HIGH REPETITION RATE LASER BEAMLINE CONTROL SYSTEM*

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Abstract

ELI-Beamlines will be a high-energy, high repetition-rate laser pillar of the ELI (Extreme Light Infrastructure) project. It will be an international user facility for both academic and applied research, scheduled to provide user capability from the beginning of 2017.

As part of the development of L1 laser beamline we are developing a prototype control system. The beamline repetition rate of 1 kHz with its femtosecond pulse accuracy puts demanding requirements on both control and synchronization systems. A low-jitter high-precision commercial timing system will be deployed to accompany both EPICS- and LabVIEW-based control system nodes, many of which will be enhanced for real-time responsiveness. Data acquisition will be supported by an in-house time-stamping mechanism relying on sub-millisecond system responses. The synergy of LabVIEW Real-Time and EPICS within particular nodes should be secured by advanced techniques to achieve both fast responsiveness and high data-throughput.

INTRODUCTION

ELI Beamlines Czech Republic will provide a facility for physics experiments offering four petawatt class laser beamlines and six experiment halls. Most of the facility systems will be developed in-house using local resources. There is an on-going development of the common laser front-ends and the first beamline, L1, situated in prototyping laboratories. The pulse distribution switch-yard and experimental target chambers are being designed, and preparations for facility services (vacuum, cryogenics, etc.) are on-going.

From the laser technology point of view, ELI beamline is composed of a laser oscillator, continuous-wave diode pump lasers, regenerative and multi-pass amplifiers, second harmonic generators, optical parametric power amplifiers and pulse compressors.

Since development milestones are quite close, we are procuring the majority of subsystems and selecting ready-to-use technologies, both for the control systems and laser hardware.

CONTROL SYSTEM OVERVIEW

For the purposes of this outline of the L1 beamline control system, we focus only on the “laser technology” control system (CS). The Personal Safety System (PSS) is being simultaneously designed at ELI, yet the system is segregated from the laser technology CS and considered independent. The laser technology CS merely monitors PSS status and automatically reacts to PSS interlock trips. PSS has to be managed from the very beginning of beamlines development because light intensities sufficient to cause permanent blindness from scattered light and skin burns are present in every beamline hall. There is a simple PSS at the beamline prototyping site used for daily operation.

Another segregated system is the Machine Interlock System (MIS), which offers automatic protection against unintended damage of laser technology. We are also developing MIS prototype in parallel, with the goal to keep it close to, but independent of the CS. MIS monitoring and trip actions are continuously included in CS.

Nevertheless the laser technology CS deals with the majority of SCADA tasks. The requirements on the CS are further complicated by the 1 kHz repetition rate and the fs or ps duration of all seed and pump lasers in L1.

Survey on CS Hardware

From the CS point of view, the L1 beamline control will be covered by: slow- and fast-controllers, a timing/triggering system, motion control and image acquisition devices.

Apart from usual sensors (for thermometry, hygrometry, flow, etc.) we will interface a variety of COTS (Commercial off-the-shelf) devices for beam diagnostics; spectrometers, power-meters, etc. CS integration of these specialist devices can be tricky due to inconvenient HW buses, proprietary protocols and limited SW integration support from manufacturers.

We expect tens of fast-photodiode detectors with a maximum of tens of picoseconds rise-time. These will scan ultra-short laser pulses and will push the speed requirements on Data Acquisition (DAQ) cards to giga-samples per second. A standalone high-speed system is currently being developed for picosecond-level jitter stabilization in Optical Parametric Chirped-Pulse Amplifiers (OPCPA). It will be deployed six-times in total for different laser amplifiers. The system includes a PXIe (PCI eXtensions for Instrumentation - Express variant) chassis with high-speed digitizer and FPGA processing. Fast closed-control-loop at 1 kHz drives piezo-actuators to compensate jitter in amplifier optics.

Various electro-optical devices like pulse-pickers and Pockels cells are also frequent. These devices and their high-speed control HW require precise timing and triggering in the sub-nanosecond range. Requirements on timing are such that a standalone system for electronic timing is being commissioned (refer to the next section for details).

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Optical setups require many piezo-actuators and simple tip-tilt adjustment of components. Together with automatic flip-mirror actuators and shutters, these represent the majority of the motion control requirements. Complex motion control is required here for high power beam compressors; however, these large components will be mostly tendered with motion control already included.

Dozens of mega-pixel cameras will supervise beam parameters and optical components at slow rate (< 10 fps). Some will be followed by image processing SW to detect possible damage to observed optic components. We have already evaluated some COTS gigabit-Ethernet cameras with satisfying results.

At least six 1000 fps high-speed cameras will be deployed as part of a real-time diagnostics package to monitor beam quality in the high-power OPCPA stages. These cameras require adequate triggering, bus and processing power. A prototype system based on a Camera-Link CMOS camera capturing a 0.25 MPix frame at 1 kfps shows promising initial results.

Preferences in CS Hardware An Ethernet-based network is a perfect solution for HW interface, as a field bus, and for CS data exchange. Slow- and medium- speed controllers were prototyped using an Industrial PC based on the PICMG 1.3 form factor. These controllers interface a variety of serial and Ethernet devices while keeping compatibility with control system SW and scalability for slow and medium speed I/O. Following high-speed requirements we have chosen the PXIe platform for CS prototyping. In conjunction with its real-time aware SW platform it has proven to be a flexible and powerful, if expensive, solution for our requirements.

CS Software Implementation

We are pursuing an open-source SW solution for the SCADA system – especially when there is a large number of community projects in relevant large-scale physics experiments. With a priority put on a ready-to-use system, it was not hard to narrow down the list of options and begin prototyping. We have chosen the Experimental Physics and Industrial Control System (EPICS) for the L1 prototype control system. Adopting EPICS version 3 and extending it with the Control System Studio (CSS) – its control panel builder and middle-layer services – has a number of advantages. There is no immediate need for programming. Capability of deterministic operation is well proven (crucial for the high repetition rate). Future upgrades with EPICS v4 will outperform limitations of the v3 and help with integration of high-level CS services.

Nevertheless we still had to resolve the implementations of proprietary equipment interfaces and fast control loops which utilize new COTS components. For fast deployment and flexibility, our choice for prototyping is LabVIEW. To suit our requirements we prefer the embedded forms of deployment – Real-Time targets – such as the CompactRIO family of devices, converted industrial PCs, and embedded PXIe controllers [1] We also see the advantage in full support of high-performance HW like DAQ cards and industrial cameras, especially given the tight schedule imposed by the first operational demonstration of L1 in 2016 Thus, as is the case in a large number of facilities to date, it will be necessary for us to explore the many options for interfacing LabVIEW and EPICS without sacrificing real-time determinism or causing performance bottlenecks.

CS Architecture The proposed CS architecture (Fig. 1) recognises a slow and fast data path on its middle-layer where all data should be accessible using EPICS Channel Access (CA). Both should be implemented as separated CS networks, however bridged to one another in a controlled way. The slow (Standard CA) network is already prototyped using EPICS-Base CA. The fast network will employ some of the real-time CA network designs. It has been suggested to us to utilize Xenomai RTnet driver with modified EPICS v3 controllers to gain on CA update-rate up to ≈ 3 kHz – ideal for the L1 laser. Having CA compatibility here will ease on need of non-standard or in-house developed CS services and also data archiving services will gain here. Furthermore we do not want to lose the opportunity to have both asynchronous (bulked) and synchronous (small bits) data exchange on the CS middle-layer.

To fit in the LabVIEW-based fast controllers into the middle-layer we have proposed a dedicated real-time network (Fast Controllers Network). Implementation details of the network are still being considered; however, it should support fast-loops over its controllers and some fast remote I/O platforms that are not using full-fledged controllers (e.g.: EtherCAT based I/O). We plan to focus our efforts on "RT Master to RT Slave" controllers implementation, then to clarify the Fast Controllers Network implementation and its bridging to CA network.

TIMING AND FREQUENCY SYNCHRONIZATION

Coherent measurements at physics experiments require a long-term and wide-band stable time-base. The beamlines' laser oscillators and particular signal sources at ELI have to be locked to a main frequency reference. State-of-the-art optical technologies offer sub-10 femtosecond jitter locking accuracy of remote electronic and laser sources [1]; however, only a comprehensive scheme can conveniently manage synchronized operation of all ELI sub-systems. Timing requirements will be some of the most stringent in a facility of this scale when pulse-pulse temporo-spatial target alignment of two or more of the laser sources (each with hundreds of meters optical path) to the femtosecond level will be added to the capabilities of ELI in its next phase of development.

[1] these systems run Wind River's VxWorks or the IntervalZero Phar Lap RTOS derivative and NI ETS 2011. However, an interesting new addition for 2013 is LabVIEW support for Linux RTOS [2].

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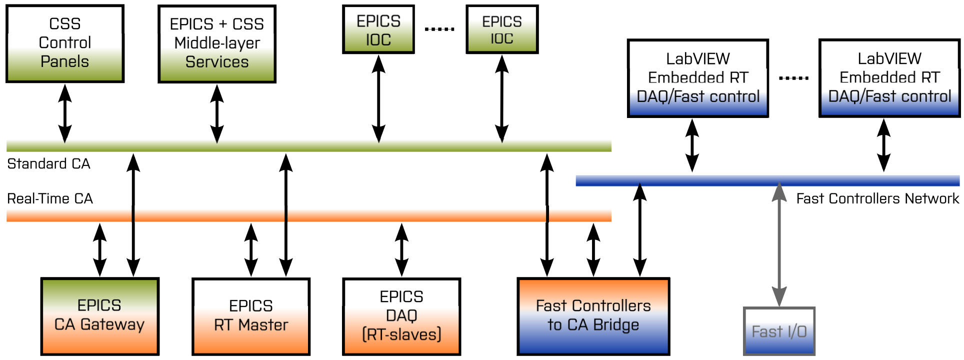

Figure 1: Proposed control system SW architecture including EPICS and LabVIEW controllers.

In order to meet the future aims of ELI, a femtosecond pulse, mode-locked Optical Master Oscillator (OMO) is required with < 25 fs integrated absolute jitter in the crucial 1 kHz $\rightarrow$ 10 MHz optical band, locked below 1 kHz to a GPS reference with excellent phase noise[2]. This overcomes the comparatively poor drift performance of all-optical oscillators. Using stabilized optical fibres, e.g.: [3], all laser oscillator front-ends (FE) can be precisely locked to sub-fs relative jitter using an optical-optical synchronization scheme based on cross-correlators. This tight requirement should ensure a high probability of overlap using optical pulses of ≈ 20 fs duration, although this is still a long way from coherent addition.

Laser beamlines usually employ many electro-optical devices (pulse-pickers, electro-optical modulators) to control timing sequences and pulse distribution. Generally, it is not worth using stabilized fibres just to synchronize such electro-optical devices. For this an Electronic Timing System (ETS) has been proposed to complete the timing and frequency synchronization scheme. The ETS provides synchronization at level of tens of picoseconds in both jitter and accuracy; and further introduces an absolute time scale (time stamp). The requirement for electronic event generation to ≈ 15 ps accuracy is required for fine control of pump laser and seed laser pulse overlap in some front-end amplifiers driven by electro-optical modulators.

The proposed timing and frequency synchronization scheme (Fig. 2) provides two primary frequency references both derived from the OMO. A stabilized fiber output (240 MHz), at first, which is primarily intended for laser FEs. And next, a high-frequency ultra-low-noise clock output (4800 MHz) derived from the 20$^{\text{th}}$ harmonic[3] of the optical signal will be generated locally for electronically locked devices. The frequency reference for the ETS master units can be derived from this. All three synchronization facilities are offered to ELIs' subsystems.

We assume the ETS triggers will be frequently required with target dependent configurations, so there is a local master unit offered to each (refer to the next section for details).

Electronic Timing System (ETS)

The ETS provides centralized timing and control. However, each beamline requires different and sometimes independent timing sequences – especially beamlines that will run at different repetition rates (1 kHz down to 10 Hz). To segregate different timing domains and to support independent timing, a local ETS master is proposed to each beamline and major system. Each ETS master provides a downlink to control and synchronize its event receivers (EVRs). EVRs are expected to provide physical outputs in form of electrical trigger signals.

Analysing requirements on ETS, we needed a scalable system able to trigger hundreds of electronic devices at high accuracy and over long distances. We compared various ETS platforms, however only one fulfilled all the requirements. Systems using only electronic synchronization (e.g.: [5, 6]) were not able to maintain required jitter figure over whole ETS network. A promising platform was expected from joint development on PXI Delay Generator [7, 8] however a proven jitter performance of a large scale optical timing network was missing. The White Rabbit [9] is well designed for large-scale facilities, however it was not able to meet our highest accuracy requirement.

Micro-Research Finland (MRF), [10], offers an FPGA-based solution in the form of expansion cards to known HW form-factors. Master and receiver cards are interconnected using a proprietary link protocol over a standard telecommunication optical link, which can be then easily extended up to few km using standard fibers (although splitters are proprietary). Receivers are equipped with universal I/O modules to provide physical interfaces applicable with various standards (TTL, LVPECL, optical, etc.). The system functionality is pre-configured in FPGAs and offers both synchronous and event-driven timing. Centralized setup and on-line control is also available.

The FE of the first laser (L1) uses a prototype setup based on the MRF platform currently, with great results. The prototype includes ten standard triggers, six precision-delay triggers (10 ps steps for pulse delay setting) and eight

[2] better than -160 dBc/Hz at 1 kHz and 10^{-11} Allen deviation in 1 s
[3] Using recent methods with negligible added jitter from AM-PM noise conversion [4]

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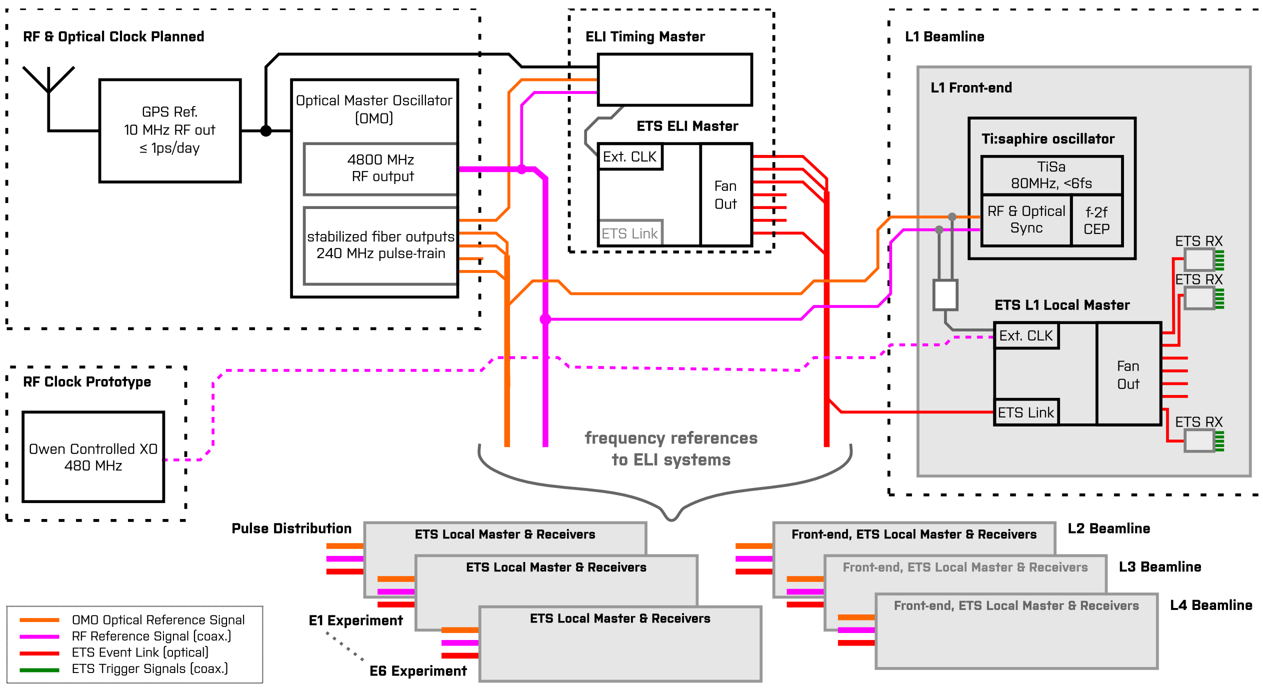

Figure 2: Timing and frequency synchronization scheme.

high precision triggers (pulse width step is ≈ 208 ps in addition to 10 ps delay step). We also commissioned a SW interface which employs an EPICS server, offering automated control and accompanied with a graphical interface on the CSS platform.

CONCLUSIONS

ELI's L1 beamline development milestones are directing us to prefer ready-to-use technologies and fulfil beamline's control requirements in terms of precision timing, fast control and fast data acquisition. Since the L1 CS prototype is supposed to be a starting point for ELI facility, we cannot underestimate the needs of other systems here. Our efforts always include considerations whether our prototypes match with facility needs.

Adopting EPICS version 3 and extending it with the Control System Studio has a number of advantages – no immediate need for programming, capability of deterministic operation, future upgrades with EPICS v4 to outperform v3 limitations and to ease integration of high-level CS services.

Proprietary equipment and fast control loops utilizing new COTS components are being prototyped using LabVIEW with preferences on its embedded forms of deployment. It will be necessary for us to explore the many options for interfacing LabVIEW and EPICS without sacrificing real-time determinism or causing performance bottlenecks.

We plan to focus our efforts on real-time CA implementation, then to clarify the Fast Controllers Network implementation and its bridging to CA network.

Continuous work on ELI's "Timing and frequency synchronization scheme" is further expected. ETS timestamping has to be thoroughly designed and evaluated under real-operation stress tests using both real-time CS networks.

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