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* 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.

  \[
  \text{time reference} \rightarrow \text{clock}
  \]

- 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

Plot taken from [1]

Explosion in Timekeeping
Performance has Provided
Major Benefit to Society
During this Millennium

Year - A.D.

Time Stability in Seconds per Day

0.1 ps
1 ps
10 ps
100 ps
1 ns
10 ns
100 ns
1 µs
10 µs
100 µs
1 ms
10 ms
100 ms
1 s
10 s
100 s
1 ks
10 ks
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 \textit{hardware based}
  - Slow timing at revolution clock level \textit{“event” based}

- Trigger signals are often referred to as: \textit{fiducials}

- \textit{Synchronization} is a local task implemented at the different \textit{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
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 \( \tau_{\text{S-band}} = 330\text{ps} \)
  - circular acc. 500MHz machine \( \tau_{500\text{MHz}} = 2\text{ns} \)

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 \( (\sigma_B \approx 20\text{ps}) \)
- 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 \( \text{ps}_{\text{RMS}} \)
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 4\(^{th}\)GLS
- 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 \(20\text{ps}_{\text{RMS}}\) to \(<100\text{fs}_{\text{RMS}}\))
  - massive **adoption of fs laser** oscillators and amplifiers
  - order of magnitude **lower repetition rate** of light pulses
- We are transitioning from the \(10\text{ps}_{\text{RMS}}\) to the \(10\text{fs}_{\text{RMS}}\) regime
BST system architecture: 3GLS

- Master Oscillator
- Master Timebase (fast timing)
- Event Generator (slow timing)
- Triggers / fiducials:
  - Bunch Clock (Gun, Inj/Ext)
  - Storage Ring Clock

- Machine Timing Client #1
- Machine Timing Client #2
- Machine Timing Client #n

- User Timing Client #1
- User Timing Client #2

- Event Receiver #1
- Event Receiver #2
- Event Receiver #3

- Event

- Machinery
  - Gun RF
  - LINAC RF
  - Booster RF
  - Storage Ring RF
  - INJ / EXTR - ACTION ELEMENTS
  - SINGLE PASS DI AGS
  - TIME RESOLVED EXPERIMENT

- Phase Reference
- Reference Transmit (co-ax or FO)

- Master Oscillator
- Reference Transmit (co-ax or FO)
BST system architecture: 4GLS

- Master Oscillator
- Reference Transmit (co-ax or FO)
- Machine Timing Client #1
- Machine Timing Client #2
- Machine Timing Client #n
- User Timing Client #1
- User Timing Client #2
- Event Receiver #1
- Event Receiver #2
- Event Receiver #3
- Event Generator (slow timing)
- Triggers / fiducials: Bunch Clock (photo Gun)

- PHOTO GUN RF
- PHOTO GUN LASER
- LINAC RF (LLRF)
- BUNCH ARRIVAL MONITOR
- SINGLE PASS DI AGS
- SEEDING LASER
- TIME RESOLVED EXPERIMENT
- USER LASER

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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.
Exercise: measuring the jitter of a synchronous counter

- Typically on a Storage Ring (SR) you need to generate the **Revolution Clock** (CK\text{REV}) signal

  \[ \text{CK}_{\text{REV}} = \frac{f_{RF}}{\text{Harmonic Number}} \]

  Harmonic Number is the number of buckets of the SR

  ELETTRA: \( f_{RF} = 499.654 \text{MHz}, \, h_N = 432, \, f_{BC} = 1.156 \text{MHz} \)

- The CK\text{REV} is used both for turn-by-turn measurement on SR and for beam-lines detector synchronization

- The CK\text{REV} may be easily generated with ECL counter, using the \( f_{RF} \) as the clock signal

- Typical value for the jitter of CK\text{REV} wrt RF is \(<5\text{ps}_{\text{RMS}}\)
Some definitions: Allan deviation [1]

- A frequency stability diagram, $s_y(t)$, 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 $\Rightarrow$ Quartz Crystal Oscillator,
  - RB $\Rightarrow$ Rubidium Gas-Cell Frequency Standard,
  - CS $\Rightarrow$ Cesium-beam Frequency Standard,
  - HM $\Rightarrow$ Active Hydrogen-Maser Frequency Standard
- The equation for the two-sample variance may be written as follows:

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

where the brackets, $\left\langle \cdot \right\rangle$, denote an infinite time average.

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Name</th>
<th>Expression</th>
</tr>
</thead>
<tbody>
<tr>
<td>AVAR</td>
<td>Two-Sample or Allan Variance</td>
<td>$\sigma_y^2(\tau) = \frac{1}{2} \left\langle \left( \Delta y \right)^2 \right\rangle$</td>
</tr>
<tr>
<td>MVAR</td>
<td>Modified Allan Variance</td>
<td>Mod. $\sigma_y^2(\tau) = \frac{1}{2\tau^2} \left\langle \left( \Delta^2 x \right)^2 \right\rangle$</td>
</tr>
<tr>
<td>TVAR</td>
<td>Time Variance</td>
<td>$\sigma_x^2(\tau) = \frac{1}{6} \left\langle \left( \Delta^2 x \right)^2 \right\rangle$</td>
</tr>
</tbody>
</table>

- Stability Ranges of Various Frequency Sources for 1 kHz Bandwidth
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 $\text{BW}_{-3\text{dB}} \text{ [GHz]}$
  the following approximated formulas hold, time expressed in ns:

  - Rise Time (from 10% to 90%) $t_{\text{RISE}} = \frac{0.35}{\text{BW}_{-3\text{dB}}}$
  - Full Width Half Maximum $\text{FWHM} = \frac{0.45}{\text{BW}_{-3\text{dB}}}$
  - Sigma (for a gaussian pulse) $\sigma = \frac{\text{FWHM}}{2.35}$
  - RMS value (for a gaussian distribution) $A_{\text{RMS}} = \frac{A_{pk-pk}}{4}$

**some examples**
- a “3GHz scope” may be suitable to measure pulses with rise time of $\approx 110\text{ps}$
- 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

<table>
<thead>
<tr>
<th>DUT</th>
<th>Jitter of ...</th>
</tr>
</thead>
<tbody>
<tr>
<td>- a counter/divider</td>
<td>terminal count (TC) wrt Ref</td>
</tr>
<tr>
<td>- a laser stabilization unit</td>
<td>synchronized laser pulses wrt Ref</td>
</tr>
<tr>
<td>- a transmission channel</td>
<td>received signal wrt transmitted</td>
</tr>
<tr>
<td>- a “LINAC”</td>
<td>bunch arrival time wrt RF</td>
</tr>
</tbody>
</table>
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

Machine Reference

R&S gen. $f_c = 1\, \text{GHz}$

Trigger

Tek Scope BW = 6 GHz

Power splitter

Input CH1

Carrier

AD9510 : 32

A\textit{g}i\textit{l}ent Pulse Gen.

Trigger (modulation IN)

Linear B-PSK Modulator

Phase Modulated

MT\textit{E}Q Fiber Transm.

Remote Station

Mixer

MT\textit{E}Q Fiber Receiver

Low Pass Filter $f = 550\, \text{MHz}$

Amplifier

300m Fiber Spool

Local Station

Machin e Reference

CERN

CAS

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Jitter measurement techniques: time domain

Binary Phase Shift Keying (B-PSK) of the 1GHz carrier (0, $\pi$)
Jitter measurement techniques: time domain

Jitter of a trigger pulse sent over FO wrt the Reference

\[ \Delta t = 1.52\mu s \quad (L=300\text{m}) \]
Jitter measurement techniques:

time domain

2.53ps mean RMS jitter

2359 acquisitions
Technological issues

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:

\[
\Delta t \approx \frac{1}{Bs} \cdot \left( \sqrt{\frac{S}{N}} \right)^{-1}
\]

\[
S = \frac{Ps}{N} = \frac{Ps}{P_N}
\]

\[
\Delta t \approx \frac{1}{Bs} \cdot \left( \sqrt{\frac{Ps}{N_0B_s}} \right)^{-1} = \sqrt{\frac{N_0}{PsB_s}}
\]

\[
\Delta t \approx \frac{1}{Bs} \cdot \left( \sqrt{\frac{Ps}{N_0B_F}} \right)^{-1} = \sqrt{\frac{N_0B_F}{PsB_s^2}}
\]

\[Ps\] signal power
\[N_0\] noise sp. density

Courtesy of:
prof. M Vidmar
Uni LJ SLO

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

- **COAX (broadband)**
  \[ B=1\text{GHz}, \ P_s=1\text{mW}, \ P_N=k_B T B = 4.14 \times 10^{-12}\text{W} \]
  \[ \Delta t = 10^{-9} \sqrt{\frac{4.14 \times 10^{-12}}{10^{-3}}} = 64.34\text{fs} \]

- **COAX (narrowband)**
  \[ B_s=1\text{GHz}, \ B_F=10\text{MHz}, \ P_s=1\text{mW}, \ P_N = k_B T B_F = 4.14 \times 10^{-14}\text{W} \]
  \[ \Delta t = 10^{-9} \sqrt{\frac{4.14 \times 10^{-12}}{10^{-3}}} = 6.43\text{fs} \]

- **FIBER, broadband non-coherent** (envelope)
  \[ B=10\text{GHz}, \ S/N \approx 90\text{dB}^+ \]
  \[ \Delta t = 10^{-10} \sqrt{10^{-9}} = 3.16\text{fs} \]

- **FIBER, coherent**
  \[ B_S=200\text{THz}, \ B_F=10\text{GHz} \rightarrow S/N \approx 60\text{dB} \]
  \[ \Delta t = \frac{1}{2} 10^{-14} \sqrt{10^{-6}} = 0.05\text{fs} \]

^+ Comm Rx: \( P_{\text{OPT}} = -25\text{dBm} \rightarrow (S/N)_{\text{elec}} = 20\text{dB} \); if \( P_{\text{OPT}} = 10\text{dBm} \rightarrow 20 + (35 \times 2) = 90\text{dB} \
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]

- **$f_0 = \text{carrier}$**
- **Noise power vs. carrier power [dBc/Hz]**
- **Phase Noise**
- **Sidebands**
- **1Hz band**

**Graph Details**:
- Vertical axis: Power
- Horizontal axis: Frequency
- Points of interest:
  - $f_0$ = carrier frequency
  - $fo$ and $fo + fm$
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:

\[
N = \text{noise power}[\text{dBc}] = \int_{f_{\text{low}}}^{f_{\text{high}}} \ell(f) df
\]

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

\[
\text{RMS PhaseJitter}[\text{rads}] = \sqrt{10^{10} \cdot 2}
\]

In time units:

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

In linear terms:

\[
J_{\text{rms}} = \frac{1}{2\pi f_c} \sqrt{2 \int_{10}^{10^6} L(f) df}
\]

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<sub>RMS</sub>. The RMS jitter calculation of 0.72ps<sub>RMS</sub> is a small proportion of the maximum jitter.

\[
\text{IntegrationOfCurve} = \int_{12\text{kHz}}^{20\text{MHz}} L(f) df = -63\text{dBc}
\]

\[
\text{RMSJitter} = \sqrt{10^{-63} \times 2} = 1415e^{-6} \text{Radians}
\]

\[
\text{RMSJitter} = \frac{1415e^{-6}}{2 \times \pi \times 312.5 \times 10^6} = 0.72\text{ps}(\text{rms})
\]
Frequency domain measurement techniques [6]

- There are dedicated instruments for “phase noise”
- Agilent Signal Source Analyzer (SSA) 5052A
- It measures 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\textsubscript{RMS}**

PN in [10kHz-10MHz] range
Measured value is **73.6fsec\textsubscript{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 $46\text{fs}_{\text{RMS}}$
Frequency domain measurement techniques

- The Australian company Poseidon Scientific Instruments (PSI) 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

<table>
<thead>
<tr>
<th>Block</th>
<th>Expected Jitter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference oscillator</td>
<td>≈ps to 10fs</td>
</tr>
<tr>
<td>phase reference for all the sub-systems</td>
<td></td>
</tr>
<tr>
<td>Master Time-base (Event system)</td>
<td>≈ns to 10s ps</td>
</tr>
<tr>
<td>trigger</td>
<td></td>
</tr>
<tr>
<td>bunch clock</td>
<td></td>
</tr>
<tr>
<td>injection / extraction</td>
<td></td>
</tr>
<tr>
<td>beam-line triggers</td>
<td></td>
</tr>
<tr>
<td>Distribution system (coaxial vs. Fiber Optic)</td>
<td>down to 10fs</td>
</tr>
<tr>
<td>phase reference</td>
<td></td>
</tr>
<tr>
<td>Triggers</td>
<td></td>
</tr>
<tr>
<td>Interface to the Control System</td>
<td>100ps to &lt;10ps</td>
</tr>
</tbody>
</table>
BST building blocks:
Reference (μ-wave) Oscillator – R(M)O

- The RO is generating the machine RF
  - CW sinusoidal oscillator; $P_{\text{OUT}}=15-20\text{dBm}$; (ultra) low phase noise
  - S-band ($f_{\text{RO}}\approx3\text{GHz}$) RO for a LINAC
  - in 3GLS RO operates at a lower frequency ($500\text{MHz}=f_{\text{S-band}}/6$)
- 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 $\approx\text{ps}$ down to $\approx\text{fs}_{\text{RMS}}$
  - PN measurement BW = 10Hz to 10MHz
- Also 2 ROs can be used
  - when $f_{\text{RF LINAC}} \neq n \times f_{\text{RF RING}}$
  - locked using the 10.7MHz REF OUT / REF IN

*Remember: set the two ROs to the same RF when injecting*
BST building blocks: Reference $\mu$-wave Oscillator
Rohde & Schwartz (R&S)

R&S SMA100A
$F_c=3\text{GHz} \rightarrow 52\text{fs}_{\text{RMS}} [10-10\text{MHz}]$

R&S SMF100A
$F_c=3\text{GHz} \rightarrow 44\text{fs}_{\text{RMS}} [10-10\text{MHz}]$

Typical SSB phase noise with internal reference oscillator
(with enhanced phase noise performance and R&S'SMA-B22 FM/PM modulator)
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 $\mu$-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)

<table>
<thead>
<tr>
<th>Offset</th>
<th>Predicted at 6.00 GHz</th>
<th>Measured at 6.00 GHz</th>
<th>Predicted at 3.00 GHz</th>
<th>Measured at 3.00 GHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 Hz</td>
<td>-97 dBC/Hz</td>
<td>-95 dBC/Hz</td>
<td>-102 dBC/Hz</td>
<td>-99 dBC/Hz</td>
</tr>
<tr>
<td>100 Hz</td>
<td>-126 dBC/Hz</td>
<td>-126 dBC/Hz</td>
<td>-132 dBC/Hz</td>
<td>-134 dBC/Hz</td>
</tr>
<tr>
<td>1 kHz</td>
<td>-155 dBC/Hz</td>
<td>-155 dBC/Hz</td>
<td>-157 dBC/Hz</td>
<td>-155 dBC/Hz</td>
</tr>
<tr>
<td>10 kHz</td>
<td>-174 dBC/Hz</td>
<td>-173 dBC/Hz</td>
<td>-166 dBC/Hz</td>
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<tr>
<td>100 kHz</td>
<td>-185 dBC/Hz</td>
<td>-185 dBC/Hz</td>
<td>-170 dBC/Hz</td>
<td>-174 dBC/Hz</td>
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<tr>
<td>1 MHz</td>
<td>-188 dBC/Hz</td>
<td>-188 dBC/Hz</td>
<td>-171 dBC/Hz</td>
<td>-176 dBC/Hz</td>
</tr>
<tr>
<td>10 MHz</td>
<td>-188 dBC/Hz</td>
<td>-189 dBC/Hz</td>
<td>-172 dBC/Hz</td>
<td>-177 dBC/Hz</td>
</tr>
</tbody>
</table>
## BST building blocks:
Reference $\mu$-wave Oscillator comparison table

<table>
<thead>
<tr>
<th>generator</th>
<th>carrier freq [GHz]</th>
<th>offset from carrier</th>
<th>jitter [fs]</th>
<th>Phase jitter [deg]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>dBc/Hz</td>
<td>10 100 1.000 10.000 100.000 1.000.000 10.000.000</td>
<td>10-10M 100-10M</td>
<td>10-10M 100-10M</td>
</tr>
<tr>
<td>PSI - SLCO OSC</td>
<td>6.00 guar</td>
<td>-77 -120 -150 -168 -180 -180</td>
<td>9,226 0,292</td>
<td>0,199 0,00063</td>
</tr>
<tr>
<td></td>
<td>6.00 typ</td>
<td>-84 -126 -155 -173 -185 -185</td>
<td>4,18 0,152</td>
<td>0,009 0,00033</td>
</tr>
<tr>
<td>PSI - DIVIDER</td>
<td>3.00 guar</td>
<td>-92 -122 -149 -162 -167 -170</td>
<td>4,28 0,89</td>
<td>0,00463 0,00097</td>
</tr>
<tr>
<td></td>
<td>3.00 typ</td>
<td>-97 -130 -155 -165 -174 -176</td>
<td>2,246 0,432</td>
<td>0,00243 0,00046</td>
</tr>
<tr>
<td>R&amp;S SMF100A</td>
<td>3.00 meas</td>
<td>-72 -100 -130 -138 -138 -150</td>
<td>44 8,39</td>
<td>0,0484 0,009</td>
</tr>
<tr>
<td></td>
<td>10,00 meas</td>
<td>-63 -80 -110 -120 -120 -133</td>
<td>57,6 20,38</td>
<td>0,207 0,0733</td>
</tr>
<tr>
<td>R&amp;S SMA100A</td>
<td>3.00</td>
<td>-78 -88 -118 -131 -129 -143</td>
<td>52,1 25,7</td>
<td>0,0563 0,0277</td>
</tr>
<tr>
<td>Anritsu 2020</td>
<td>3.00 computed</td>
<td>-65 -90 -110 -117 -120 -135</td>
<td>117,1 47</td>
<td>0,126 0,051</td>
</tr>
<tr>
<td></td>
<td>3.00 meas ST</td>
<td></td>
<td>5052A 107,6</td>
<td>74 0,116</td>
</tr>
<tr>
<td></td>
<td>3.00 data sheet</td>
<td>-60 -98 -104 -108 -107 -105</td>
<td>-110 975</td>
<td>1,05</td>
</tr>
<tr>
<td>Aeroflex 2040</td>
<td>1.00 meas</td>
<td>-75 -95 -122 -144 -145 -145</td>
<td>126,5 0,045</td>
<td></td>
</tr>
</tbody>
</table>
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: **2005 Nobel Laureate in Physics**
John L. Hall and Theodor W. Hansch:

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

Congratulations to our founding partner Theodor Hänsch who has been awarded with the Nobel Prize in Physics 2005 for his contributions to the development of laser-based precision spectroscopy, including the optical frequency comb technique. The Nobel Prize awarded technology has been the starting point for our company Menlo Systems.

Congratulations also to John L. Hall and Roy Glauber who share the prize together with Ted Hänsch.
OMO is a Fiber laser operating at $\lambda = 1550\text{nm}$
- It is able to provide sub-ps (150fs$_{\text{RMS}}$ 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
- **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)
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 ($\lambda=1550\text{nm}$) 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
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-ps-domain)
A saturable absorber ensures higher intensity $\leftrightarrow$ higher gain
Given constant intra-cavity energy, the stable solution is a localized solution (a single pulse)
In the femtosecond domain:
\textbf{Dispersion} and \textbf{Nonlinearity} dominate pulse shaping and, for soliton-like pulses, balance these effects $\rightarrow$ very short pulses
At Lawrence Berkeley National Laboratory (LBNL) there is a parallel effort ongoing (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 $\lambda=1500\text{nm}$).

Diagram:

- Stabilized CW laser
- Amplitude modulator
- Fan-out
- Optical phase stabilized fiber
- Receiver and signal processor
- Output to user

RF source
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

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

Fiber laser cavity

Regenerative Feedback

EDFA  OBPF  MZ  PZT fiber stretcher

BPF  PD  ODL

28 May - 6 June 2008  Le Normont, Dourdan, France
Phase locking to an external $\mu$-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

98fs RMS jitter in 10Hz-1.6MHz

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).

28 May - 6 June 2008  Le Normont, Dourdan, France
Passively mode locked (PML) fiber laser by MENLOSYSTEMS gmbh

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

![Diagram of BST building blocks](image)
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**

![Diagram of BST building blocks: Event system](image)
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

SLS Timing system structure; based on “event” system

Reference generation
- Master Oscillator(s) @ 500MHz
- Booster revolution clock (1.111MHz)
- Storage ring rev. clock (1.042MHz)
- BO & SR coincidence clock (69.4kHz)

Linac timing
- Linac gun timing: Presettable delay cards (KEK TD4V)
  - precision to RF (2 ns)
  - jitter 4 ps RMS

Overall timing
- Pulsed magnets
- BPMs
- Magnet & RF ramp trigger
- Diagnostics over 100 EVRs

Master Timing IOC
- Event generation and distribution
- Operation sequences
- Filling pattern control
- RF frequency control

Linac timing
- bunch clock
  - Booster revolution clock (1.111MHz)
  - Storage ring rev. clock (1.042MHz)
  - BO & SR coincidence clock (69.4kHz)

Beamline master
- Event receivers and generators can be cascaded -> add a sub-branch for a BL
- Needs coordination of event allocation

Beamline timing
- Beamline have its own timing events multiplexed with machine timing, but not interfering with other branches

28 May - 6 June 2008  Le Normont, Dourdan, France
References

[8] PSI see at: www.psi.com.au