Control system architecture for the L1 laser at ELI Beamlines

Jack Naylon, Tomáš Mazanec, Alan Greer**, Chris Mayer**, Martin Horáček, Bedřich Himmel, Marc-André Drouin, Karel Kasl, Jakub Horáček, Pavel Škoda, Pavel Bakule and Bedřich Rus

Institute of Physics AVČR, v.v.i., Prague, Czech Republic
** Observatory Sciences Ltd., Cambridge, UK
Extreme Light Infrastructure

Network of user facilities focusing on nuclear physics, attosecond science, and secondary source generation

Managed independently and developed autonomously within host institutes until post-2018
Spot the difference!

ELI-BL Grand Opening was on Monday October 19...
ELI Beamlines Facility in Prague

4 laser beamlines
6 experimental halls
Offices, labs and workshops for 300 staff
L3 laser hall

L4 compressor hall

Experiment floor transport corridor

Photos September 2015
The lasers at ELI-BL

L1 oscillator
Ti:sapphire
80 MHz, <8ns
RF master clock
Er:fiber clock

L1 front end
ps OPCPA preamps
Thin-disk preamps

Master timing

Pump thin disk
Yb:YAG
Compressor
ns-ps
ps OPCPA
Compressor
ps-fs
100 mJ / <20 fs / 1 kHz

L2

Pump DPSSL multislab
Yb:YAG
10 J
100 J

OPCPA Stage 1 chain

OPCPA Stage 2 chain

Compressor
20 J / <15 fs / 10 Hz
2 J / <15 fs / 10 Hz

L3

Pump DPSSL multislab
Nd:glass
200 J

Oscillator
Ti:sapphire pre-amplifier

Oscillator
OPCPA front end

Compressor
Ti:sapphire power amp

10 PW compressor

30 J / 20 fs / 10 Hz
1 J / 20 fs / 10 Hz

L4

Nd:glass CPA chain

Compressor

1.5 kJ / 150 fs
1.8 kJ / 0.5-5 ns
~150 J / 150 fs

E1
Apps in molecular, biomedical & material sciences

E2
XUV / X-ray generation

E3
Plasma physics lab astrophysics

E4
High-field “exotic” physics

E5
Electron acceleration

E6
Proton acceleration
## Laser summary

<table>
<thead>
<tr>
<th>Beamline</th>
<th><strong>L1</strong></th>
<th><strong>L2</strong></th>
<th><strong>L3</strong></th>
<th><strong>L4</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak power</td>
<td>&gt; 5 TW</td>
<td>PW</td>
<td>≥ PW</td>
<td>10 PW</td>
</tr>
<tr>
<td>Energy in pulse</td>
<td>100 mJ</td>
<td>≥ 15 J</td>
<td>≥ 30 J</td>
<td>≥ 1.5 kJ</td>
</tr>
<tr>
<td>Pulse duration</td>
<td>&lt; 20 fs</td>
<td>≤ 15 fs</td>
<td>≤ 30 fs</td>
<td>≤ 150 fs</td>
</tr>
<tr>
<td>Rep rate</td>
<td>1 kHz</td>
<td>10 Hz</td>
<td>10 Hz</td>
<td>1/60 Hz</td>
</tr>
<tr>
<td>Supplier</td>
<td>Commercial pump lasers (Trumpf Scientific &amp; …)</td>
<td>STFC RAL major supplier and technology developer</td>
<td>LLNL major contractor</td>
<td>National Energetics &amp; EKSPLA major contractor</td>
</tr>
<tr>
<td>IoP activities on control systems</td>
<td><strong>Complete control system and integration</strong></td>
<td><strong>Complete control system and integration</strong></td>
<td>Integration and joint software development</td>
<td>Integration and collaboration on HW &amp; SW</td>
</tr>
</tbody>
</table>

---

**IoP**

**Laser summary**

<table>
<thead>
<tr>
<th><strong>Beamline</strong></th>
<th><strong>L1</strong></th>
<th><strong>L2</strong></th>
<th><strong>L3</strong></th>
<th><strong>L4</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak power</td>
<td>&gt; 5 TW</td>
<td>PW</td>
<td>≥ PW</td>
<td>10 PW</td>
</tr>
<tr>
<td>Energy in pulse</td>
<td>100 mJ</td>
<td>≥ 15 J</td>
<td>≥ 30 J</td>
<td>≥ 1.5 kJ</td>
</tr>
<tr>
<td>Pulse duration</td>
<td>&lt; 20 fs</td>
<td>≤ 15 fs</td>
<td>≤ 30 fs</td>
<td>≤ 150 fs</td>
</tr>
<tr>
<td>Rep rate</td>
<td>1 kHz</td>
<td>10 Hz</td>
<td>10 Hz</td>
<td>1/60 Hz</td>
</tr>
<tr>
<td>Supplier</td>
<td>Commercial pump lasers (Trumpf Scientific &amp; …)</td>
<td>STFC RAL major supplier and technology developer</td>
<td>LLNL major contractor</td>
<td>National Energetics &amp; EKSPLA major contractor</td>
</tr>
<tr>
<td>IoP activities on control systems</td>
<td><strong>Complete control system and integration</strong></td>
<td><strong>Complete control system and integration</strong></td>
<td>Integration and joint software development</td>
<td>Integration and collaboration on HW &amp; SW</td>
</tr>
</tbody>
</table>
Most laser control is not *technically* challenging...

Mostly sub-kHz diagnostics, slow feedback, modest AI/OO Ch. counts, 50 cameras, 150 *simple* motion axes, 1k control points per laser

...however there are still many challenges

ELI-BL’s rep-rate lasers require real-time control systems and machine intelligence – very new compared to <1/hour shot rates

Resources for control systems underestimated

Difficult to attract skilled, experienced staff – limited salaries, competition from IT sector, no ‘fame’

Greenfield project & cutting-edge laser tech – no experience base was available & laser requirements often changing

Strict tendering rules and laws make purchasing a nightmare
Some general challenges...

Industrial laser manufacturers generally in-house basic electronics – no market for ‘industrial quality’ laser electronics at OK prices

Some HW is very specific with only 1 or 2 suitable vendors – e.g., autocorrelators, wavefront sensors, deformable mirrors, dispersion correction – no incentive to customise SW/drivers/interface

Laser diagnostic & equipment vendors generally do not appreciate control system integration

Predominance of ‘quick and easy’ USB-Windows solutions only suitable for laboratory research environment

Poor integration options and/or terrible drivers – LabVIEW is usually the only alternative to custom applications for Windows
A good architecture aims for **scalable, adaptable, maintainable** and **reliable** integration but must consider project constraints:

**Project**
- Technically modest
- Medium scale
- Real-time intelligence
- Low manpower
- Limited budget
- No prior experience
- Changing requirements
- Strict tendering rules
- DIY electronics required
- Vendor driver support

**Architecture**
- Avoid uTCA, PXI
- Distributed reusable HW/SW modules
- Real-time OS & FPGA
- Simple software, easy hardware
- Low cost HW platform
- Avoid C++ & Java development
- Fast, flexible development platform
- Single vendor, volume order (NI!)
- Leverage modular IO for electronics
- LabVIEW essential; integration focus
Our control system architecture

Configuration and archiving
- Database
- HMI servers
- Top level sequencer
- Facility interface

Integration layer network
- Integration layer
- Device layer network
  - IOC
  - MSS controller
  - PSS controller

Device layer network
- Ethernet devices
- Serial devices
- USB devices
- ERIO FPGA targets
- Low-level A & D I/O

Services layer
- State machine and scripts
- KVM matrix
- Visualisation and UI

Status & monitoring (EPICS)
- Status control (EPICS) & configuration (MySQL)

Interlock permissives
- MSS failure signals (24V logic)
- Modbus

Facility safety systems monitoring
- SafetyNET
- KVM matrix

Device communications (e.g., VISA)
Our control system architecture

**Services layer**
- CentOS server
- IHSE Draco Tera Gateway server
- Enterprise MySQL

**Integration layer**
- EPICS
- Large switch 10G for services layer
- Moxa industrial GbE switches
- NI Real-Time 1U servers RMC-8354 with 4-port GigE NI PCIe-8233

**Device layer**
- Moxa serial device servers & ioLogik
- Cameras directly connected
- Icron USB extenders
- ERIOs NI 9147 & NI 9149 C-series modules
- Cameras directly connected

Facility safety systems monitoring
- SafetyNET switches
- Remote head(s)
- Interlock permissives
Many solutions exist with various advantages and disadvantages*

Shared memory on VxWorks (LANL+Cosylab)
Hypervisor shared memory - Hyppie (LNLS)
ActiveX CA (ORNL-SNS)
CaLab Win DLL (HZB-BESSYII)
DCOM Win API via EPICS driver (STFC-ISIS)

DIM Interface (GSI+CERN)
LV-native EPICS implementation (ORNL-SNS)

DSC Module via Shared Variables (NI)
LV-native CA (Observatory Sciences)

*surveyed 2014 - not an exhaustive list! Credit goes to: various presentations at EPICS collaborations and NIWeek by Alexander Zhukov, ORNL; GSI wiki summary [wiki.gsi.de/cgi-bin/view/Epics/]; Tech Talk [http://www.aps.anl.gov/epics/tech-talk/]
Basically works, but...
Project has been put on ice (NI’s unofficial warning in 2013)
Network SVs must be used (slow, unstable, poor scalability)
Not a full implementation (PVs on server-side have only few fields)
Missing fields confuse clients (e.g., Control System Studio)
Type-casting bugs (string and integer)

Early testing with the NI EPICS module

Demonstration LabVIEW camera server on RMC-8354 using NI EPICS module to link to a Control System Studio secondary display (developed 2012-2013)
Existing codebase was upgraded for ELI-BL by OSL – almost final release

CA Server has **full** support for basic record types: ai/ao, bi/bo, longin/longout, mbbi/mbbo, stringin/stringout, **waveform**

Polymorphic for standard LabVIEW types: I8, I16, I32, SGL, DBL, STR, Boolean, arrays of these – typecasting as appropriate
Access methods: caGet, caPut, dbPut, dbGet, caMonitor

Easy to use, simple LabVIEW code

Should be ‘virtualisable’

Add ‘SocketSetReuseAddr=TRUE’ to LabVIEW INI file to share UDP port with multiple instances

All source code was provided by OSL

ELI-BL will not customise – will continue to work with OSL if any additional features required
Testing ongoing at ELI and National Energetics (L4 laser)

Performance is good but library is quite large – streamlining would be needed for low-end cRIOs...

LabIOC testing results

Scalar PV repeated access

LabIOC testing results

Testing ongoing at ELI and National Energetics (L4 laser)

Performance is good but library is quite large – streamlining would be needed for low-end cRIOs...
Process model based on QSM (simpler than Actor Framework)
Messages must go through local Sequencer (message broker)
Data in hierarchical current value table (DVR variant attribute)
Around 20 processes completed, 10 more in development

So far one Virtual IOC is deployed

ELI-BL LabVIEW library

>7000 VIs

4 full-time developers
Hierarchical state machine model has been extremely useful for integration
Good communication tool for contractors and stakeholders
Works well in the software architecture too – rigid but highly testable and deterministic
L1: Three separate picosecond grating compressors in one 4m chamber. 68 motorized axes. Tendered with EPICS interface using NI module. Now working on LabIOC upgrade...

Assembly in March 2015

CSS control panel
Integration challenges and successes 2

L2: Bryton cryogenic cooling system (150K He)
Specified state machine in contract (very positive)
Machine and personnel safety integration to SIL-2
Integrated via EPICS IOC and Modbus

Trial CSS control panel for state machine

System state specification
L4: Timing and sync delivered by IoP to ensure successful integration later

All lasers have same system

First test of LabIOC package

Integrates EPICS MRF with LabVIEW Holzworth controller

Provides low-jitter triggers, RF references and PTP sync
Contact:
Dr Jack Naylon
jack.naylon@eli-beams.eu
www.eli-beams.eu
Institute of Physics
Na Slovance 2
182 21 Praha 8
Prague
Czech Republic

Thanks to:
Funding bodies: ERDF and ESF under operational programs ECOP and RDIOP
Observatory Sciences (Booth 8!):
www.observatorysciences.co.uk
Gary Johnson and the HAPLS team at LLNL
Article: str.llnl.gov/january-2014/haefner
Chris Malato and the L4 team at National Energetics/EKSPLA: nationalenergetics.com
Tomáš Mazanec and the rest of the LCS team!
Requirements:

**Commercially-supported product** – not another project for us!

**LV-native** – Pharlap now and future-proof for NI Linux-RT

**Minimum specialist knowledge required** (EPICS, Linux, C++...)

**Simple LabVIEW interface** – no LVOOP (idiot-proof!)

Both NI’s EPICS client/server module and the solutions offered by Observatory Sciences seemed to meet these RQs
Our progress

- Prototype sequencer still in test
- Archive database is not integrated with EPICS
- Mix of LV and CSS panels still, no KVM matrix yet
- LabVIEW IOCs still waiting for EPICS integration
- 6 physical IOCs running in L1 laser, 15 planned
- Currently only camera data is being buffered
- Simple devices such as chillers and PSUs have EPICS integration
- No facility interface yet – waiting for testbed

Deployment

- Machine safety network
- MSS controller
- PSS controller
- Interlock systems are operational – upgraded as new systems come online

Development

- Concept

Device layer network

- Working solutions for cameras, stepper motors, piezo actuators, spectrometers, energy meters, PSDs, Timing & sync system, support (PSUs, chillers, vacuum) – not all perfect!
- Autocorrelators & SPIDER close to completion
- Still to do: wavefront sensor, deformable mirror(s), Dazzler

Integration layer network

- IOC
- KVM matrix
- Facility interface

Services layer

- Database
- HMI servers
- Top level sequencer
- Facility interface

Key

- IOCs
- MSS
- PSS
- USB over Ethernet
- USB devices
- KVM matrix
- LabVIEW IOCs still waiting for EPICS integration
- Simple devices such as chillers and PSUs have EPICS integration
- Currently only camera data is being buffered
- No facility interface yet – waiting for testbed
- Interlock systems are operational – upgraded as new systems come online

Autocorrelators & SPIDER close to completion
Still to do: wavefront sensor, deformable mirror(s), Dazzler