Beam Synchronous Timing

(BST)

- Mario Ferianis –

Sincrotrone Trieste

Outline

- What is a Synchronization / Timing System
- Why do we need Beam Synchronous Timing
- BST system architecture
- Some definitions
- Jitter measurement techniques
- BST building blocks
- Implementation examples
- Technological issues

What is a Synchronization / Timing System

- The **synchronization** *(after the greek verb: συγχρονιζω = to be/to happen at the same time)* **of a system** can be defined:

  its property of sharing a common ***time reference***

- Generally speaking, a *synchronous system* is made of:
  - a *timing* system ➔ to generate and distribute the **time reference**
  - the *synchronization* system ➔ to keep the sub-systems **locked** to the **time reference**
  - its different **synchronized** sub-systems (timing system **clients**)
- We frequently refer to: *Timing & Synchronization system*
- The *synchronized sub-systems* can then operate at fixed relative time instants

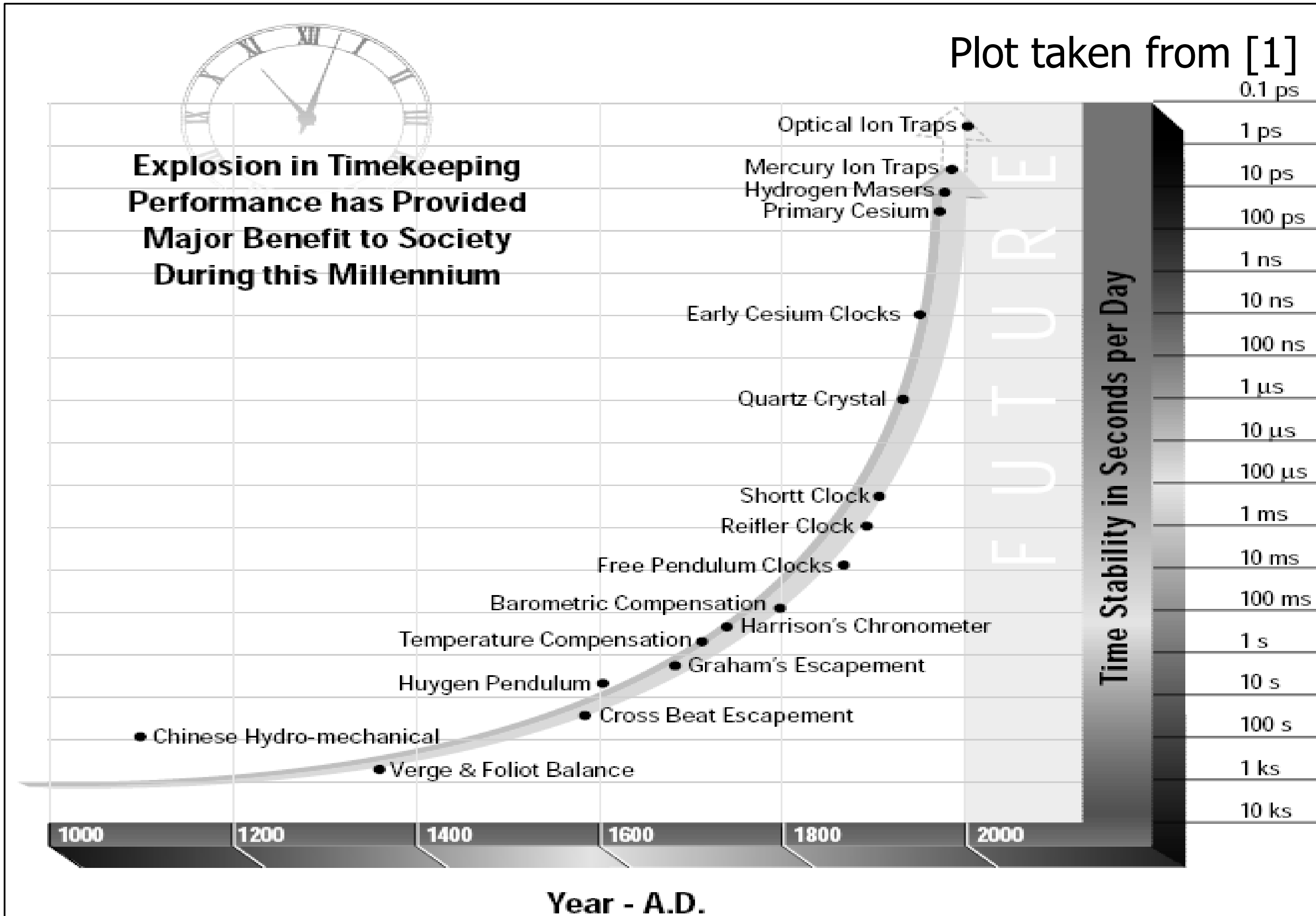
What is a Synchronization / Timing System

- Synchronization is also *timekeeping* **[1]** which requires the coordination of events to operate a system in unison
- In electronics, there are "synchronous counters" sharing the same ***clock*** to provide output changes at the same time

time reference → clock

- The preservation of the synchronization over a long term is called **stability**: a synchronous system is said to be *stable* when its *synchronization is kept over long times*, order of magnitude larger than the "event" (several clock periods)
- *Stability requires synchronization* whereas the opposite is *not always true* (a synch. system may not be stable)

What is a Synchronization / Timing System



What is a Synchronization / Timing System

- In accelerators, we deal with **Beam Synchronous Timing**; we need to synchronize the sub-systems to the bunches
- High energy particle accelerators are based on **Radio Frequency** (**RF**) accelerating structures:
  - linear accelerator: multi gap accelerating structures (acc. sections)
  - circular accelerator: multi or single gap acc. structures (cavities)
- The RF is the *alternating high frequency voltage* feeding the accelerating structures
- The RF represents the **time reference** of the Beam Synchronous Timing system
- The RF is also referred to as the **Machine Reference**
- Both *Linear* and *Circular* accelerators need to be operate synchronously

What is a Synchronization / Timing System

- A BST system has to fulfill the following tasks **[2]**:
  - To generate and remotely distribute the Phase Reference
  - To trigger fast sub-systems
  - To trigger slow systems
  - To interface to the Control System
- According to the required resolution, in a BST system we may identify:

Fast timing	*at bunch level*	*hardware based*
Slow timing	*at revolution clock level*	*"event" based*

- Trigger signals are often referred to as: *fiducials*
- *Synchronization* is a local task implemented at the different *Clients* of the timing system

Why do we need BST

A BST may be used for many different purposes

- to allow for an efficient acceleration (low losses)
- to allow for high quality beam generation (constant energy)
- to allow for an efficient injection (linear to circ. , circ. to circ.)
- to implement "beam time structure" and topping-up
  single / few, multi bunch, camshaft/pilot bunch
- to trigger fast, turn-by-turn measurements
- to generate *events*
- to acquire *time consistent* sets of data from the field
- to allow for operation of time resolved beam-lines
- to enable pump–probe experiments

THE CERN ACCELERATOR SCHOOL

Why do we need BST

- The **RF** (or one of its harmonic, when used) is the highest frequency signal in the accelerator
- The frequency of the RF defines the *minimum bunch time separation* for that particular accelerator; some examples:

- linear acc.	**1.3GHz** (DESY structures)
(**LINAC**)	**2.998** or **2.856GHz** (EU / US S-band)
- circular acc.	≈**500MHz** (3rd gen. Light Source cavities)
	352MHz (CERN / ESRF/ SOLEIL)

- …and therefore:

- linear acc.	S-band LINAC	➔	$\tau_{S\text{-band}}$ = 330ps
- circular acc.	500MHz machine	➔	τ_{500MHz} = 2ns

- In **3rd Generation Light Sources** (3GLS), where the radiation is produced by bunches circulating in a Storage Ring, the typical time duration of the radiation pulses is in the order of some 10s of ps ($\sigma_B \approx 20$ps)
- This value along with the period of the accelerating RF is setting the requirement for the "jitter" of the associated BST
- A typical jitter value is in the order of few ps_{RMS}

Why do we need BST: new machines

- The trend is to **E-UV/soft x-rays coherent** light sources generating sub-100fs pulses (SASE / seeded FELs) **[3]**
- These LINAC based sources are called also 4thGLS
- Currently are: in operation or commissioning or construction
- Passing from 3GLS to 4GLS the specifications of the BST have become **more and more stringent**
- Reasons for that are:

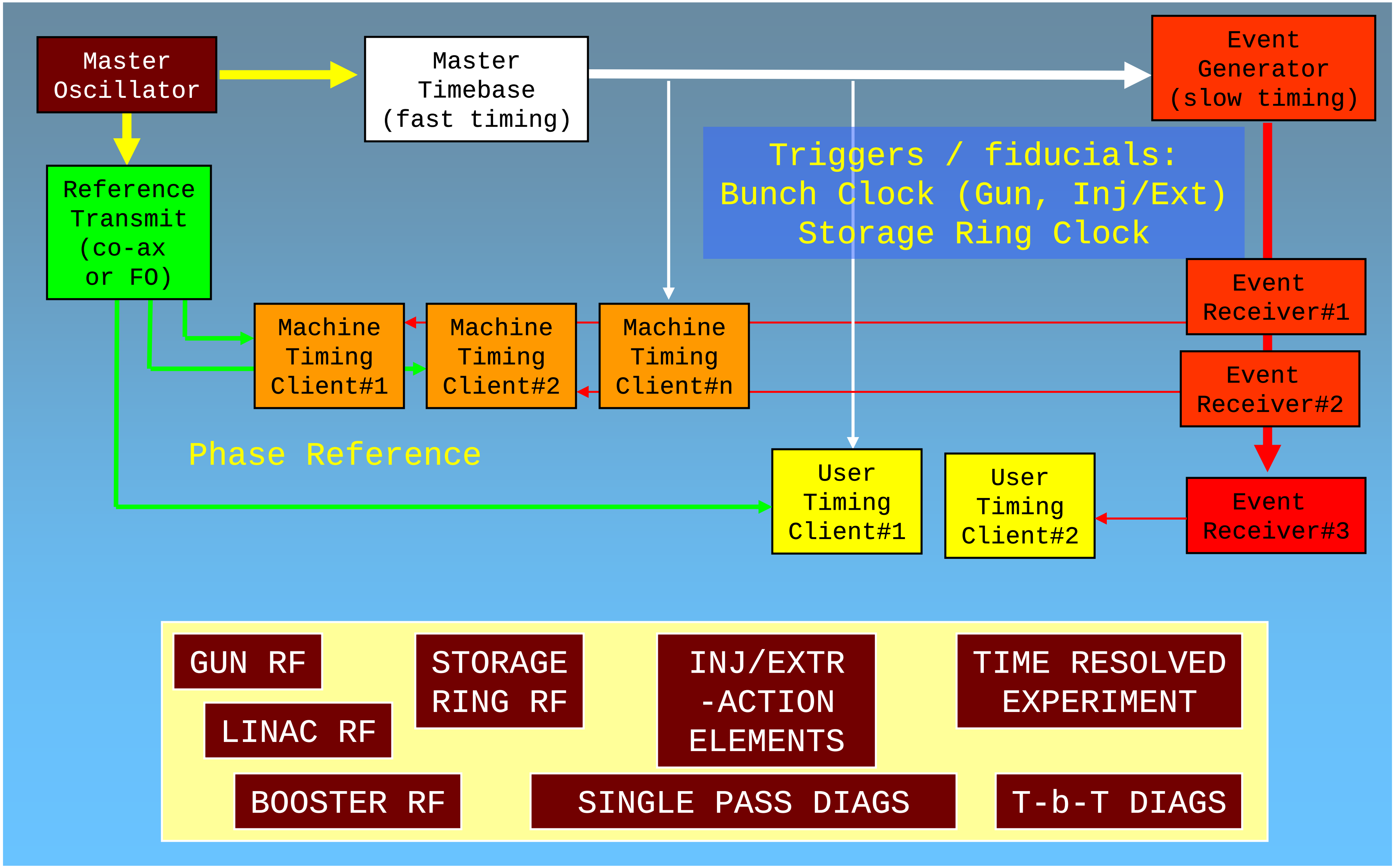
  - **very high time-domain accuracy** on the operation of the main sub-systems for achieving design performances

  - **shorter bunches** (from 20ps$_{RMS}$ to <100fs$_{RMS}$)

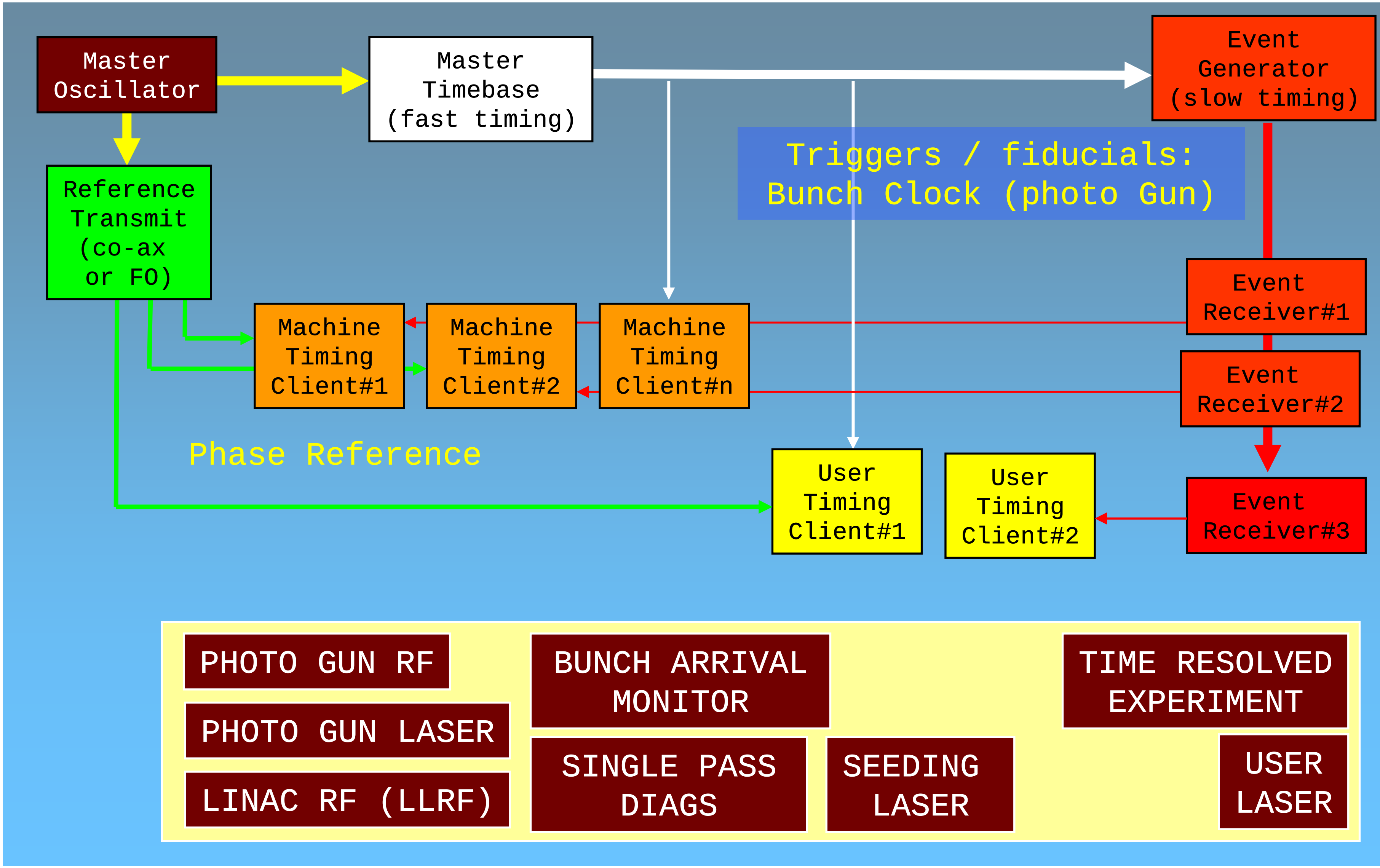
  - massive **adoption of fs laser** oscillators and amplifiers

  - order of magnitude **lower repetition rate** of light pulses
- We are transitioning from the *10ps$_{RMS}$* to the *10fs$_{RMS}$* regime

BST system architecture: 3GLS



BST system architecture: 4GLS



Some definitions **[1]**

- how precisely synchronized a system is?
  - well, how much is the jitter?
- what is jitter?
- with respect to what?
- how do I measure the jitter?
  - time or frequency domain measurement…
- and what about drift?

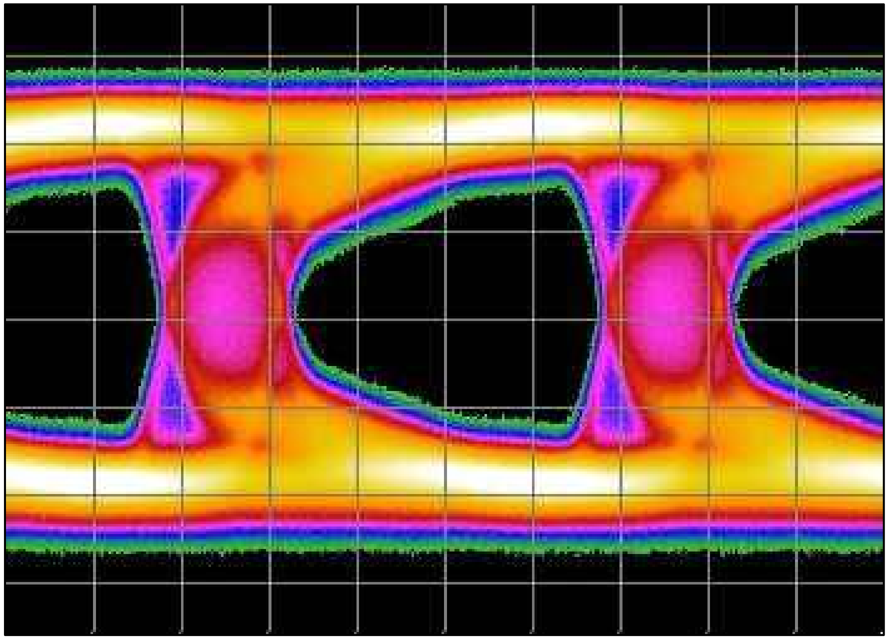
Some definitions: jitter

- *Irregular, random movement; also* **:** vibratory motion
- a *natural event* that involves a change in the position or location of something
- a fluctuation in a **transmission signal**. The term is used in several ways, but it always refers to some offset of time and space from the norm. For example, in a network transmission, jitter would be **a bit arriving either ahead or behind a standard clock cycle**
- the slight movement of a transmission signal in time (i.e. phase) that can introduce errors and loss of synchronization
- **small rapid variations in a waveform** resulting from fluctuations in the voltage supply or mechanical vibrations …

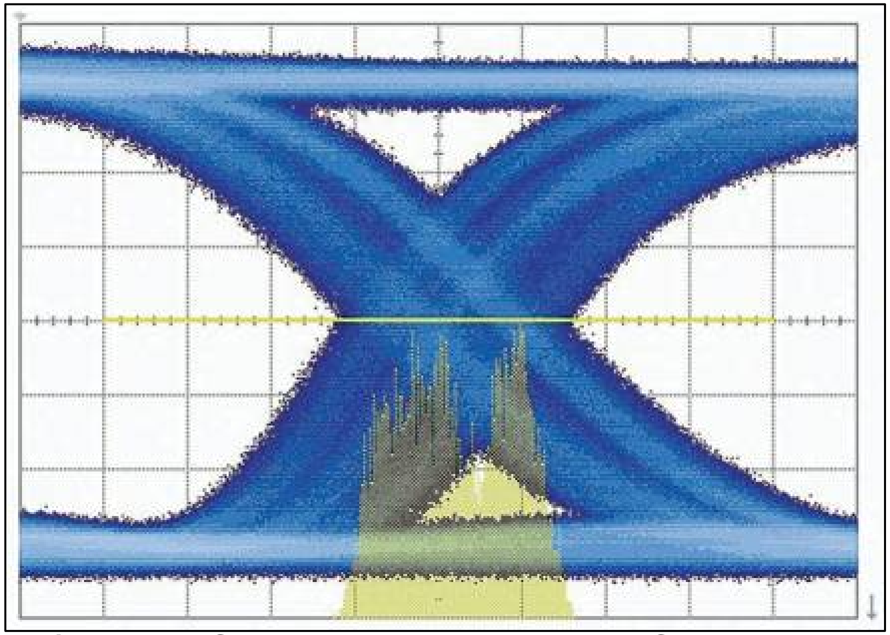
Some definitions: jitter

- in the context of BST, we are interested in **timing jitter** or **phase noise** which may be defined as:

  the distribution of the *zero crossing-to-reference time difference* measured on many subsequent representations of the signal that occur over the observation time



"eye diagram" of a digital data stream



distribution of zero-crossing w.r.t. reference

Exercise: measuring the jitter of a synchronous counter

- Typically on a Storage Ring (SR) you need to generate the **Revolution Clock** (CK_{REV}) signal
- $CK_{REV} = f_{RF}$ / Harmonic Number

  Harmonic Number is the number of buckets of the SR

  ELETTRA: f_{RF} = 499.654MHz, h_N=432, f_{BC}=1.156MHz
- The CK_{REV} is used both for turn-by-turn measurement on SR and for beam-lines detector synchronization
- The CK_{REV} may be easily generated with ECL counter, using the f_{RF} as the clock signal
- Typical value for the jitter of CK_{REV} wrt RF is <5ps_{RMS}

Some definitions: Allan deviation **[1]**

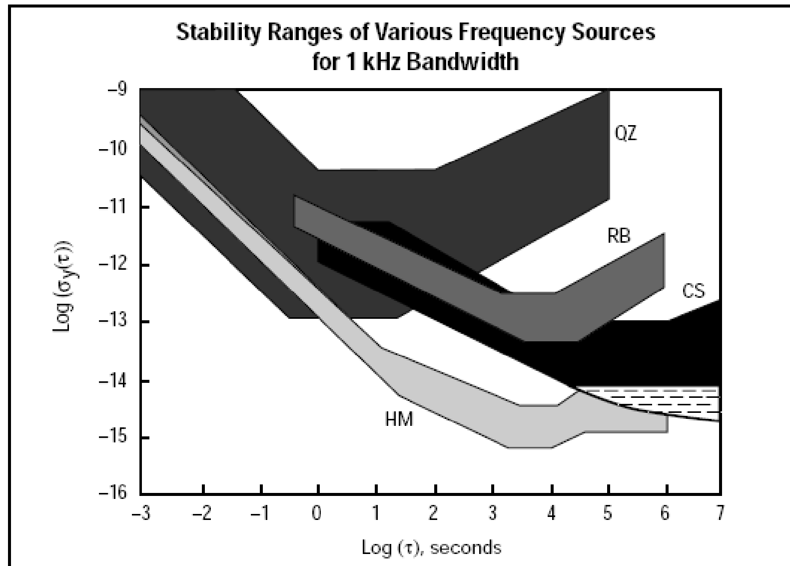
- A frequency stability diagram, sy(t), for most of the precision clocks and oscillators used widely within the time and frequency community and by an ever increasing number of users of precision timing devices.
- The dashed region at the bottom of the cesium (CS) stability plot shows the improved long-term stability of the HP 5071A Frequency Standard.
  - QZ ➔ Quartz Crystal Oscillator,
  - RB ➔ Rubidium Gas-Cell Frequency Standard,
  - CS ➔ Cesium-beam Frequency Standard,
  - HM ➔ Active Hydrogen-Maser Frequency Standard
- The equation for the two-sample variance may be written as follows:

David W. Allan

$$\sigma_y^2(\tau) = \frac{1}{2\tau^2}\left\langle \left(\Delta^2 x\right)^2 \right\rangle = \frac{1}{2}\left\langle \left(\Delta y\right)^2 \right\rangle$$

where the brackets, < >, denote an infinite time average.

Abbreviation	Name	Expression
AVAR	Two-Sample or Allan Variance	$\sigma_y^2(\tau) = \frac{1}{2}\left\langle (\Delta y)^2 \right\rangle = \frac{1}{2\tau^2}\left\langle (\Delta^2 x)^2 \right\rangle$
MVAR	Modified Allan Variance	$\text{Mod. } \sigma_y^2(\tau) = \frac{1}{2\tau^2}\left\langle (\Delta^2 \bar{x})^2 \right\rangle$
TVAR	Time Variance	$\sigma_x^2(\tau) = \frac{1}{6}\left\langle (\Delta^2 \bar{x})^2 \right\rangle$



Jitter measurement techniques

- Time domain measurement techniques
  - based on fast oscilloscopes (real time / sampling)
  - relative (i.e. trigger to CH1)
  - limits set by time base accuracy
  - down to ≈ ps level
- Frequency domain measurement techniques
  - based on phase noise measurement
  - absolute (internal ref.) or relative (need ref signal)
  - Signal Source Analyzer
  - down to the <10fs level

Jitter measurement techniques: time domain

- The measurement of jitter in time-domain is limited to a resolution of $0.5ps_{RMS}$ (oscilloscope time-base)
- This value is not absolute as it is improving with the increase of the bandwidth (BW) in modern oscilloscopes
- The wider the bandwidth, the more accurate has to be the time-base of the oscilloscope
- Increase of the sampling rate (50GS/s) leads to higher sensitivity in time to amplitude errors
- With time domain techniques we are measuring the *pk-pk envelope* of the jitter
- No information about the spectral components of jitter

Some useful formulas

- Given the system bandwidth **BW$_{-3dB}$** [**GHz**]
  the following approximated formulas hold, time expressed in ns:

- Rise Time (from 10% to 90%) ________________ $t_{RISE} = \frac{0.35}{BW_{-3dB}}$

- Full Width Half Maximum ________________ $FWHM = \frac{0.45}{BW_{-3dB}}$

- Sigma (for a gaussian pulse) ________________ $\sigma = \frac{FWHM}{2.35}$

- RMS value (for a gaussian distribution) ________________ $A_{RMS} = \frac{A_{pk-pk}}{4}$

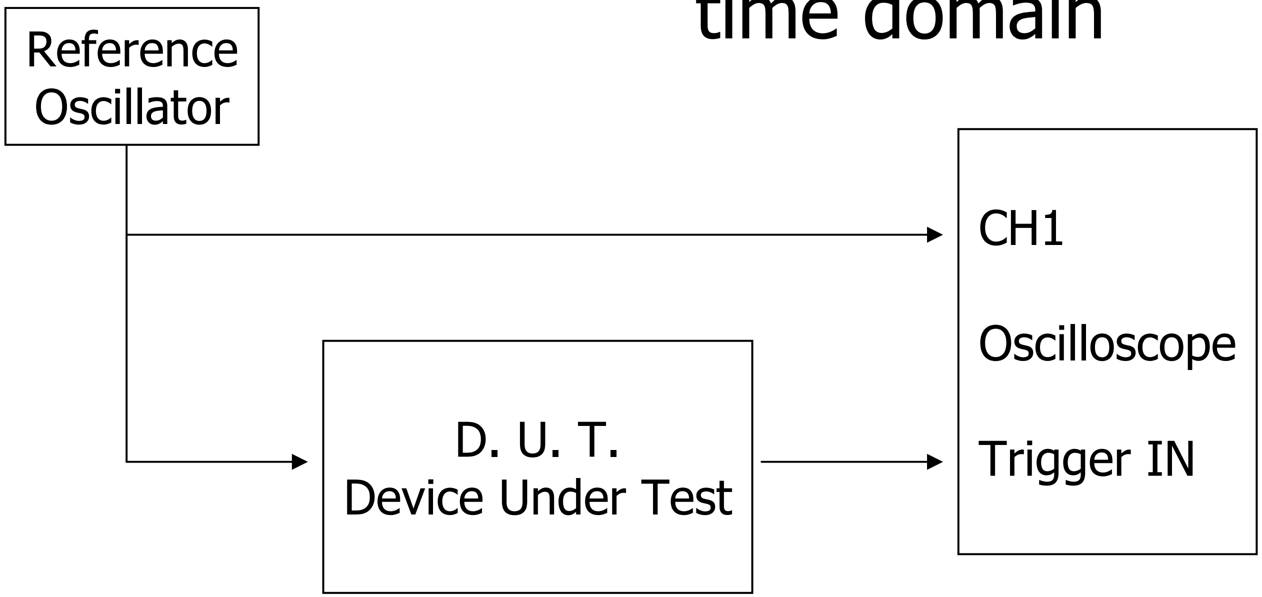
some examples

- a "3GHz scope" may be suitable to measure pulses with rise time of ≈ 110ps

- to observe a 50ps slope the scope needs to have BW>7GHz

Note: as the period of a 3GHz signals is 330ps, 110ps is less than half the period…

Jitter measurement techniques: time domain



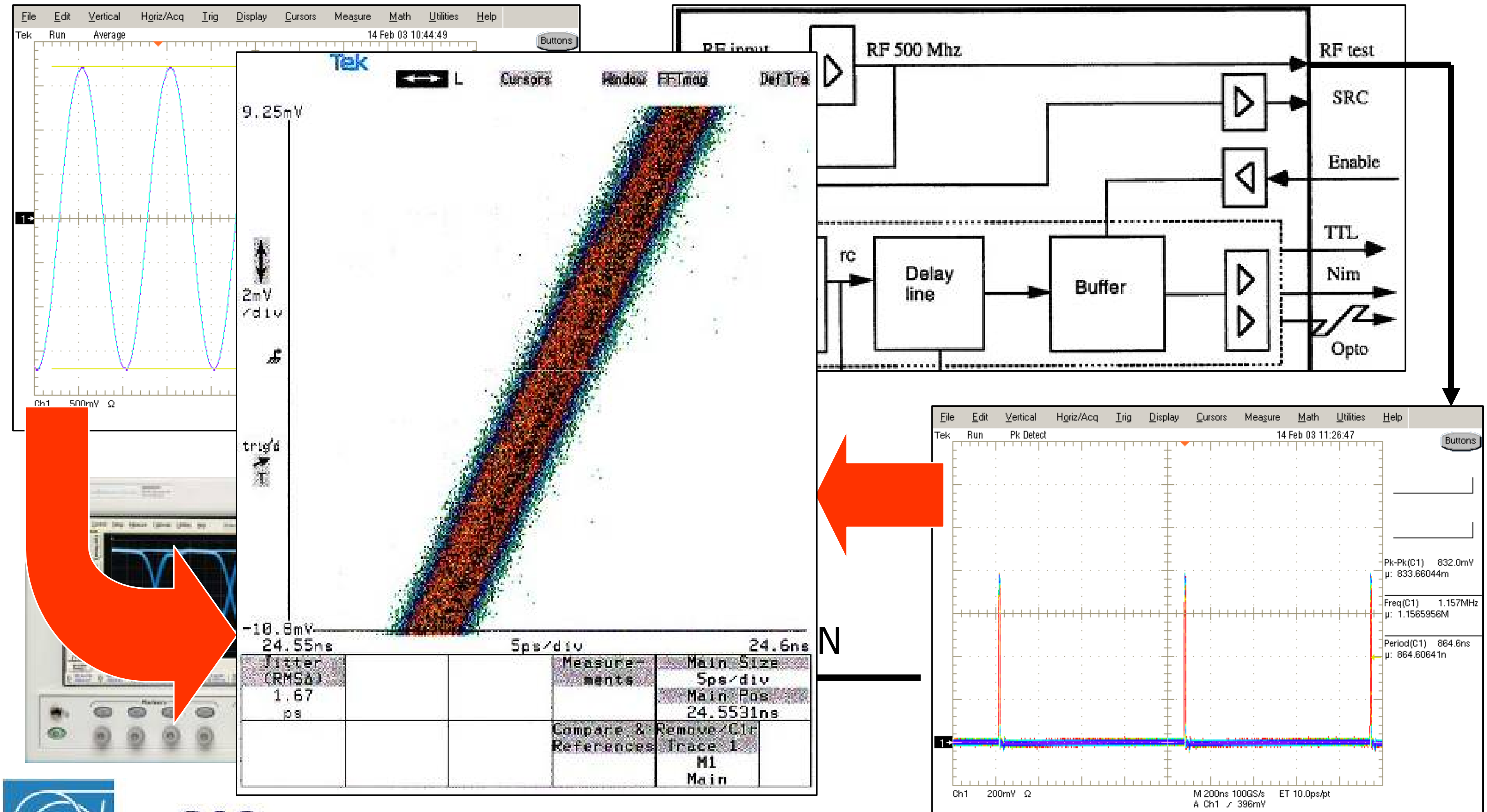
You are measuring the jitter of the DUT with respect to the Reference ($f_{TRIG}<f_{CH1}$)

Some examples

DUT	Jitter of …
- a counter/divider	terminal count (TC) wrt Ref
- a laser stabilization unit	synchronized laser pulses wrt Ref
- a transmission channel	received signal wrt transmitted
- a "LINAC"	bunch arrival time wrt RF

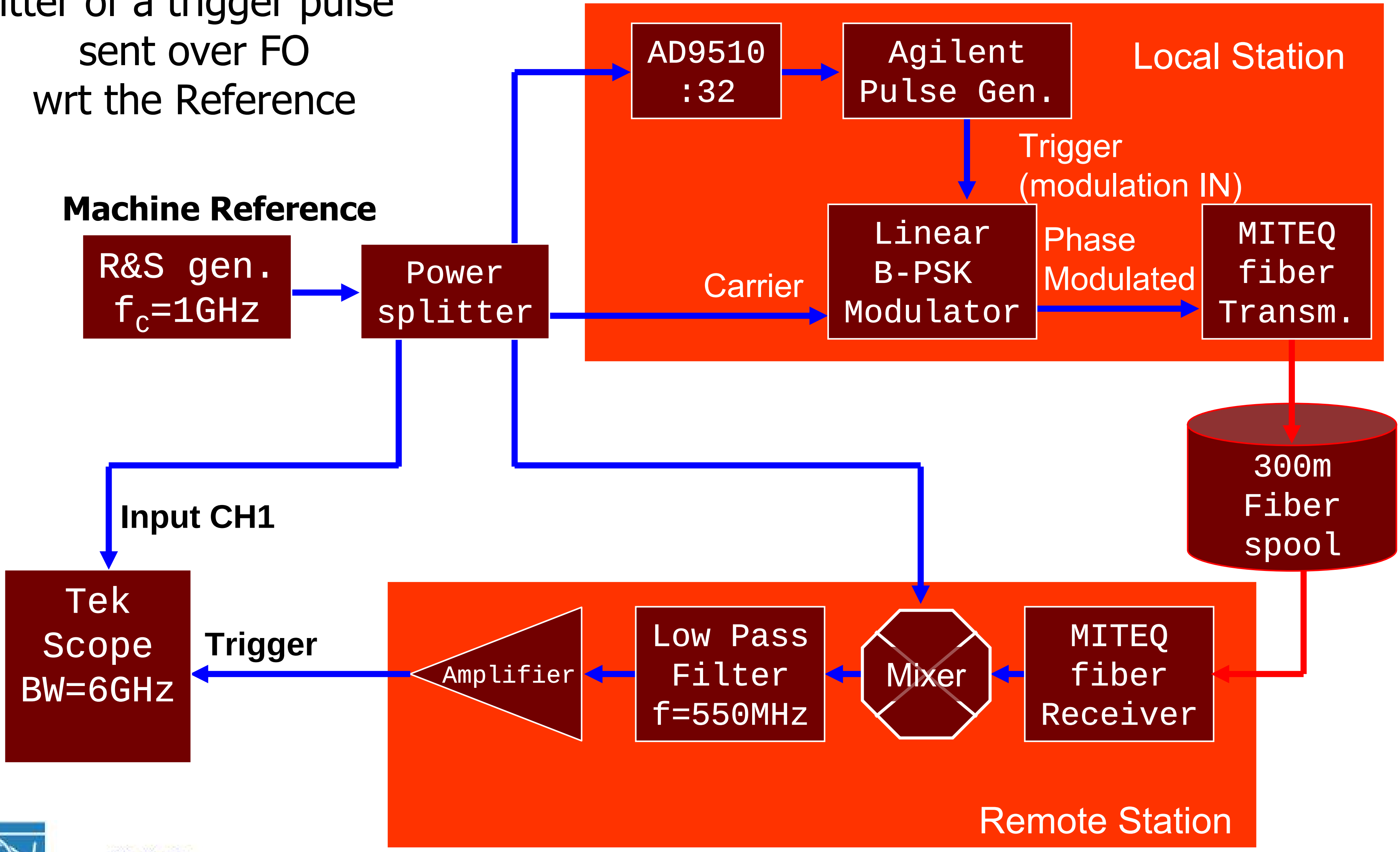
Jitter measurement techniques: time domain

Measuring the jitter of a synchronous counter



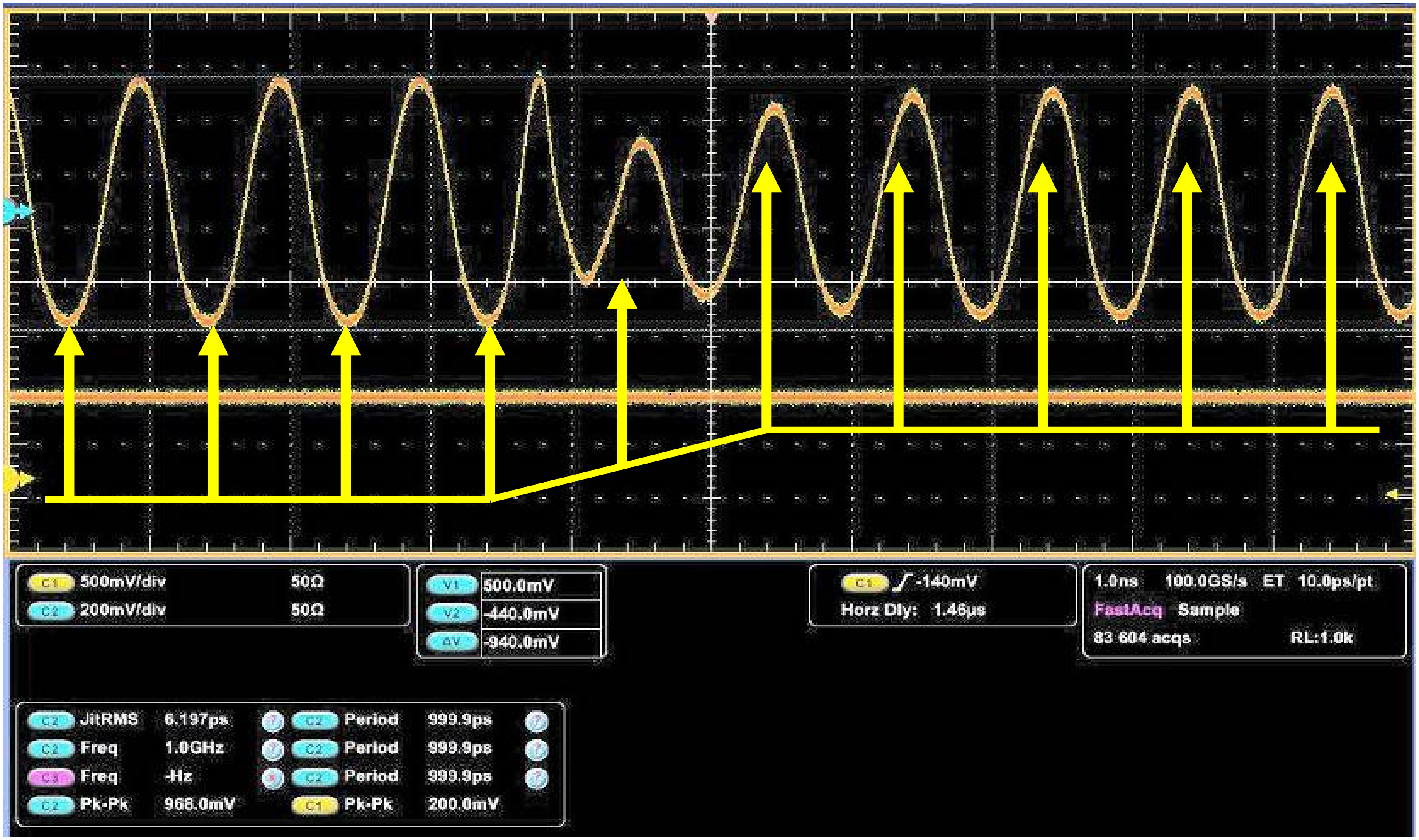
Jitter measurement techniques: time domain

Jitter of a trigger pulse
sent over FO
wrt the Reference



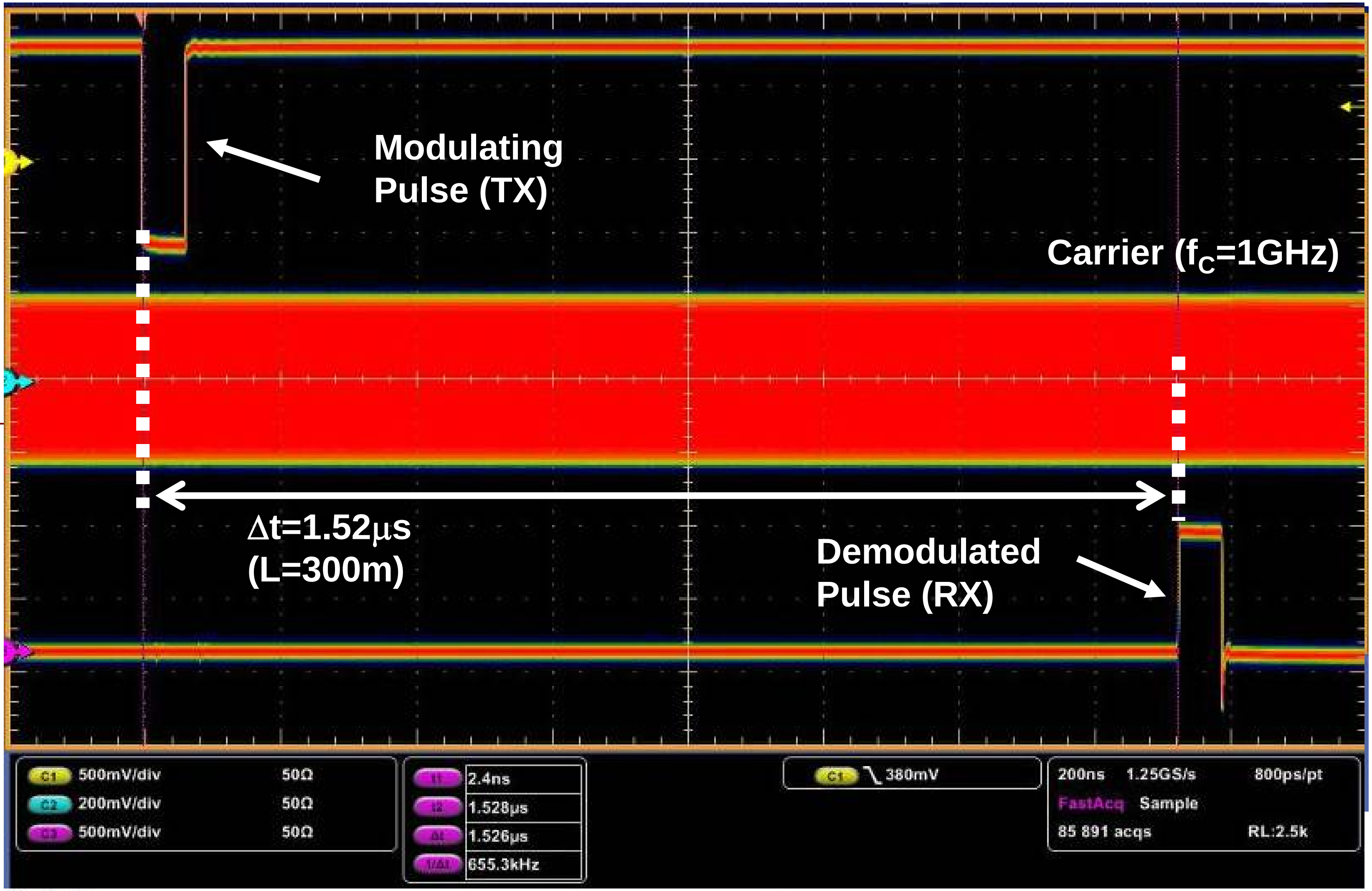
Jitter measurement techniques: time domain

Binary Phase Shift Keying (B-PSK) of the 1GHz carrier (0, π)

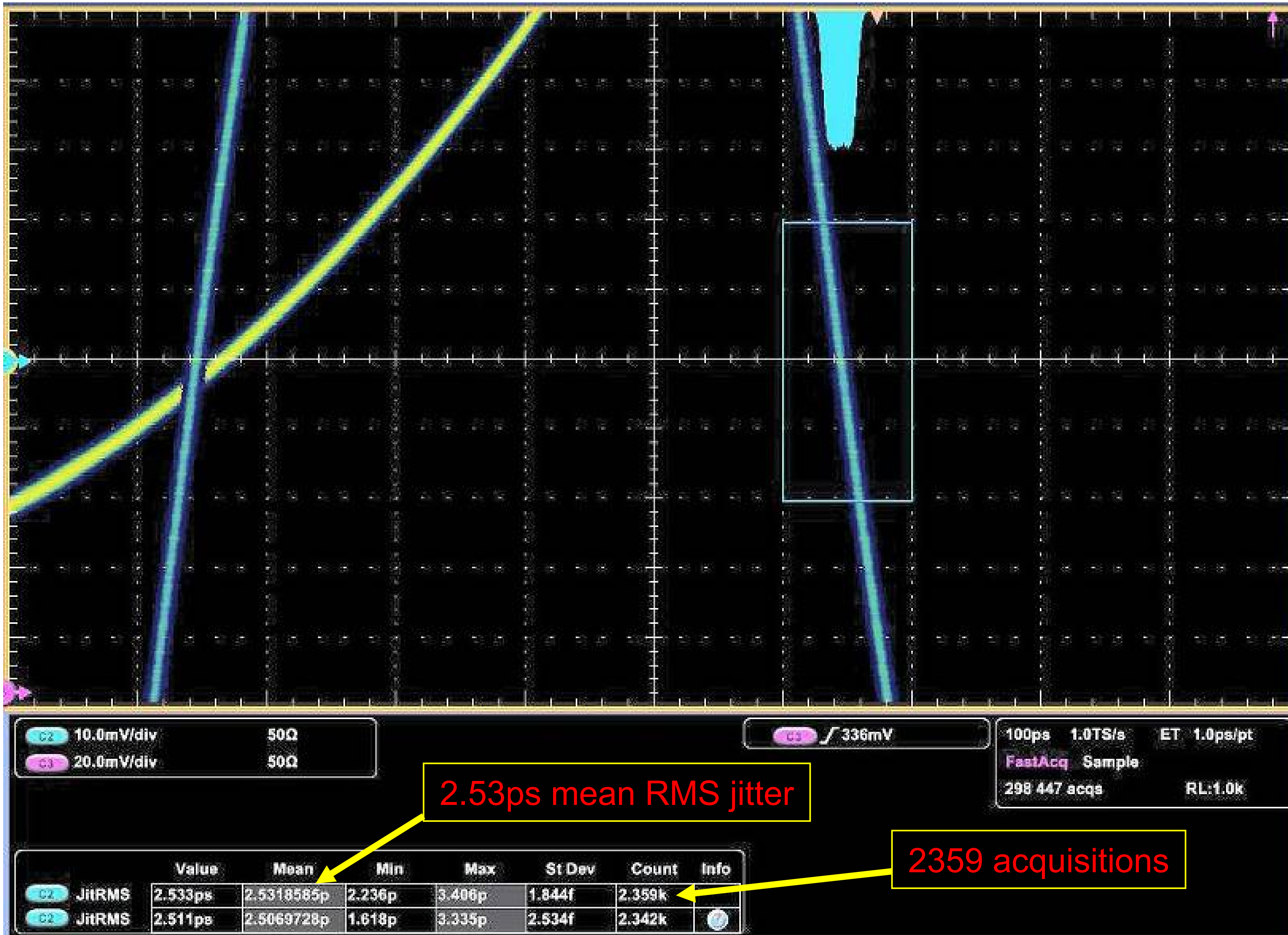


Jitter measurement techniques: time domain

Jitter of a trigger pulse sent over FO wrt the Reference



Jitter measurement techniques: time domain



Sources of jitter in a transmission system

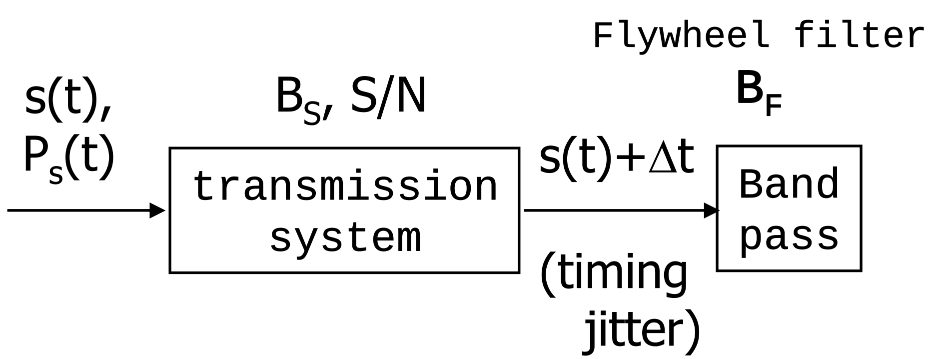
- S/N ratio
- jitter + drift in the remote station
- long term drift due to temperature etc.
- To estimate S/N contribution to jitter
- a simple model:

$$\Delta t \cong \frac{1}{B}\cdot\left(\sqrt{\frac{S}{N}}\right)^{-1}$$

$$\frac{S}{N} = \frac{P_s}{N_0 B} = \frac{P_S}{P_N}$$

$$\Delta t \cong \frac{1}{B_S}\cdot\left(\sqrt{\frac{P_S}{N_0 B_S}}\right)^{-1} = \sqrt{\frac{N_0}{P_S B_S}}$$

$$\Delta t \cong \frac{1}{B_S}\cdot\left(\sqrt{\frac{P_S}{N_0 B_F}}\right)^{-1} = \sqrt{\frac{N_0 B_F}{P_S B_S^2}}$$



P_s signal power
N_0 noise sp. density

Courtesy of:
prof. M. Vidmar
Uni LJ SLO

Technological issues: estimation of the *minimum jitter* for different transmission systems

- **COAX** *(broadband)*
  $B=1GHz$, $Ps=1mW$, $P_N=k_BTB = 4.14*10^{-12}W$
  $\Delta t = 10^{-9}\ SQRT(4.14*10^{-12}/10^{-3}) =$ **64.34fs**

- **COAX** *(narrowband)*
  $Bs=1GHz$, $B_F=10MHz$, $Ps=1mW$, $P_N= k_BTB_F= 4.14*10^{-14}W$
  $\Delta t = 10^{-9}\ SQRT(4.14*10^{-12}/10^{-3}) =$ **6.43fs**

- **FIBER, broadband non-coherent** (envelope)
  $B=10GHz$, $S/N \approx 90dB$†
  $\Delta t = 10^{-10} * SQRT(10^{-9}) =$ **3.16fs**

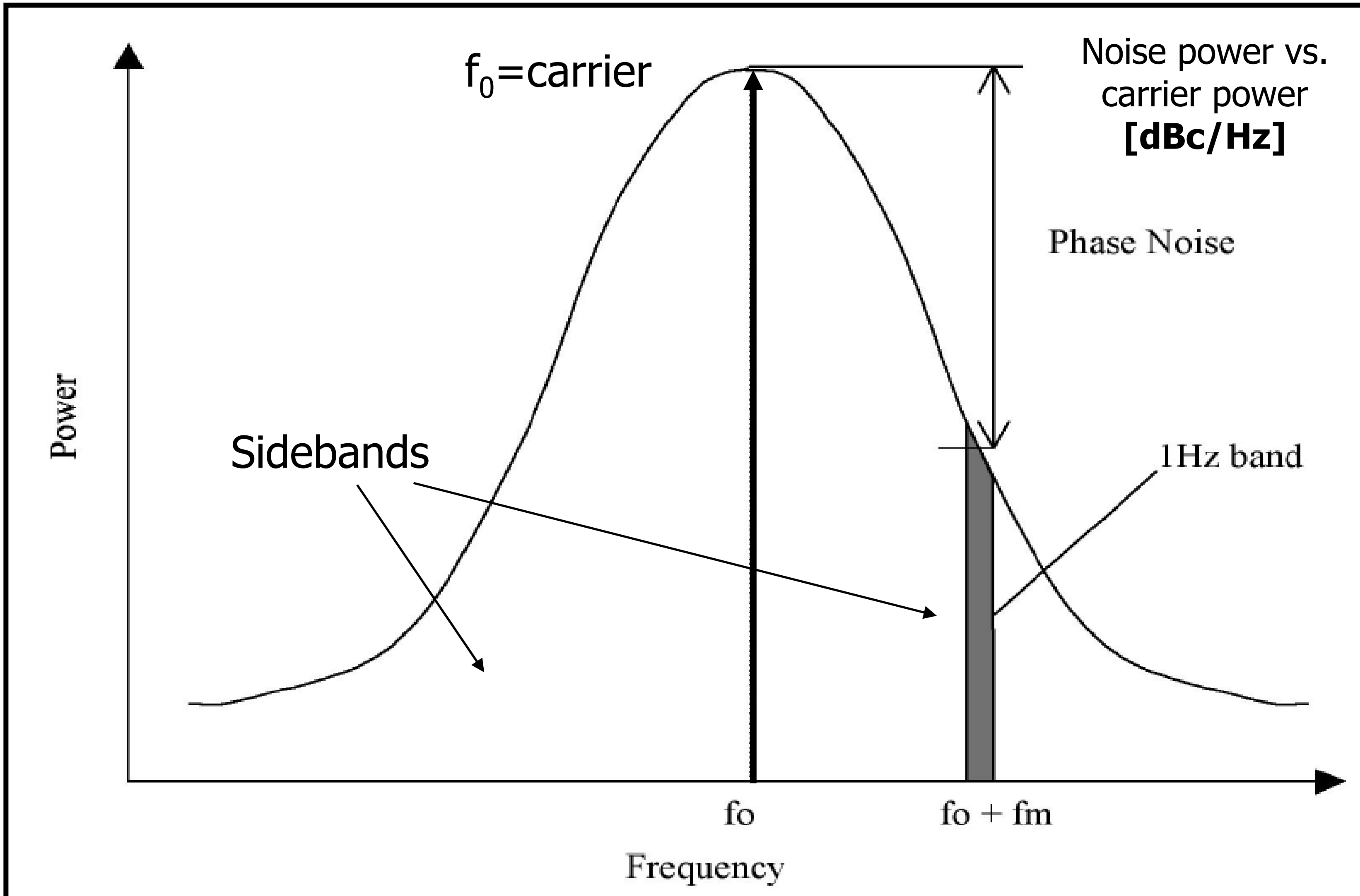
- **FIBER, coherent**
  $B_S=200THz$, $B_F=10GHz \rightarrow S/N \approx 60dB$
  $\Delta t = ½\ 10^{-14} * SQRT\ (10^{-6}) =$ **0.05fs**

†Comm Rx:P_{OPT}=-25dBm→(S/N)elec=20dB; if P_{OPT}=10dBm → 20+(35x2)=90dB

Frequency domain measurement techniques

- Jitter is also referred to as "phase noise"
- To reduce / eliminate jitter it is very important to investigate about its spectral components
- Phase noise is described by the its *power spectrum*
- Narrowband jitter contributors maybe easily identified (and eliminated):
  - 50Hz (and harm.) AC noise
  - piezo electric resonances
- Spectral measurements, based on coherent demodulation techniques, have a dynamic range much larger than time domain measurements

Frequency domain measurement techniques: phase noise plot **[4]**



Frequency domain measurement techniques: phase noise plot **[1, 4]**

There are five different noise types used to model time and frequency devices:

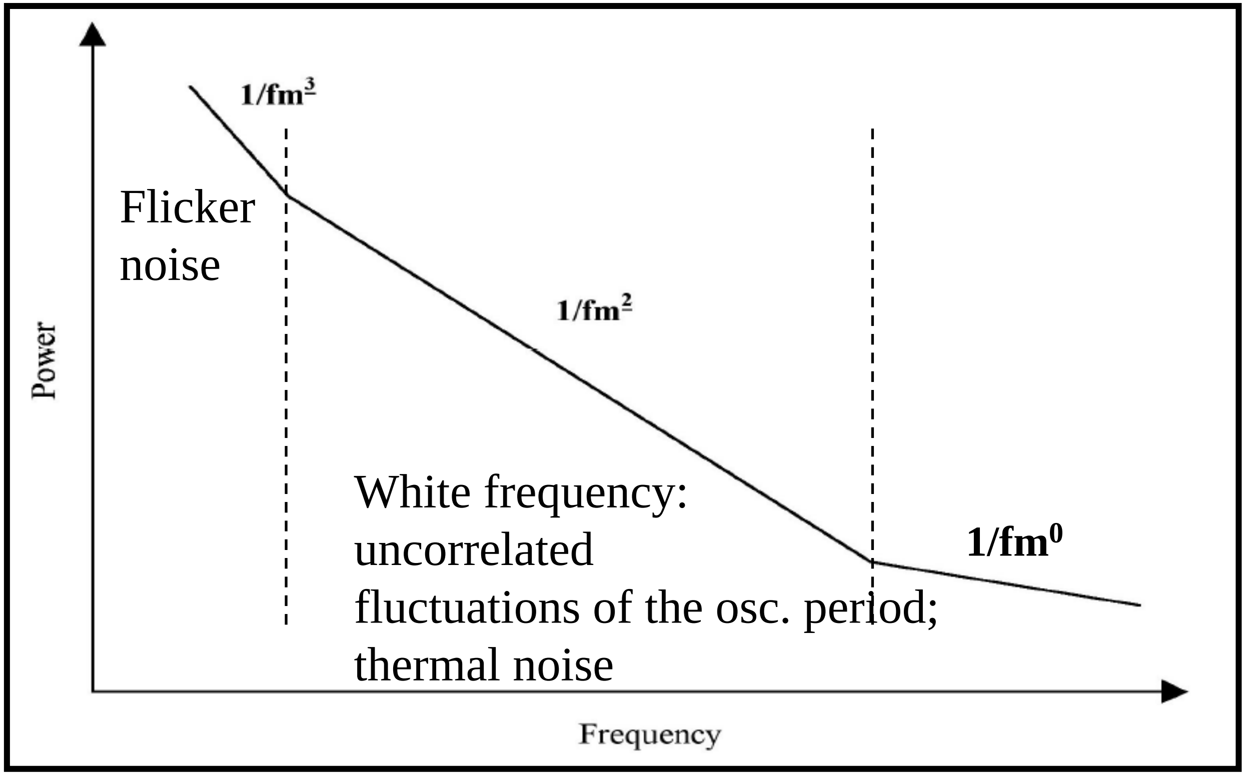
white-noise time or phase modulation (PM)

flicker or 1/f PM

white-noise (random and uncorrelated) frequency modulation (FM)

flicker-noise or 1/f FM

random-walk FM



Frequency domain measurement techniques: from phase noise to jitter **[4]**

The power level of the phase modulating noise (jitter producing) in the bandwidth of interest:

$$N = noise\_power[dBc] = \int_{f_{low}}^{f_{high}} \ell(f)\,df$$

This equation can be used to determine the RMS jitter caused by this noise power:

$$RMS\_PhaseJitter[rads] = \sqrt{10^{\frac{N}{10}} \cdot 2}$$

In time units:

$$RMS\_PhaseJitter[\sec] = \frac{Jitter(rads)}{2 \cdot \pi \cdot f_{osc}}$$

In linear terms:

BW=[10Hz to 10MHZ]

$$Jrms = \frac{1}{2\pi f_c}\sqrt{2\int_{10}^{10^6} L(f)\,df}$$

*there are available "on-line" calculators for converting Single Side Band (SSB) phase noise to jitter; see: **[5]**. **Disclaimer**: this calculator is intended to educate and illustrate only. Final designs should be proofed by appropriate simulation*

Frequency domain measurement techniques: phase noise plot [4]

Example [4]: the RMS jitter value for a 312.5-MHz oscillator can be calculated using the noise power values plotted above. Integrating the phase noise curve for the 12 kHz-to-20 MHz interval yields a figure of -63dBc

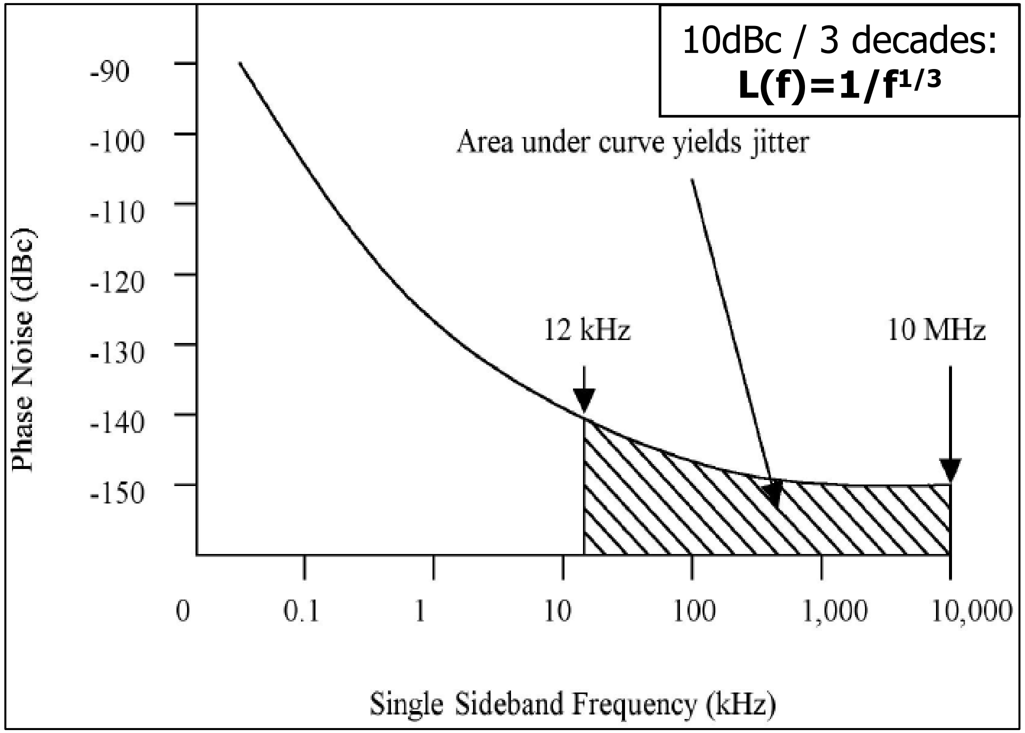
The same 312.5 MHz oscillator will have a typical *total jitter* value in the region of $5ps_{RMS}$

The RMS jitter calculation of $0.72ps_{RMS}$ is a small proportion of the maximum jitter

$$IntegrationOfCurve = \int_{12kHz}^{20MHz} £(f)df = -63dBc$$

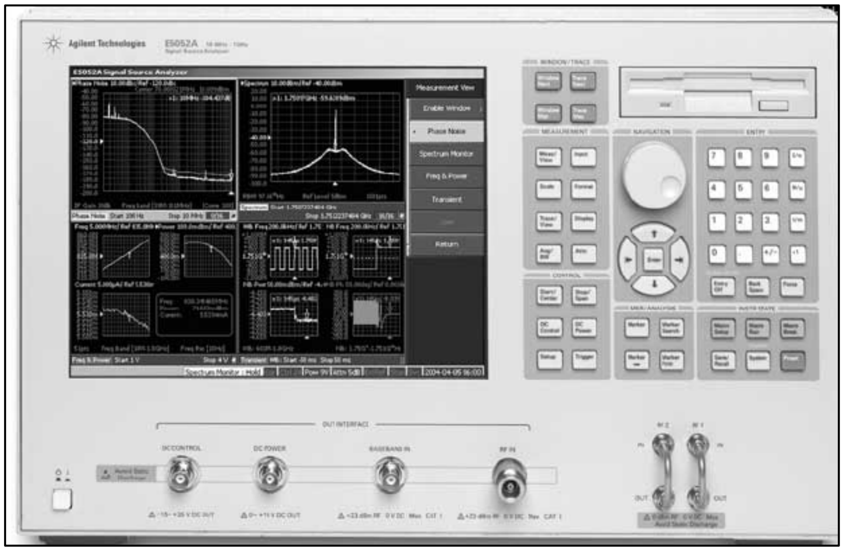
$$RMSJitter = \sqrt{10^{\frac{-63}{10}}} * 2 = 1415e^{-6} Radians$$

$$RMSjitter = \frac{1415e^{-6}}{2 * \pi * 312.5 * 10^{6}} = 0.72 ps(rms)$$



Frequency domain measurement techniques [6]

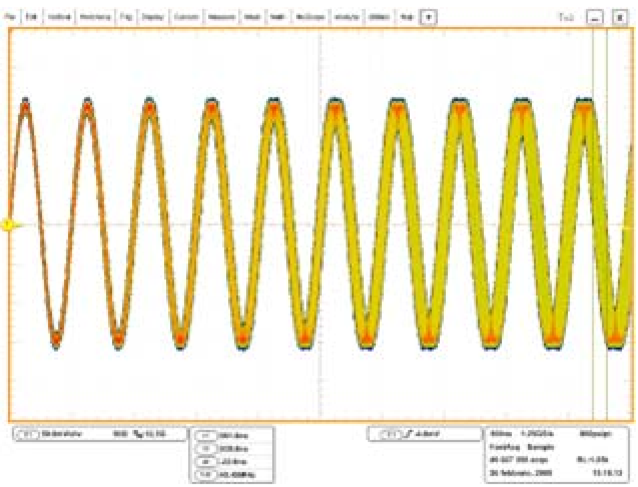
- There are dedicated instruments for “phase noise”
- Agilent Signal Source Analyzer (SSA) 5052A
- It measure the absolute jitter (wrt the internal reference)



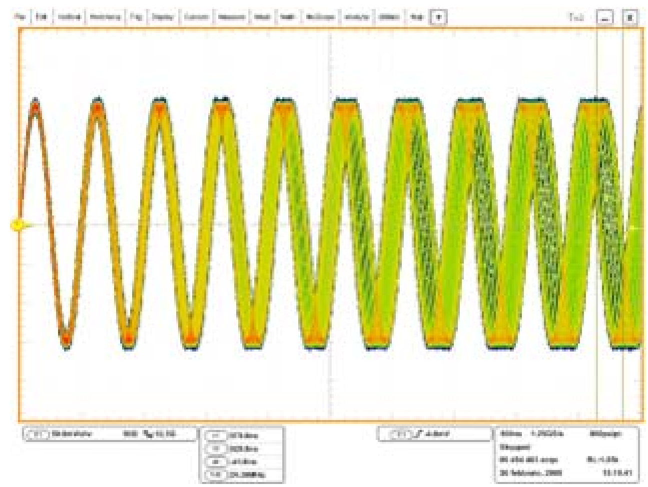
Major contributors to SSA’s breakthrough performance:
- the built-in **low-noise reference source**
- the **cross-correlation technique** that further reduces the test system noise.

The cross-correlation technique essentially cancels **noise by taking the vector sum** of the measurement results of two independent measurement channels.

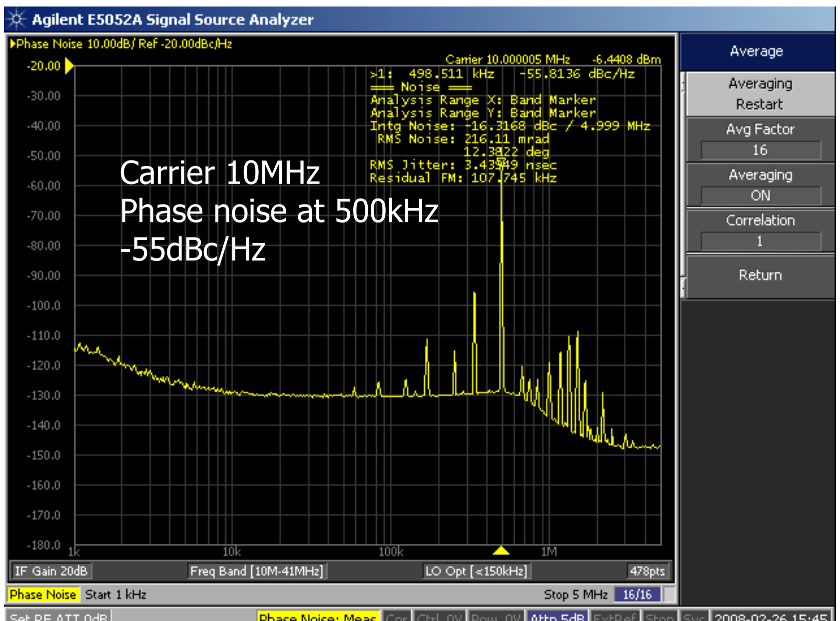
Frequency domain measurement techniques: phase modulated 10MHz carrier 500kHz modulating at different modulation depth

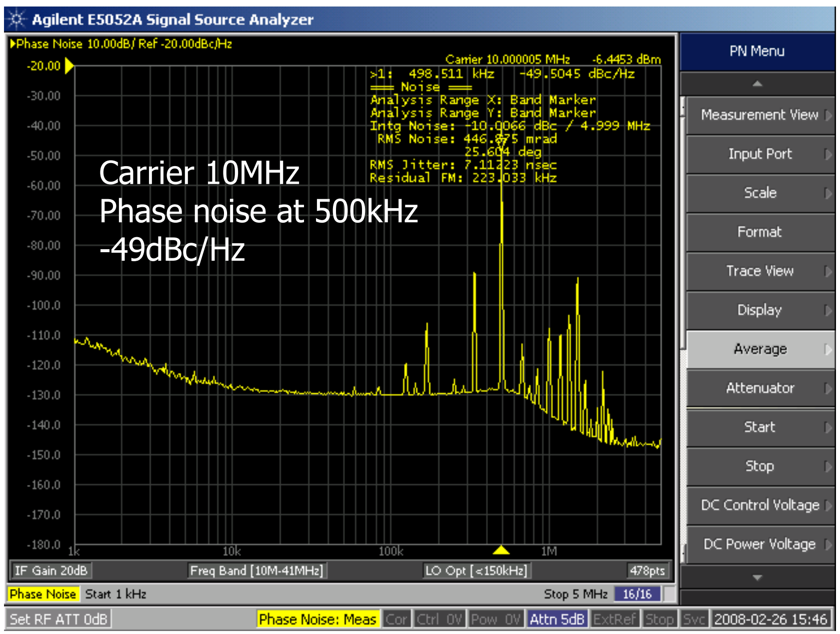


Mod. Index = 0.2rad



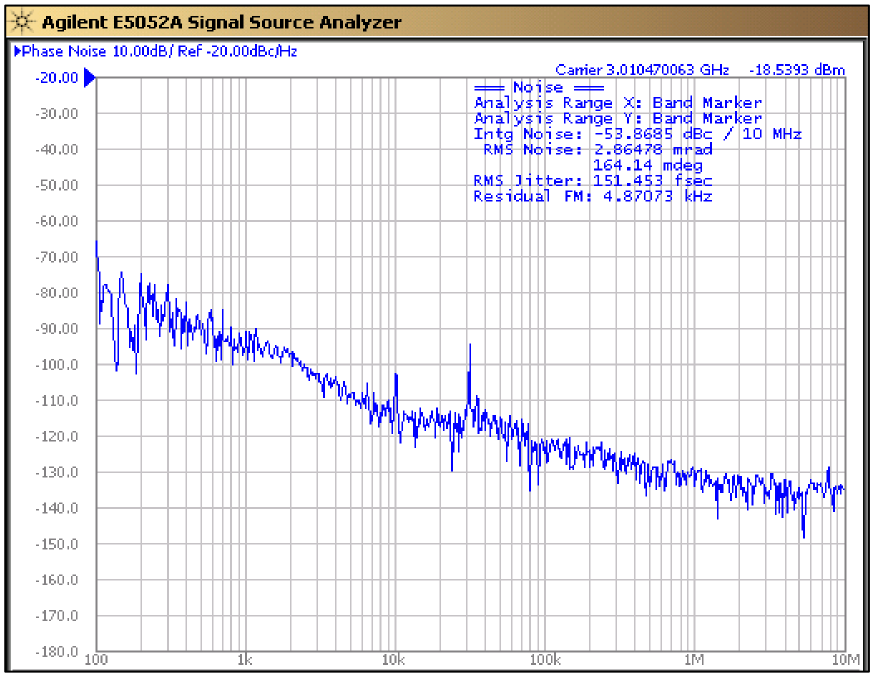
Mod. Index = 0.5rad





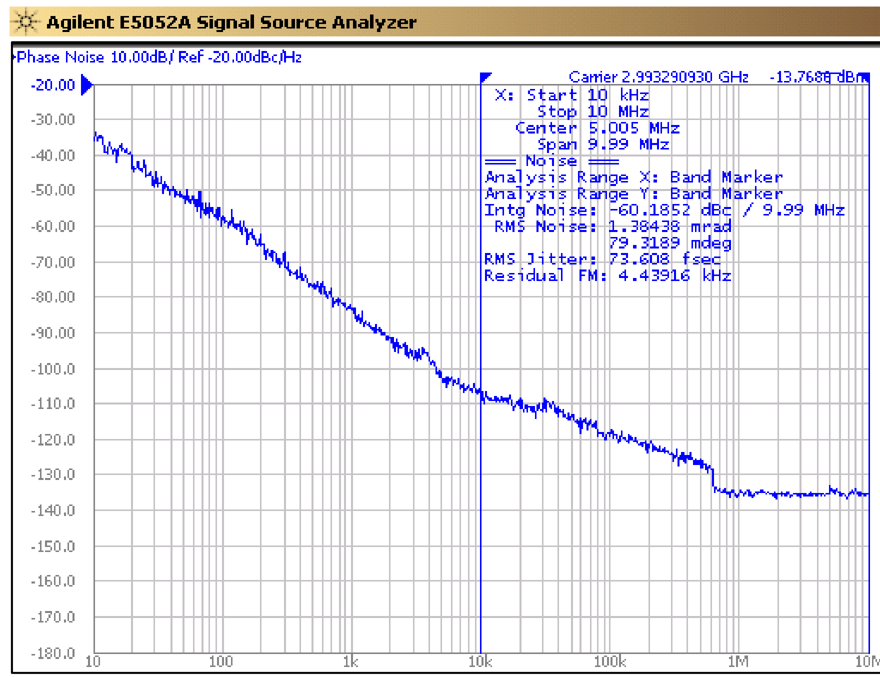
Frequency domain measurement techniques: measurement of phase noise of a 3GHz fiber laser oscillator

- When measuring the phase noise always check the integration bandwidth
- The instruments automatically locks to the highest signal at the input (carrier)
- Noise floor is as low as few fs



PN in [100Hz-10MHz] range

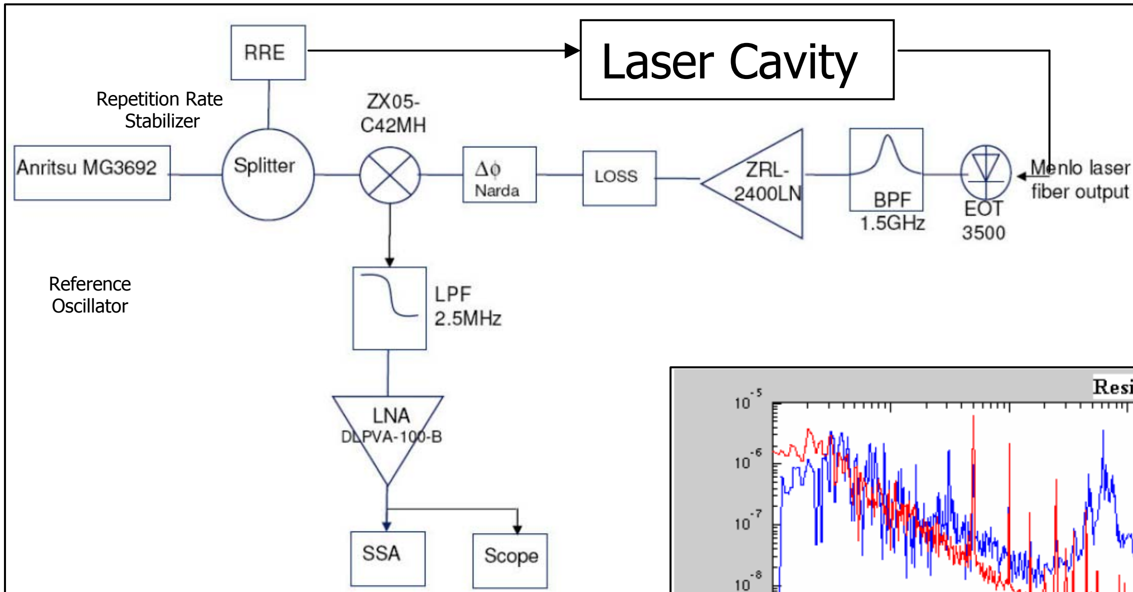
Measured value is **151.5fsec$_{RMS}$**

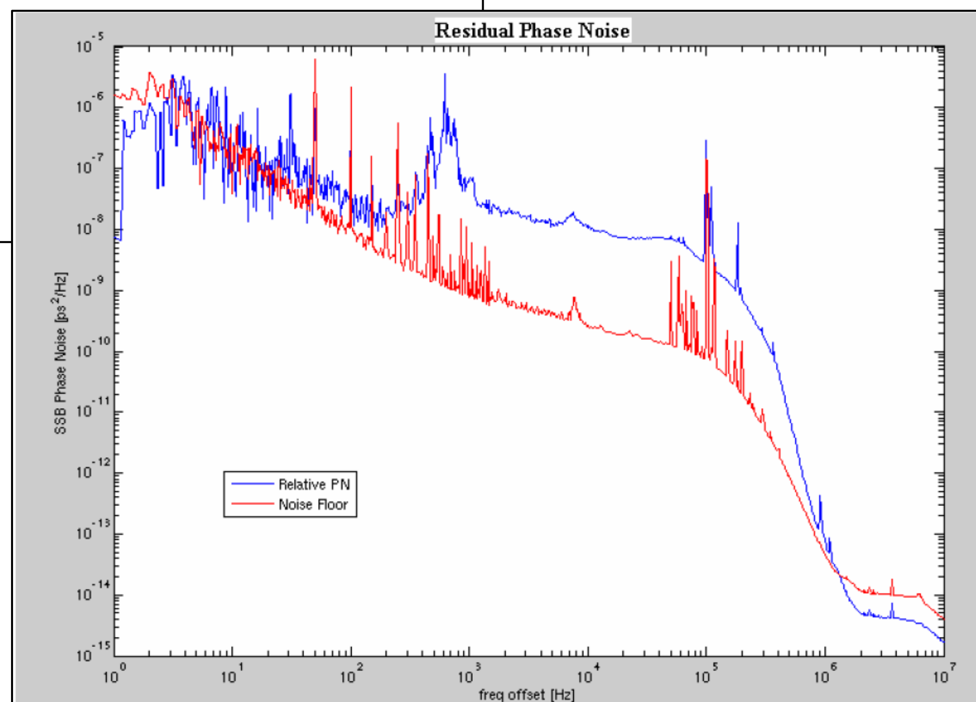


PN in [10kHz-10MHz] range

Measured value is **73.6fsec$_{RMS}$**

Frequency domain measurement techniques: relative phase noise measurement [7] fiber laser wrt RF reference oscillator





- The measure the phase noise wrt the reference
- The value of the relative jitter measured is $46fs_{RMS}$

Frequency domain measurement techniques

- The Australian company *Poseidon Scientific Instruments* (PSI) **[8]** proposes the ODIN series of products
- The **ODIN-320A** is a compact phase noise analyzer
- ODIN can measure in real time:

  - SSB Spectral Density of Phase fluctuations, L(f)
  - DSB Spectral Density of Phase fluctuations, S(f)
  - Spectral Density of Fractional frequency fluctuations, $S_y(f)$
  - Spectral Density of Amplitude noise fluctuations, M(f)
  - Phase Noise (PM) Cross Spectrum
  - Amplitude Noise (AM) Cross Spectrum
- Mainframe unit+receiver bay (s)

  - OR-102: 5MHz to 1GHz receiver
  - OR-101: 6 to 1 GHz receiver
  - OR1-105A: 18GHz receiver
  - OD-103: delay line

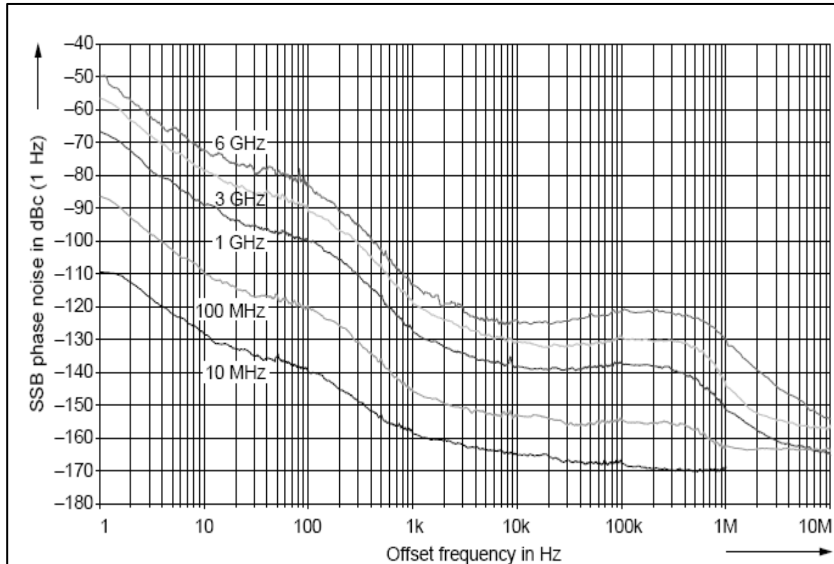
BST building blocks

block	*expected jitter*
▪ **Reference oscillator**	≈ps to 10fs
phase reference for all the sub-systems	
▪ **Master Time-base** (Event system)	≈ns to 10s ps
trigger	
bunch clock	
injection / extraction	
beam-line triggers	
▪ **Distribution system** (coaxial vs. Fiber Optic)	
phase reference	down to 10fs
Triggers	100ps to <10ps
▪ **Interface to the Control System**	

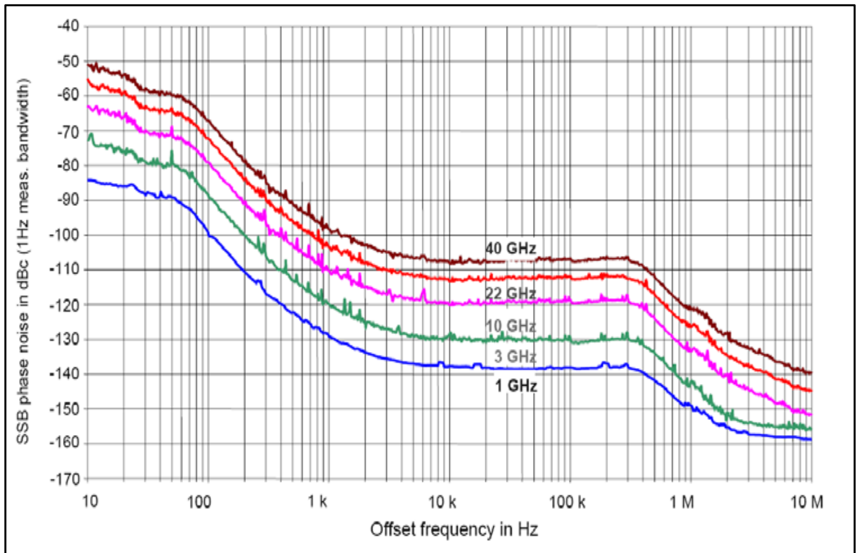
BST building blocks: Reference (μ-**wave**) Oscillator – R(**M**)O

- The RO is generating the machine RF
  - CW sinusoidal oscillator; P_{OUT}=15-20dBm; (ultra) low phase noise
  - S-band ($f_{RO}\cong$3GHz) RO for a LINAC
  - in 3GLS RO operates at a lower frequency (500MHz=$f_{S\text{-band}}$/6)
- The RO sets the ultimate performance of the whole BST in terms of jitter and stability
- Phase Noise (**PN**) for COTS *(commercial–off-the-shelf)* RO ranges from ≈ps down to ≈fs_{RMS}
  - *PN measurement BW* = 10Hz to 10MHz
- Also 2 ROs can be used
  - when $f_{RF\ LINAC} \neq n \times f_{RF\ RING}$
  - locked using the 10.7MHz *REF OUT / REF IN*
- *Remember: set the two ROs to the same RF when injecting*

BST building blocks: Reference μ-wave Oscillator
Rohde & Schwartz (R&S)



Typical SSB phase noise with internal reference oscillator
(with enhanced phase noise performance and R&S®SMA-B22 FM/φM modulator)



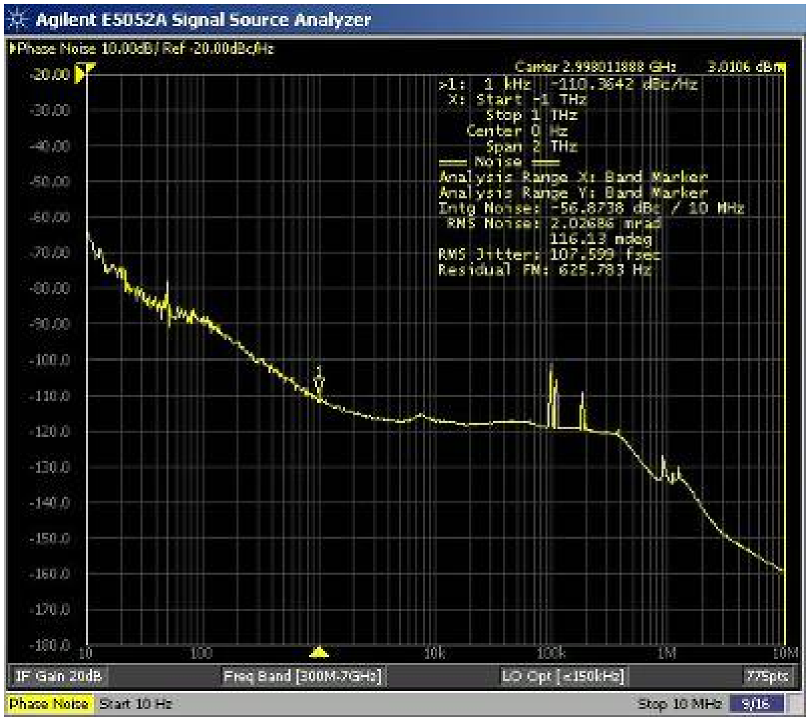
Single sideband phase noise for various frequencies (each with the R&S®SMF-B1 OCXO reference oscillator option)

R&S **SMA100A**
Fc=3GHz -> 52fs$_{RMS}$ [10-10MHz]

R&S **SMF100A**
Fc=3GHz -> 44fs$_{RMS}$ [10-10MHz]

CAS THE CERN ACCELERATOR SCHOOL

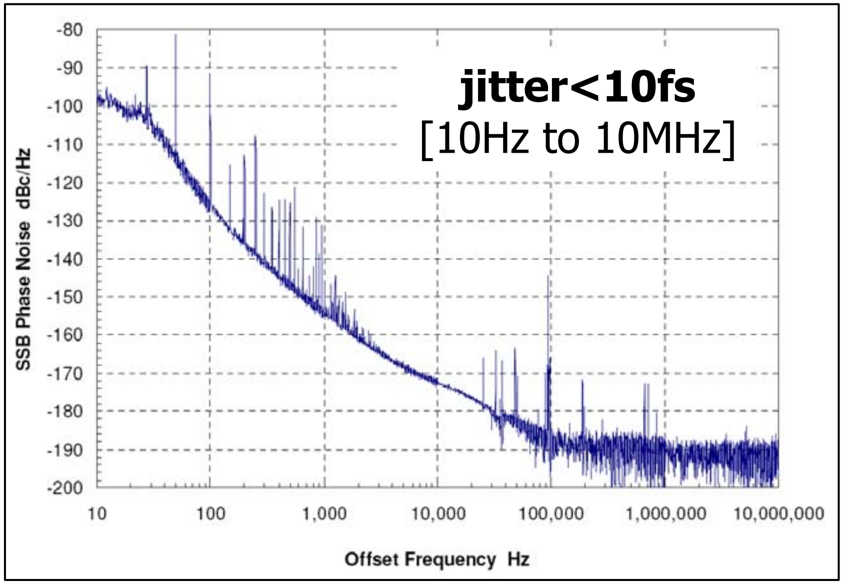
BST building blocks: Reference μ-wave Oscillator **Anritsu** MG37020A



Fc=3GHz 107fs$_{RMS}$ [10Hz-10MHz]

Fc=6GHz 85fs$_{RMS}$ [10Hz-10MHz]

BST building blocks: Reference μ-wave Oscillator
Poseidon Scientific Instruments (PSI) **[8]**
Sapphire Loaded Cavity Oscillator (SLCO)



Phase noise plot of the 6GHz Oscillator

Phase noise of the:
6GHz Oscillator
3GHz divider
(predicted and *measured)*

Offset	Predicted at 6.00 GHz	Measured at 6.00 GHz	Predicted at 3.00 GHz	Measured at 3.00 GHz
10 Hz	-97 dBc/Hz	~ -95 dBc/Hz	-102 dBc/Hz	-99 dBc/Hz
100 Hz	-126 dBc/Hz	-126 dBc/Hz	-132 dBc/Hz	-134 dBc/Hz
1 kHz	-155 dBc/Hz	-155 dBc/Hz	-157 dBc/Hz	-155 dBc/Hz
10 kHz	-174 dBc/Hz	-173 dBc/Hz	-166 dBc/Hz	-166 dBc/Hz
100 kHz	-185 dBc/Hz	-185 dBc/Hz	-170 dBc/Hz	-174 dBc/Hz
1 MHz	-188 dBc/Hz	-188 dBc/Hz	-171 dBc/Hz	-176 dBc/Hz
10 MHz	-188 dBc/Hz	-189 dBc/Hz	-172 dBc/Hz	-177 dBc/Hz

BST building blocks: Reference μ-wave Oscillator comparison table

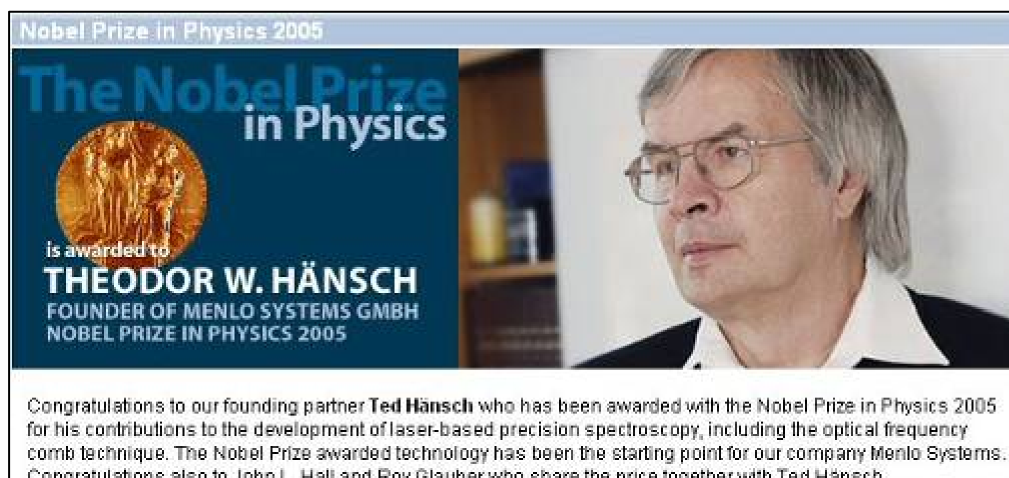
Phase noise comparison chart

generator	carrier freq [GHz]	dBc/Hz	offset from carrier 10	100	1.000	10.000	100.000	1.000.000	10.000.000	jitter [fs] 10-10M	jitter [fs] 100-10M	Phase jitter [deg] 10-10M	Phase jitter [deg] 100-10M
PSI - SLCO OSC	6,00	guar	-77	-120	-150	-168	-180	-180	-180	9,226	0,292	0,0199	0,00063
PSI - SLCO OSC	6,00	typ	-84	-126	-155	-173	-185	-185	-185	4,18	0,152	0,009	0,00033
PSI - DIVIDER	3,00	guar	-92	-122	-149	-162	-167	-170	-170	4,28	0,89	0,00463	0,00097
PSI - DIVIDER	3,00	typ	-97	-130	-155	-165	-174	-176	-176	2,246	0,432	0,00243	0,00046
R&S SMF100A	3,00	meas	-72	-100	-130	-138	-138	-150	-158	44	8,39	0,0484	0,009
	10,00	meas	-63	-80	-110	-120	-120	-133	-152	57,6	20,38	0,207	0,0733
R&S SMA100A	3,00		-78	-88	-118	-131	-129	-143	-157	52,1	25,7	0,0563	0,0277
Anritsu 37 020	3,00	computed	-65	-90	-110	-117	-120	-135	-160	117,1	47	0,126	0,051
	3,00	meas ST							5052A	107,6	74	0,116	
	3,00	*data sheet*	*-60*	*-88*	*-104*	*-108*	*-107*	*-105*	*-110*	*975*		1,05	
Aeroflex 2040	1,00	meas	-75	-95	-122	-144	-145	-145	-153	126,5		0,045	

Technological trends: let’s go optical

- the minimum achievable jitter
- the physical extension of new 4GLSs (from 100s m up to km)
- availability of suitable **Optical** Master Oscillator
- well suited for synchronizing key comp. (lasers)
- use of already developed Optical Comm. components
  - *stay optical as far as possible*
- optical cables: economically viable and “*easy to route*”
- Also: <u>**2005 Nobel Laureate in Physics**</u>
  John L. Hall and **Theodor W. Hansch:**

“for their contributions to the development of laser-based precision spectroscopy, including the optical frequency comb technique”



BST building blocks:
Optical Master Oscillator (OMO)

- OMO is a Fiber laser operating at λ=1550nm
- It is able to provide sub-ps (150fs$_{RMS}$ typ.) optical pulse train
- Repetition rate of the opt. pulses: 40MHz up to 250MHz
- **Passively mode locked** (PML) fiber laser
- The gain in the cavity is provided by fiber amplifier (pump diode)
- Phase lock the OMO to the RMO to stabilize the lower part of PN spectrum
- A number of commercial products are already today available:
  - **MENLOSYSTEMS** *http://www.menlosystems.com/*
  - **ONEFIVE** *http://www.onefive.com/femtosecond.htm*
  - **TOPTICA PHOTONICS** *http://www.toptica.com/page/products.php*
- **Harmonically Mode Locked (HML)** fiber laser are also available
- They may operate at higher repetition rate (40GHz)
- Typically used as Optical Telecom system test-bed
- Therefore the PN spectrum has contribution at each revolution harmonics
- Suitable for narrow band timing clients

BST building blocks: Optical Master Oscillator R&D at RLE/MIT, MA USA **[9]**

(Research Laboratory in Electronics)

- The group is leaded by prof. F. X. Kaertner
- This group is involved in the deployment of **Pulsed Optical Clock** systems to **fs accelerator timing** (namely the **fs Machine Reference generation**) since the very beginning (effort started by DESY, H. Schlarb and A. Winter)
- Their efforts are not only devoted to the implementation and full in-field characterization of a sub-10fs RMS jitter fiber laser (OMO), but also in the study and implementation of so-called *optical stabilized links* (**fs Machine Reference distribution**)
- Elettra is participating to this effort to implement the FERMI Optical Timing system
- The sub-10fs RMS target has been already demonstrated in the laboratory for:

  - the OMO and the stabilized links ()

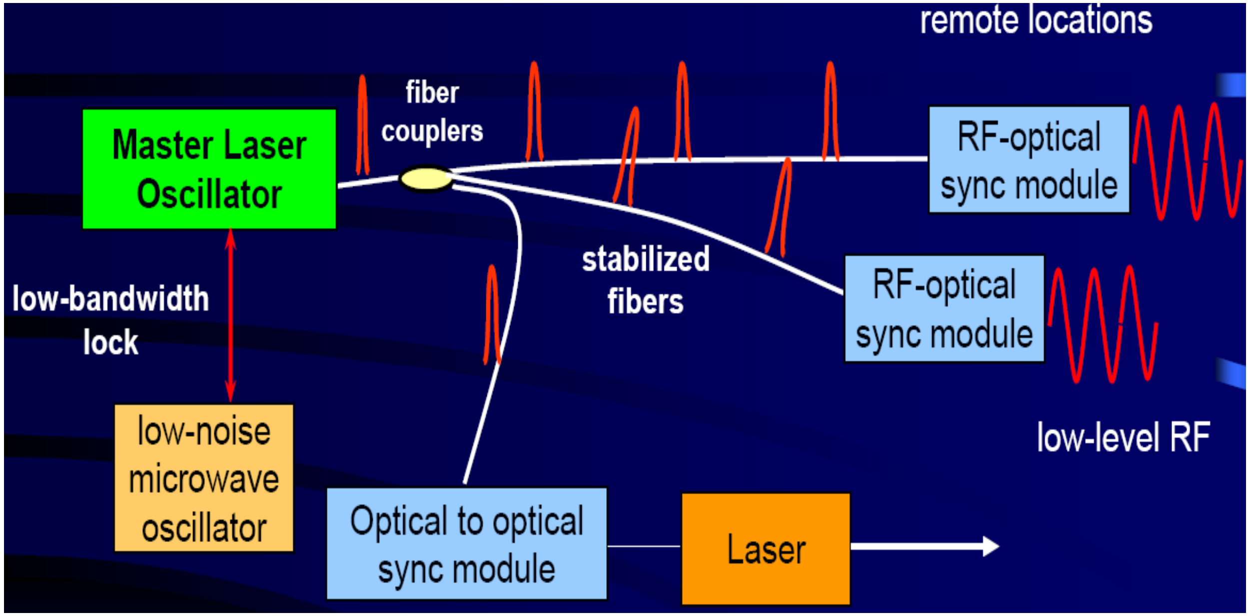
  - both for jitter and long term stability ()

  - RF extraction from the optical pulse stream (DESY)

BST building blocks: Optical Master Oscillator R&D at RLE/MIT, MA USA

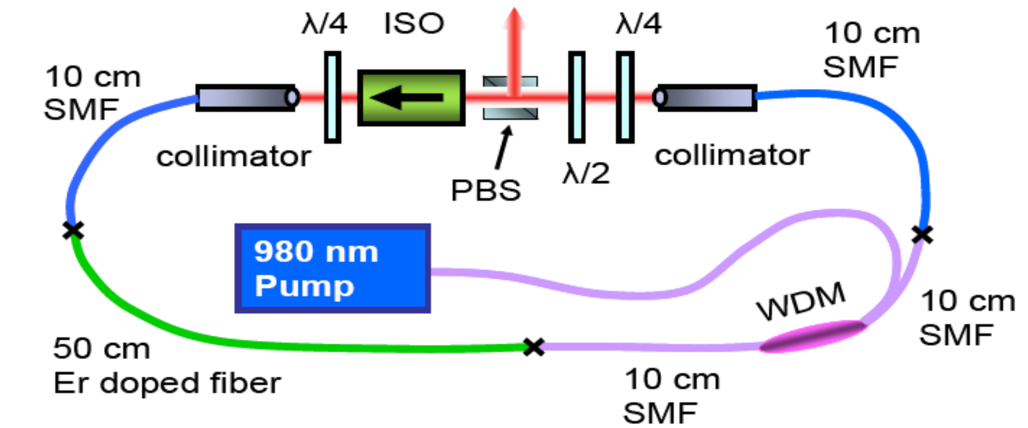
- The **Pulsed Optical Clock** concept is based on the generation of an optical pulse train in a fiber laser, phase-locked to a μ-wave reference osc.
- The optical pulses (λ=**1550nm**) are then distributed to the timing clients by means of stabilized single-mode fiber optic links
- At the (remote) client, the optical pulses

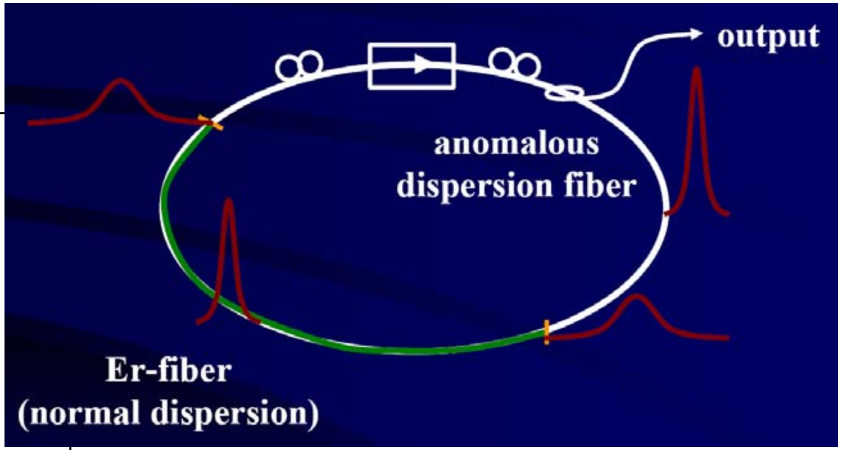
- directly used **as optical** (cross-correlation synchronization of a remote laser oscillator)
- converted **O/E** for the synchronization of **electrical** clients



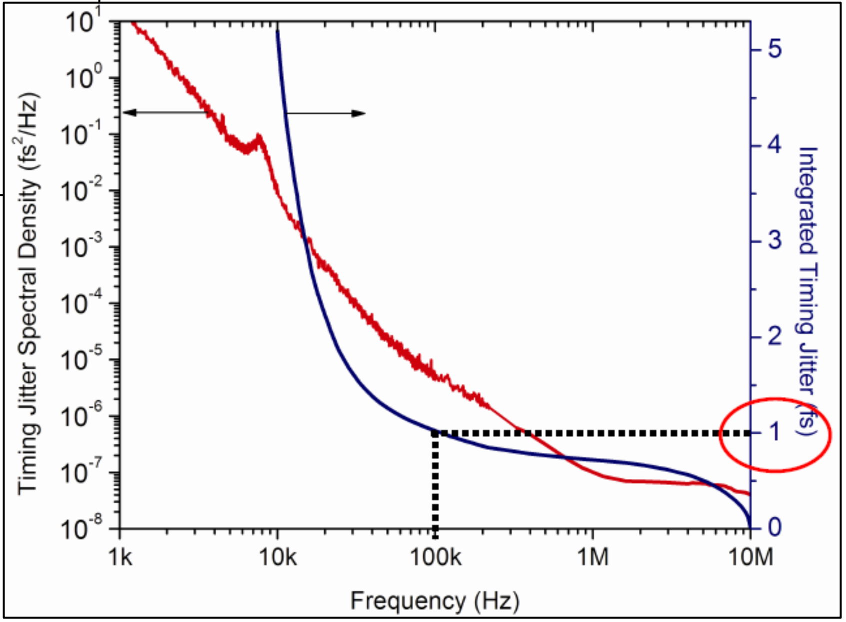
BST building blocks: Optical Master Oscillator R&D at RLE/MIT and DESY

- The 200MHz *soliton* fiber laser **[10, 11]**



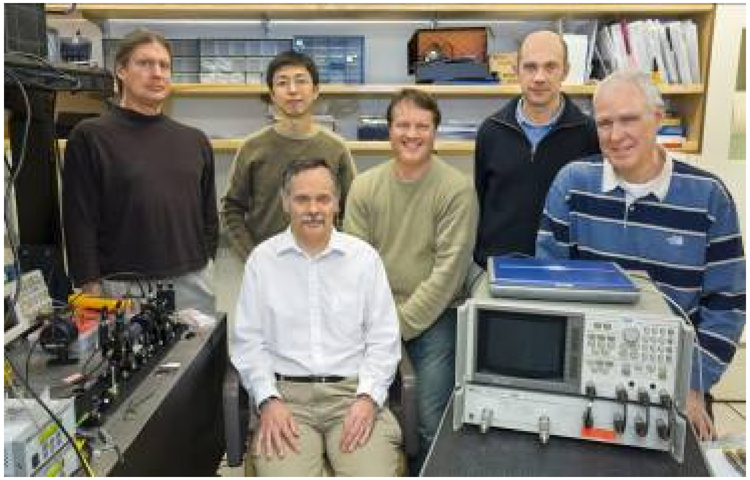


- 200 MHz fundamentally mode locked soliton fiber laser
- 167 fs pulses
- 40mW output power

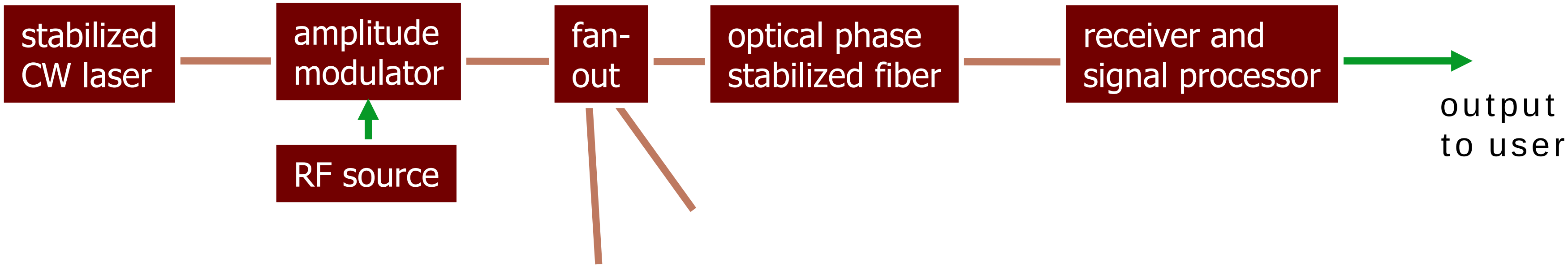


Pulse builds up by itself from noise (ns-psdomain)
A saturable absorber ensures higher intensity <=> higher gain
Given constant intra-cavity energy, the stable solution is a localized solution (a single pulse)
In the femtosecond domain:
Dispersion and **Nonlinearity** dominate pulse shaping and, for soliton-like pulses, balance these effects ➔ very short pulses

BST building blocks: CW Optical Clock R&D at LBNL, CA USA **[12, 13]**

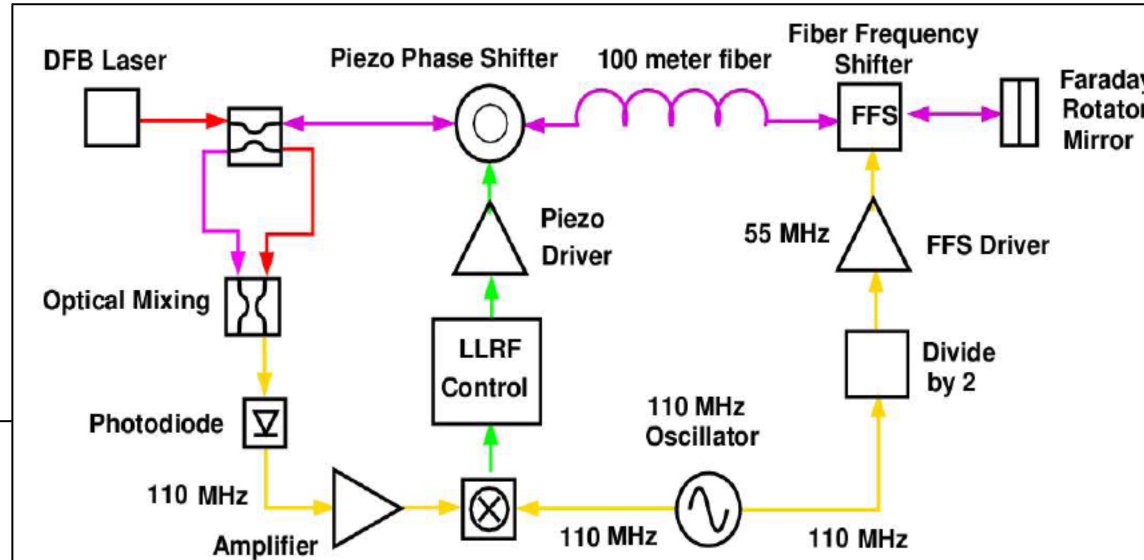


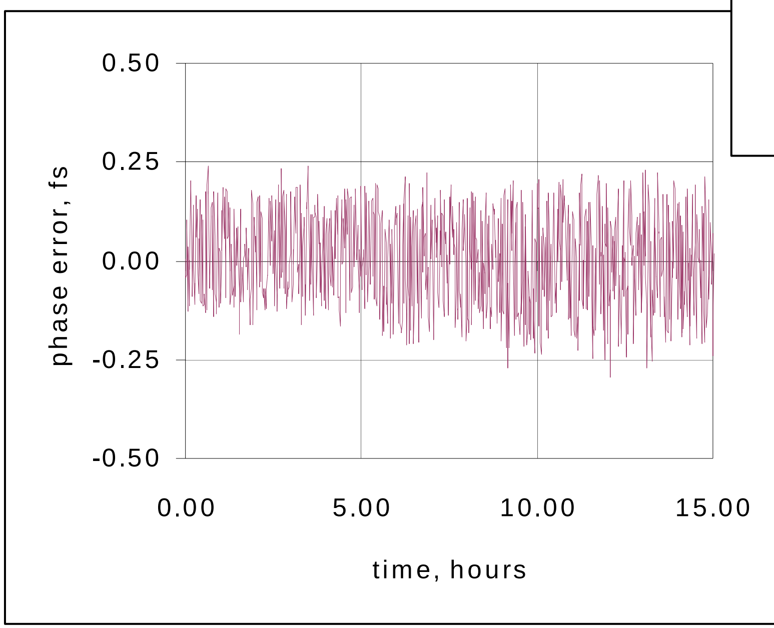
- At Lawrence Berkeley National Laboratory (LBNL) there is a parallel effort on going (J. Staples and R. Wilcox principal investigators) to distribute the RF (optically) with fs jitter
- To adopt a long coherence Continuous Wave (CW) laser at 1550nm
- To transmit the RF (3GHz) by amplitude modulating the CW laser
- To stabilize the FO links using the Optical Mixing concept working at the optical carrier frequency (200THz for λ=1500nm)



BST building blocks: CW Optical Clock R&D at LBNL, CA USA **[12, 13]**

Heterodyning preserves phase relationships
1 degree at optical = 1 degree RF
1 degree at 110 MHz = 0.014 fsec at optical
Gain 10^5 leverage over RF-based systems in phase sensitivity





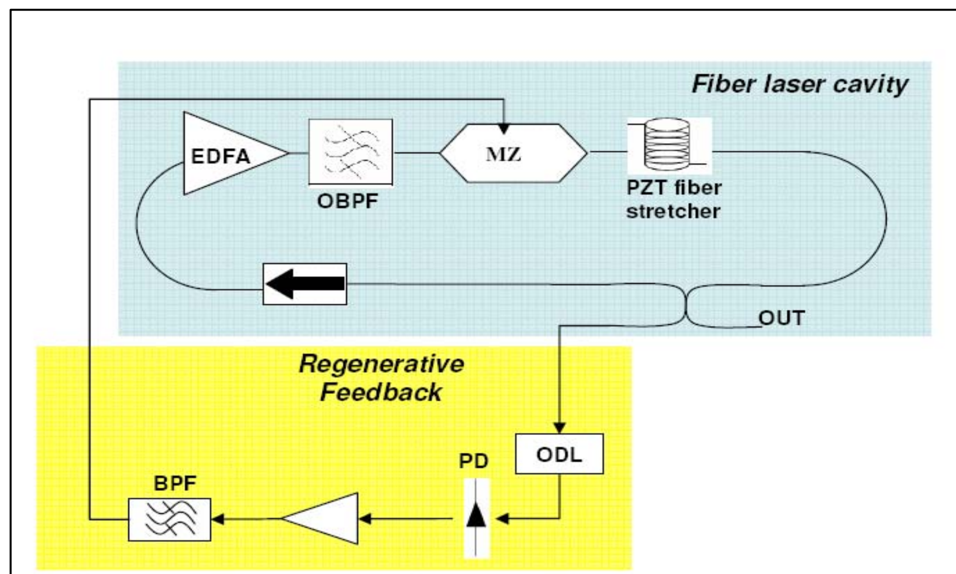
Phase jitter of 110MHz = phase jitter of 200THz
Time jitter is divided by frequency ratio

480ps RMS at 110MHz = 0.26fs RMS at optical
Loop bandwidth is ~2kHz

BST building blocks: Optical Master Oscillator (OMO)

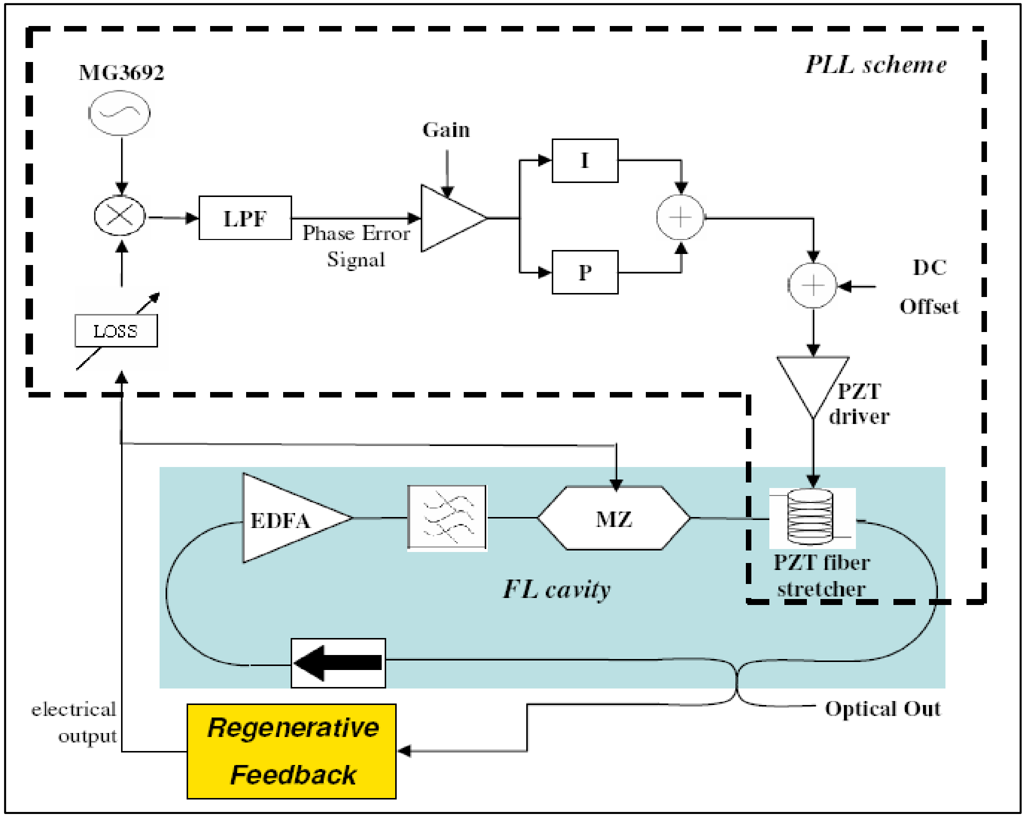
- Harmonically mode locked laser developed by CNIT Pisa IT **[14]**
- Fully characterized at Elettra in the frame of the EUROFEL Design Study (FP6 EU) **[15]**
- The high repetition rate is actually an Harmonic of the cavity round trip frequency

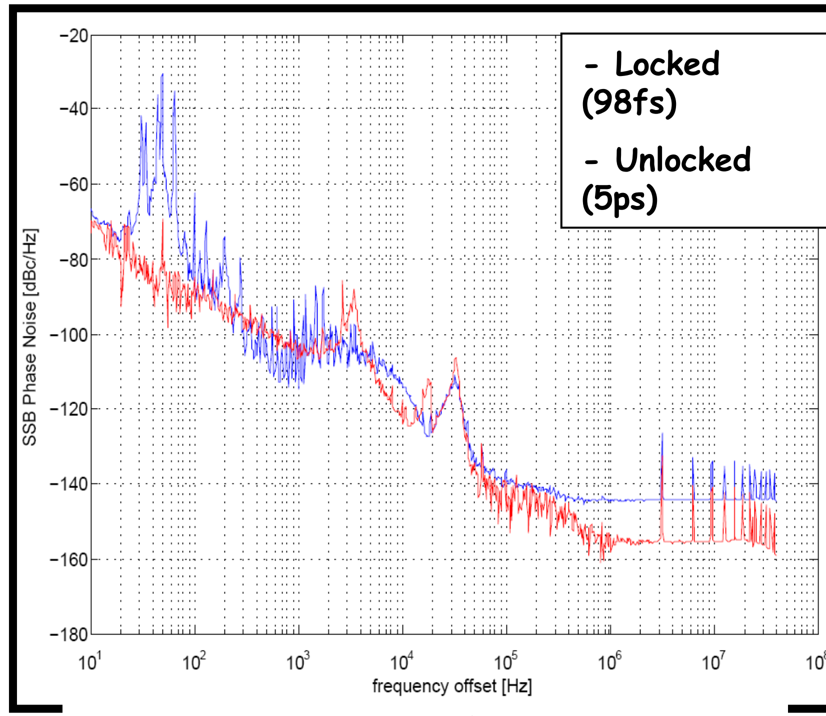
Repetition Rate	2997.924 MHz 2998.010 MHz
Pulsewidth FWHM	< 10 ps
Spectral Bandwidth	< 0.9 nm in the range 1540-1570 nm
Average Power	> 7 dBm on optical port 1 > -3 dBm on optical port 2
Electrical Clock Power	> 15 dBm on electrical port 1 and 2
SNR	> 50 dB
Side Band Suppression	> 70 dB
Polarization State	Linear (aligned to slow axis)
Jitter	< 200 fs in 100Hz-10MHz
Linewidth	10 kHz in regenerative configuration
Operating Voltage	100-240 V AC
Operating Temperature	5-25 °C
Power consumption	< 250 W
Warm-up time to stabilization	2 hours



BST building blocks: Optical Master Oscillator (OMO)

- Phase locking to an external μ-wave oscillator **[15]**

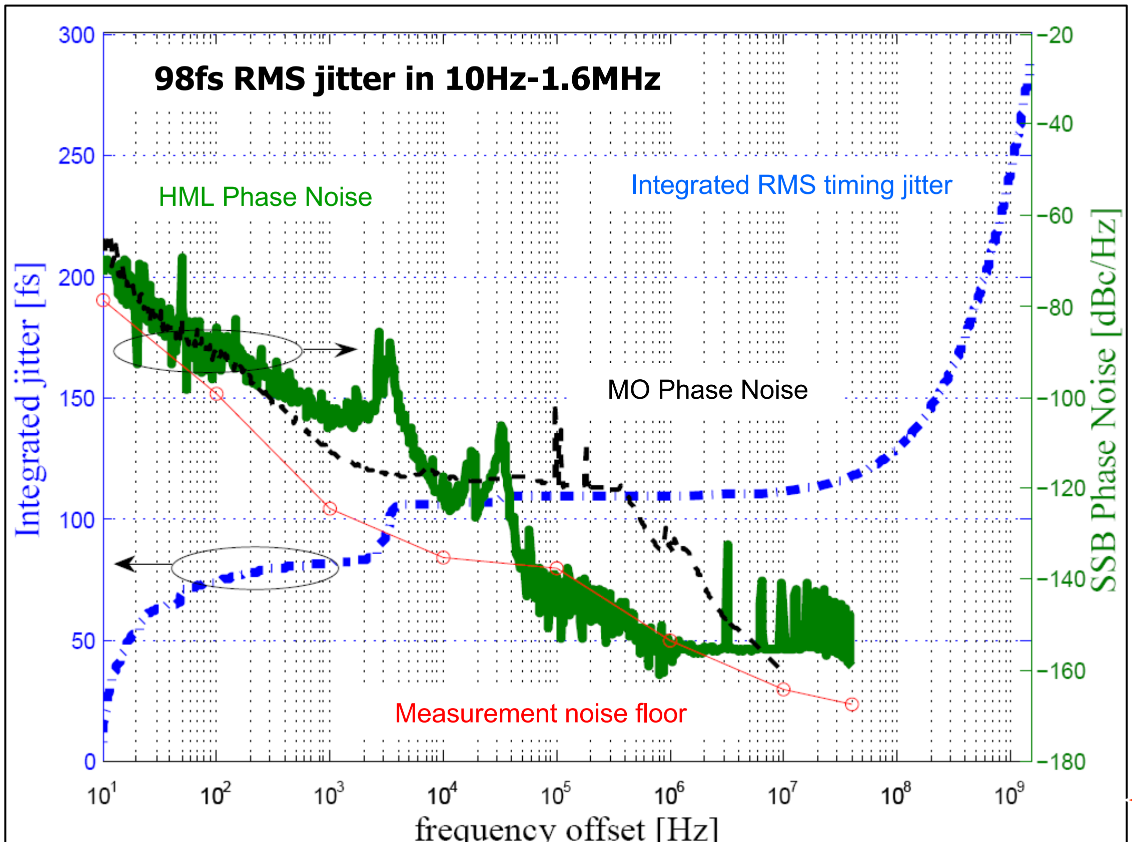


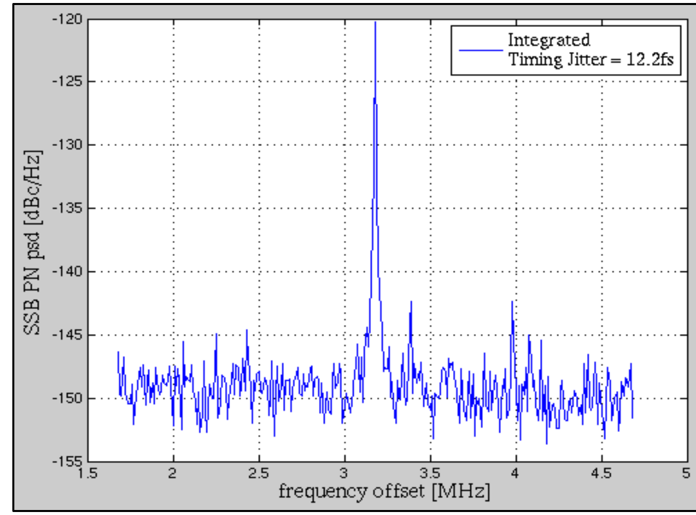


Comparison between locked (red) and unlocked (blue) HML fiber laser

BST building blocks: Optical Master Oscillator (OMO)

- Harmonically mode locked laser **[15]**
- In HML there are 2 kind of PN contribution:
  - Correlated Noise (up to $f_0 / 2$)
  - Uncorrelated Noise (up to $f_{RR} / 2$): ***Supermodes***





1st supermode normalized power spectral density (**12.2fs**)

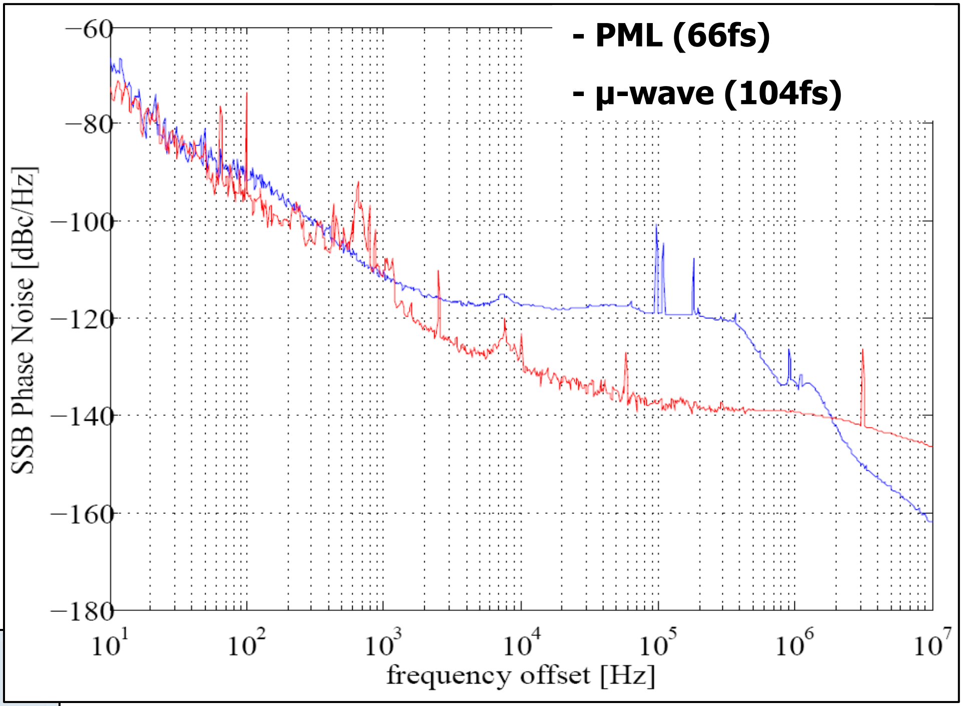
Left axes: integrated RMS timing jitter up to 1.5GHz (blue). Right axes: SSB phase noise of the HML laser (green) and the reference MO (black). Interpolated SSA phase noise floor (red).

BST building blocks: Optical Master Oscillator (OMO)

- Passively mode locked (PML) fiber laser by MENLOSYSTEMS gmbh **[16]**

TECHNICAL SPECIFICATIONS

	TC780-150
Output Port 1: Wavelength	780 nm +/- 10 nm
Average Output Power	> 60 mW
Pulse Width	< 150 fs
Spectral Width	> 10 nm
Output Port 2: Wavelength	1560 nm +/- 20 nm
Average Output Power	> 30 mW
Output port 1,2	Freespace, linear polarized
Repetition Rate	100 MHz +/- 1 MHz, fixed
Repetition Rate Instability	+/- 10 Hz (freerunning, over 1 h)
Line Voltage	100/115/230 VAC
Line Frequency	50/60 Hz
Power Consumption	120 VA
Storage Temperature	10 °C - 40 °C

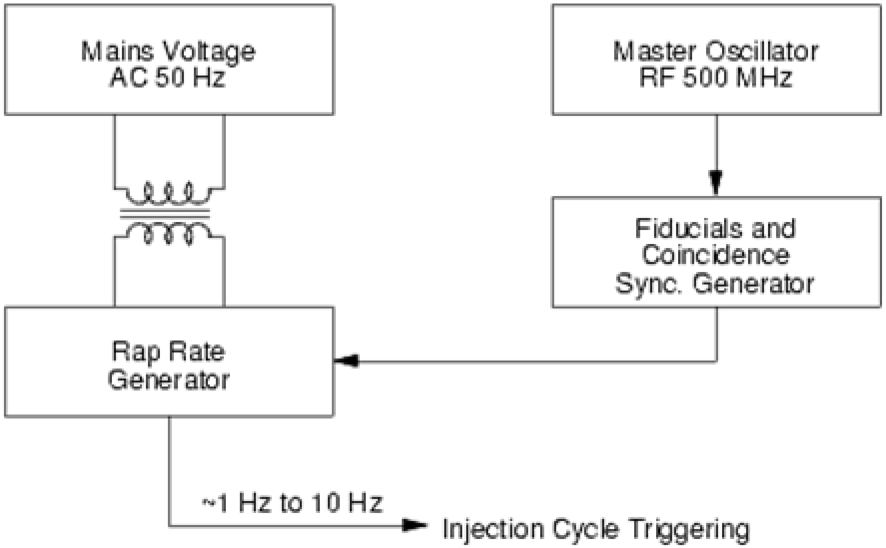


The PML fiber laser shows performances in term of timing jitter even better than the curent RMO in term of timing jitter.

Locking reduces the drift of the Repetition Rate

BST building blocks: Event system [17]

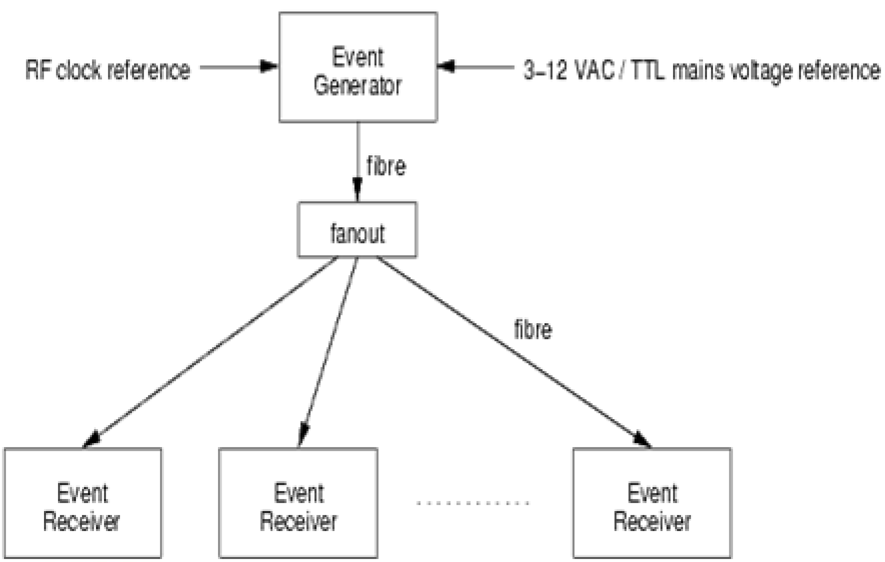
- Developed at ANL (Argonne Nat. Lab., USA)
- Expanded at SLS
- Finally commercially available at: Micro-Research Finland Oy [17]
- Synchronization to the mains voltage is required to keep the beam intensity and quality stable on consecutive shots
- Synchronization to the coincidence frequency (Booster / Storage Ring) is necessary to be able to target the electrons of a single trigger to a specific RF bucket in the storage ring.

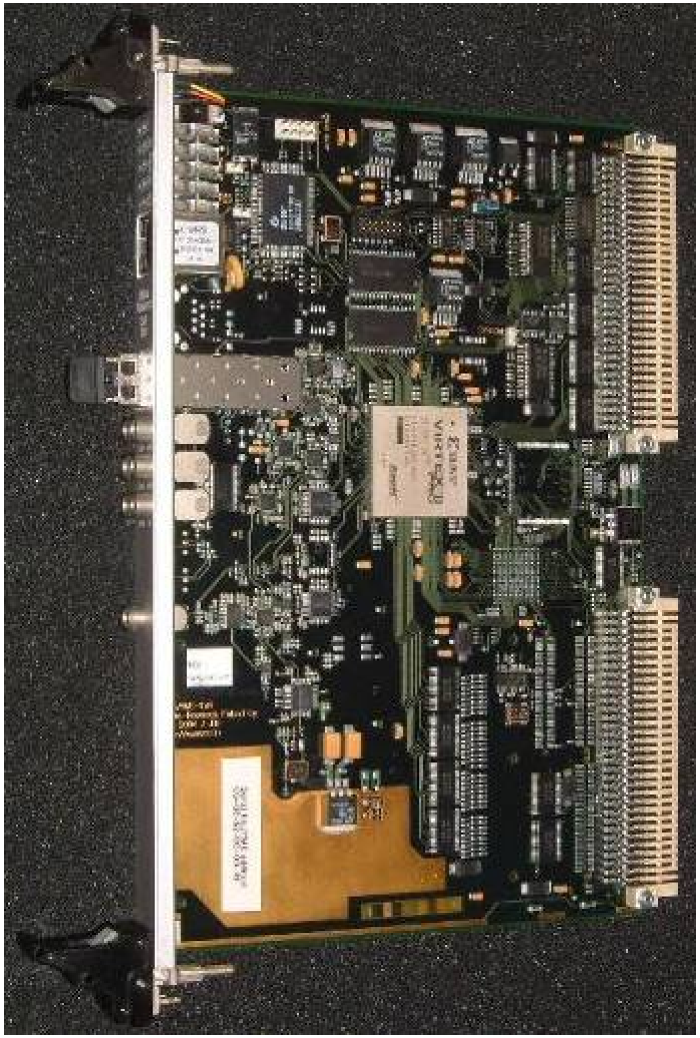


BST building blocks: Event system **[17]**

- The Event Generator (EVG) is responsible of creating and sending out timing events to an array of Event Receivers located at the various timing clients
- The data flow over Optical Cable
- RF frequency input up to 1 GHz
- Highly configurable

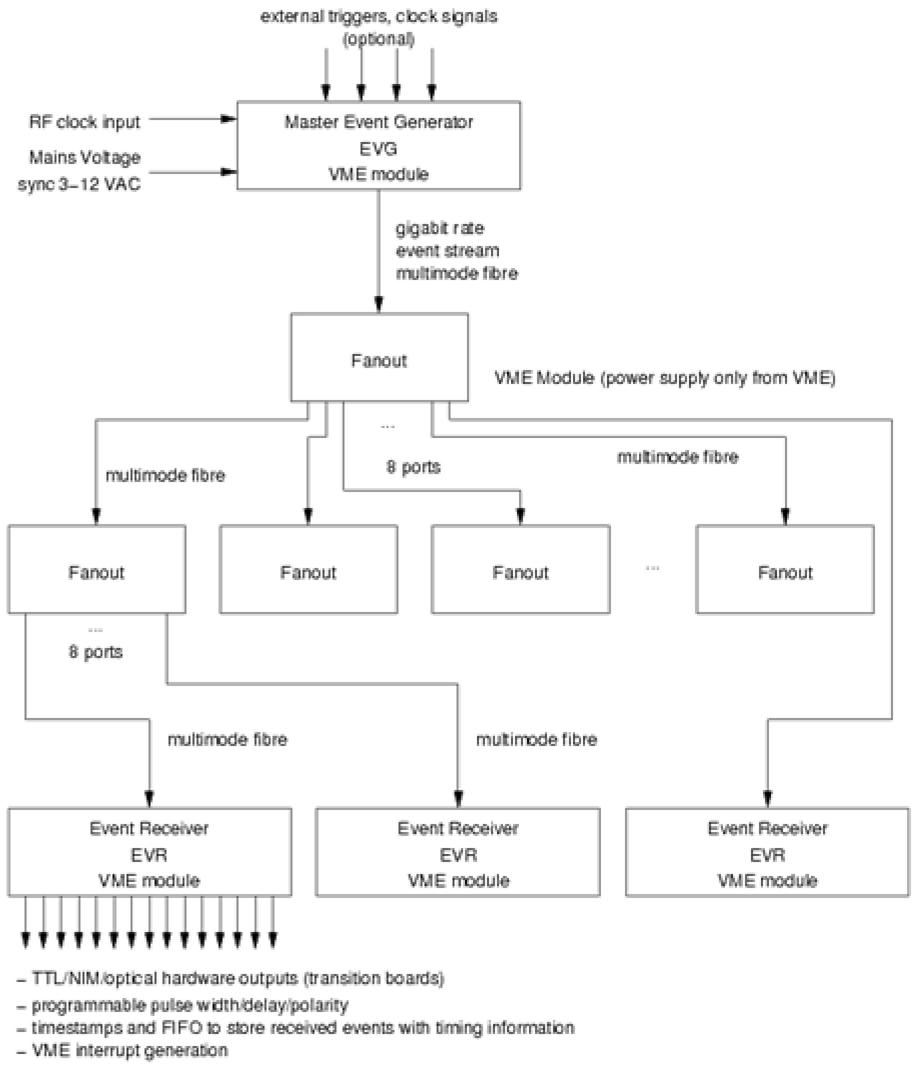
EVG-200 →

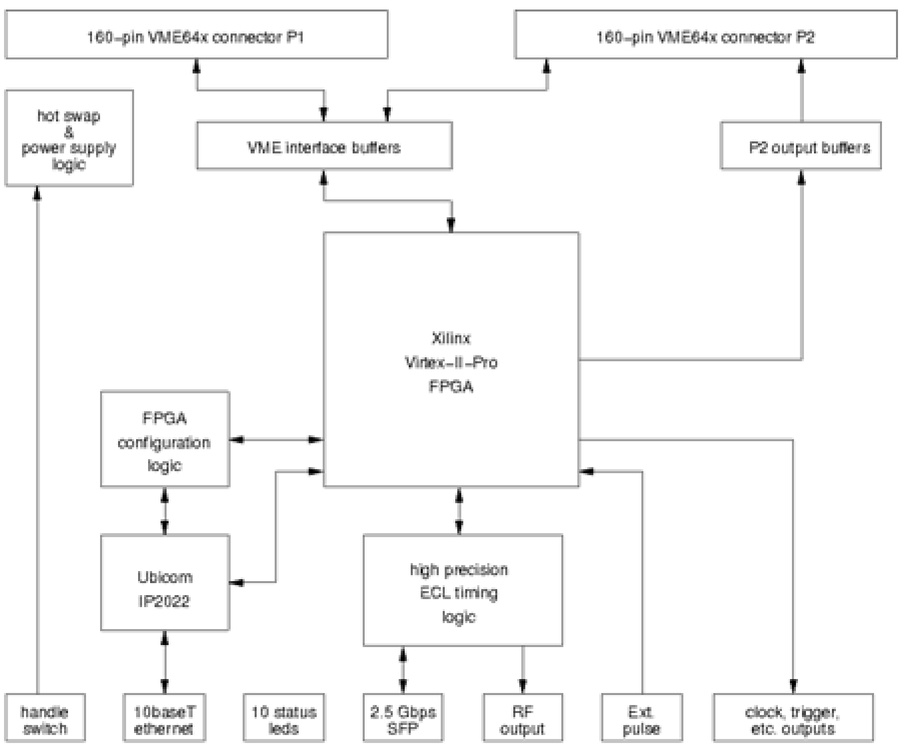




BST building blocks: Event system **[17]**

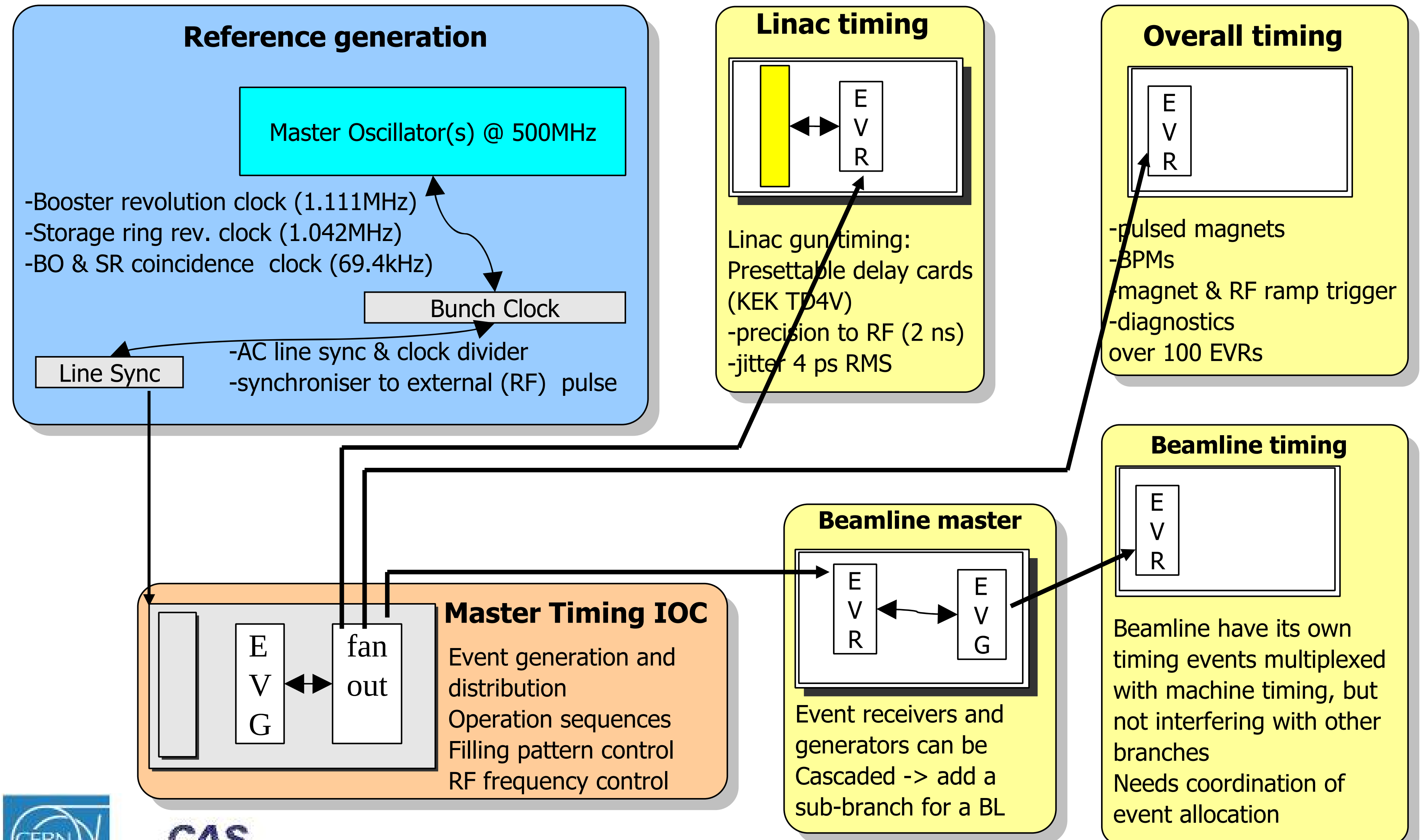
- The Block diagram show the different combination of EVG (generator) and EVR (receiver)
- Below a detailed block diagram of an Event receiver
- Fast analogue I/O is provided as well





BST building blocks: master time base **[18]**

- SLS Timing system structure; based on “event” system



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[17] Micro-Research Finland Oy, see at http://www.micro-researchfinland.fi/contact.html

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