

Development of Control Systems and Applications for the Cornell ERL Electron Source Laser System

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Recent research efforts at the Cornell University Laboratory for Elementary Particle Physics (LEPP) have focused on the development and implementation of a novel Energy Recovery Linac (ERL) system, with the potential to become a world leader in the propagation of ultra-intense, short pulse, high brilliance x-ray radiation, as a next-generation synchrotron x-ray light source. Current research has focused on the development of a high brightness, high average current electron source, with operational characteristics based on a very high voltage DC photoemission electron beam gun design. The ERL photoinjection system will be driven via photoelectric electron emission resulting from the direction of ultra-intense laser radiation onto the main electron beam gun photocathode. To account for mechanical and thermal drift effects intrinsic to the photoinjection laser and related optical components, a prototype dual-axis laser alignment system has been constructed, which includes hardware and software laser positioning controls and diagnostic feedbacks. Hardware development has included mechanical and electrical design and fabrication of dual quad photodiode detectors that will act as primary positioning feedbacks for laser input to the cathode, in addition to precise assembly of the entire positioning system, from beam placement, to piezoelectric actuator controlled mirror and photodiode detector configuration. Control system software modules were written in the UNIX based programming environment EPICS (Experimental Physics and Industrial Control System). Within EPICS, software protocol controls were created for actuator manipulation and readout, as well as real-time beam spot position monitoring. Currently, the laser positioning system GUI provides a capable user interface for single-channel, manual actuator control and position monitoring. Initial tests have encouraged further development of EPICS-based software controls to interface with upgraded multi-channel drivers, allowing for integrated real-time feedback positioning loops for ERL electron source laser system operation.

I. INTRODUCTION

A fundamental requirement for the success of modern large-scale experimental physics structures has been the development of advanced control systems, which allow for precise monitoring and adjustment of analog and digital data acquisition and system control components. As large-scale experimental facilities generally require the accurately synchronized functionality of many thousands of control and feedback points, the importance of centralized software and hardware control system development is noted. Examples of experimental physics structures that rely on the operation of complex control systems include high energy density physics facilities such as the OMEGA inertial confinement fusion laser system at the University of Rochester Laboratory for Laser Energetics (LLE), in Rochester, New York[1]

and the ASDEX Upgrade magnetic confinement fusion Tokamak at the Max-Planck-Institute for Plasma Physics (MIPP) in Garching, Germany[2]. In addition, control system development is vital for the success of ground and satellite-based astrophysical observatories such as the W. M. Keck Observatory, in Mauna Kea, Hawaii[3], as well as on next-generation accelerator physics systems including the Deutsches Elektronen Synchrotron (DESY) facility in Hamburg, Germany[4], and the proposed Cornell University Laboratory for Elementary Particle Physics (LEPP) Energy Recovery Linac (ERL) system, located in Ithaca, New York.[5] Upon completion and integration with the existing Cornell High Energy Synchrotron Source (CHESS)[6], the Cornell ERL will be able to propagate coherent, short pulse, high brilliance x-ray radiation, as a next-generation synchrotron x-ray light source.[7] It is the design and deployment of control systems for the prototype Cornell ERL facility that will constitute the primary focus of this work.

As a large-scale linear accelerator based experiment, the Cornell ERL will require operation of mechanical controls, instrumentation, and diagnostic support devices that will exist throughout thousands of meters of beam line. Currently, ERL main system components are being developed at the Cornell LEPP, including a novel photoinjection system that is driven by a high brightness, high average beam current (100 mA) electron source.[8] The electron source will exist as a negative electron affinity, very high voltage DC photoemission electron beam gun, to operate at potentials up to 750 kV.[7] As the source will operate via photoelectric emission for electron beam propagation, an intense laser radiation source will be utilized. The existing laser system which has been developed for use on the ERL employs a master oscillator-power amplifier (MOPA) design able to produce 2 ps, 40 nJ pulses, at an operational wavelength of 520 nm, which will be upgraded to allow for 130 W average infrared power and a 1300 MHz repetition rate.[7, 8] For photoemission to occur, the drive laser is directed onto the ERL high quantum efficiency cesium and nitrogen trifluoride activated photocathode, following detailed pulse-shaping and optimization of beam quality.[8] To achieve the demanding conditions for optimum ERL operation, precise beam placement on the central cathode region must be achieved over non-trivial timescales. As mechanical and thermal drift effects are intrinsic to the photoinjector laser system and associated optical components, a prototype dual-axis laser alignment system has been constructed, which includes hardware and software laser positioning controls and diagnostic feedbacks able to allow for remote realignment to optimized beam placement on the ERL photocathode. The investigation, which follows, documents the hardware and communication system development that was required to allow for remote control and monitoring of beam position, through software modules written in the UNIX based EPICS (Experimental Physics and Industrial Control System) programming environment.

II. ERL LASER POSITIONING SYSTEM HARDWARE AND COMMUNICATIONS STRUCTURE

The organization of large-scale accelerator-based physics facilities is often arranged to resemble a distributed control system structure.[9] Distributed control systems utilize a hardware, communications, and software infrastructure that is intentionally modularized at each observable scale to increase system efficiency. Modularity in the case of the distributed control system refers to the manner by which each component of a large experiment is able to be independently developed, deployed and monitored, with the ability to readily interface and adapt to dynamically changing system requirements, while also not propagating unnecessary

operational interdependence to other system elements to limit individual functionality. The Cornell ERL facility uses such a design, with modularity inherently repeated when viewing the system from a top-to-bottom approach, with the entire superstructure comprised of modular main system components constructed from independent diagnostic and control systems, each of which have a modular design at the device and instrumentation level. FIG. 1 illustrates the hierarchical modularity of the Cornell ERL, tracing experimental organization from the largest to smallest scales of the facility. Here, the entire ERL system is organized

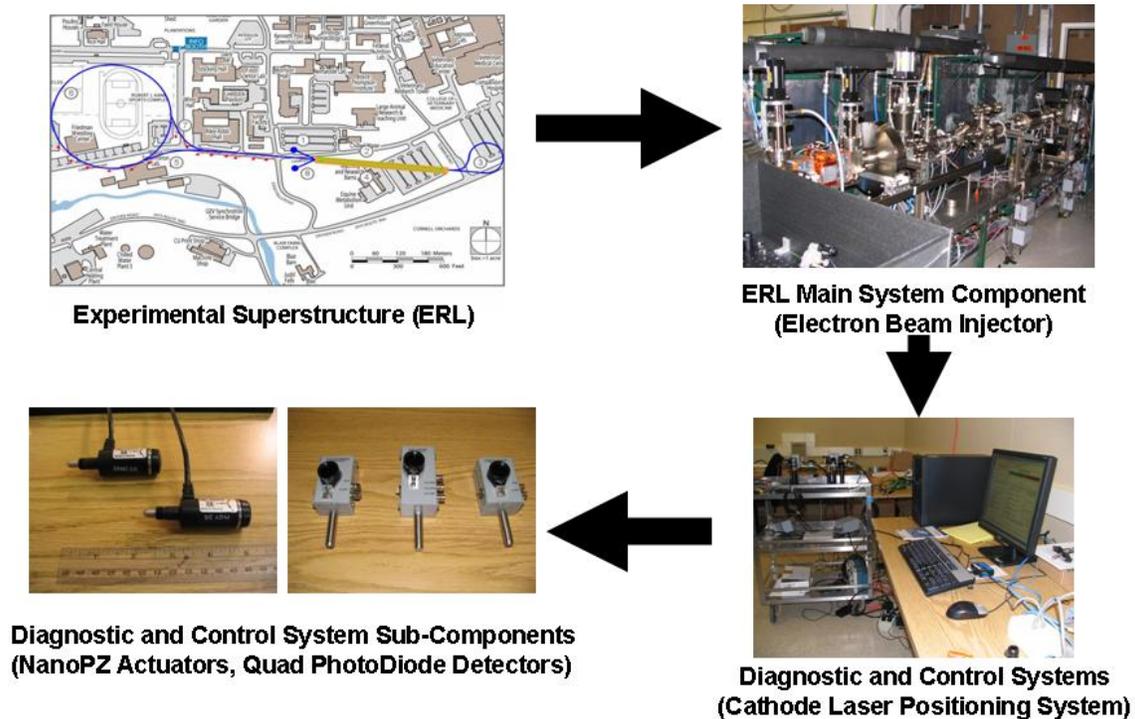


FIG. 1: The modular distributed control system infrastructure of the Cornell ERL facility.

as a superstructure constructed out of eight main system components (photoinjector, linac, turning ring, CHESS, etc.). Each of the main system components are subdivided into various individual diagnostic and control systems. For the photoinjection electron source main system component, the photocathode laser positioning system constitutes a primary diagnostic and control system. This positioning system is then furthermore partitioned at the device level between control mechanisms (e.g. nano-piezoelectric actuators) and diagnostic feedback instruments (e.g. quad photodiode detectors). In practice, hardware systems on each of these magnitudes can be individually operated and tested before total ERL system integration, allowing for a faster and more flexible experimental development schedule. The final level of organization of the ERL as a distributed control system occurs through software development, in which software routines used to control each individual system component are collected into a centralized Input/Output Controller (IOC) and related front panel through an environment such as EPICS.[9] The manner in which EPICS software modularity is integrated into the development structure to emulate existing hardware system organization on the ERL, and the laser positioning system is discussed in further detail in the next section.

The overall communications infrastructure of the ERL photocathode laser positioning

system is illustrated in FIG. 2. In keeping with the modular logic of the distributed control

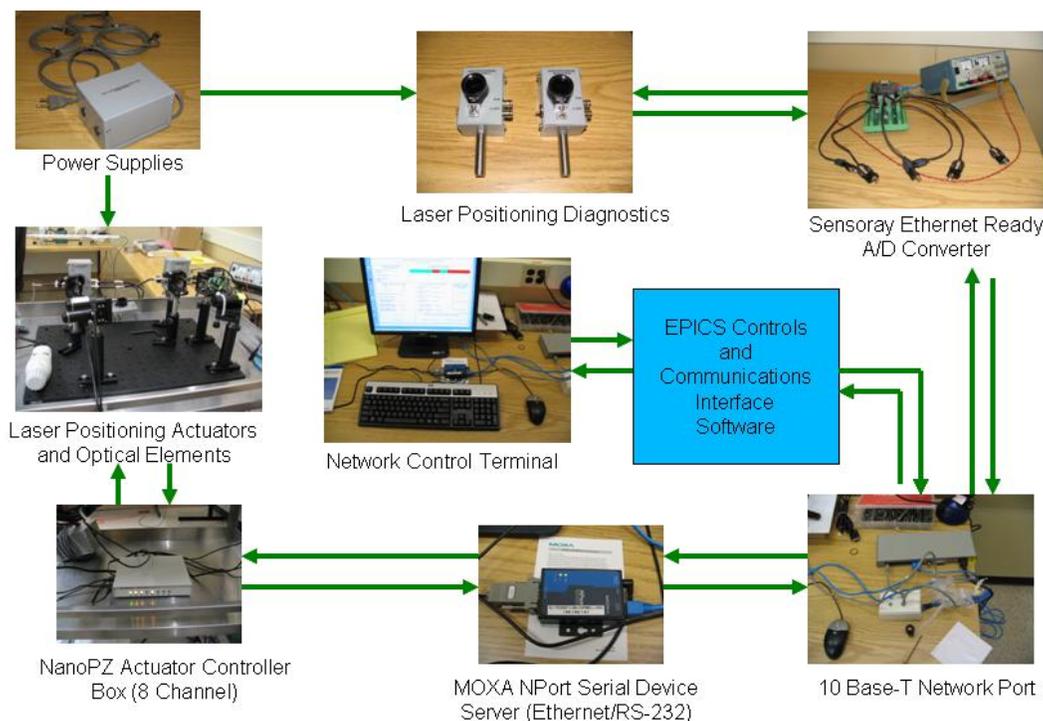


FIG. 2: The dual branch control and diagnostic communications infrastructure of the Cornell ERL prototype photocathode laser positioning system.

system, the laser positioning system hardware is divided between alignment controls and diagnostic feedbacks. Control and feedback components exist within separate branches of the system, to limit communications dependence. The developed EPICS control software relies on Ethernet dependent TCP/IP, with control and feedback components assigned separate IP addresses. Hence, the entire control system may be administered via remote network access wherever an internet connection is available around the globe. Tracing each branch of the system from device to centralized EPICS controls, we have the following. For the laser positioning actuators and attached optical elements, first communication is made from each PZA12 nano-piezoelectric actuator, with an eight channel NanoPZ actuator controller PZC-SB switchbox via a RS-485 connection.[10] The RS-485 is then output to a RS-485 to RS-232 conversion interface connection, which is connected to a single-port MOXA NPort serial device server RS-232 to 10/100M Ethernet connection.[11] The MOXA NPort, which is digitally assigned an individual IP address, is then fed into a central 10 Base-T network port. The diagnostic feedbacks are organized from a pair of quad photodiode detectors with voltage sum, and x- and y-difference CPC connectors. The six CPC outputs are connected via coaxial cabling to a 16 channel Sensoray Model 2509, Rev. E. Ethernet ready analog-to-digital (A/D) converter.[12] The Sensoray device is also assigned an IP address, which is achieved by manual installation of shunts in a hexadecimal field-programmable format for each byte of the IP address.[13] Ethernet output from the Sensoray A/D terminal block is also connected to the 10 Base-T network port, which is itself connected to a central network control terminal, with configured communications interface (e.g. IP configuration) software, and EPICS base control packages installed. It is through this divided communications

structure that hardware modularity is maintained (i.e. if an error were to occur in the control branch, the diagnostic branch would only be affected in experimental result, rather than losing functionality entirely).

The experimental design of the optical and mechanical structures of the ERL photocathode laser positioning system depends highly on the interaction between the communications-separated modular diagnostic and system control components. A generalized overview of the diagnostic and control hardware components interfaced in the prototype laser positioning system is given in FIG. 3. For system testing and alignment purposes, a Class IIIb World

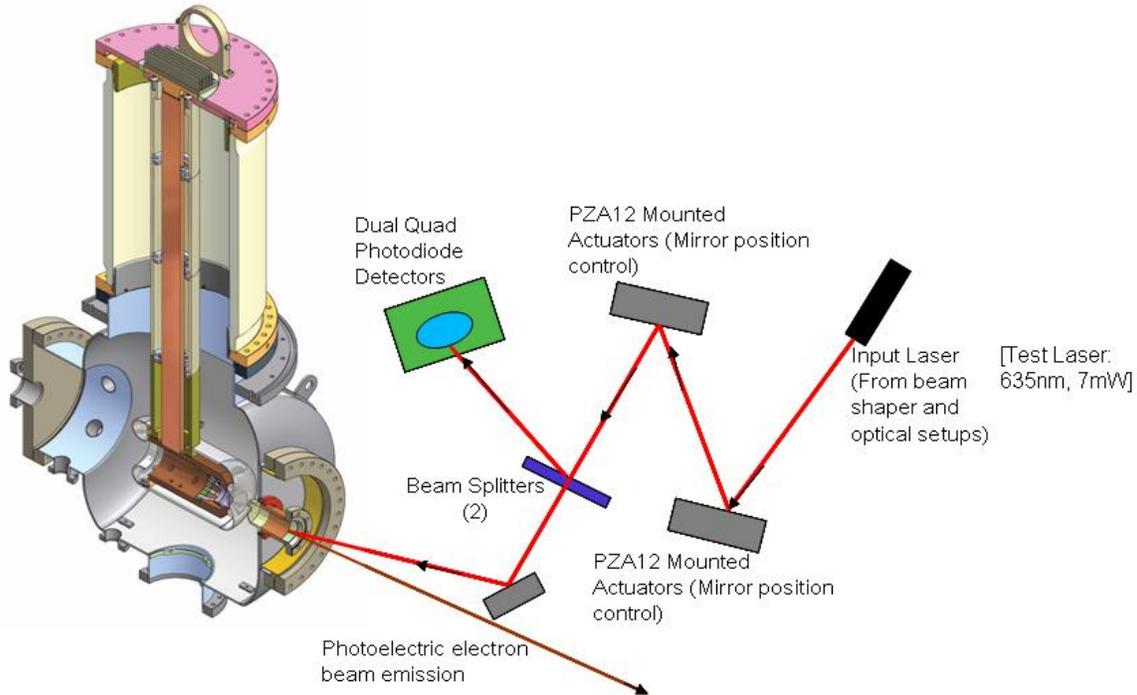


FIG. 3: Generalized overview of primary diagnostic and control system components of Cornell ERL prototype photocathode laser positioning system.

Star Tech TECRL-7GC-635 thermoelectrically cooled red diode laser module was used.[14] The laser was operated under a linearly polarized optical regime, at a wavelength of 635 nm and a power of 7 mW. The manufacturer quoted RMS noise (0-20 MHz) was less than 0.5 percent, and the beam shape was adjusted to be nearly circular, with an operational diameter maintained between 2 and 3 mm.[14] Test laser positioning was optically achieved on the prototype alignment system using a pair of ThorLabs 1 inch diameter dielectric coated plane mirrors mounted to individual dual-axis adjustable kinematic mirror mounts.[15]

To allow for precise, computer controlled dual axis adjustment of each steering mirror, Newport PZA12 linear nano-piezoelectric actuators were installed in place of each manual mirror mount screw adjustment port.[10] The piezoelectric actuator operates under the fundamental principle of the inverse piezoelectric effect, in which certain 'piezoelectric' crystalline structures (e.g. quartz), when attached to an electrical source, will exhibit continuous mechanical deformation directly proportional to the magnitude of the applied voltage.[16] The direct piezoelectric effect, in contrast, proceeds oppositely, where mechanical stress applied to a piezoelectric crystalline structure results in the production of an electric charge.[16]

Selection of nano-piezoelectric actuators over other more conventional positioning devices for remote mirror adjustment was found through scale and performance capabilities. The small construction of piezoelectric actuator devices provides an advantage over standard stepping motors for the adjustment of small optical elements. The dimensions of the PZA12 actuators used in the laser positioning system range between 2.93 in. and 3.42 in. in length, with a chassis diameter of 0.83 in., which allows for two actuators to be mounted to a single mirror mount.[10] In addition, piezoelectric actuator devices can achieve nearly continuous linear adjustment using the inverse piezoelectric effect, whereas the motion of stepper motors is inherently discrete. As illustrated in FIG. 4(a), stepper motors are only able to achieve a discrete stepping precision through the rotation of a permanent magnet attached to a screw by creating temporary electromagnetic polarity when applying current to wire windings within the motor.[17] Stepper motors also require the continued application of holding current to maintain position between uses. Piezoelectric actuators do not face such limitations, as the variation of applied voltage results in the near-continuous expansion and contraction of the piezoelectric material, which in the PZA12 setup is mounted similarly as illustrated in FIG. 4(b), where the piezoelectric material is coupled to mechanical elements that frictionally drive a nut and screw system, that move the actuator arm directionally.[10] Also, since the loss of applied current after power down will not result in further deformation of the piezoelectric material, a holding current is not required to maintain position between uses. The PZA12 actuators employed for this system are quoted to have a 30 nm sensitivity within a 12.5 mm range of travel, and can reach a motional precision of 160 nm per step, each of which are divided into 16 microsteps, yielding a precision of 10 nm per microstep.[10] In spite of the apparent advantages of nano-piezoelectric devices, repeatability issues can propagate during long term use, resulting from frictional slipping between the piezoelectric materials and the nut and screw system, however testing on the laser positioning system suggested positional aberration of less than 10 microsteps at higher jog speeds reaching 10,000 microstep/s.[10] The addition of software and hardware feedbacks allowed for the real-time monitoring of beam spot position and related PZA12 error correction during testing.

The primary instrumentation used for laser beam spot position diagnosis and feedback were dual quad photodiode detectors. As direct insertion of the photodiode detector diagnostics to the beam line would result in complete attenuation and blockage of the beam from reaching the photocathode target region, microscope slide beam splitters were utilized to direct a small percentage of the laser radiation from the beam line onto the active silicon array of the quad photodiode detectors. Quad photodiode detectors operate using a circular photosensitive silicon array that is divided into four quadrants, as illustrated in FIG. 5.[17] When focused optical light is directed onto the active array, photocurrent signals are produced and then converted to corresponding voltages using a current-to-voltage amplifier module installed to the photodiode detector card itself.[18] The unique manner by which voltages from each of the four quadrants are read out allows for position monitoring of incident laser radiation. For the ERL prototype laser positioning system, a Pacific Silicon Sensor Inc. QP50-6SD2 quad photodiode sum and difference amplifying detector was used.[18, 19] With this photodiode diagnostic, three analog feedback parameters were available for conversion to digital signal by the aforementioned Sensoray A/D terminal block, namely: vertical voltage differences between the bottom and top pairs of photosensitive quadrants, horizontal voltage differences between the left and right pairs of photosensitive quadrants, and total voltage signal sum for all four quadrants combined. The QP50-6SD2 operates with current-to-voltage amplification gain of 10^4 , hence, yielding the following rela-

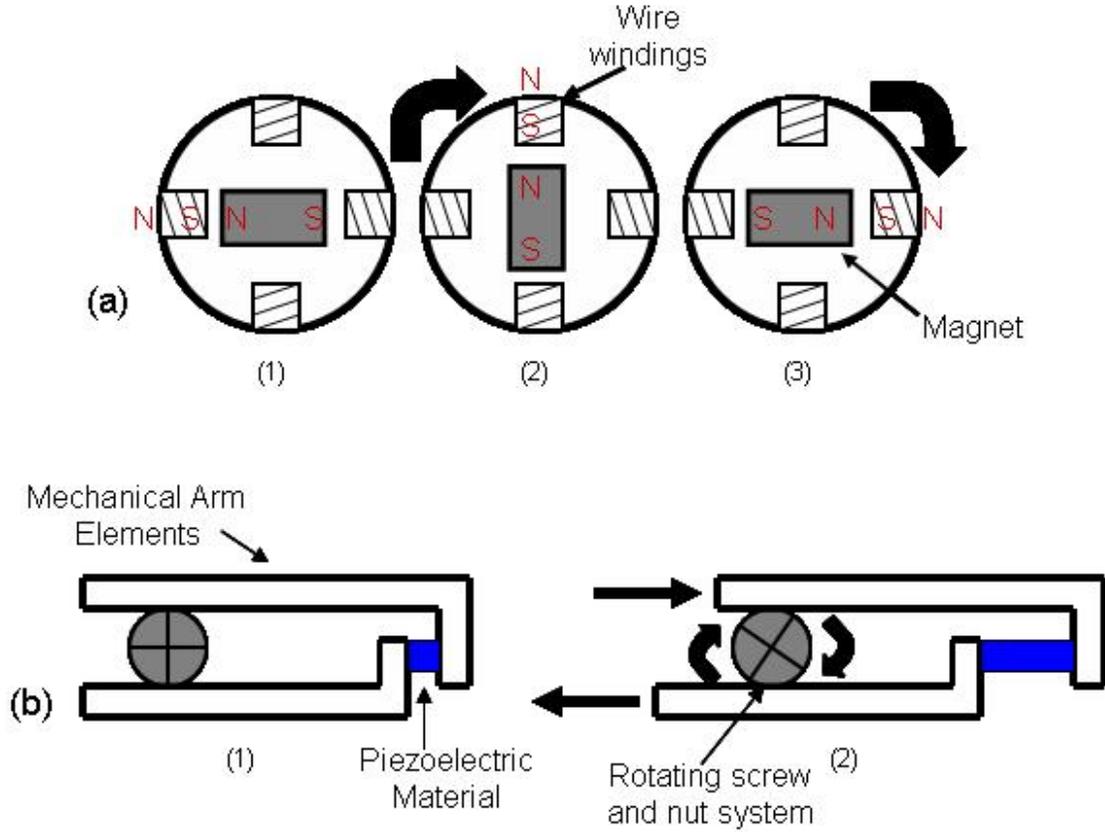


FIG. 4: Stepper motor compared to Piezoelectric motion systems. (a) Stepper motor magnet rotating discretely through positions (1), (2) and (3) as temporary polarity is electrically produced at each wire winding position. (b) General piezoelectric motion. At (1) mechanical arm elements are at rest with no attached electrical source to deform the piezoelectric material. At (2) an electrical source is applied, resulting in expansion of the piezoelectric material, hence forcing the lower mechanical arm element into motion to frictionally rotate the nut and screw system by compression.

relationship between photo induced current on the array quadrants, and the resultant sum and difference voltages (with quadrants corresponding to those in FIG. 5):

$$V(\text{Bottom} - \text{Top}) = [I(3, 4) - I(1, 2)] * 10^4 \quad (1)$$

$$V(\text{Left} - \text{Right}) = [I(2, 3) - I(1, 4)] * 10^4 \quad (2)$$

$$V(\text{Sum}) = I(1, 2, 3, 4) * 10^4 \quad (3)$$

where $V(\text{Bottom-Top})$ is the bottom minus top quadrant pair voltage, $V(\text{Left-Right})$ is the left minus right quadrant pair voltage, $V(\text{Sum})$ the sum of voltages from all four quadrants, $I(A,B)$ indicates the sum of photo induced currents from quadrants A and B, and $I(A,B,C,D)$ indicates the sum of photo induced currents from all four quadrants of the photodiode detector.[18] As the QP50-6SD2 photodiode detectors received for use on this system only included independent card and active array components, custom interface electronics, power supplies, and mechanical mounting chassis were designed and constructed prior to

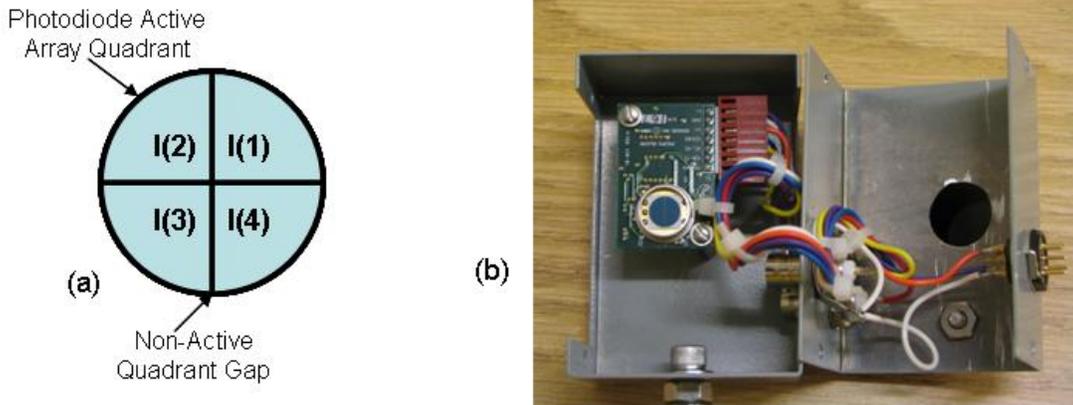


FIG. 5: Photodiode detector quadrant current assignments. (a) Schematic of photocurrent division between four quadrants in the active silicon array of the photodiode detector. The non-active gap between quadrants is also indicated. (b) Image of quad photodiode detector card and active photosensitive array, mounted with interface electronics.

deployment of feedback diagnostics. Electronic schematics and images of the completed interface electronics and power supplies for the quad photodiode detectors can be found in FIG. 6. Mechanical construction of the diagnostic chassis utilized BUD boxes modified for card mounting, input/output electronic feedthrus, and optical filter mounting, to allow for attenuation of ambient light present in the experimental environment.[20] Sum and difference voltage signal outputs were connected from corresponding photodiode card pins to BNC feedthrus, and ± 15 V and ground power supply inputs were connected from a 5-pin voltage feedthru connection to corresponding card pins. As illustrated in the previously mentioned figure, power supply element construction was completed using a Kepco TDK Power Supply AC in to ± 15 Volt DC out conversion unit.[21]

With the characteristics of all essential hardware components of the ERL prototype laser positioning system well defined, it is important to now discuss the theory that was utilized for precise optical beam positioning, and the mechanical configuration that was required to achieve these goals. FIG. 7 includes a schematic and image of the final prototype optical steering control and diagnostic feedback design, modeled according to the method of Grafstroem, et. al., as described in the referenced article from New Focus.[17, 22] Following emission from the test laser, the beam is reflected off of the first PZA12 controlled mirror, onto the second PZA12 controlled mirror, and then through two beam splitters before being directed out of the positioning system and onto a final stationary mirror within the ERL photoinjector vacuum system, which directs the beam to its final placement on the photocathode target region. The use of two dual-axis controlled mirrors allows for separate beam positioning control of the two points on the beam line that are monitored by the quad photodiode detectors. Essentially, the x- and y-positioning of the first mirror defines the placement of point A on the second mirror, which forms a fixed origin for the positioning beam line (see figure). The first beam splitter and photodiode detector is placed close to the second mirror (less than 10cm away) to continually image the position of point A, defining the first point in the diagnostic position line. The second beam splitter and photodiode detector is placed as far as possible (about 30 cm) from the second mirror down the beam line (with respect to system constraints), hence allowing for the imaging of point B on the

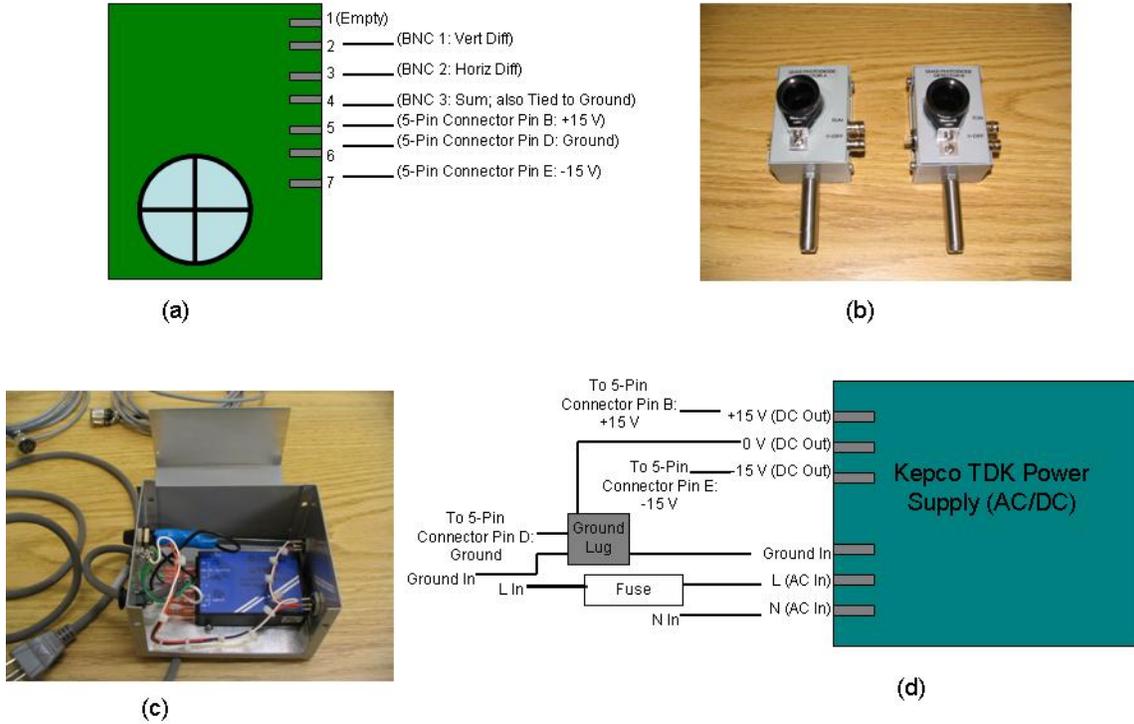


FIG. 6: Electronic schematics and images of the completed interface electronics and power supplies for the quad photodiode detector diagnostics. (a) Electrical wiring diagram of quad photodiode detector interface electronics. (b) Image of completed quad photodiode detector diagnostics (mounted with interface electronics). (c) Image of completed quad photodiode detector custom power supply. (d) Wiring diagram of quad photodiode detector power supply electronics (fuse characteristics: 3 A, 250 V).

beam line, which can be positioned through the mechanical adjustment of the second dual axis controlled mirror. Point B, in principle, represents the output beam placement of the positioning system onto the photocathode target. Generally, positioning is then achieved by adjusting the first mirror to account for drift effects of the laser input and to define the constant origin in space, and then using the second mirror to point the beam to the desired location on the centroid of the photocathode. By allowing the first mirror and photodiode detector to allow for the definition and monitoring of point A and the second mirror and photodiode detector to allow for the definition and monitoring of point B, it is suggested that feedback and software control systems may be simplified, since independence would occur between the definition of each point defining the beam line input, therefore allowing for separation of feedback loops in the control software logic.[17] During system operation, beam alignment is initially achieved and then maintained using a three step process.[18] First, the input beam is directed onto the active arrays of the connected photodiode detectors until a maximum voltage readout is observed. This maximum indicates that the entire beam has been placed onto the photosensitive region, where the beam diameter is maintained to be less than the maximum array diameter of 7.8 mm, but greater than the 1 mm non-active gap size between photodiode quadrants.[18] Once this maximum is reached, x-axis slewing

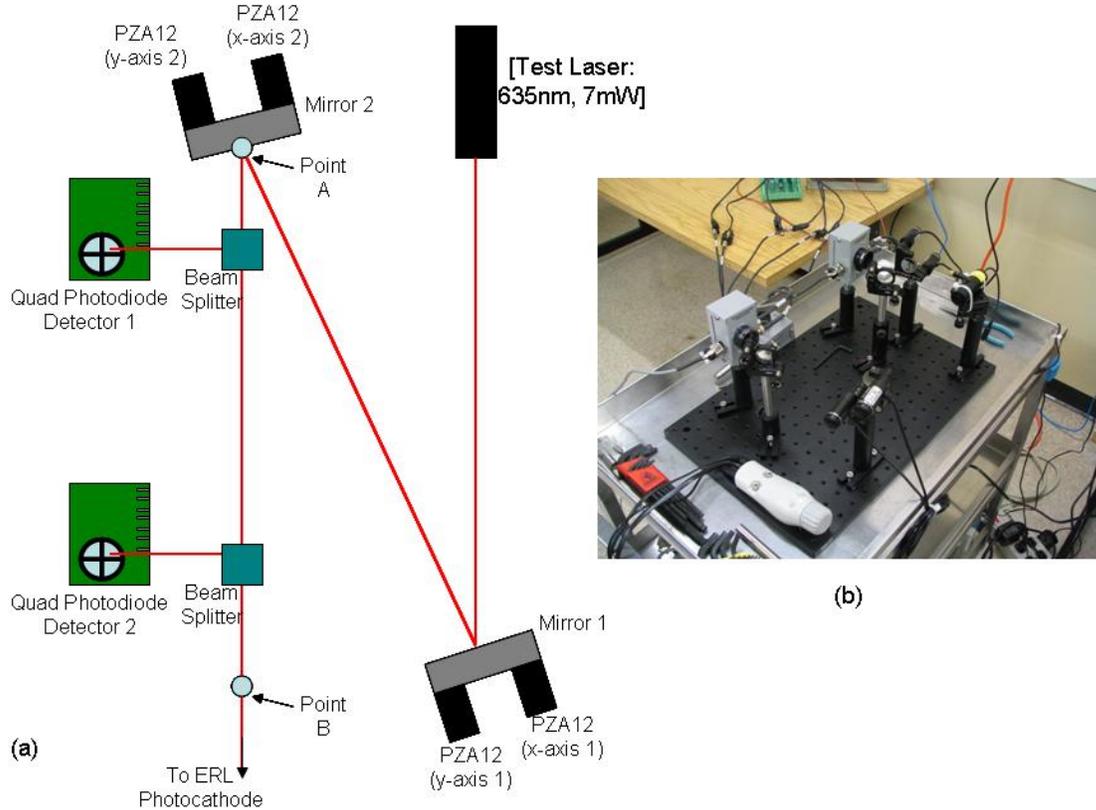


FIG. 7: Schematic and image of the final prototype optical steering control and diagnostic feedback design. (a) Optical beam pointing schematic with beam line locations A and B indicated. (b) Image of completed Cornell ERL prototype photocathode laser positioning system.

is performed until the absolute value of the horizontal voltage difference is minimized (approaching zero), indicating that half of the beam spot is in the right two quadrants, while the other half lies in the left two quadrants. Finally, similar y-axis slewing takes place, until the absolute value of the vertical voltage difference is minimized (also approaching zero), with an analogous positioning effect for beam spot location as in the horizontal case. By performing this procedure, the beam spot is mathematically shown from the equations presented earlier in this section to reside in the centroid of the photodiode detector field of view. With the hardware and communications structure of the ERL laser positioning system now well-defined, software controls could then be written to allow for automated beam positioning, which is documented in the section, which follows.

III. EPICS SOFTWARE CONTROL SYSTEM STRUCTURE AND CONCEPT OF DEVELOPMENT

EPICS (the Experimental Physics and Industrial Control System) is a UNIX based software environment, which allows for the development of control and monitoring software for system component parameters on large scale experimental physics and industrial manufacturing systems. Originally developed and maintained by researchers at the Advanced Photon Source (APS) located at Argonne National Laboratory, EPICS is currently utilized

as a primary control system software environment at several large-scale experimental and accelerator-based physics facilities worldwide, including the Tri-University Meson Facility (TRIUMF) operated in part by the University of British Columbia in Vancouver, British Columbia, in addition to the Berliner Elektronenspeicherring-Gesellschaft für Synchrotronstrahlung (BESSY), located in Berlin, Germany.[23, 24] EPICS has also been selected for primary usage on the Cornell ERL project, due to its various open-source advantages over pre-packaged control system software, such as LabView from National Instruments.[25] Due to the widespread use of EPICS among experimental physicists worldwide, the open-source architecture utilized by this environment have allowed for the growth of an extensive online library of software modules configured for use with many scientifically relevant and commercially available instruments and control device models. EPICS code is structured to be a scalable software emulator of distributed control system formatting, with fully modularized elements able to issue and receive commands to and from a large number of parameter nodes across system components. In addition, EPICS offers a real-time input/output control (IOC) structure reliant on system channel access allowing for control, data acquisition, and analysis along a supervisory control and data acquisition (SCADA) structure over an arbitrary number of system elements.[9] Examples of channel access IOCs might include an output control channel for mechanical opening and closing of a vacuum system gate valve, while related input control channels could include gate valve position status, and pressure readings to either side of the gate valve.[9] EPICS therefore is used as an interface to consolidate readout, status, and communication between interdependent control devices, through a text-based programming language that is modular (see the paragraph, which follows), easy to learn, and able to be integrated with base level programming commands and languages, including those in C and ASCII.[9] Advanced "real-world" functions of EPICS include alarm handling and safety measures. Alarm handling is accounted for to notify a human operator of the location and nature of system issues as they arise, pre-defined by the user for parameter values out of range. EPICS scripts also have the capability to deploy safety protocols to avert potentially dangerous situations automatically in the absence of operator control (e.g. voltage shutoff, automatic closure of gate valves, etc.)[9] The EPICS GUI, called the Extensible Display Manager (EDM), is also designed as a graphical front panel for easy visualization and manual control of remote experimental devices, using a standard keyboard/mouse interface. Unlike many pre-packaged control system GUIs, the look and format of EDM is fully user customizable, allowing for specific emulation of physical controls and gauges found on the actual control devices in use on a system (e.g. slider bars, switches, buttons, plots, meters, etc.)[9] With EDM, users are able to create GUI functionality and visual style that can replace commercial device software through integration into a single system, allowing for an environment independence aiding GUI operator training and use (hence, an operator is allowed to become familiar with one style and format of controls governing many devices, instead of requiring training on many disparate software environments for each device). In spite of several of these clear advantages, EPICS requires a complex initial build structure and procedure with many necessary packages, each with a non-uniform method of configuration, however these initial delays are often outweighed by the reduced timescales of software development itself. Currently, a majority of ERL controls are run through EPICS base package release 3.14.8.2, however an EPICS base package release 3.14.9 build was completed and entered into the ERL concurrent version system (CVS) repository on 14 June 2007, as an upgrade platform for current and future software modules.[9]

The software modularization of EPICS controlled systems is intentionally designed to

emulate the modularized hardware structure of large-scale distributed control systems. For the specific example of the Cornell ERL, distributed control system software is set up via the hierarchical EPICS structure, using EDM as a large-scale interface to organize many IOCs, each built from several database records, which in turn are comprised of numerous low-level device protocols. An illustration of the software structures existing on each level of the ERL experimental structure is shown in FIG. 8. Tracing these software structures

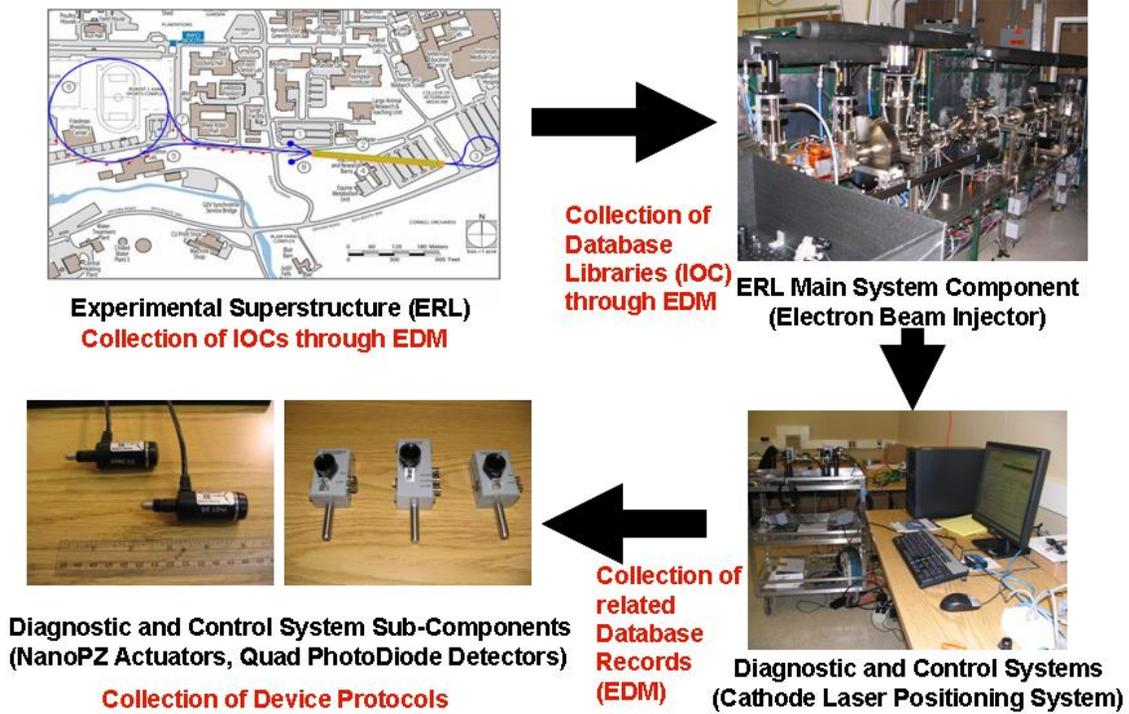


FIG. 8: Diagram of ERL hierarchical EPICS distributed control system structure overlaid with corresponding scaled hardware structures.

from the smallest to largest components of the ERL, we have the following. At the smallest scale, individual software classes, referred to as device protocols, are written to define base functionality of individual input or output commands for each device parameter available. In the case of the PZA12 actuators, there are a defined set of possible base ASCII commands that are available for use to alter and read actuator and switchbox parameters, each of which are separated into and assigned individual protocol classes. In order to properly parse and issue these ASCII commands, the EPICS package StreamDevice2 is used for a communications interface.[26] Such commands include controller box reset, actuator motion relative to a current position, setting of travel limits, reading of active channel, etc. For the laser positioning quad photodiode detector diagnostics, base C commands were interfaced at the protocol level to read out sum and difference voltages, as well as allowing for soft channel reset on the Sensoray A/D terminal block. As a result, at the protocol level, division of actions into separate classes allows for continued functionality of specific functions even if one action function were to fail. Also, this partitioning is able to allow for a modularized selection of sets of actions to be divided between devices, at the higher database record level. At the next scaling level, the entire ERL prototype laser positioning system is comprised of two separate database records, partitioned according to hardware modularization between

control and diagnostic branches (i.e. between PZA12 actuator controls, and quad photodiode detector feedbacks). Each database record consists of a set of desired device protocol class calls; however at this level the characteristics of each base function (the manner in which each operates) can be defined. Let us take as an example the laser positioning system protocol 'read Pos 01', used for reading the position of the active actuator connected physically to channel 01 of the eight channel PZC-SB switchbox.[10] If issued as a raw protocol, 'read Pos 01' would simply read the integer position value of the active actuator, however within the database record, characteristics may be assigned to the output value, including parameter description, related units, and input type, as well as definitions of the type of data acquisition being used. In this case, the protocol is made active through a continuous scan of the position channel parameter, at a defined interval of 500 ms. In addition, alarm parameters may also be assigned to indicate motion outside of database-defined upper and lower bounds, and the severity of the alarm associated with displacement out of actuator range. Sample blocks of device protocol and database record code are included in FIG. 9 for PZA12 actuator controls. The ERL prototype photocathode laser positioning system

(a)

```

actuatorMotionRel.proto - /mnt/disk1/tmp/bschmitt/epics/R3.14.8.2/ioc/test...
File Edit Search Preferences Shell Macro Windows Help
# Title: actuatorMotionRel.proto
# Author: B.L. Schmitt
# Date: 3 August 2007
#
# Purpose: Protocol file used to execute motion of 'nn' microsteps relative
# to current position on active NanoPE actuator currently connected
# to NanoPE controller box.
#
# Usage: actuator_Motion_Rel
#
# actuator_Motion_Rel - Protocol allowing for user definition and
# execution of a move of 'nn' microsteps
# relative to current position on active
# NanoPE actuator currently connected to
# NanoPE controller box.
#
#-----
# Definition of initial carriage return and line feed
# delimiters used within the protocol.
#
# Terminator = CR LF;
#
# Allow for user definition and execution of a move of
# 'nn' microsteps relative to current position on active
# NanoPE actuator.
#
actuator_Motion_Rel
{
  out "IPR %d";
  @init { out "IPR?"; in "IPR? %d"; }
  wait 1000;
  out "ISM";
}
# End of Protocol File.

```

(b)

```

nanopz.db - /mnt/disk1/tmp/bschmitt/epics/R3.14.8.2/ioc/test_area/nanopz_motor...
File Edit Search Preferences Shell Macro Windows Help
#
# Database dfanout record definition for the distribution
# of alarm actuator motion low limit.
#
record(dfanout, "ERL_Control_Room:alarm_Motion_Lo_Limit")
{
  field(DESC, "Distribute Alara Limits")
  field(OUTE, "ERL_Control_Room:read_Pos_01_LOLO")
  field(OUTF, "ERL_Control_Room:read_Pos_02_LOLO")
  field(OUTG, "ERL_Control_Room:read_Pos_03_LOLO")
  field(OUTH, "ERL_Control_Room:read_Pos_04_LOLO")
}
#
# Database record definitions for NanoPE Controller Box
# protocol 'actuator_Motion_Rel'
#
record(ao, "ERL_Control_Room:actuator_Motion_Rel")
{
  field(DESC, "Move Actuator 'nn' steps")
  field(UTYP, "stream")
  field(OUT, "actuatorMotionRel.proto actuator_Motion_Rel ERL_Control_Room")
  field(INP, "msSteps")
}
#
# Database record definitions for NanoPE Controller Box
# protocol 'actuator_Motion_Jog'
#
record(bi, "ERL_Control_Room:actuator_Motion_Jog")
{
  field(DESC, "Move Actuator at Jog Speed")
  field(UTYP, "stream")
  field(INP, "actuatorMotionJog.proto actuator_Motion_Jog ERL_Control_Room")
}
#
# Database record definitions for NanoPE Controller Box
# protocol 'actuator_Motion_Stop'
#
record(bi, "ERL_Control_Room:actuator_Motion_Stop")
{
  field(DESC, "Stop all actuator motion")
  field(UTYP, "stream")
  field(INP, "actuatorMotionStop.proto actuator_Motion_Stop ERL_Control_Room")
}
#
# Database record definitions for NanoPE Actuator 01
# protocol 'read_Pos_01'
#
record(ai, "ERL_Control_Room:read_Pos_01")
{
  field(DESC, "NanoPE Actuator 01 Position")
  field(UTYP, "stream")
  field(INP, "@readPosition.proto read_Pos_01 ERL_Control_Room")
  field(EQU, "msSteps")
  field(SCAN, "5 second")
  field(MINL, "1000000")
  field(MINR, "1000000")
  field(MINL, "1000000")
  field(MINR, "1000000")
  field(LLSV, "MINOR")
}

```

FIG. 9: Sample Cornell ERL prototype laser positioning code. (a) Device protocol class for the definition of actuator motion relative to current position. (b) Database record class defining the characteristics of functionality for PZA12 actuator protocols.

was written using 35 control and diagnostic device protocols, split into actuator and quad photodiode detector database records. Packed together, device protocols and database records (along with base software) constitute a complete IOC (illustrated in FIG. 10), which are scaled together at the ERL main system component level, after which collections of IOCs are used together to form the entire software system for the ERL experimental superstructure. The graphical organization and centralization of controls written for each device control and diagnostic system is illustrated in FIG. 11, for currently existing ERL

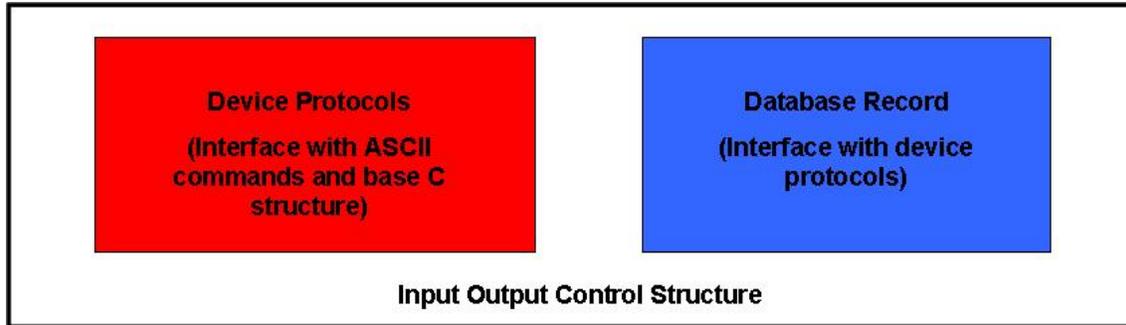


FIG. 10: Organizational diagram of the Input/Output Control (IOC), comprised of device protocol and database record classes in EPICS.

photocathode components. Onto this panel will be installed the completed front panel EDM

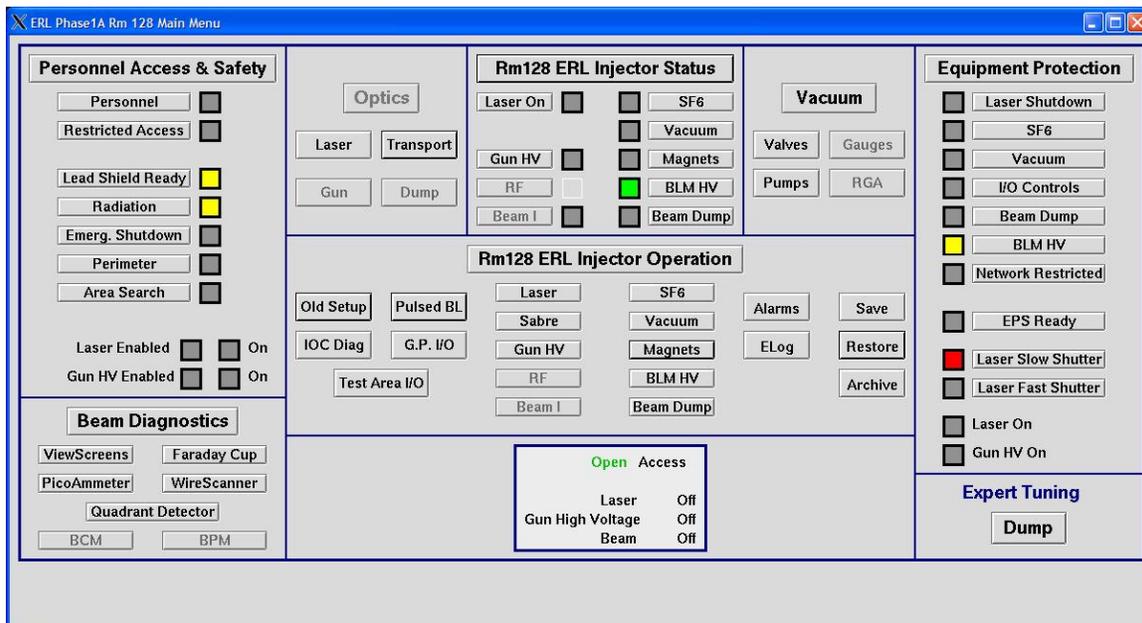


FIG. 11: Cornell ERL prototype photoinjection system control system main EDM front panel.

software that has been completed for system operator interaction with the ERL photocathode laser positioning system. The completed ERL photocathode laser positioning system front panel EDM running in execute mode appears in FIG. 12. The motivation for graphical organization within the laser positioning system EDM controls was again as an emulation of system modularity, partitioning between device controls and feedbacks. For example, actuator position monitors are separated from actuator position controls, and furthermore, NanoPZ controller box commands and active characteristics are separated as well. In this view, the operator is able to determine the channels of the controller box that are connected to a functional actuator, as well as initiate relative motion, set actuator displacement limits, among other characteristics. FIG. 13 displays actuators connected to channels 02 and 03 with out of range motion, and the resultant alarm display associated with triggered alarm parameters. The quad photodiode detector diagnostic monitors are included as sub panel

links from the front control panel, and two representations of the detector voltage sum and difference values are illustrated in FIG. 14 and FIG. 15. FIG. 14 represents the real-time voltage feedback values displayed using a visual gauge format as an emulation of an analog voltmeter, while FIG. 15 replaces these gauges with real-time data logging stripcharts, indicating past and present voltage levels corresponding to beam position. As a visual alternative to these data representations, real-time beam spot positioning monitors are represented in FIG. 16. By plotting the current voltage horizontal and vertical difference values each 100 ms, the user is able to view virtually the motion of the beam spot on the detector active array following adjustments, on a real-time basis. As a result, the integration of EPICS as a primary software control environment for the ERL laser positioning system allows for both an efficient code structure, as well as a capable and dynamic user interface.

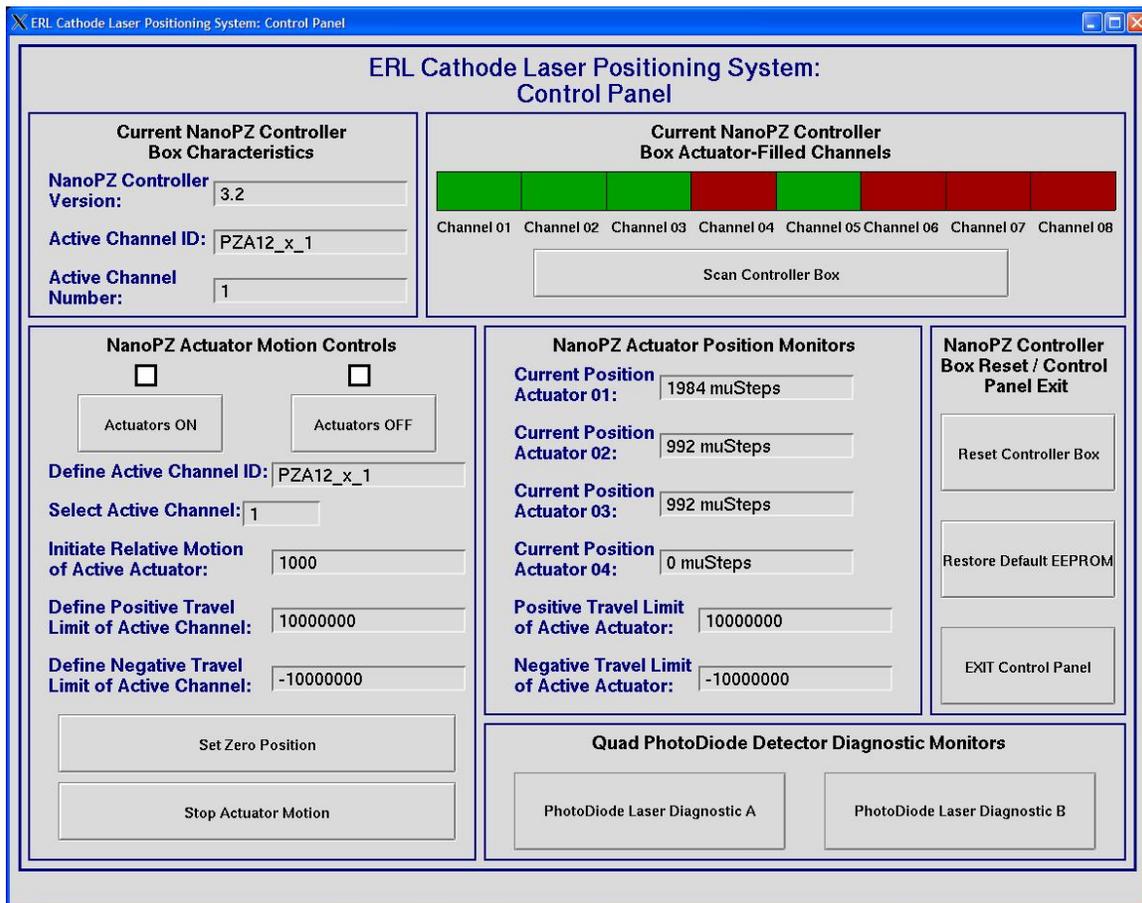


FIG. 12: Completed ERL photocathode laser positioning system front panel EDM (running in execute mode).

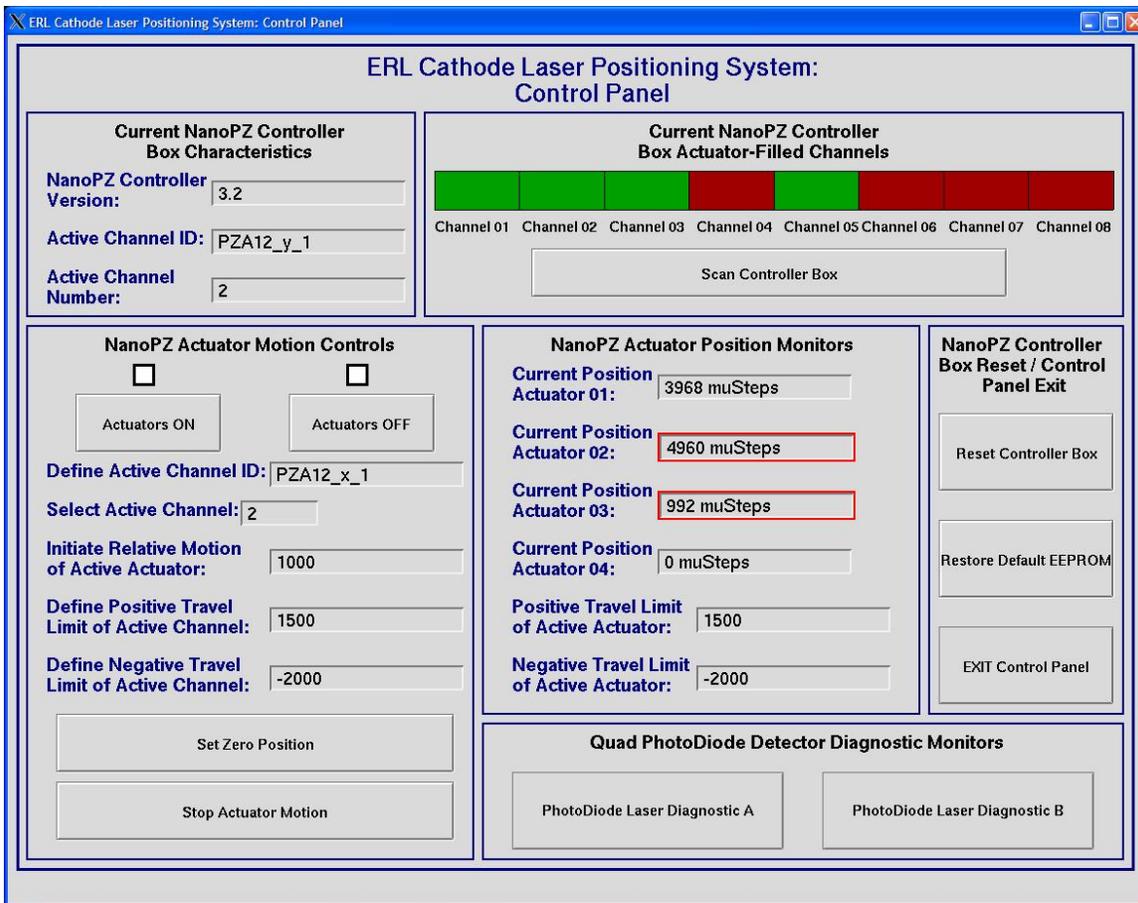


FIG. 13: Completed ERL photocathode laser positioning system front panel EDM (running in execute mode with alarm parameters triggered).

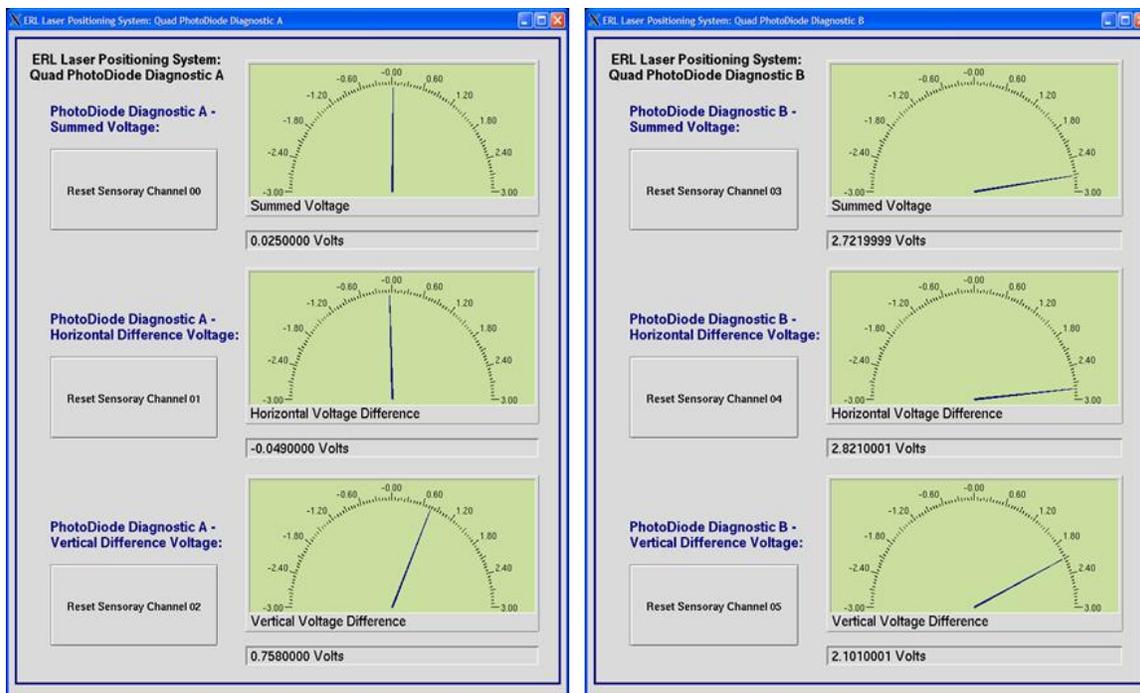


FIG. 14: Completed ERL photocathode laser positioning system sub-panel EDM (photodiode analog gauge emulation diagnostic monitors).

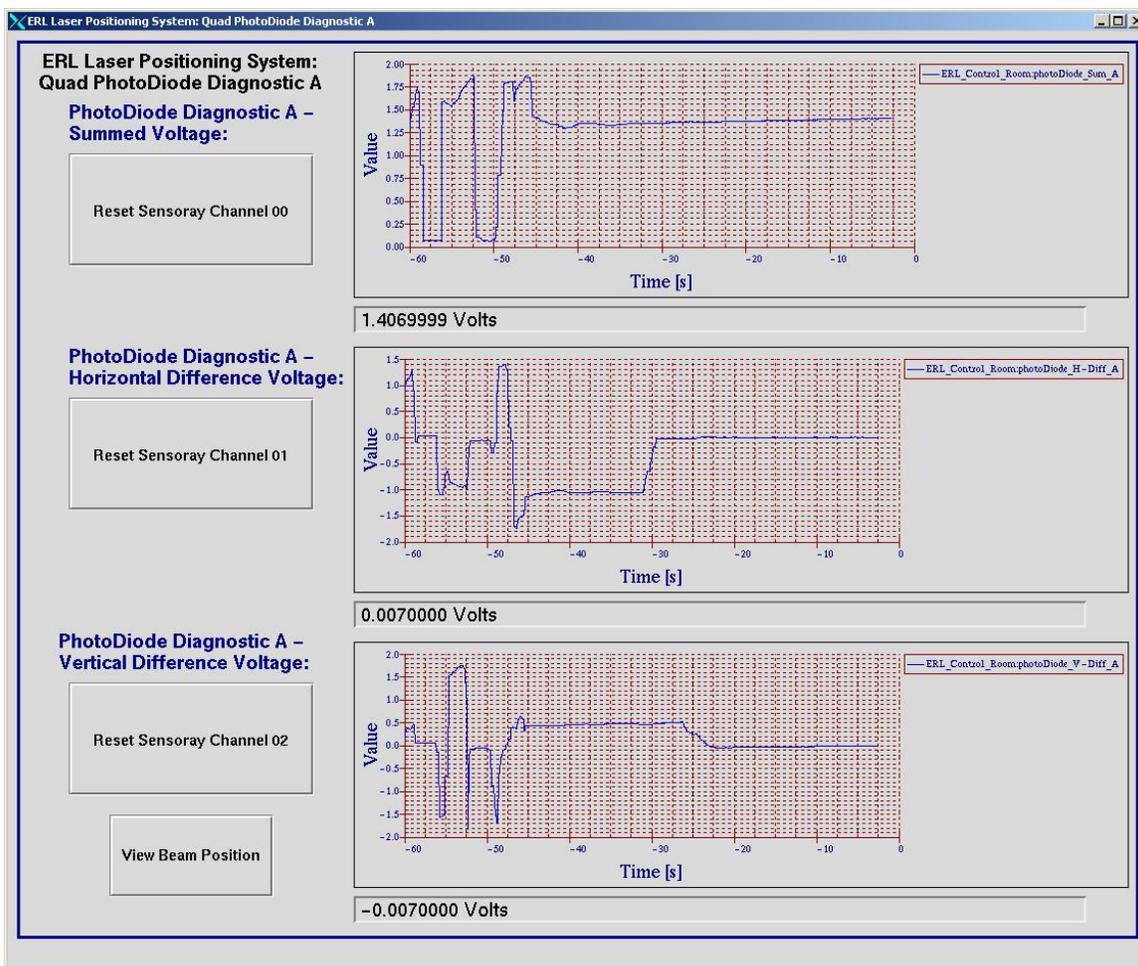


FIG. 15: Completed ERL photocathode laser positioning system sub-panel EDM (photodiode stripchart log diagnostic monitors).

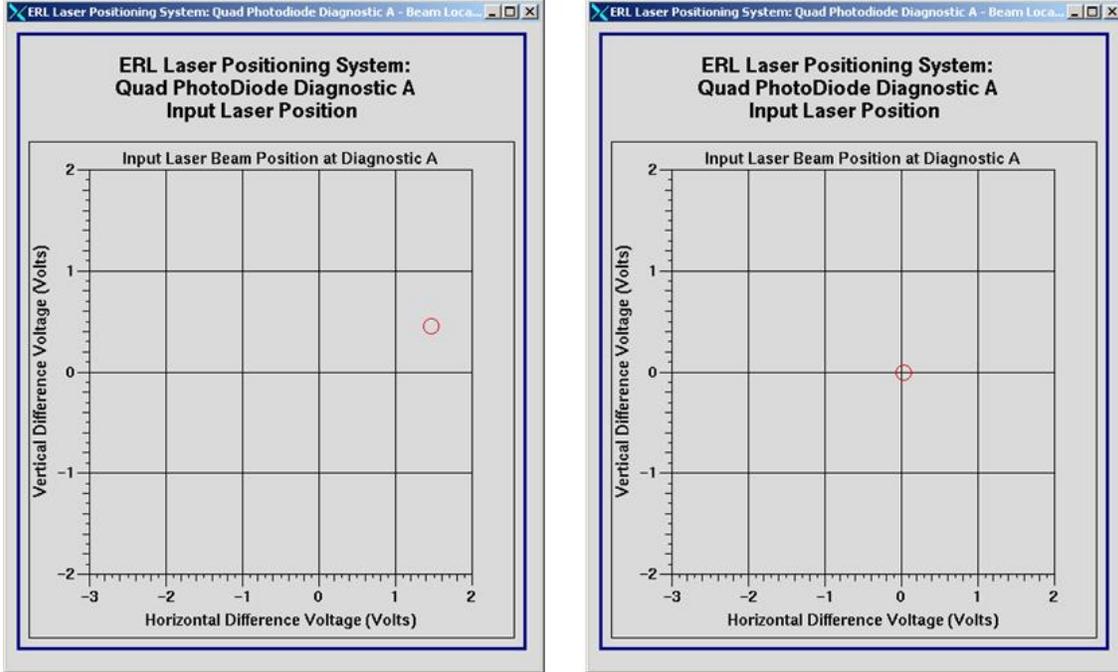


FIG. 16: Completed ERL photocathode laser positioning system sub-panel EDM (real-time beam spot monitor plots).

IV. CONCLUSIONS

Throughout this investigation, the theory and procedure utilized to construct and program a fully functional laser positioning system for the Cornell ERL photoinjection system has been discussed. Despite the ability of a user to now remotely adjust nanopiezoelectric driven actuators for the adjustment of optical elements, and hence beam position, in addition to quad photodiode detector laser position diagnostic feedback, several challenges remain. First, while use of a low intensity test laser allowed for a proof-of-principle demonstration of the prototype positioning system, interfacing with the more intense ERL photoinjection laser will allow for better representative signals of beam position over noise levels propagated by ambient environmental light sources. In addition, the currently utilized PZC-SB switchbox only allows for single-channel access for actuator control, hence requiring the user to manually index between four channels to achieve one iteration allowing for centroid positioning of the input laser. This has proven impractical to continually account for drift effects, and places a limit on the speed by which alignment can be accomplished manually or automatically in the future. As a result, current ERL laser positioning system development focuses on several objectives. First, the hardware and software components of the existing single channel access prototype positioning system developed here will be installed and deployed directly to the ERL photoinjection system. Next, a custom multi-channel actuator controller box interface will be developed and interfaced with current EPICS laser positioning system software. This will then finally allow for the design and writing of an automated beam positioning script, that can automatically align the beam placement in real-time without manual user adjustment. Development of this second generation automatic photocathode laser positioning system will be presented in the near future, with the

confidence that present achievements will continue to contribute to the ultimate success of the Cornell ERL system.

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