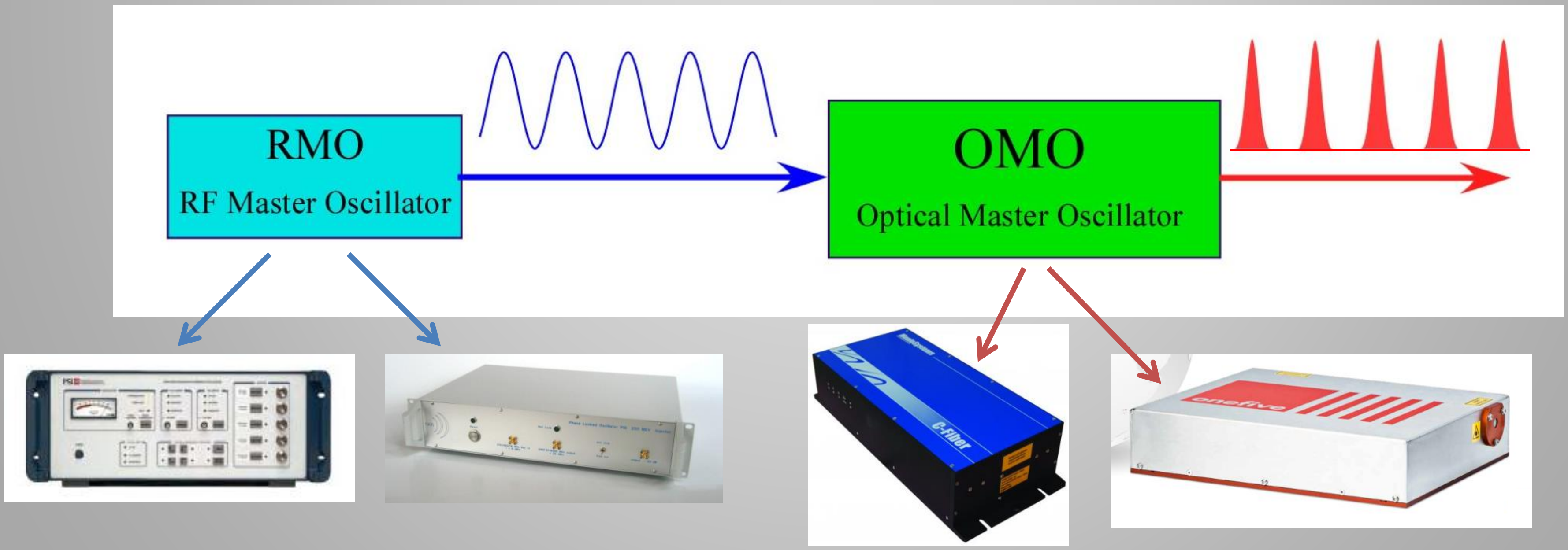
All sub-systems need to be ***continuously re-synchronized*** by a ***common master clock*** that has to be distributed to the all "clients" spread over the facility with a star network architecture.

DEFINITIONS: Master Oscillator

The ***Master Oscillator*** of a facility based on particle accelerators is typically a ***good***(*), ***low phase noise*** µ-wave generator acting as timing reference for the machine sub-systems. It is often indicated as the ***RMO*** (***RF Master Oscillator***).

The timing reference signal can be distributed straightforwardly as a pure sine-wave voltage through coaxial cables, or firstly encoded in the repetition rate of a pulsed laser (or sometimes in the amplitude modulation of a CW laser), and then distributed through optical-fiber links.

Optical fibers provide ***less signal attenuation*** and ***larger bandwidths***, so optical technology is definitely preferred for synchronization reference distribution, at least for large facilities.



(*) the role of the phase purity of the reference will be discussed later

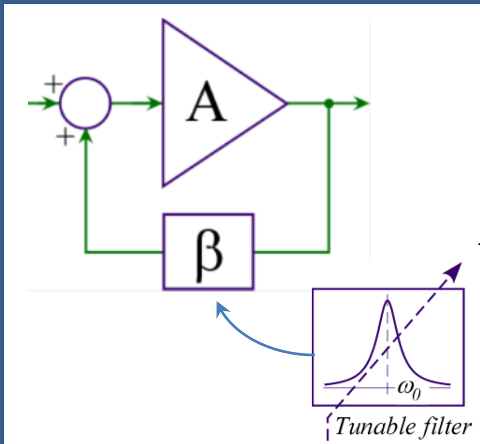
RF Reference (Master) Oscillators

RF

RF reference oscillator are typically based on positive-feedback network.

Barkhausen Criterion:

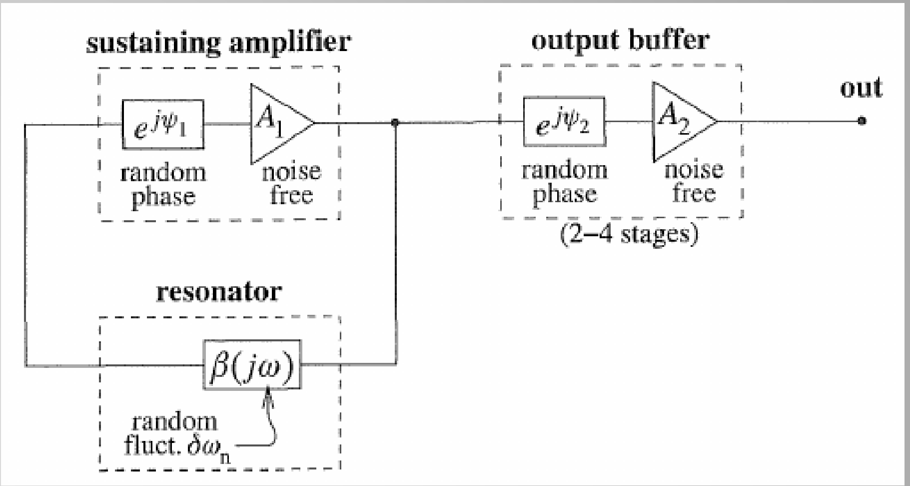
Systems breaks into oscillations at frequencies where the loop gain $H = A\beta$ is such that:

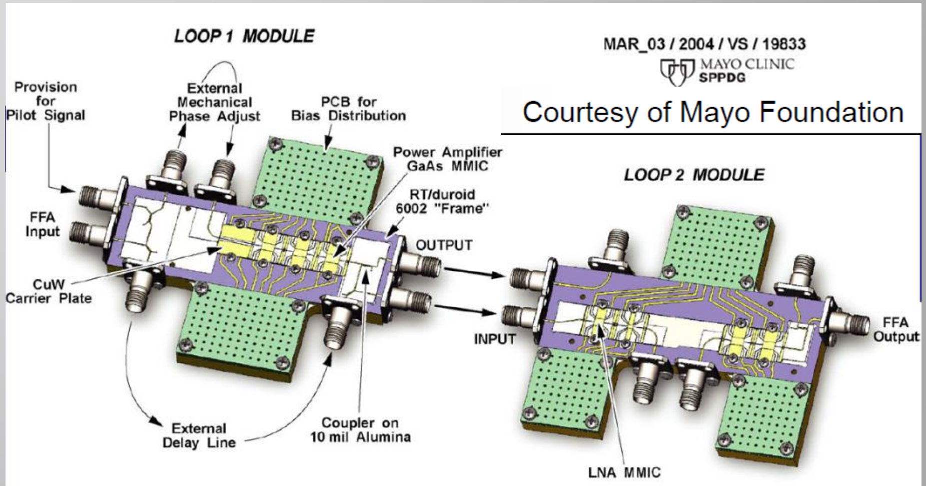


$$|H(j\omega)| = 1;$$

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

Noise present at various stages (sustaining and output amplifiers, frequency selection filter, ...) needs to be minimized by proper choice of components, layout, shielding, etc. ... Good RF oscillators may exhibit low phase noise density in the lower side of the spectrum (*f*< *1kHz*).





D. A. Howe and A. Hati

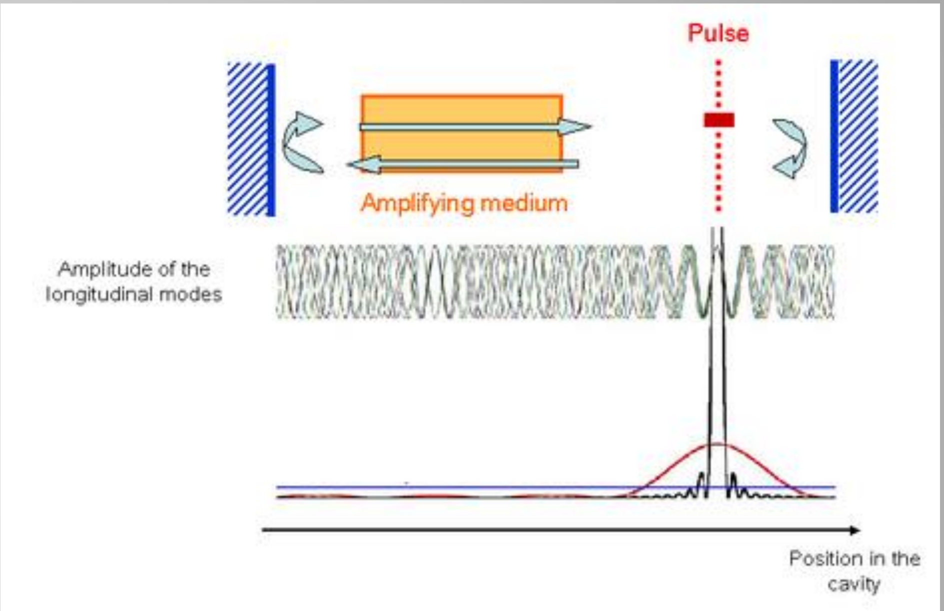
National Institute of Standards & Technology (NIST), Boulder, CO, USA

Optical Master Oscillators

A. Gallo, Timing and Synchronization, Warsaw (PL), Sept. 27 – Oct. 9 2015

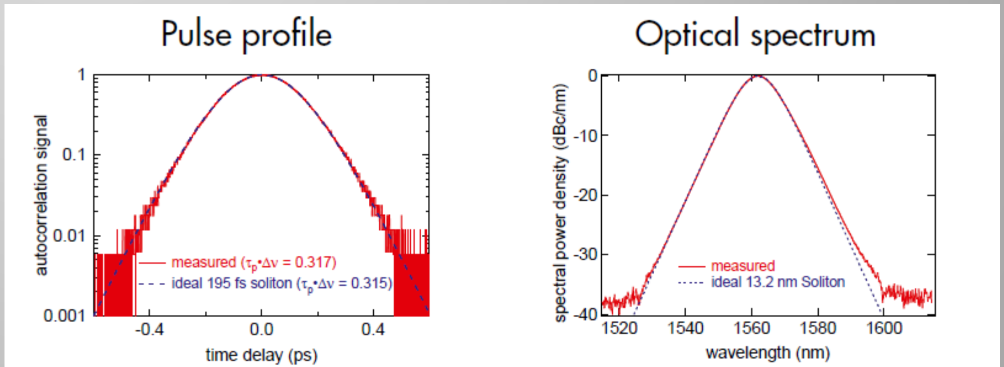
Optical: mode-locked lasers

A ***mode-locked laser*** consists in an ***optical cavity*** hosting an active (amplifying) medium capable of sustaining ***a large number of longitudinal modes*** with frequencies $\nu_k = k\nu_0 = kc/L$ within the bandwidth of the active medium, being L the cavity round trip length and k integer. If the modes are forced to ***oscillate in phase*** and the medium emission BW is wide, and a ***very short pulse*** (≈100 fs) travels forth and back in the cavity and a sample is coupled out through a leaking mirror.



Origami onefive

Laser specifications	Origami - 05	Origami - 08	Origami - 10	Origami - 15
Center wavelength	**513 – 535 nm**	**765 – 785 nm**	**1025 – 1070 nm**	**1530 – 1586 nm**
Pulse Duration[1,2]	<100 – 230 fs	<60 – 200 fs	<70 – 400 fs	<80 – 500 fs
Avg. output power (up to)[2]	100 mW	30 mW	250 mW	120 mW
Pulse energy (up to)[2]	1.2 nJ	0.7 nJ	5 nJ	2 nJ
Peak power (up to)[2]	10 kW	4.5 kW	30 kW	15 kW
Pulse repetition rate[2]	20 MHz – 1.3 GHz			
Spectral bandwidth	transform-limited ($\tau_p \cdot \Delta\nu \sim 0.32$)			
Beam quality	$M^2 < 1.1$, TEM_{00}			
PER	> 23 dB			
Amplitude noise (24 h)	< 0.2% rms, < 0.5% pk-pk			
Center wavelength drift	< 0.1 nm pk-pk			
Laser output	collimated free space (fiber output optional)			



http://www.onefive.com/ds/Datasheet%20Origami%20LP.pdf

DEFINITIONS: Jitter vs. Drift

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.

Jitter = fast variations, caused by inherent residual lack of coherency between oscillators, even if they are locked at the best;

Drift = slow variations, mainly caused by modifications of the environment conditions, such as temperature (primarily) but also humidity, materials and components aging, …

The boundary between the 2 categories is somehow arbitrary. For instance, synchronization errors due to mechanical vibrations can be classified in either category:

Acoustic waves → Jitter

Infrasounds → Drift

For pulsed accelerators, where the beam is produced in the form of a sequence of bunch trains with a certain repetition rate (10 Hz ÷ 120 Hz typically), the ***rep. rate value*** itself can be taken as a reasonable definition of the ***boundary*** between ***jitters*** and ***drifts***.

In this respect, ***drifts*** are phenomena significantly ***slower*** than ***rep. rate*** and will produced effects on the beam that can be ***monitored*** and ***corrected*** pulse-to-pulse.
On the contrary, ***jitters*** are ***faster*** than ***rep. rate*** and will result in a pulse-to-pulse ***chaotic scatter*** of the beam characteristics that has to be minimized but that ***can not*** be actively ***corrected***.

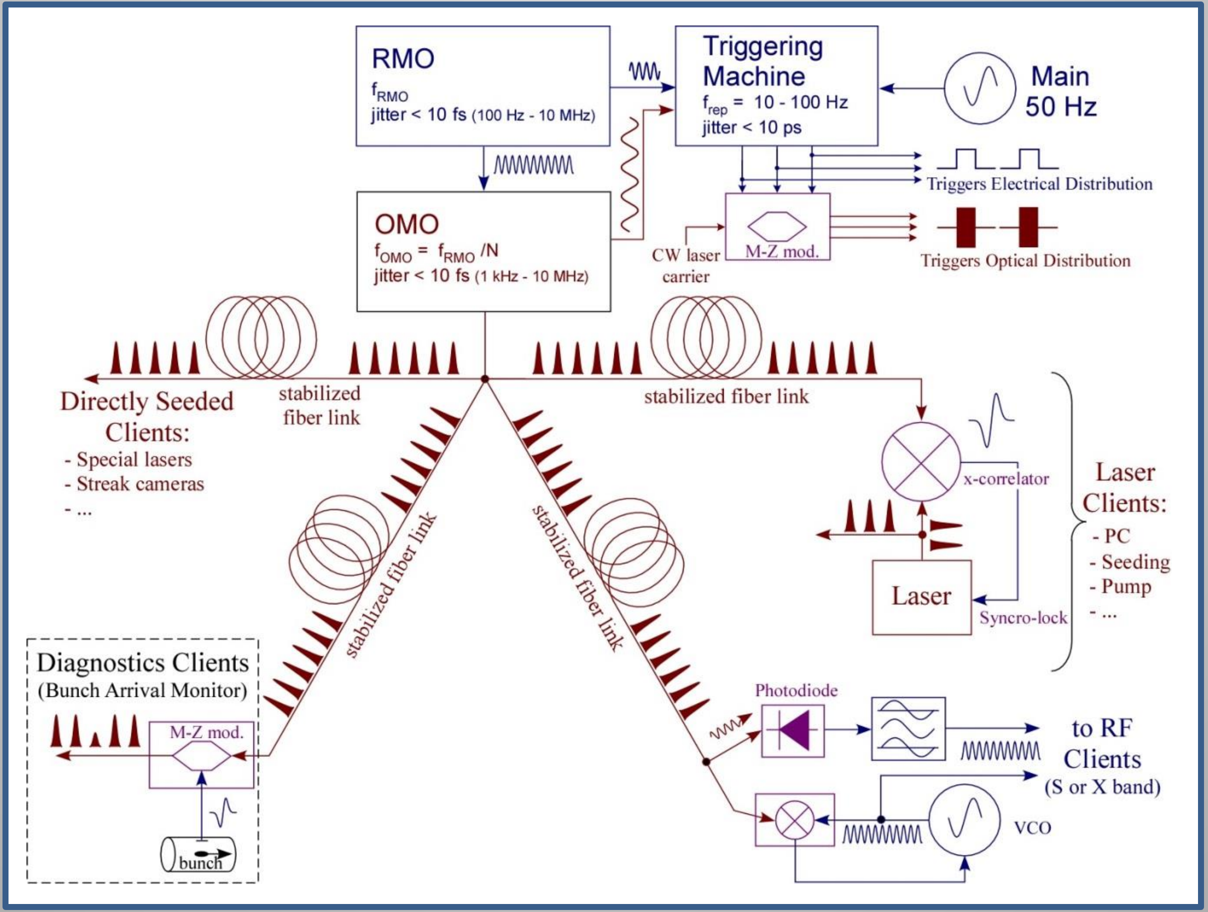
Drift → Nasty

Jitter → Killer

DEFINITIONS: Synchronization System Tasks

Tasks of a Synchronization system:

- ✓ Generate and transport the reference signal to any client local position with constant delay and minimal drifts;
- ✓ Lock the client (laser, RF, ...) fundamental frequency to the reference with minimal residual jitter;
- ✓ Monitor clients and beam, and apply delay corrections to compensate residual drifts.



BASICS

- ***Fourier and Laplace Transforms***
- ***Random Processes***
- ***Phase Noise in Oscillators***

BASICS: Fourier and Laplace Transforms

Transforms summary

Transforms	Fourier - $\mathscr{F}$	Laplace - $\mathscr{L}$
Definition	$X(j\omega) = \int_{-\infty}^{+\infty} x(t)\, e^{-j\omega t}\, dt$	$X(s) = \int_{0}^{+\infty} x(t)\, e^{-st}\, dt$
Inverse transform	$x(t) = \frac{1}{2\pi} \int_{-\infty}^{+\infty} X(j\omega)\, e^{j\omega t}\, dt$	$x(t) = \frac{1}{2\pi i} \int_{\gamma - j\cdot\infty}^{\gamma + j\cdot\infty} X(s)\, e^{st}\, dt$
Transformability conditions	$\int_{-\infty}^{+\infty} \lvert x(t)\rvert^2\, dt \neq \infty$	$x(t) = 0 \text{ if t} < 0;\ x(t) \cdot e^{-\sigma t} \xrightarrow[t \to +\infty]{} 0$
Linearity	$\mathscr{F}[a\, x(t) + b\, y(t)] =$ $= a\, X(\omega) + b\, Y(\omega)$	$\mathscr{L}[a\, x(t) + b\, y(t)] =$ $= a\, X(s) + b\, Y(s)$
Convolution product	$(x * y)(t) \stackrel{\text{def}}{=} \int_{-\infty}^{+\infty} x(t+\tau) \cdot y(\tau) d\tau$ $\mathscr{F}[(x * y)(t)] = X^*(\omega) \cdot Y(\omega)$	$(x * y)(t) \stackrel{\text{def}}{=} \int_{0}^{t} x(t+\tau) \cdot y(\tau) d\tau$ $\mathscr{L}[(x * y)(t)] = X^*(s) \cdot Y(s)$
Derivative	$\mathscr{F}\left[\frac{dx}{dt}\right] = j\omega \cdot X(\omega)$	$\mathscr{L}\left[\frac{dx}{dt}\right] = s \cdot X(s)$

Random process summary

- Stationary process: statistical properties invariant for a t' time shift $x(t) \rightarrow x(t+t')$
- Ergodic process: statistical properties can be estimated by a single process realization
- Uncorrelation: if $x(t)$ and $y(t)$ are 2 random variables completely uncorrelated (statistically independent), then:

$$(x+y)^2_{rms} = x^2_{rms} + y^2_{rms} \quad and \quad \sigma^2_{x+y} = \sigma^2_x + \sigma^2_y \qquad with \quad \sigma^2_x \stackrel{\text{def}}{=} \overline{x^2} - \bar{x}^2$$

Power spectrum:

rms and standard deviation of a random variable $x(t)$ can be computed on the basis of its Fourier transform. Strictly speaking, a function of time $x(t)$ with $x_{rms} \neq 0$ cannot be Fourier transformed since it does not satisfy the transformability necessary condition.

$$\int_{-\infty}^{+\infty} |x(t)|^2 dt = A \neq \infty \quad \xrightarrow{\text{would imply}} \quad x^2_{rms} = \lim_{T \to \infty} \frac{1}{T} \int_{-T/2}^{+T/2} |x(t)|^2 dt = 0$$

If $x(t)$ represents a current or a voltage signal, it can be Fourier transformed provided that it carries a ***finite quantity of energy***. But we might be interested in treating random (noise) signals characterized by a ***non-zero average power*** ($x^2_{rms} \neq 0$) carrying an unlimited amount of energy.

Random process summary

However, for practical reasons, we are only interested in observations of the random variable $\mathrm{x}(t)$ for a ***finite time*** $\boldsymbol{\Delta T}$. So we may truncate the function outside the interval $[-\Delta T/2, \Delta T/2]$ and remove any possible limitation in the function transformability. We also assume $\mathrm{x}(t)$ real.

$$x_{\Delta T}(t) = \begin{cases} x(t) & -\Delta T/2 \le t \le \Delta T/2 \\ 0 & elsewhere \end{cases}$$

The truncated function $x_{\Delta T}(t)$ is Fourier transformable. Let $X_{\Delta T}(f)$ be its Fourier transform. We have:

$$x_{rms}^2 = \lim_{\Delta T \to \infty} x_{\Delta T rms}^2 = \lim_{\Delta T \to \infty} \frac{1}{\Delta T} \int_{-\infty}^{+\infty} x_{\Delta T}^2(t)\, dt = \lim_{\Delta T \to \infty} \frac{1}{\Delta T} \int_{-\infty}^{+\infty} |X_{\Delta T}(f)|^2\, df \overset{\mathrm{def}}{=} \int_0^{+\infty} S_x(f)\, df$$

Parseval's theorem

$$with \;\; S_x(f) \overset{\mathrm{def}}{=} \lim_{\Delta T \to \infty} 2 \cdot \frac{|X_{\Delta T}(f)|^2}{\Delta T}$$

The function $S_x(f)$ is called "***power spectrum***" or "***power spectral density***" of the random variable $x(t)$. The time duration of the variable observation ΔT sets the minimum frequency $f_{min} \approx 1/\Delta T$ containing meaningful information in the spectrum of $x_{\Delta T}(t)$.

BASICS: LTI Transfer Functions

Fourier and Laplace transforms are used to compute the response of ***Linear Time Invariant*** (***LTI***) systems:

time domain

$$\delta(t) \longrightarrow \boxed{\text{LTI system}} \longrightarrow h(t)$$

Green's function

$$v_i(t) \longrightarrow \boxed{\text{LTI system}} \longrightarrow v_i(t) * h(t)$$

Fourier transform

$$e^{j\omega t} \longrightarrow \boxed{\text{LTI system}} \longrightarrow H(j\omega)e^{j\omega t}$$

$$V_i(j\omega) \longrightarrow \boxed{\text{LTI system}} \longrightarrow V_i(j\omega) \cdot H(j\omega)$$

Laplace transform

$$e^{st} \longrightarrow \boxed{\text{LTI system}} \longrightarrow H(s)e^{st}$$

$$V_i(s) \longrightarrow \boxed{\text{LTI system}} \longrightarrow V_i(s) \cdot H(s)$$

LTI system Transfer functions

Noise power spectra

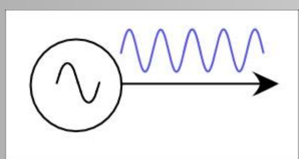
$$S_i(\omega) \longrightarrow \boxed{\text{LTI system}} \longrightarrow |H(j\omega)|^2 \cdot S_i(\omega)$$

BASICS: Phase Noise in Oscillators

The most important task of a Synchronization system is to ***lock firmly*** each ***client*** to the ***reference*** in order to minimize the residual jitter. In fact each client can be described as a local oscillator (electrical for RF systems, optical for laser systems) whose main frequency can be changed by applying a voltage to a control port.

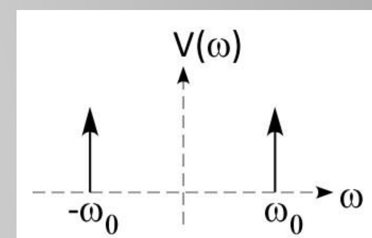
Before discussing the lock schematics and performances, it is worth introducing some ***basic concepts*** on ***phase noise*** in ***real oscillators***.

Ideal oscillator

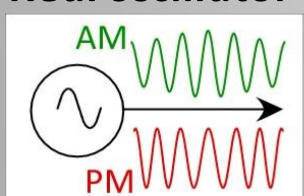


$$V(t) = V_0 \cdot cos(\omega_0 t + \varphi_0)$$

Ideal Spectrum

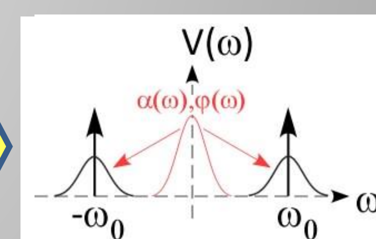


Real oscillator



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

Real Spectrum



In real oscillators the amplitude and phase will always fluctuate in time by a certain amount because of the unavoidable presence of noise. However, by common sense, a well behaving real oscillator has to satisfy the following conditions:

$$|\alpha(t)| \ll 1; \quad \left|\frac{d\varphi}{dt}\right| \ll \omega_0$$

BASICS: Phase Noise in Oscillators

A real oscillator signal can be also represented in ***Cartesian Coordinates*** $(\alpha, \varphi) \rightarrow (v_I, v_Q)$:

$$V(t) = V_0 \cdot cos(\omega_0 t) + v_I(t) \cdot cos(\omega_0 t) - v_Q(t) \cdot sin(\omega_0 t)$$

$$if\ v_I(t), v_Q(t) \ll V_0 \quad \Rightarrow \quad \alpha(t) = v_I(t)/V_0, \quad \varphi(t) = v_Q(t)/V_0$$

Real oscillator outputs are ***amplitude*** (***AM***) and ***phase*** (***PM***) ***modulated*** carrier signals. In general it turns out that ***close to the carrier*** frequency the contribution of the ***PM noise*** to the signal spectrum ***dominates*** the contribution of the ***AM noise***. For this reason the lecture will be focused on phase noise. However, amplitude noise in RF systems directly reflects in energy modulation of the bunches, that may cause bunch arrival time jitter when beam travels through dispersive and bended paths (i.e. when $R_{56} \neq 0$ as in magnetic chicanes).

Let's consider a real oscillator and neglect the AM component:

$$V(t) = V_0 \cdot cos[\omega_0 t + \varphi(t)] = V_0 \cdot cos\left[\omega_0 \left(t + \tau(t)\right)\right] \quad \text{with} \quad \tau(t) \equiv \varphi(t)/\omega_0$$

The statistical properties of $\varphi(t)$ and $\tau(t)$ qualify the oscillator, primarily the values of the standard deviations σ_φ and σ_τ (or equivalently φ_{rms} and τ_{rms} since we may assume a zero average value). As for every noise phenomena they can be computed through the ***phase noise power spectral density*** $S_\varphi(f)$ of the random variable $\varphi(t)$.

Again, for practical reasons, we are only interested in observations of the random variable $\varphi(t)$ for a finite time ΔT. So we may truncate the function outside the interval $[-\Delta T/2, \Delta T/2]$ to recover the function transformability.

$$\varphi_{\Delta T}(t) = \begin{cases} \varphi(t) & -\Delta T/2 \le t \le \Delta T/2 \\ 0 & elsewhere \end{cases}$$

Let $\Phi_{\Delta T}(f)$ be the Fourier transform of the truncated function $\varphi_{\Delta T}(t)$. We have:

$$\varphi^2_{\Delta T rms} = \frac{1}{\Delta T}\int_{-\infty}^{+\infty} \varphi^2_{\Delta T}(t)dt = \frac{1}{\Delta T}\int_{-\infty}^{+\infty} |\Phi_{\Delta T}(f)|^2 df = \int_{f_{min}}^{+\infty} S_\varphi(f)\,df \;\; with \;\; S_\varphi(f) \stackrel{\text{def}}{=} 2\frac{|\Phi_{\Delta T}(f)|^2}{\Delta T}$$

Again, the time duration of the variable observation ΔT sets the minimum frequency $f_{min} \approx 1/\Delta T$ containing meaningful information on the spectrum $\Phi_{\Delta T}(f)$ of the phase noise $\varphi_{\Delta T}(t)$.

IMPORTANT: we might still write

$$\varphi^2_{rms} = \lim_{\Delta T \to \infty} \varphi^2_{\Delta T rms} = \int_0^{+\infty} \left(2 \cdot \lim_{\Delta T \to \infty} \frac{|\Phi_{\Delta T}(f)|^2}{\Delta T}\right) df = \int_0^{+\infty} S_\varphi(f)\,df$$

but we must be aware that φ_{rms} in some case ***might diverge***. This is physically possible since the ***power*** in the carrier does only ***depend*** on ***amplitude*** and ***not*** on ***phase***. In these cases the rms value can only be specified for a given observation time ΔT or equivalently for a frequency range of integration $[f_1, f_2]$.

BASICS: Phase Noise in Oscillators

We have:

$$\varphi_{rms}^2\Big|_{\Delta T} = 2\cdot\int_{f_{min}}^{+\infty}\mathcal{L}(f)\,df \quad with \quad \mathcal{L}(f) = \begin{cases} \dfrac{|\Phi_{\Delta T}(f)|^2}{\Delta T} & f \ge 0 \\ 0 & f < 0 \end{cases}$$

The function $\mathcal{L}(f)$ is defined as the "*Single Sideband Power Spectral Density*"

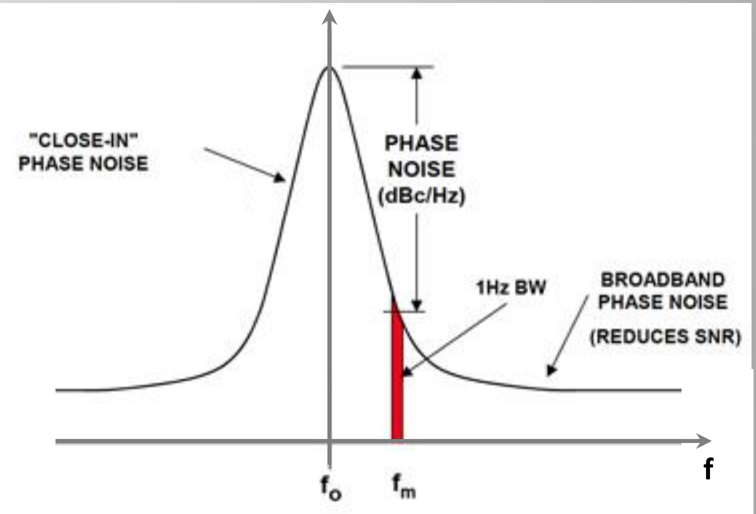
$$\mathcal{L}(f) = \frac{power\ in\ 1\ Hz\ phase\ modulation\ single\ sideband}{total\ signal\ power} = \frac{1}{2}S_\varphi(f) \leftarrow IIIE\ standard\ 1139-1999$$

Linear scale → $\mathcal{L}(f)\ units\ \equiv\ Hz^{-1}$

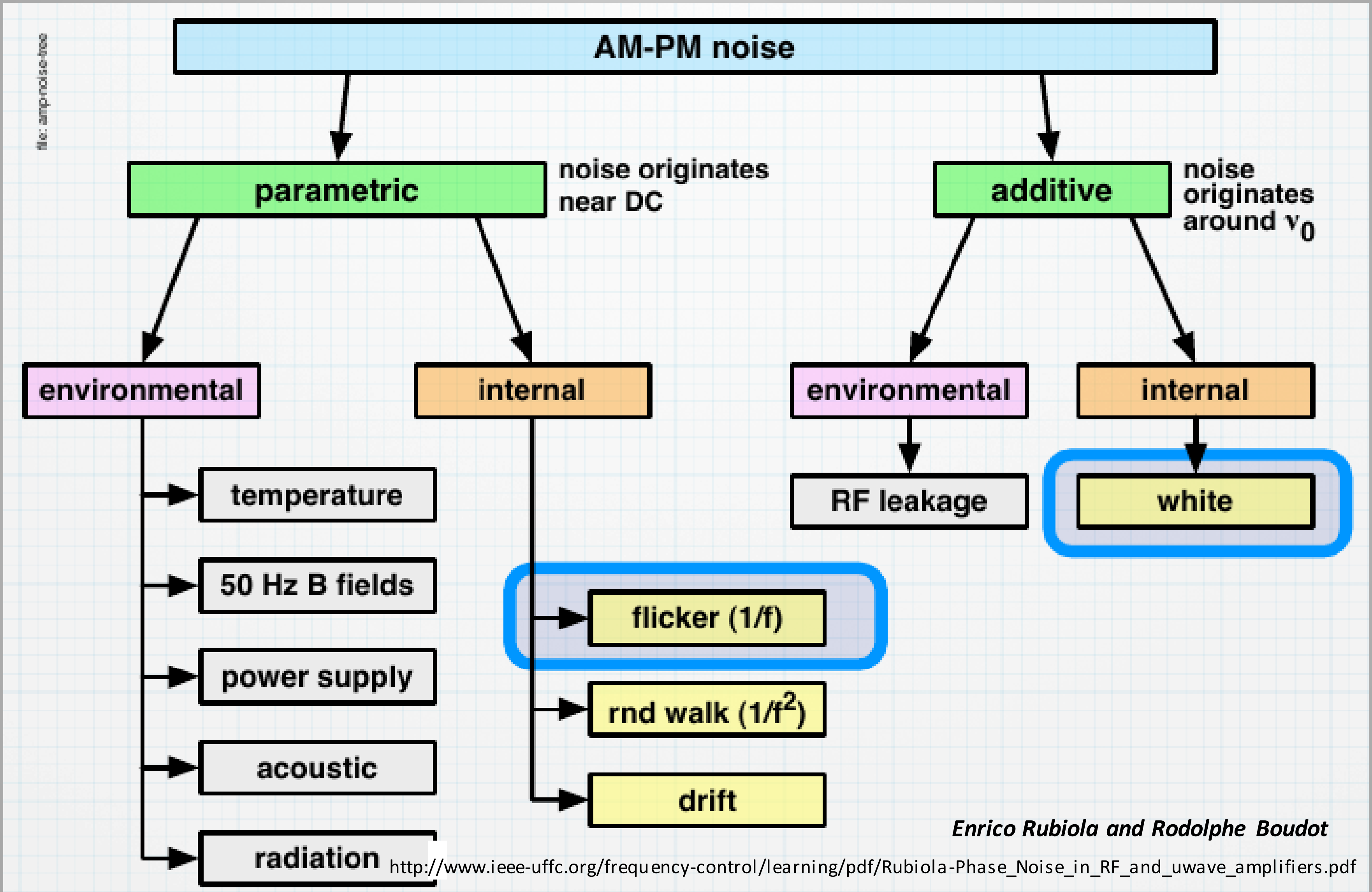
Log scale → $\mathbf{10}\cdot\mathrm{Log}[\mathcal{L}(f)]\ units\ \equiv\ dBc/Hz$

CONCLUSIONS:

- ✓ Phase (and time) jitters can be computed from the spectrum of $\varphi(t)$ through the $\mathcal{L}(f)$ - or $S_\varphi(f)$ - function;
- ✓ Computed values depend on the integration range, i.e. on the duration ΔT of the observation. Criteria are needed for a proper choice (we will see …).



BASICS: Phase Noise Nature and spectra



Enrico Rubiola and Rodolphe Boudot

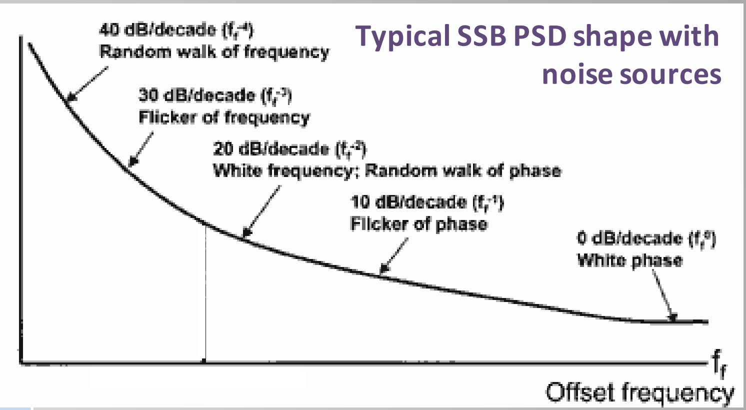
http://www.ieee-uffc.org/frequency-control/learning/pdf/Rubiola-Phase_Noise_in_RF_and_uwave_amplifiers.pdf

BASICS: Phase Noise Nature and spectra

$$S_{FM}(f) \xrightarrow[]{F\ or\ L\ transforms} S_{PM}(f) = S_{FM}(f)/f^2$$

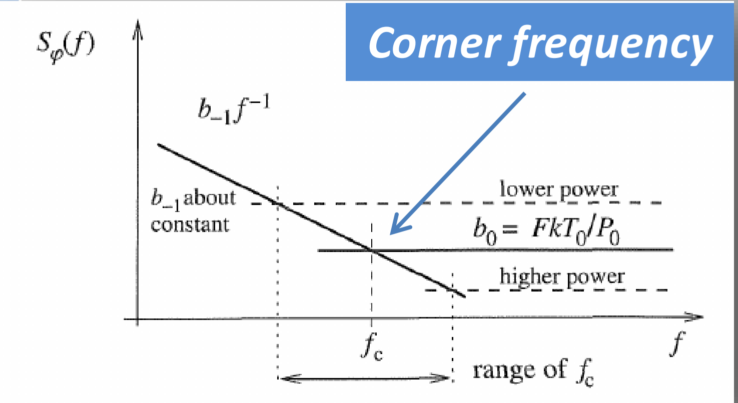
	Type	Origin	$S_\varphi(f)$
f^0	White	*Thermal noise of resistors*	$F \cdot kT/P_0$
	Shot	*Current quantization*	$2q\bar{\imath}R/P_0$
f^{-1}	Flicker	*Flicking PM*	b_{-1}/f
f^{-2}	White FM	*Thermal FM noise*	$b_0^{FM} \cdot \frac{1}{f^2}$
	Random walk	*Brownian motion*	b_{-2}/f^2
f^{-3}	Flicker FM	*Flicking FM*	$\frac{b_{-1}^{FM}}{f} \cdot \frac{1}{f^2}$
f^{-4}	Random walk FM	*Brownian motion → → FM*	$\frac{b_{-2}^{FM}}{f^2} \cdot \frac{1}{f^2}$
f^{-n}	…	*high orders …*	

$$F \stackrel{\text{def}}{=} SNR_{in}/SNR_{out}$$



Typical SSB PSD shape with noise sources

Corner frequency



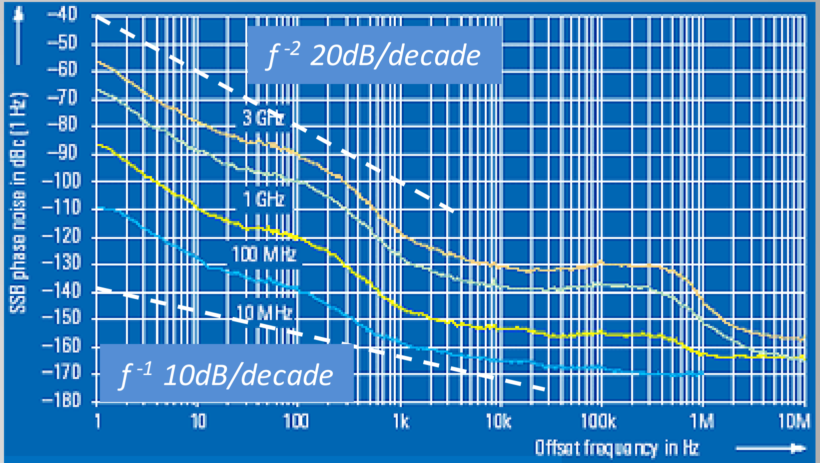
BASICS: Phase Noise examples

Time jitter can be computed according to:

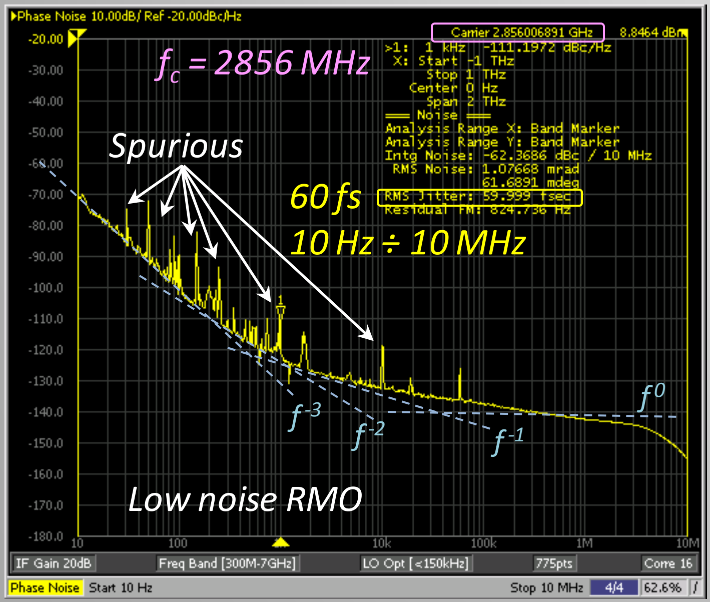
$$\sigma_t^2 = \frac{\varphi_{rms}^2}{\omega_c^2} = \frac{1}{\omega_c^2}\int_{f_{min}}^{+\infty} S_\varphi(f)\, df$$

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

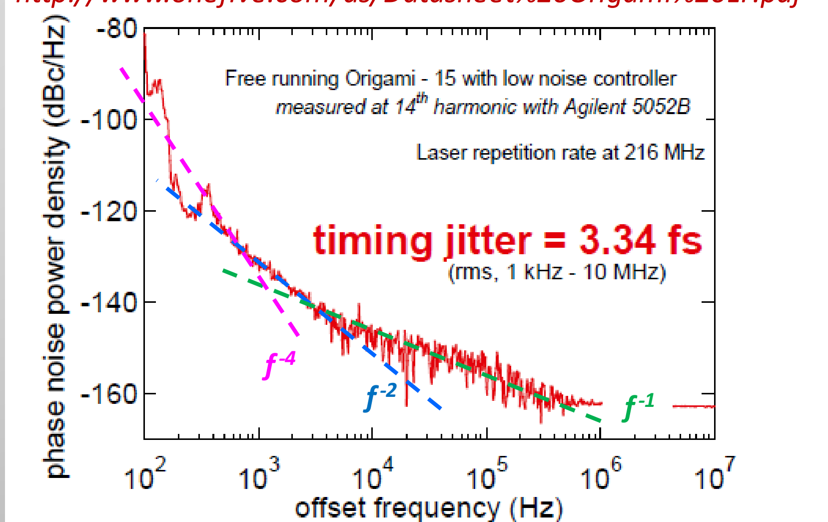
Phase noise spectral densities of different oscillators have to be compared at same carrier frequency ω_c or scaled as ω_c^{-2} before comparison.



Commercial frequency synthesizer



http://www.onefive.com/ds/Datasheet%20Origami%20LP.pdf



OMO – Mode-locked laser – f= 3024 MHz

BASICS

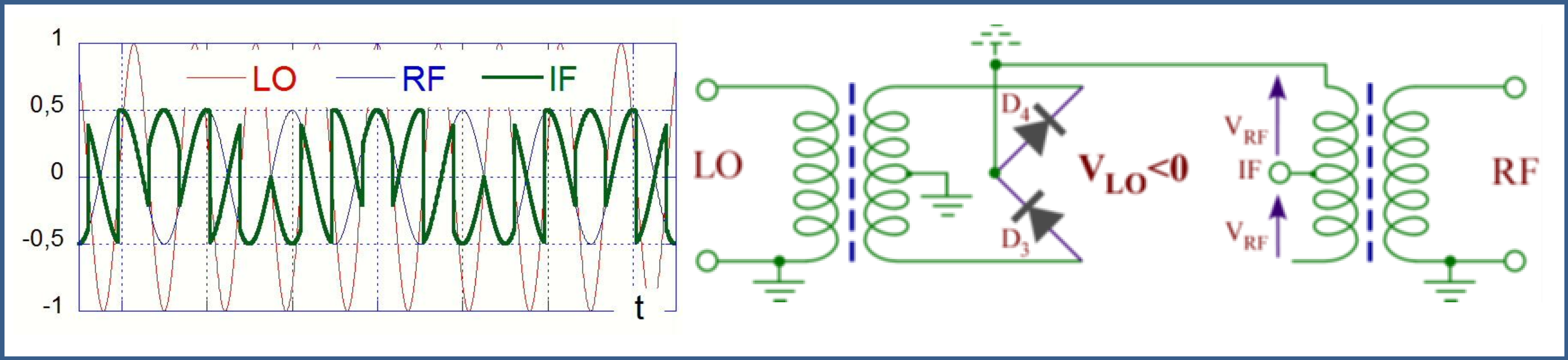
- Phase Detectors
- Phase Locked Loops

BASICS: Phase Detectors – RF signals

Phase detection on RF signals

The **Double Balanced Mixer** is the **most diffused RF device** for frequency translation (up/down conversion) and detection of the relative phase between 2 RF signals (LO and RF ports). The LO voltage is differentially applied on a diode bridge switching on/off alternatively the D_1-D_2 and D_3-D_4 pairs, so that the voltage at IF is:

$$V_{IF}(t) = V_{RF}(t) \cdot \mathrm{sgn}\left[V_{LO}(t)\right]$$



$$V_{RF}(t) = V_{RF} \cdot \cos\left(\omega_{RF} t\right); \quad V_{LO}(t) = V_{LO} \cdot \cos\left(\omega_{LO} t\right)$$

$$V_{RF} << V_{LO}$$

$$V_{IF}(t) = V_{RF}\cos(\omega_{RF}t) \cdot \mathrm{sgn}\left[\cos(\omega_{LO}t)\right] = V_{RF}\cos(\omega_{RF}t) \cdot \sum_{n=odds} \frac{4}{n\pi}\cos(n\omega_{LO}t) =$$

$$= \frac{2}{\pi} V_{RF}\left[\cos((\omega_{LO}-\omega_{RF})t) + \cos((\omega_{LO}+\omega_{RF})t) + intermod\ \ products\ \right]$$

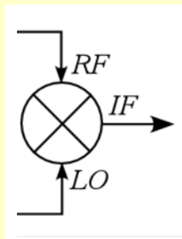
BASICS: Phase Detectors – RF signals

Phase detection on RF signals

If $f_{LO} = f_{RF}$ the IF signal has a DC component given by: $\left. V_{IF} \right|_{DC} = \langle V_{IF}(t) \rangle = k_{CL} A_{RF} \cos\varphi$

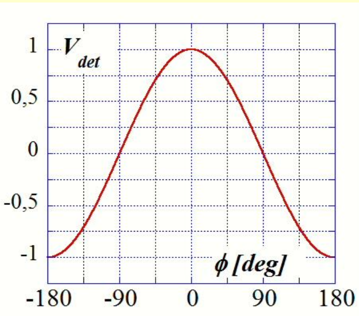
$$A_{RF} \cos(\omega t + \varphi)$$

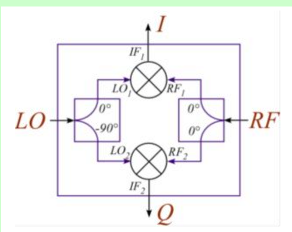
$$A_{LO} \cos(\omega t)$$



$$V_{det} = V_{IF} = V(\varphi) + \textit{high harm.}$$

$$A_{RF} << A_{LO} \;\Rightarrow\; V_{det}(\varphi) = k_{CL} A_{RF} \cos\varphi$$





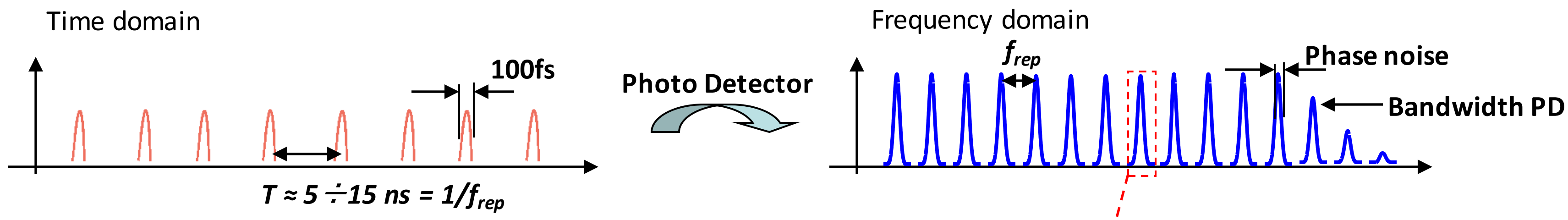
$$\begin{cases} V_I = k_{CL} A_{RF} \cos(\varphi) \;+ \textit{high harmonics} \\ V_Q = k_{CL} A_{RF} \sin(\varphi) \;+ \textit{high harmonics} \end{cases} \Rightarrow \begin{cases} A_{RF} \div \sqrt{V_I^2 + V_Q^2} \\ \varphi = \arctan\left(V_Q / V_I\right) + \dfrac{\pi}{2}\left[1 - \mathrm{sgn}(V_I)\right] \end{cases}$$

$$\left. \frac{dV_{det}}{d\varphi} \right|_{\varphi = \pm\pi/2} = \mp k_{CL} A_{RF} \underset{\substack{CL = 6dB \\ A_{RF} = 1V}}{\approx} 5 \div 10\, mV/Deg \underset{f_c = 10GHz}{\approx} 15 \div 30\, mV/ps$$

- ✓ Passive
- ✓ Cheap, Robust
- ✓ Wideband

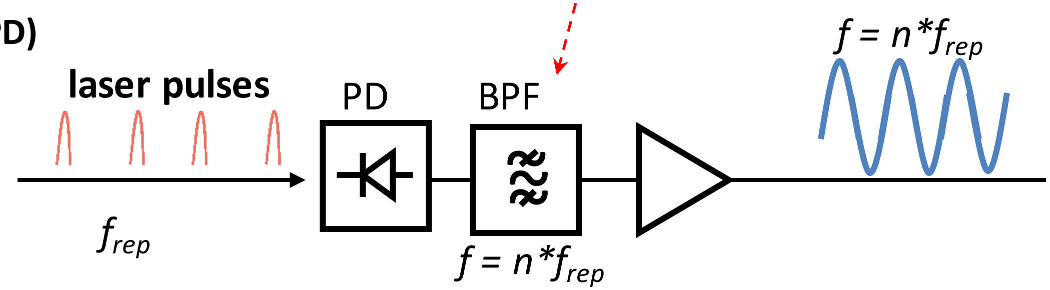
- ✓ Sensitivity proportional to level, AM → PM not fully rejected
- ✓ Noise figure *F ≈ CL*
- ✓ Good sensitivity but lower wrt optical devices

BASICS: Phase Detectors – RF vs. Optical



Direct conversion with photo detector (PD)

– Low phase noise
– Temperature drifts (0.4ps/C°)
– AM to PM conversion (0.5-4ps/mW)

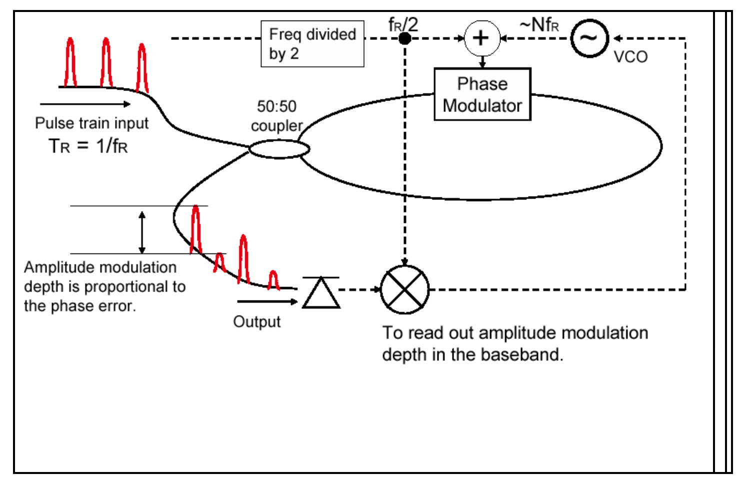


Phase detection between RF and Laser – Sagnac Loop Interferometer or BOM-PD

Recently (< 10 years) special devices to perform direct measurements of the relative phase between an RF voltage and a train of short laser pulses have been developed

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

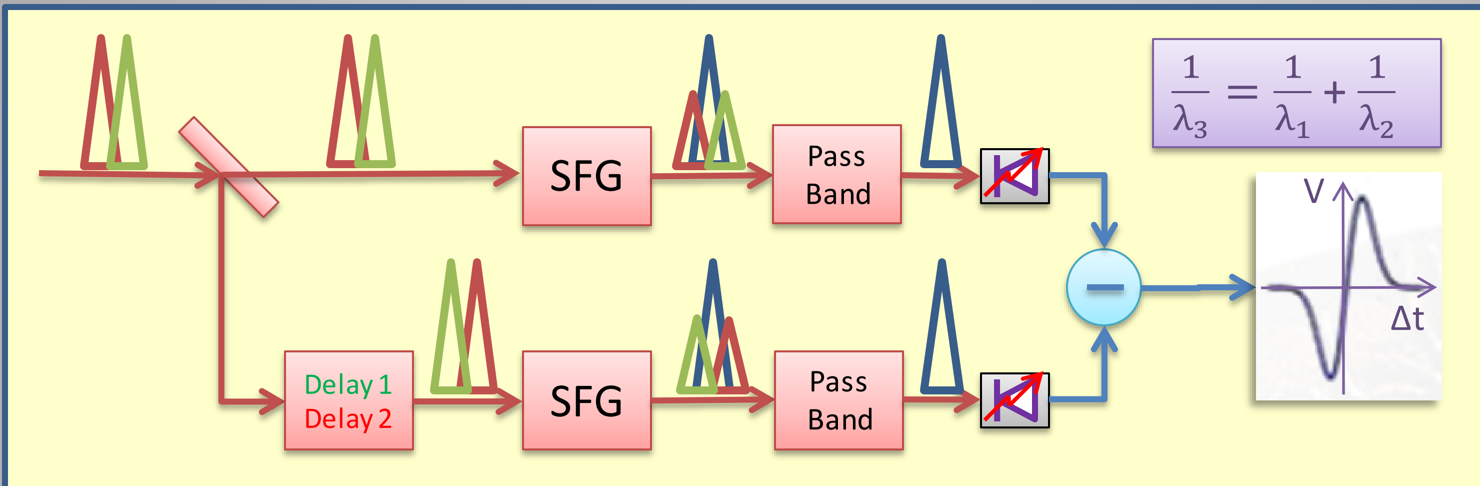
Results:
f=1.3GHz jitter & drift < 10 fs rms ***limited by detection!***



Slide from ***H. Schlarb***

BASICS: Phase Detectors – Optical vs. Optical

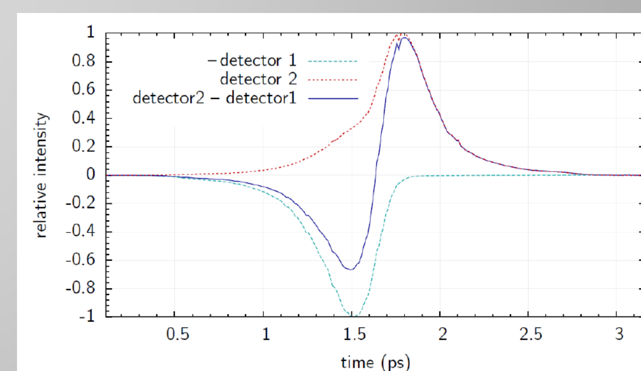
Balanced cross correlation of very short optical pulses ($\sigma_t \approx 200\ fs$) provides an ***extremely sensitive*** measurement of the ***relative delay between*** 2 pulses.



The two pulses have orthogonal polarization and generate a shorter wavelength pulse proportional to their time overlap in each branch by means of non-linear crystal.

In a second branch the two polarizations experience a differential delay $\Delta T = T_1 - T_2 \approx \sigma_t$. The amplitudes of the interaction radiation pulses are converted to voltages by photodiodes and their difference is taken as the detector output V_0.

If the initial time delay between the pulses is exactly $\Delta T/2$ then clearly $V_0 \approx 0$ (balance), while it grows rapidly as soon as initial delay deviates.

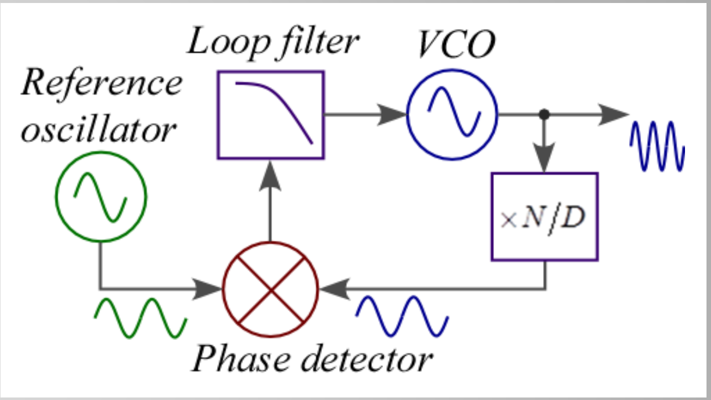


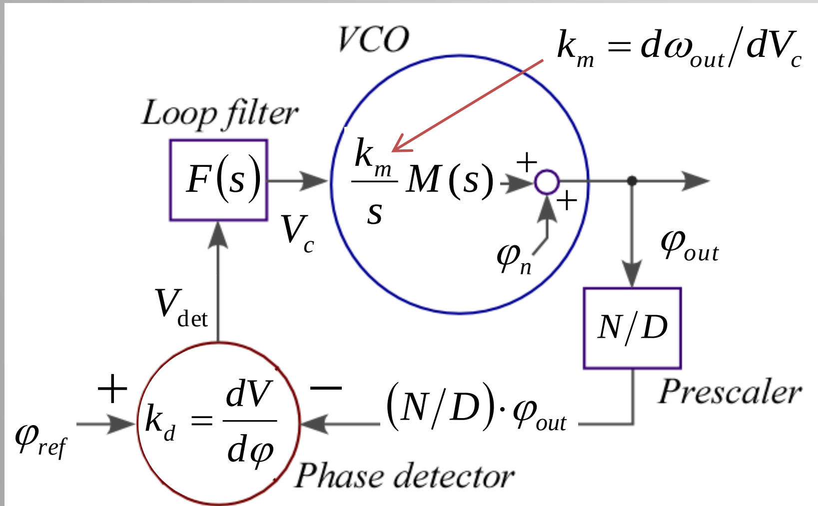
Detection sensitivity up to 10 mV/fs achievable with ultra-short pulses!!!

BASICS: Phase Locked Loops

PLLs are a very **general subject** in RF electronics, used **to synchronize oscillators** to a **common reference** or to **extract the carrier** from a **modulated signal** (FM tuning). In our context PLLs are used to ***phase-lock the clients*** of the synchronization system ***to the master clock*** (RMO or OMO). The building blocks are:

- A VCO, whose frequency range includes *(D/N)* f_{ref};
- A phase detector, to compare the scaled VCO phase to the reference;
- A loop filter, which sets the lock bandwidth;
- A prescalers or synthesizer (N/D frequency multiplier, N and D integers) if different frequencies are required.





PLL linear model

PLL transfer function

VCO noise

$$\varphi_{out}(s) = \frac{D}{N}\frac{H(s)}{1+H(s)}\varphi_{ref}(s) + \frac{1}{1+H(s)}\varphi_n(s)$$

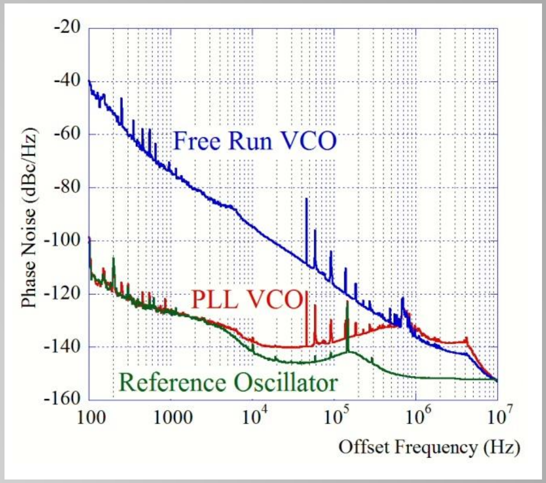
$$\text{with } H(s) = \frac{N}{D}\frac{k_d k_m}{s}F(s)M(s)$$

freq-to-phase conversion — *loop filter* — *VCO mod. bandwidth*

Loop filters provide **PLL stability**, tailoring the frequency response, and **set loop gain** and **cut-off frequency**.

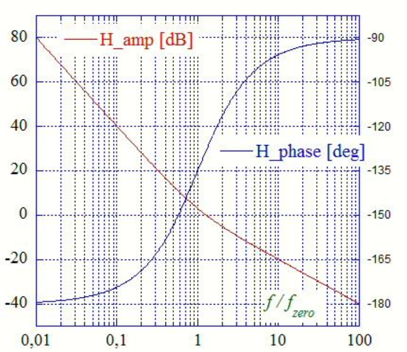
The **output phase** spectrum is **locked** to the **reference** if **|H(jω)|>>1**, while it returns similar to the **free run VCO** if **|H(jω)|<1**.

A flat-frequency response loop filter gives already a pure integrator loop transfer function thanks to a pole in the origin (*f=0*) provided by the dc frequency control of the VCO.

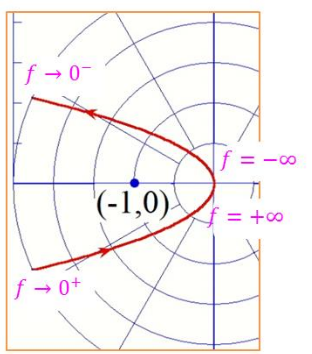


Loop filters properly designed can improve the PLL performance:

- ✓ By furtherly increasing the low-frequency gain and remove phase err. offsets due to systematic VCO frequency errors, by means of extra poles in the origin (integrators) compensated by zeroes properly placed;
- ✓ By enlarging the PLL BW through equalization of the frequency response of the VCO modulation port.

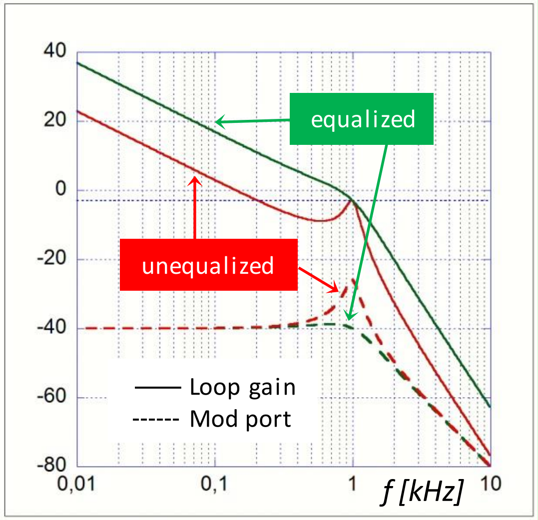


Bode plot of the PLL loop gain



Nyquist locus

A very steep frequency response can be obtained (slope = 40 dB/decade) in stable conditions (see Nyquist plot).



Equalization of the VCO modulation port frequency response allows increasing the loop gain.

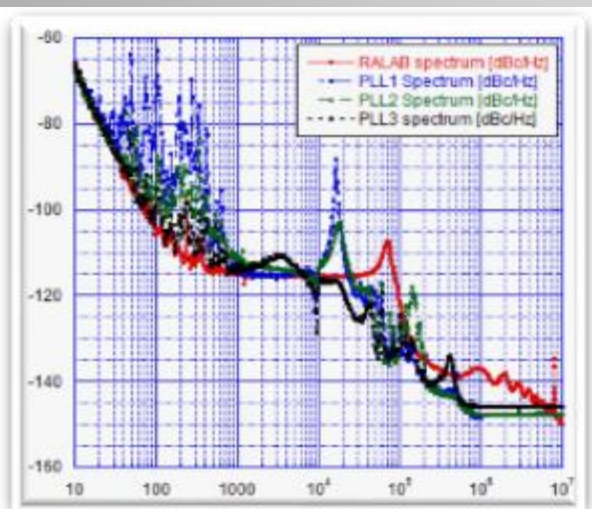
BASICS: Phase Locked Loops

What is ***peculiar*** in ***PLLs*** for clients of a ***stabilization system*** of a Particle Accelerator facility ?

✓ Both the reference and client oscillators can be either RF VCOs or laser cavities. Phase detectors are chosen consequently;

✓ Laser oscillators behave as VCOs by trimming the cavity length through a piezo controlled mirror.

- ➢ Limited modulation bandwidth (≈ *few kHz typical*);
- ➢ Limited dynamic range ($\Delta f/f \approx 10^{-6}$), overcome by adding motorized translational stages to enlarge the mirror positioning range;
- ➢ At frequencies beyond PLL bandwidth (*f > 1 kHz*) mode-locked lasers exhibit excellent low-phase noise spectrum.



RMO
$\sigma_t \approx 85$ fs
10 Hz – 10 MHz

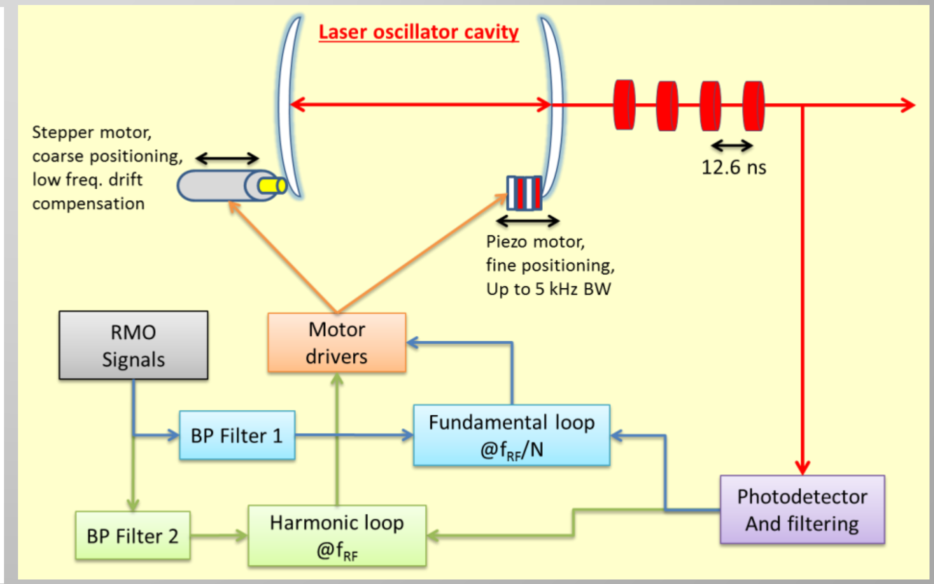
Laser:

PLL flat
$\sigma_t \approx 230$ fs

PLL + 1 s=0 pole
$\sigma_t \approx 85$ fs

PLL + 2 s=0 poles
$\sigma_t \approx 70$ fs

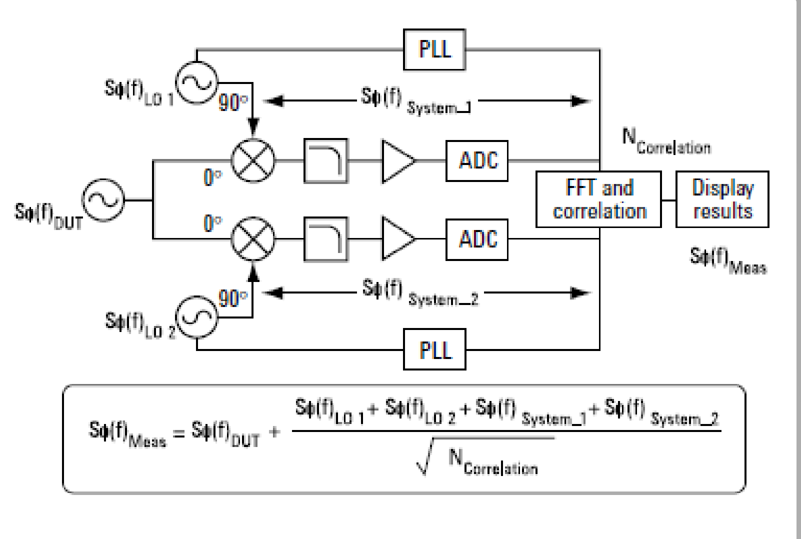
SSB phase noise of a locked OMO for different loop filters



BASICS: Precision PN Measurements

Signal Source Analyzers SSA are dedicated instruments integrating an optimized set-up for precise phase noise measurements.

Two low noise LO oscillators are locked to the DUT signal. The instrument sets the cut-off frequency of the 2 PLLs well below the minimum frequency of the selected span.

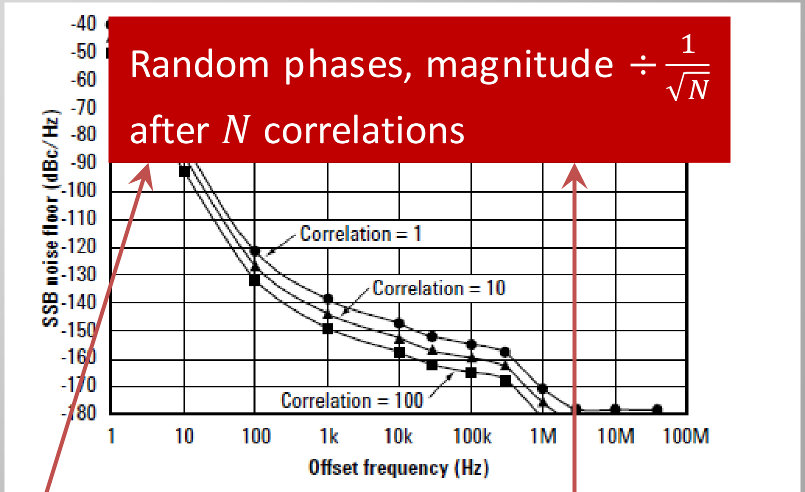


$$S\phi(f)_{Meas} = S\phi(f)_{DUT} + \frac{S\phi(f)_{LO\,1} + S\phi(f)_{LO\,2} + S\phi(f)_{System\_1} + S\phi(f)_{System\_2}}{\sqrt{N_{Correlation}}}$$

The phase noise of the DUT $\varphi_{DUT}(t)$ is simultaneously measured wrt the 2 LOs:

$$\Delta\varphi_k(t) = \varphi_{DUT}(t) - \varphi_{LO,k}(t) \xrightarrow{\mathcal{F}-\text{trans}}$$

$$\longrightarrow \Delta\Phi_k(f) = \Phi_{DUT}(f) - \Phi_{LO,k}(f) \qquad k = 1,2$$



Random phases, magnitude $\div \frac{1}{\sqrt{N}}$ after N correlations

The cross correlation function $r(\tau)$ of $\Delta\varphi_1(t)$ and $\Delta\varphi_2(t)$, and its Fourier transform $R(f)$ are:

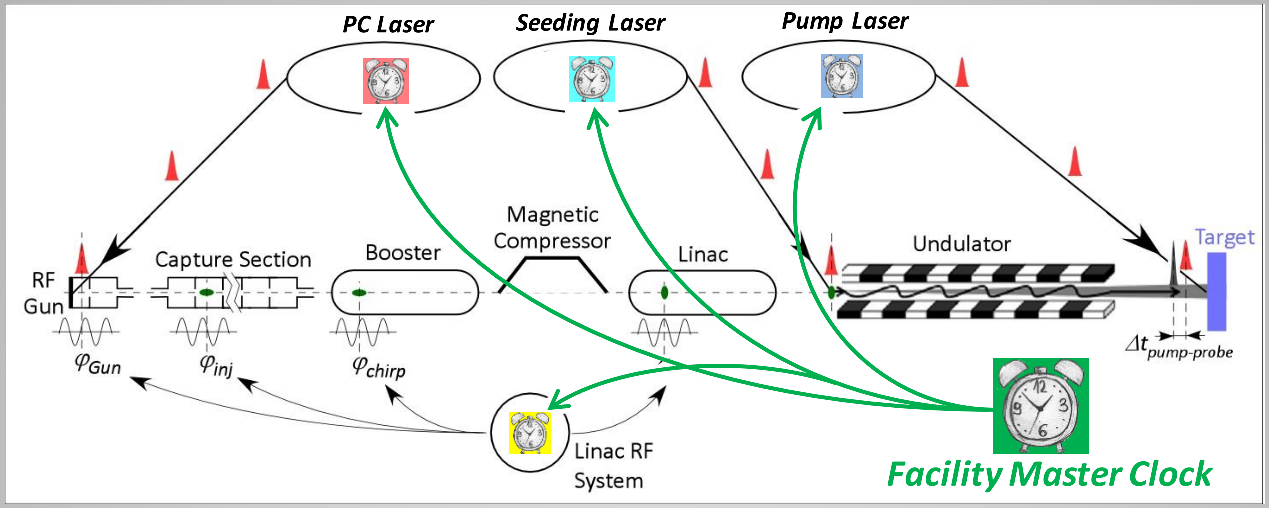
$$r(\tau) = \int_{-\infty}^{+\infty} \Delta\varphi_1(t) \cdot \Delta\varphi_2(t+\tau)\, dt$$

$$R(f) = \Delta\Phi_1^*(f) \cdot \Delta\Phi_2(f) = |\Phi_{DUT}(f)|^2 - \Phi_{DUT}(f) \cdot \left(\Phi_{LO,1}^*(f) + \Phi_{LO,2}(f)\right) + \Phi_{LO,1}^*(f) \cdot \Phi_{LO,2}(f)$$

Performances of Synchronization Systems

- ***Client Residual Jitter***
- ***Stabilized Reference Distribution***

Residual jitter of clients



A client with a free-run phase noise φ_{i_0} once being PLL locked to the reference with a loop gain $H_i(j2\pi f)$ will show a residual phase jitter φ_i and a phase noise power spectrum S_i according to:

$$\varphi_i = \frac{H_i}{1+H_i}\varphi_{ref} + \frac{1}{1+H_i}\varphi_{i_0} \rightarrow \quad S_i(f) = \frac{|H_i|^2 S_{ref}(f) + S_{i_0}(f)}{|1+H_i|^2}$$

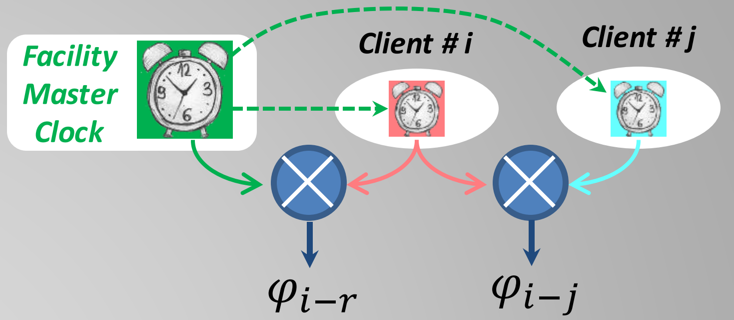
Incoherent noise contributions

Client absolute residual time jitter

$$\sigma_{t_i}^2 = \frac{1}{\omega_{ref}^2}\int_{f_{min}}^{+\infty} \frac{|H_i|^2 S_{ref}(f) + S_{i_0}(f)}{|1+H_i|^2}\, df$$

Residual jitter of clients

But we are finally interested in relative jitter between clients and reference $\varphi_{i-r} = \varphi_i - \varphi_{ref}$, and among different clients $\varphi_{i-j} = \varphi_i - \varphi_j$:



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

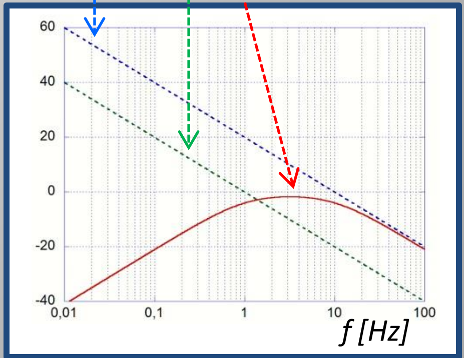
Client residual relative time jitter $$\sigma_{t_{i-r}}^2 = \frac{1}{\omega_{ref}^2} \int_{f_{min}}^{+\infty} \frac{S_{ref}(f) + S_{i_0}(f)}{|1 + H_i|^2} df$$

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

$$\sigma_{t_{i-j}}^2 = \frac{1}{\omega_{ref}^2} \int_{f_{min}}^{+\infty} S_{i-j}(f)\, df$$

Residual relative time jitter between clients i-j

If $H_i \neq H_j$ 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 between the cutoff frequencies of the 2 PLLs. That's why **a very low RMO phase noise** is specified in a **wide spectral region** including the cut-off frequencies of all the client PLLs (0.1÷100 kHz typical).

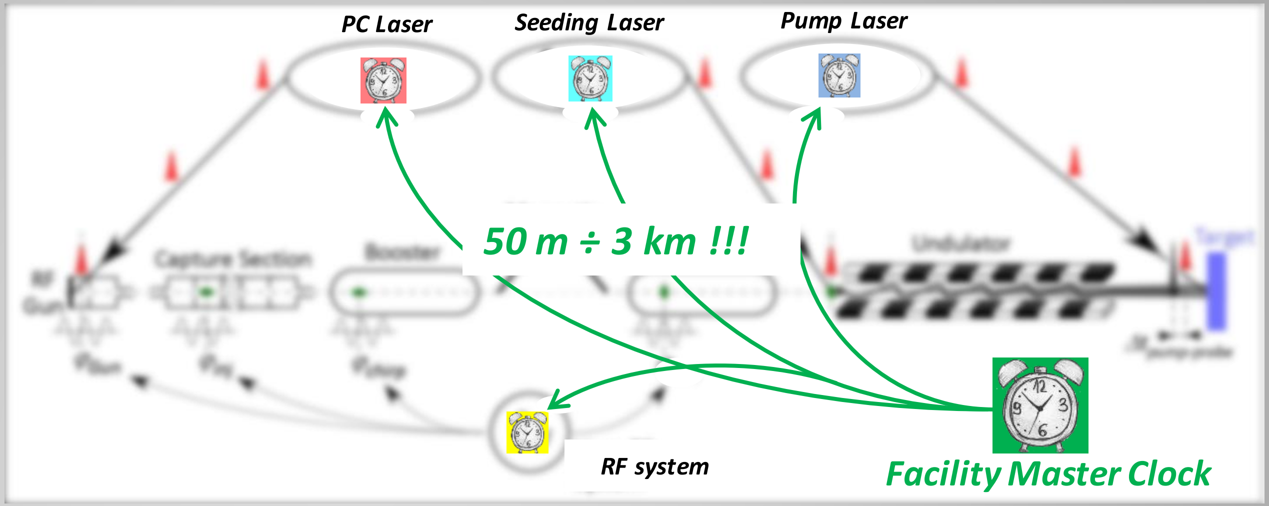


Drift of the reference distribution

Client ***jitters*** can be reduced by ***efficient PLLs*** locking to a local copy of the reference.

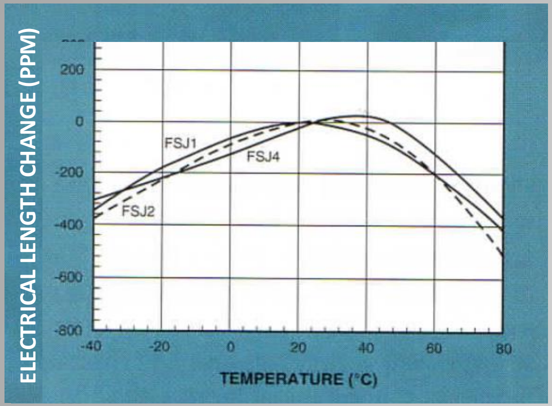
Reference distribution ***drifts*** need to be ***under control*** to preserve a good facility synchronization.

Depending on the facility size and specification the reference distribution can be:



RF based, through coaxial cables	Optical based, through fiber links
✓ *Passive (mainly) / actively stabilized* ✓ *Cheap* ✓ *Large attenuation at high frequencies* ✓ *Sensitive to thermal variations (copper linear expansion ≈ $1.7\ 10^{-5}$/°C)* ✓ *Low-loss 3/8" cables very stable for $\Delta T \ll 1$°C @ $T_0 \approx 24$ °C*	✓ *Pulsed (mainly), also CW AM modulated* ✓ *High sensitivity error detection (cross correlation, interferometry, …)* ✓ *Small attenuation, large BW* ✓ *Expensive* ✓ *Active stabilization always needed (thermal sensitivety of fibers)* ✓ *Dispersion compensation always needed for pulsed distribution*

Drift of the reference distribution



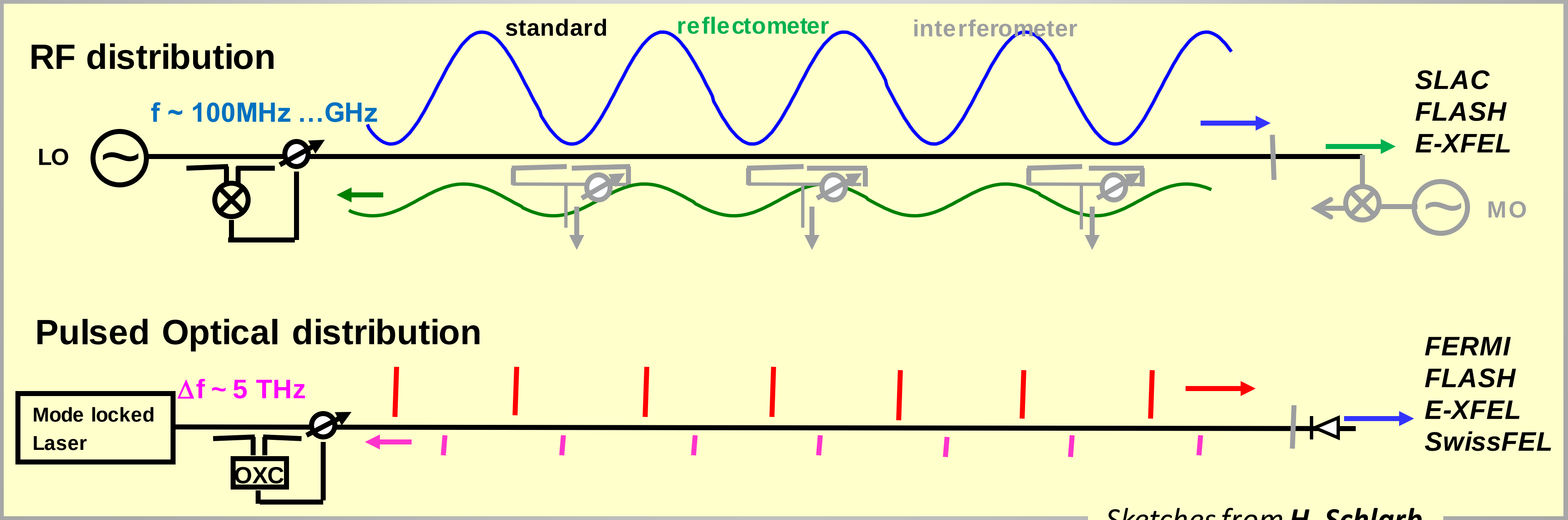
Around some optimal temperature T_{opt} cable physical elongation is compensated by dielectric constant variation. PPM relative delay variation is:

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

For a 3/8" cable (FSJ2): $T_{opt} \approx 24\,°C,\ T_c \approx 2\,°C.$ Good enough?

$L \approx 1\,km \rightarrow \tau \approx 5\,\mu s \rightarrow \Delta\tau/\tau \approx 5fs/5\mu s \approx 10^{-3} PPMs$!!!

ACTIVE LINK STABILIZATION REQUIRED !!!

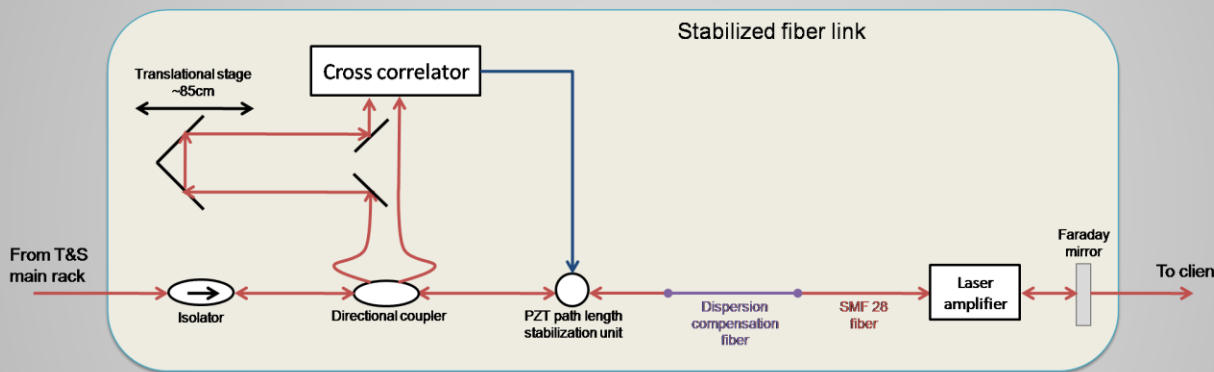


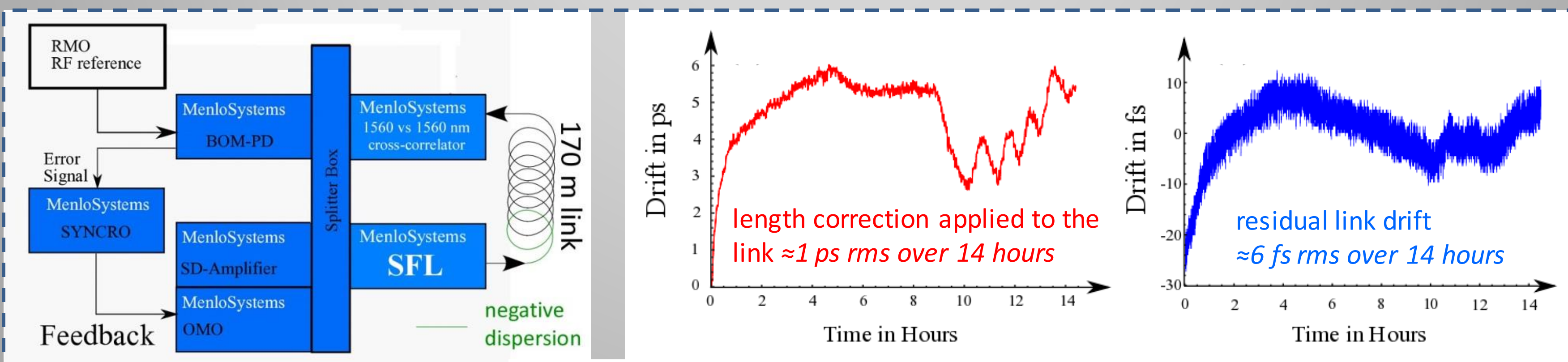
Sketches from ***H. Schlarb***

Drift of the reference distribution

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 ($\approx 100\ fs$).





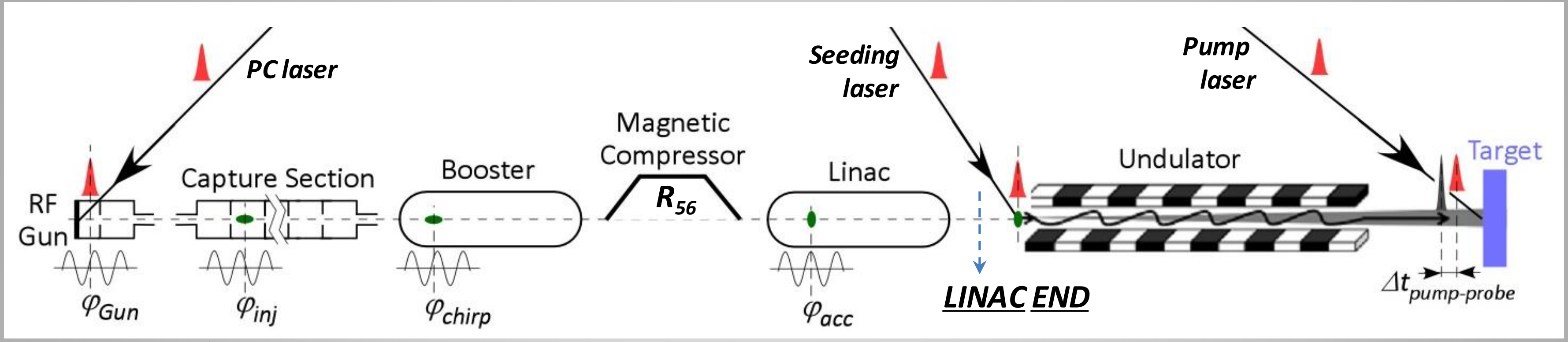
Courtesy of MenloSystems GmbH

Beam Synchronization

- *Effects of Client Synchronization Errors on Bunch Arrival Time*
- *Bunch Arrival Monitors*

Beam synchronization

How beam arrival time is affected by synchronization errors of the sub-systems?



Perfect synchronization → the time (or phase) T_i of all sub-systems properly set to provide required beam characteristics at the Linac end, where the bunch centroid arrives at time T_b.

Perturbations of subsystem phasings Δt_i will produce a change Δt_b of the beam arrival time.

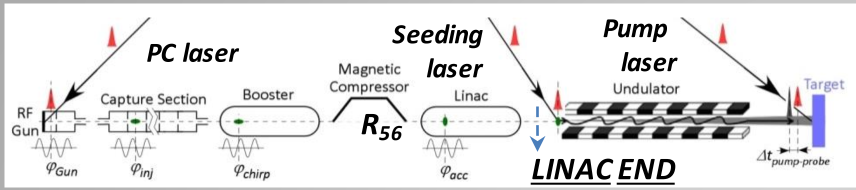
First-order approximation:

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

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.

Beam synchronization



How beam arrival time is affected by synchronization errors of the sub-systems?

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

$$a_{PC} \approx 0.7; a_{RF_{GUN}} \approx 0.3; others\ a_i \approx 0$$

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

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

Compression can be staged (few compressors acting at different energies). Bunch can be overcompressed (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

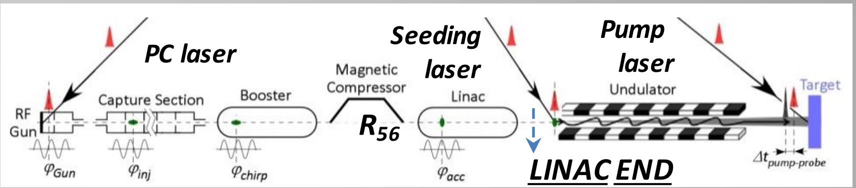
$$a_{RF_{CS}} \approx 1; |a_{PC}|, |a_{RF_{GUN}}| \ll 1;\ others\ a_i \approx 0$$

The bunch gains also an Energy-time chirp. RF and magnetic compressions can be combined.

Particle distribution within the bunch and shot-to-shot centroid distribution behave similarly, but values of coefficients a_i might be different since space charge affects the intra-bunch longitudinal dynamics.

Beam synchronization

Bunch Arrival Time Jitter



If we consider uncorrelated residual jitters of 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:

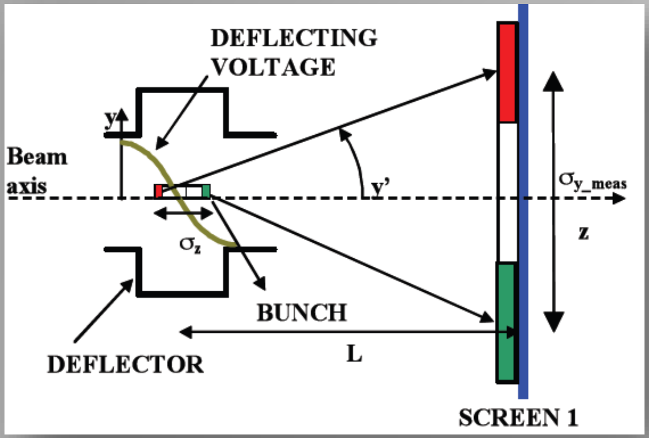
$$\sigma_{t_{b-j}}^2 = (a_j - 1)^2 \sigma_{t_j}^2 + \sum_{i \neq j} a_i^2 \, \sigma_{t_i}^2$$

EXAMPLE: PC laser jitter $\sigma_{t_{PC}} \approx 70\ fs$, RF jitter $\sigma_{t_{RF}} \approx 30\ fs$

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

Beam arrival time measurement: RF deflectors

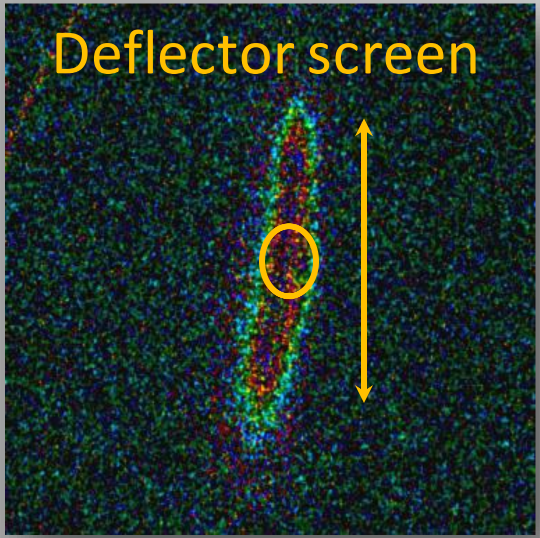


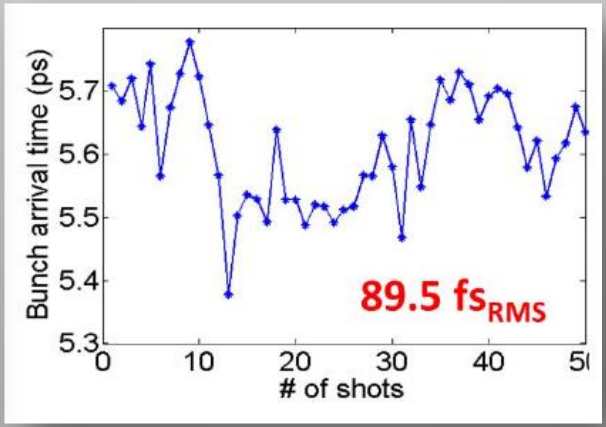
The beam is ***streaked*** by a ***transverse RF cavity*** on a ***screen***. The image is captured by a camera. Longitudinal charge distribution and centroid position can be measured.

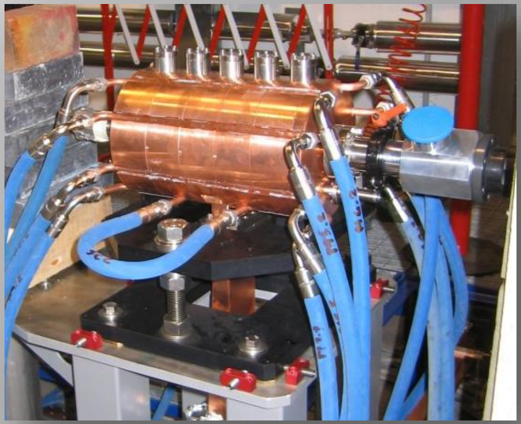
- ✓ Works typically on single bunch. Bunch trains can be eventually resolved with fast gated cameras;
- ✓ Destructive (needs a screen ...)
- ✓ Measure bunch wrt to RF (relative measurement)
- ✓ with a spectrometer → long. phase space imaging - $(z, \epsilon) \rightarrow (y, x)$

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

Achievable resolution down to ≈ 10 fs



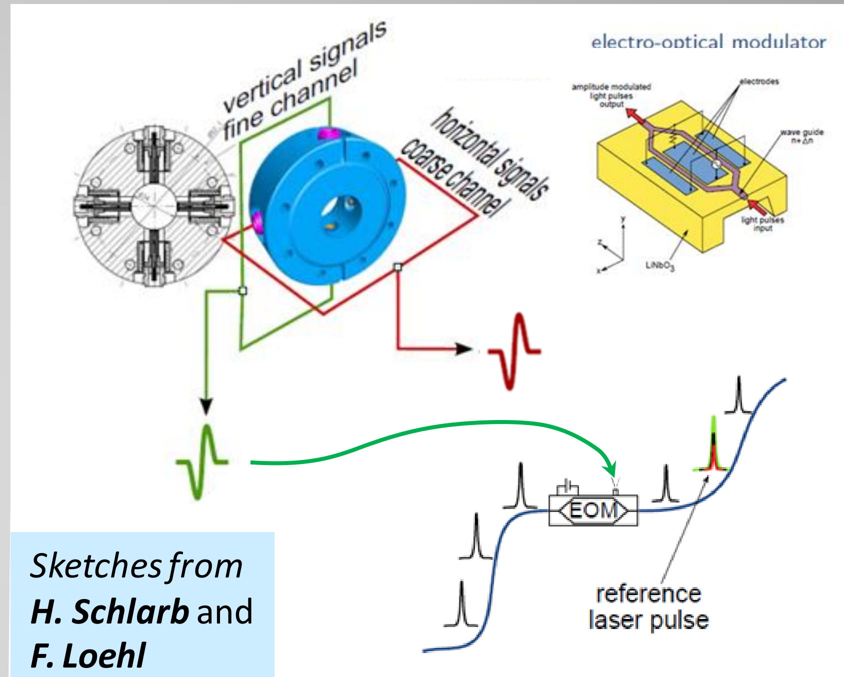




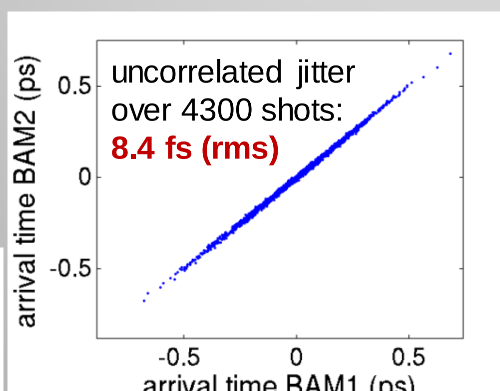
Beam arrival time measurement: Electro-optical BAM

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.

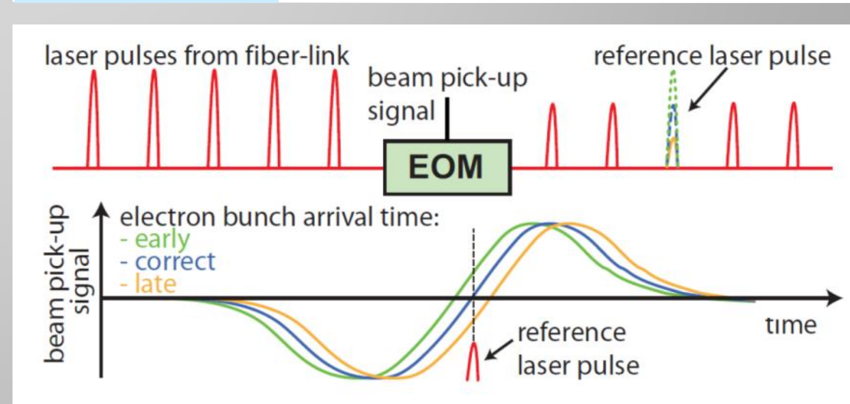
- ✓ Works very well on bunch trains;
- ✓ Non-intercepting;
- ✓ Measure bunch wrt to a laser reference (OMO);
- ✓ Demonstrated high resolution



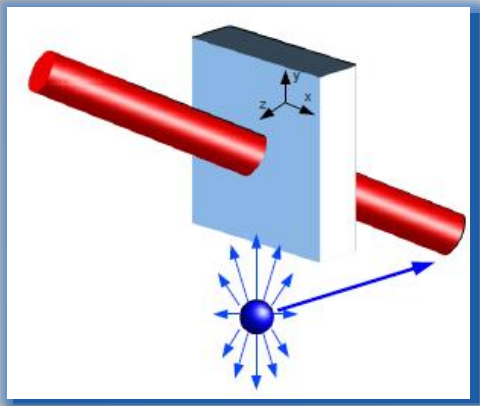
Sketches from ***H. Schlarb*** and ***F. Loehl***

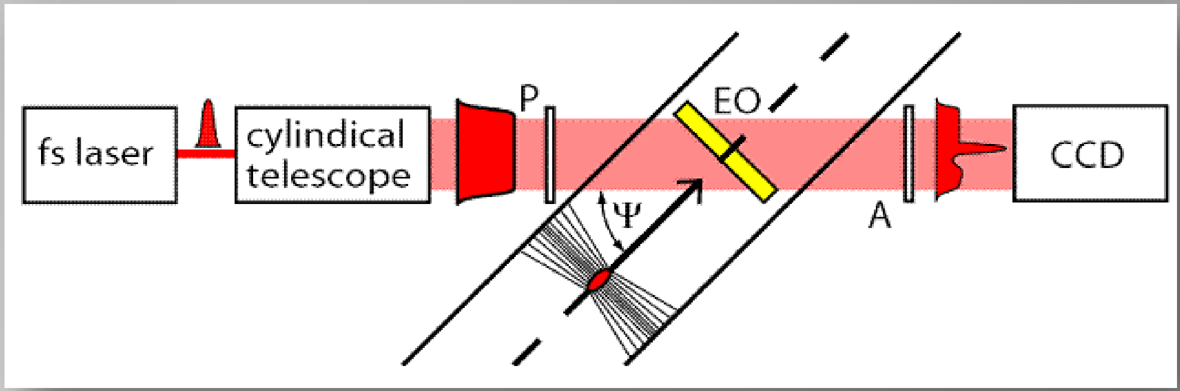


BAM 1 – 2 placed 60 m away along the beam path



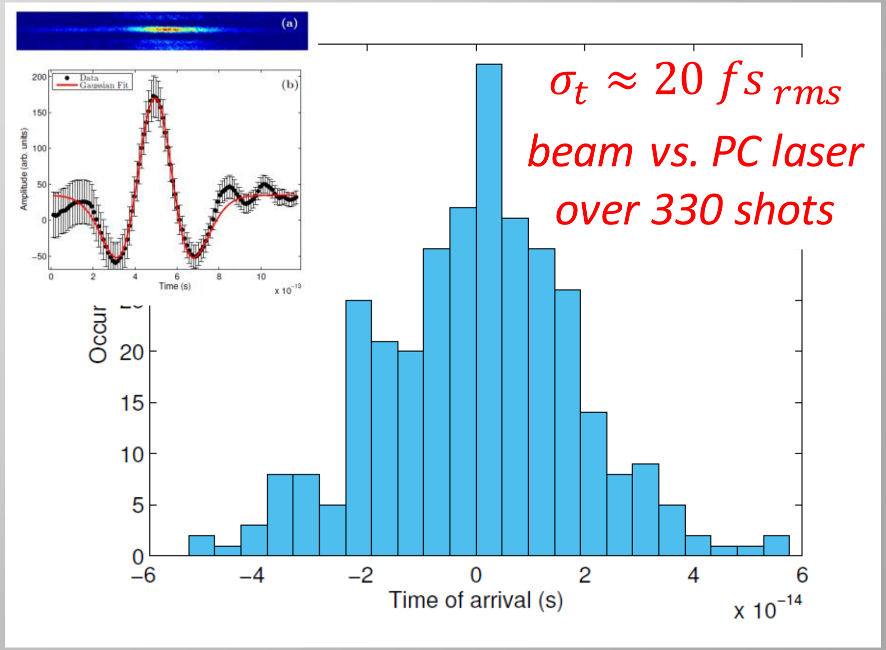
Beam arrival time measurement: EOS





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*).



CONCLUSIONS

- ✓ Timing and Synchronization has growth considerably in the last ~ 15 years as a Particle Accelerators specific discipline
- ✓ It involves concepts and competences from various fields such as Electronics, RF, Laser, Optics, Control, Diagnostics, Beam dynamics, …
- ✓ Understanding the real synchronization needs of a facility and proper specification of the systems involved are crucial for successful and efficient operation (but also to avoid overspecification leading to extra-costs and unnecessary complexity ...)
- ✓ Synchronization diagnostics (precise arrival time monitors) is fundamental to understand beam behavior and to provide input data for beam-based feedback systems correcting synchronization residual errors
- ✓ Although stability down to the *fs* scale has been reached, many challenges still remain since requirements get tighter following the evolution of the accelerator technology. The battleground will move soon to the attosecond frontier …

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