Electronic Timing System for ELI-Beamlines Lasers

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(Laser Beamlines Control Systems)
Timeline of Laser Beamlines & ELI facility

- mid 2012 – first specs, research for of-the-shelf (BME, NI, WR, GF, MRF.)
- Q3 2012 – full specs & procurement of ETS prototype (Hytec & MRF)
- Q2 2013 – running 24/7 in production in L1 Front-end laboratory
- 2013/2014 – another two Master units for L2, L3 laser beamlines
- Q3 2013/ Q1 2014 – extended specs for ELI facility with:
  - Timing & Frequency Synchronization scheme for ELI facility
  - experiment campaigns & events coordinated to absolute time
  - do not preclude Femto-second synchronization
- Q2 2014 (SE) – an Electronic Timing System design proposal & tender specs for ELI facility from scratch
- 2015 – first Laser Beamlines bits to facility site
- 2018 – first happy user in ELI facility
Scope of Laser Beamlines

- Four Laser Beamlines: up to $\approx 10 \text{ PW}$; down to $\approx 20 \text{ fs}$ pulses; up to $1 \text{ kHz}$ rep. rate

- Femto-second pulse, 80 MHz front-ends ($\approx 80\text{fs}$ RMS jitter)
- ps - ns stretched pulses
- 1 kHz to sub-Hz
- Large aperture
- Complex amplifier chains
Example: L1 Laser Front-end

- Define & control Beamline timing sequence
- Support DAQ & diagnostics
- Support FE development, e.g.: “Regen” Amp to 2kHz regime
ELI Scope is Synchronous Operation

That is:
Laser pulses will meet at the same target, e.g.: L2 & L3 in sync at E3

Threefold solution:
- Q.1 Phase locked oscillators
- A.1 Sync’ed RF clk
- Q.2 Timing sequence for each Laser
- A.2 Sync’ed triggers down to ~0.5 Hz rep.
- Q.3 Single events & campaigns
- A.3 Sync’ed mHz & wall-clock; Events sync’ed to abs. time
## Example experiment campaign

<table>
<thead>
<tr>
<th>Experiment A</th>
<th>E2</th>
<th>L2</th>
<th>L3</th>
</tr>
</thead>
<tbody>
<tr>
<td>09:05:04.xxx</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Managed by user</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Handover</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>11:59:59.000 000 000</td>
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<td></td>
</tr>
<tr>
<td>Managed by ETS</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12:00:00.000 000 000 000</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Initiate sequence!**
- Open shutters
- Arm target
- Trigger acquisition
- Interaction!

**Laser to standby**
- Laser to warmup

**Alignment mode**

**Inter-process communication**

**Managed by user**
- Prepare target
- Align lasers to target
- Prepare target

**Managed by ETS**
- Laser ready to fire
- Generate pump signal
- Trigger diodes
- Trigger diagnostics
- Trigger pump laser
- FIRE LASER
- FIRE LASER

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[OP Research and Development for Innovation]
Electronic Timing System (ETS)

Part of the "Time & Frequency Synchronization scheme" = OMO + RF + ETS

The role of ETS is:
1. Pico-second timing & trigger signals
2. Clock signals w/ programmable frequency
3. Absolute time distribution

1) ICALEPCS 2013 (THPPC089)
• ETS Master – Local Masters – Remote Receivers
• Using central RF clock shared w/ laser oscillators
Electronic Timing System (ETS)

- Expand on demand
Electronic Timing System (ETS)

- Merge w/ facility
Requirements for MRF

- Distributed >300m distant remote ETS units
- >500 triggers on physical outputs
- 120MHz event clock (8.333ns)
- Three types of triggers w/ different pulse width & pulse delay resolution (Δw, Δd)
  - Standard: [8.333ns, 8.333ns]
  - Precision-delay: [8.333ns, 10ps]
  - High-precision: [208.3ps, 10ps]

- Repetition frequencies for each trigger independently
  - from pre-configured set:
    - 1Hz, 10Hz, 100kHz, 1kHz, 2kHz, 100kHz, 40MHz
  - single-shot mode
• **External TTL signal triggered single-shot** *)
  • in sync. to arbitrary repetition rate
• < 30ps RMS jitter for triggers in general
  • e.g.: 40MHz trigger as a secondary frequency reference
• < 15ps RMS jitter for high-precision triggers
  • e.g.: L2-Laser FE Pulse-shaper EOM
• **Laser shot pulse number**
  • 1ms pulse No. available on all EVRs in real-time *)
• Centralized setup and control
  • single user interface
  • single SCADA (EPICS) interface

*) Of-The-Shelf FW modified by MRF, Hytec
ETS Time-stamping Proposal

- Software PTP (IEEE1588 v2): ~10ms jitter
- ETS Time-stamps (custom): ~10us jitter
Applications

- Pulse-pickers -- start/stop triggers w/ sub-ns delay tuning, μs width
- Pockels Cells -- start/stop triggers w/ delay step of amplifier roundtrip (e.g.: 28ns), μs width
- Electro-optic Modulators – demanding on jitter
- Support beam-path and laser pulse jitter stabilization systems

- RF circuitry sync & frequency references
- Camera triggers
- cRIO DAQ triggers
- ~GSa/s digitizers triggers
Pulse-pickers & Pockels Cells

If HV is applied on crystal (LBO, KDP...), polarization of passing beam is rotated:

- High Voltages up to e.g.: 20kV
- Fast rise/fall-times, e.g.: 4ns
- Various switching regimes
- Drivers are COTS – bipolar, double push-pull switches
- Using COTS "Splitter-box" for some:
  - replicates Start/Stop triggers
  - drives to 5Volts
  - implements additional driver safety feats.

- Sub-ns fine delay of Start/Stop triggers for good pulse contrast

- Rise-time counts, should be much less than a PP rise-time

- HV switching interferes with Start/Stop triggers,
  e.g.: 1.5V swing at 4.5V level
    [1V/div, 20ns/div]
Electro-optic Modulators

EOM in general:
- Control amplitude & phase of a laser beam
  - fine phase adjustment of laser pulses
  - magnitude modulation
- Direct modulation => signal jitter translates to laser beam

Temporal pulse-shaping for L2-FE
- Shape a CW laser beam to pulsed beam (e.g.: solid line)
- EOM test trigger requirement was 4V swing, 200ps rise-time and << 50ps RMS jitter
- Now, in-house Arbitrary Waveform Generator drives the EOM
- ETS provides just a sync trigger

Advantages of Getting MRF

- Minimal set of HW, an EVG & few EVRs, can easily drive a laser beamline
  - phase-lock to a frequency **AND** sequential triggering

- Flexible architecture & lots of features
  (upstream, EVG cascading, ring network for user data, nano-secs resolution time-stamps,...)

- Repetitive triggers running autonomously w/o user events
  - it is perfect for repetition rate based beamlines

- Low jitter w.r.t. the RF clock **AND** low jitter mutually between triggers
Advantages of Getting MRF cont.

- No delay dependent error:
  \[ \text{Err}_{\text{RMS}} = 15\text{ps} + 10^{-7} \times T_{\text{Delay}} \ [\text{ps, ps}] \]

  - Please recall, ELI is 1kHz beamline next to sub-Hz beamline next to 10Hz ...
  - Such error would put serious limitation on laser timing-sequences
  - If non-zero, e.g.: \(10^{-7}\), then the error grows to 115 ps after 1 ms, 100'015 ps after 1 s,...

- IT/Telecomm. standardized components for the link (fibers, SFPs)
  - computer shops have them on stock
  - users can go on their own w/ passive splitters
  - contrasts to a stabilized fibers, but ELI will be stuffed w/ fine FO anyway

- UNIV modules are great idea, we will make our own one day

- Community of users is open
Suggestions to Make it Even Better

• Higher event clock to match 80MHz laser oscillators
  • 1/80MHz gives 12.5ns, but it is longer than 10ns delay line of -DLY modules
  • 120MHz works fine in sync w/ every other 12.5ns pulse
  • 160MHz seems to be the best option for us now

• Increase the max. number of -DLY modules in a single EVR
  • we would rather utilize four DLY modules and two STD (instead of 2 and 4)

• HW inputs at EVGs for GPS-like devices
  • 1 PPS input to sync EVG seconds counter (another arbitrary timing information)
  • grab & transmit NMEA GPZDA time-stamp

• I like the idea of Telnet interface to EVG/EVR, could it be feasible also for cPCI?

• Linux kernel drivers for other than vanilla: e.g.: Xenomai
• ETS link fibers stabilization
  – in house or COTS, but ELI will be stuffed w/ fine FO anyway

• Cascading EVG – EVG:
  • clarify fibers hook up w/ Fan-Out
  • test upstream FIFO determinism w/ current EVG events setup

• Implement system of programmable events coordinated to absolute time
  • Deterministic & on-the-fly sequencer re-programming & table swapping
  • Time-stamp write, if GPS time used
    • in-house developed routines w/ Real-time determinism
  • Time-stamp readout (Pulse No., EvClk counter, GPS)
    • in house EPICS Time provider routine, Real-time OS & the routine
    • in house LabVIEW routine w/ RT determinism too

• More LabVIEW support (cRIO/PXI/PCIe receivers), esp. to get time-stamps
1. Synchronization sources shall start with high precision FE oscillators
   -> fluctuations of RF and timing signals are crucial for operation of lasers
      i. RF reference close to stabilized optical fibers and future femto-second backbone
      ii. Timeline of all four lasers shall origin from a single point
      iii. Absolute time-stamps distribution has to be in sync with all sources above

2. Compatibility with MRF Event Link -- to avoid a hybrid ETS and thus:
   • performance degradation
   • risk of failure
   • unexpected expenses

3. No delay dependent error -- to have stable timeline for all lasers
ETS design and implementation for Laser Beamlines also fit for ELI facility
- repetitive timing fits for repetition rate based beamlines
  => should fit for any consumers of beamlines’ pulses (e.g.: secondary sources)
- implements single shot mode for triggers
- designed w/ events coordinated to absolute-time
- requirements came from: in-house analysis & know-how of experts (e.g.: Fs Workshop)
  "Have it synchronized down to ps-level to allow fs synchronization later."

- Non-trivial design; Continuous updates are expected as RA’s & RP’s will develop
  "LEGO bricks" instead of turn-key system suits better (specs/contract changes)

- Timeline & milestones are tight, so no hiccups
Thank you for your attention

Děkuji za pozornost

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with support by Jack A. Naylon & Pavel Bakule
BACKUP SLIDES
- synchronizing HAPLS Epochs w/ T1
- few cycles to catch up
- 10 Hz feedback signal T2
• Standalone ETS box, ready-to-use
• With full set of 24 triggers
• STD & Prec. Delay for L1 development
• STD & High-Precision for L2 front-end
• Delivered by Hytec Electronics
• C-API for OS driver/EPICS driver
• EPICS server, Process Variables
• HMI interface (Control System Studio)
• ETS configured for laser rep. rates
• Open Source -> not vendor locked
• Custom extensions to EVG/EVR FPGA:
  • pulse numbering,
  • TTL-in externally triggered single-shot
• 24/7 operation from Q2 2013
• Automated control by e.g.: 10mJ Regen CS application
ANNEX 2 – ETS PERFORMANCE
Added jitter of High-precision trigger, TTL output, cPCI-EVRTG-300

Here, added jitter of LVTTL output (EVRTG on-board) is $\sim 14.5$ ps wrt. RF clock signal.
Waveform of high-precision trigger, TTL output, cPCI-EVRTG-300

Here, a 10 ns trigger pulse shows voltage level of 3.3V LVTTL output (EVRTG on-board) is ~2.88 Volts at 50 Ohm load.