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STATUS OF THE CONTROL SYSTEM FOR THE ENERGY RECOVERY LINAC bERLinPro AT HZB*

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Abstract

bERLinPro is an energy recovery linac (ERL) demonstrator project built at HZB. It features CW SRF technology for the low emittance, high brightness gun, the booster module and the recovery linac. Construction and civil engineering are mostly completed. Synchronized with device integration, the EPICS based control system is being set-up for testing, commissioning and finally operation. In the warm part of the accelerator, technology that is already operational at BESSY and MLS (e.g. CAN-bus and PLC/OPC UA) is used. New implementations like the machine protection system (MPS) and novel major subsystems (e.g. Low Level RF (LLRF), photo cathode laser) need to be integrated. The first RF transmitter has been tested and commissioned. For commissioning and operation of the facility the standard set of EPICS tools form the back-bone. A set of generic Python applications already developed at BESSY/MLS will be adapted to the specifics of bERLinPro. Scope and current project status are described in this paper.

INTRODUCTION

The goal of bERLinPro is the production of high current, high brightness, low emittance CW beams and to demonstrate energy recovery at unprecedented parameters [1]. The three stage acceleration consists of an SRF photo electron gun, an SRF booster linac with an extraction energy of 6.5 MeV and an SRF main linac module equipped with three 7-cell HOM damped cavities. All magnets and the vacuum system of the low energy injector and dump line are installed. Commissioning of the diagnostic line and the low energy part of the machine, i.e. gun / booster / linac replacement straight / dump line, the *banana* (see eponymous shape in Fig. 1) is planed for 2020,

bERLinPro is designed to show energy recovery for high current (100 mA) beams. The damping of higher order modes in the SRF linac is demanding and led to a new design of the HOM damping waveguids [2]. Availability of a proper linac module is critical.

The MESA project (Johannes Gutenberg Universität, Mainz, Germany) is planned for 1 % of the bERLinPro current, with a possible upgrade to 10 mA. For HOM-damping, the same technology as used at ELBE (HZDR) and XFEL (DESY) is in operation. Intermediate installation of the MESA linac module into bERLinPro allows to proceed towards recirculation with beam at 32 MeV and some mA at bERLinPro [3].

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OPERATIONAL MODES

Unlike cERL and cBETA, bERLinPro features numerous different use cases. These comprise the photo-electron-source only, straight diagnostic beamline, *banana* path and recirculation with and without energy recovery (see Fig. 1). Available modes also differ in beam power, bunch charge, acceleration voltage and bunch train pattern as well as methods to increase beam current. All of these and the individual operation states of accelerating units, booster and linac modules will have immediate impact and consequences on a challenging set of soft- and hardware machine protection systems and set-ups.

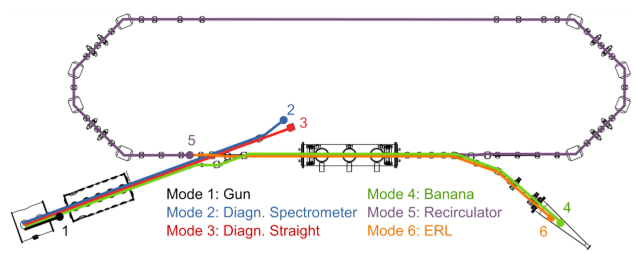

Figure 1: Basic bERLinPro layout and planned operation modes.

DEVICE INTEGRATION

The source part, consisting of an SRF photo electron gun, has already been set up in GunLab [4], where precision control of the laser guide system and the timing is presently in the works. With the beginning of installation in the bERLinPro bunker, integration of major functional blocks (e.g. laser) will be realized by remote control of 3rd party subsystems.

In March 2018 the first vacuum components for the *banana* path have been delivered, pumps and sensors are made available and are logged in the already running archiver [5] as they are installed. Similarly RF power conditioning and cryo system surveillance of cold compressors, warm vacuum pumps and the module feed boxes are well known and progress smoothly.

The various sub components of the booster and linac cryo modules are about to be addressed. At this point competing requirements for BESSY VSR [6] generate synergies, but also challenging working conditions.

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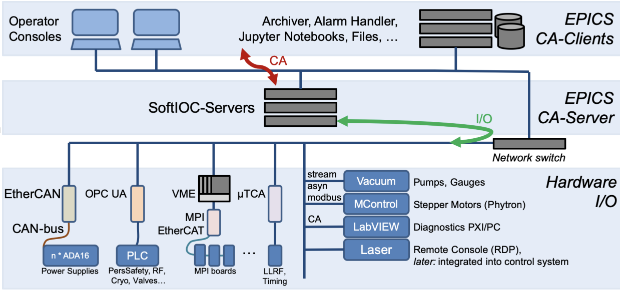

Figure 2: Simplified control-system structure.

IT-Infrastructure

Operator consoles as well as servers are strictly Linux-based. To be monitored and controlled, all relevant components need to be interfaced using an EPICS-I/O Controller (IOC) providing a Channel Access (CA) server.

Besides operator consoles and server-infrastructure (EPICS CA-client layer), all CA-servers run as SoftIOCs and perform their device-I/O via the control system network (see Fig. 2).

The network-connected I/O modules and variants differ by device-class or application.

Standard Components

Power Supplies of the beam guiding component are BESSY-standard, partly even re-used, so the control system integration follows the lines at BESSY and MLS. At the device-level, they are interfaced via ADA16 analog/digital I/O cards with an embedded controller and CAN-bus is used as a field-bus. A major difference to the setup at BESSY and MLS is, that, with the only exception of the MPS system, there are no VME-IOCs involved anymore. All CAN-I/O is performed through EtherCAN modules connected to the control system network.

PLC based systems RF systems as well as the cryo systems and the personnel safety system are all implemented using Siemens-PLCs. Communication with these systems is realized using OPC UA (OPC Unified Architecture). The SoftIOCs are communicating via the control system network to OPC UA servers that are either built into the PLC or realized as separate modules.

Vacuum System Vacuum gauges and ion getter pump power supplies are interfaced directly using serial I/O and Modbus. The various getter pumps are controlled by Cosylab microIOC - LOCO boards with actual ion getter pump currents converted to pressure equivalents.

All valves are controlled by Siemens PLCs and also interfaced via OPC UA. Switching outputs of gauges fire when configured limits of vacuum gauge readbacks are exceeded. They are connected to the PLC, which then closes surrounding valves and hence form a vacuum interlock system.

Stepper Motors All stepper motors (except of those at the SRF cavitiy tuners) are uniformly powered by Phytron motor controllers and controlled using the standard EPICS motor record.

TIMING SYSTEM AND TRIGGER DISTRIBUTION

RF Synchronization

Ultra low phase noise RF synchronization between the photocathode laser and LLRF subsystems is mandatory at bERLinPro, in order to provide stable electron bunches of variable length from 2 ps down to ~100 fs. Therefore RF generation was a challenging task with intensive effort to design and specify the best solution for bERLinPro master oscillator (MO).

Taking into consideration the shortest bunch length of ~100 fs, the arrival time jitter of the laser bunch through the approx. 35 m long transfer line into the photocathode SRF Gun and the phase stability better than 0.1 deg of the field in the SRF cavity required by the LLRF subsystem, a customized state of the art master oscillator unit has been developed by AXTAL GmbH [7] and commissioned in the timing laboratory. This 19 inch/1 U compact unit, featured with ULN OCXOs and SAW filter and delivers three phase coherent RF signals to the following subsystems:

- 10 MHz → diagnostics
- 50 MHz → laser control and diagnostics
- 1.3 GHz → RF systems, LLRF and laser

The last one is the most important frequency imposing the highest requirement in terms of phase noise and RMS jitter (0.1 deg ~ 200 fs, see Table 1).

Table 1: Lab Measured Parameters of AXTAL Master Oscillator

Reference Signal	Short RMS Phase Jitter	Max RMS Phase Jitter	Integration Region
10 MHz	60 fs	70 fs	1 Hz~1 MHz
50 MHz	60 fs	70 fs	1 Hz~10 MHz
1.3 GHz	50 fs	60 fs	1 Hz~100 MHz

Other features of the bERLinPro MO are 4 outputs per RF channel @ 13 dBm/output, an external RF input for atomic clock reference, fine adjustment of the 10 MHz ULN reference OCXO in a range ±0.5 ppm via trimmer and an interface for locking and temperature monitoring of the OCXOs. Measurement in lab has shown phase stability of the outputs to be totally unaffected from the external reference signal noise.

A network of Cellflex® 3/8" coax cables with an excellent phase drift stability of 1 ppm @ 25 °C [8], will distribute the RF signals through the facility. The longest link of about 40 m is the one from MO rack to the diagnostics patch panel. In order to cope with slow phase drift of the RF signals due to temperature change, coax cables have been distributed

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through thermally insulated pipes. A network of calibrated temperature and humidity measurementss based on OneWire sensors will be installed every 5 m along the coax cable pipes. A StreamDevice based EPICS device support has been already implemented for the OneWire to Ethernet Bridge and running already at BESSY on a SoftIOC (see Fig. 3). By knowing the temperature at each sensor, the exact distance between the temperature sensors and the phase drift characteristic of the coax cable, phase drift of the RF signals can be predicted [9] and fed into the LLRF control loop. Sensitive electronics such as the MO, LLRF-Controls and Laser-Controls will be installed in temperature stabilized racks.

Trigger Distribution

As bERLinPro is preparing the road to fulfillment of the high demanding requirements of BESSY VSR [6], doors have been opened also towards the evaluation of novel state of the art trigger distribution systems (TDS). The decision to build bERLinPro TDS on Micro Research Finland (MRF) [10] EVG/EVR-300 event products and µTCA was mainly because of three reasons: high scalabilty of the MRF TDS, which is a key issue at BESSY VSR, the elimination of the VME hardware platform due to high maintenance costs and the very mature EPICS device support provided by the EPICS community.

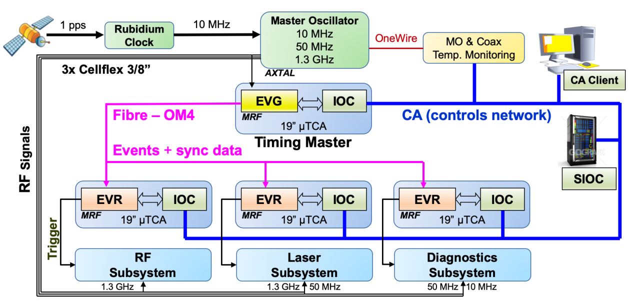

Figure 3: Schematic of timing system with master oscillator, RF distribution and trigger distribution system.

One master event generator (EVG) IOC will send trigger events at 125 MHz, clocks and data to three event receivers (EVR) IOCs through an OM4 optical fiber network in a tree topology (see Fig. 3). Through active delay compensation featured by MRF-300 series, slow phase drifts of the optical link due temperature changes are detected and compensated. Because of the three commissioning phases of bERLinPro (single bunch, burst and CW) and 6 operational modes, the trigger specification table is too complex to be shown and out of scope of this paper.

LOW LEVEL RF

For Low Level RF (LLRF) control, the same system developed and used at XFEL's gun (DESY[1]), ELBE (HZDR[2]) and MESA (JG|U[3]) has been chosen [11] and a prototype installation has been set up with help of colleagues from DESY. Each LLRF system consists of a µTCA crate containing the following components (see Fig. 4):

1. A CPU running Ubuntu Linux providing the slow control algorithms and a communication layer translating the internal DOOCS controls into EPICS using ChimeraTK [12, 13] on a locally running SoftIOC
2. An FPGA board for amplitude and field control and
3. An FPGA board for tuner control (motors and piezos)

Besides the high performance PCIe communication, the two FPGA-boards are connected via a dedicated low-latency link.

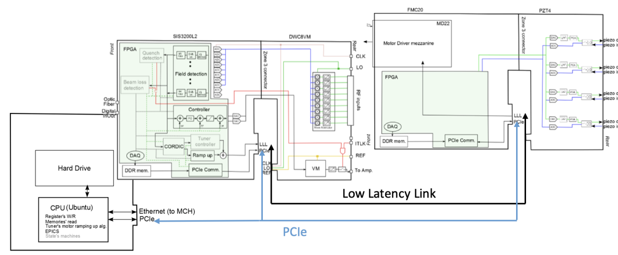

Figure 4: Structure of µTCA system: left: CPU; center: FPGA for amplitude and field control; right: FPGA for tuner control.

All six SRF cavities (1×gun, 3×booster and 2×linac) as well as the normal conducting transverse deflecting cavity in the diagnostics line will be supplied with these LLRF controllers.

To avoid applying further changes to the DESY-software, minor changes to the EPICS-IOC are being made to translate the DOOCS signal names into EPICS PV names that are compliant to the BESSY/HZB device naming convention. So far, only the amplitude and phase control servers are implemented and running on the µTCA based CPU, but in the near future, the tuners' motor control will be installed. Moreover, new firmware is currently being developed to control microphonics using a Kalman filter observer [14] and to detect quenches of the SRF cavities [15]. As a preliminary step to connect these two new features, µTCA Matlab and python bindings will be use to control them and connect them to the EPICS control system.

BEAM DIAGNOSTICS

In the recirculator of bERLinPro, various types of diagnostics have been developed in order to cover a wide range of operating modes in terms of bunch charge, repetition rate, and lateral as well as spatial distributions. Basically, there are fast and slow diagnostics - categorized according to the speed of data acquisition and data transfer. In the early commissioning phase with low beam-current, the slow detectors

[1] DESY - Deutsches Elektronen Synchrotron, Hamburg, Germany
[2] HZDR - Helmholtz-Zentrum Dresden Rossendorf, Dresden, Germany
[3] JG|U - Johannes Gutenberg Universität, Mainz, Germany

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such as screen monitors and a synchrotron-light-based halo and profile monitor are most important. These diagnostics mainly use slow CCD cameras as data acquisition devices and LabVIEW for processing of the images. Processed data like internal gain, shutter speed and trigger mode of CCD camera as well as analysis results such as lateral size and center of mass will then be transmitted to the control system.

Since it is not allowed to insert any destructive monitors when the average beam current in the recirculator is higher than 50 µA, the status of the screen monitors is also monitored carefully as a part of machine protection system.

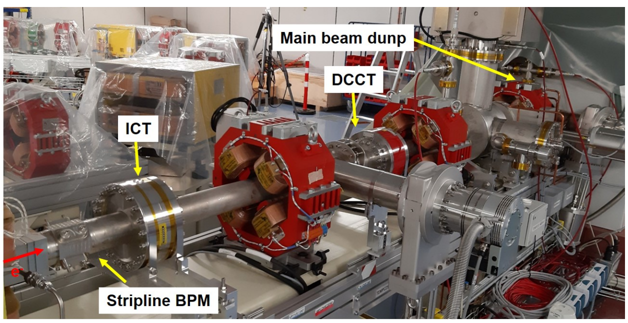

Figure 5: Stripline BPM, ICT, DCCT installed in main beam-dump line.

On the contrary, the fast diagnostics such as stripline beam position monitors (BPMs), Faraday-cups, DC- and Fast-current transformers (CTs) and beam loss monitor system are non-destructive devices (see Fig. 5). Particularly, the operable current of the stripline BPMs and CTs is higher than with the screen monitor. Therefore, it is necessary to put effort into optimizing the diagnostics system during early stages of the commissioning phase. An intuitive and flexible data acquisition system for coping with a variety of requirements is in preparation and will be fully integrated into the EPICS control system.

The analog processing unit for adjusting a signal magnitude suited for the digitizer is needed to control for covering a wide dynamic range with the requested resolution. A schematic diagram of the analog processing unit for the stripline BPM is shown in Fig. 6.

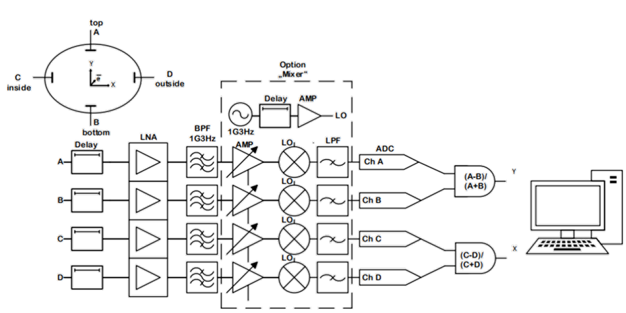

Figure 6: Schematic diagram of signal processing for the stripline BPM. This unit uses a variable amplifier adjusting the signal magnitude to be suitable for the digitizer in the current range from 0.1 mA to 100 mA.

All diagnostic data acquisition is performed using LabVIEW systems (either PC- or PXI-based) operating independently and transferring processed data to the EPICS control system.

The diagnostics setups have been tested in the laboratory to examine the limitations of stability, resolution, and accuracy for different operation modes. The installation is now underway in the bERLinPro bunker.

PERSONNEL SAFETY AND RADIATION PROTECTION SYSTEM

The personnel safety system is based on Siemens safety PLCs according to all relevant machinery safety regulations of the EU. It consists of a master-PLC and 4 decentralized I/O-blocks with ~250 I/O-points. The PLCs are communicating via dedicated Ethernet/Profibus lines.

The connection to the EPICS control system is realized using a OPC UA-Client on a Linux-SoftIOC communicating with an OPC UA-server built into the master-PLC.

Accordance of the system design and components to effective safety regulations is checked and proven using SISTEMA.

The installation of sensors and hardware has been finished. Tests and commissioning of the personnel safety system is currently in process with ~70% finished. A final acceptance test is planned for the end of 2019.

To enable logging and continuous monitoring of radiation exposure, a dosimetry system has been installed as well in the building as on ground level above the bunker and is fully operational. Up to 15 measuring points are possible with the current setup.

The same PLC-based technology is also used for the laser-interlock to prevent laser operation if any of the preconditions is violated. Shutters at the laser-hutch as well as at the photocathode-gun are closed and locked if areas are in a possibly insecure state. Hutch-doors are monitored and locked and warning-signs are controlled.

Next steps are to connect further RF-transmitters as well as the air conditioning system to the personnel safety system.

MACHINE PROTECTION SYSTEM

The machine protections system (MPS) is needed to ensure safe non-destructive operation of the machine in the different operation modes (see Figs. 1 and 7). Beam may only be extracted from the cathode if all necessary conditions are met and further extractions have to be prevented within 1 µs if any condition is violated.

To achive this, an EtherCAT based system of EtherCAT master, MPS-mainboards and MPS-I/O-boards (the latter two forming an MPS Unit) has been developed. Core components of the MPS are shown in Fig. 8:

EtherCAT Master

The EtherCAT Master is the single controlling instance of the MPS. It is connected via streamdevice socket-I/O to an EPICS SoftIOC that reflects current state and allows

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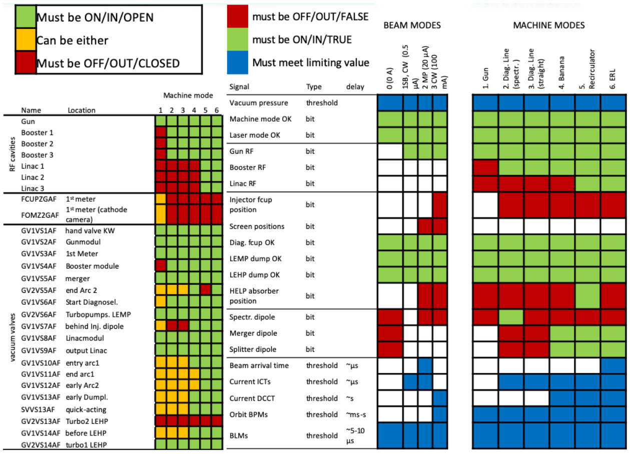

Figure 7: Various bERLinPro operation modes with required conditions and constraints.

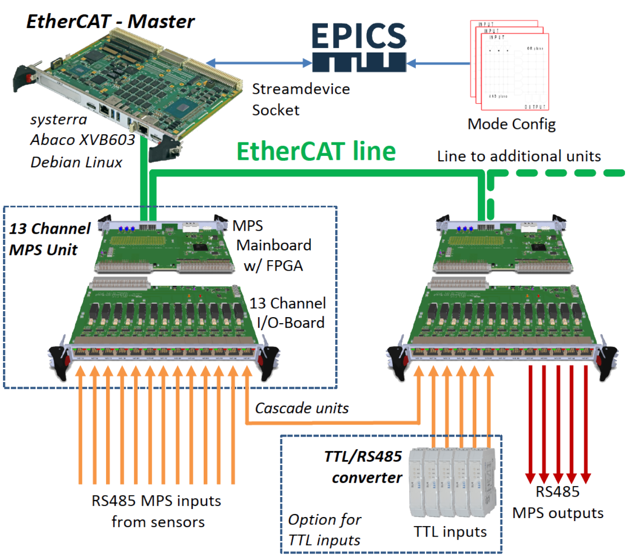

Figure 8: Machine Protection System core components.

for switching operation modes. The EtherCAT Master distributes configurations and active mode via EtherCAT to the connected MPS Mainboard. Activation of a new mode on all boards is achieved within.

MPS Mainboard

An MPS Mainboard is the FPGA board evaluating the programmed logic. It processes all MPS-inputs, drives the MPS-outputs and is programmed over the EtherCAT line. Current status of this MPS Unit is also posted to the EtherCAT Master and communicated to the EPICS control system.

13 Channel MPS I/O Board

converts from/to up to 13 RS485 input or output signals. A complete cycle (input conversion, FPGA processing and output conversion) takes ~120 ns. The I/O Board is equipped with reliable RS485 line-break detection to properly ensure safe operation.

MPS Units may be cascaded to form a hierarchical MPS with a maximum of 65535 MPS Mainboards (limited only by 16-bit IDs with ID=0 being a special case).

Inputs or outputs can optionally be equipped with TTL↔RS485 converters, if applicable.

For bERLinPro, the reaction time of the complete MPS including signal delays due to cable lengths, RS485↔TTL conversions, cascading and FPGA processing time can be assured to be well below the required 5 µs.

PHOTOINJECTOR LASER AND LASER BEAM TRANSFER LINE

The laser for operation of the RF-photoinjector has been developed and will also be installed by the Max-Born-Institute (MBI). In the end it will be fully embedded into the accelerator infrastructure and therefore be controlled by the machine control system and EPICS. This includes a concept by MBI for tight synchronicity with the RF-master oscillator already proven at accelerators of XFEL and ELBE. In addition, precautions are made to account for a slow phase drift between the RF-field in the gun-cavity and the arrival time of a laser pulse which might have accumulated along the path of the rf-waveguides and the approx. 35 m long laser beam transfer line.

The laser beam is transferred to the photo injector via an imaging system to counteract diffractive broadening and distortion. A substantial fraction of this transfer line is contained in a vacuum tube including bending mirrors and two piezomotor-driven remote controlled lenses with closed-loop linear alignment along three orthogonal axes. These are commercial systems controlled and monitored by EPICS (see Fig. 9).

The entire transfer line allows for control of laser beam spot size, -position, -position stability and the generated bunch charge at the photo-cathode and its according diagnostic.

Stepper- and servo motors will be used as actuators for mirrors, lenses and irides. End-switches, several CCD-cameras along the laser beam path and special devices for measuring laser pulse duration and pulse energy represent the main detectors.

It will be managed by one GUI displaying a summary of the laser parameters at the photo-cathode. From here further GUI's dedicated to individual parameters of the transfer line and the laserspot can be opened.

OPERATION PROGRAMS

The toolset that is standard for EPICS environments at HZB is easily adapted as the project proceeds. I.e. engineering screens become available as the device integration is deployed, data monitoring is well covered by the EPICS Archiver Appliance [5] and alarm handling is realized with *alh* (see Fig. 10) while alarm-logs will be accessible via the elastic stack. At a later point, the aging motif based alarm-handler *alh* will be superseded by the CSS/phoebus alarm-server.

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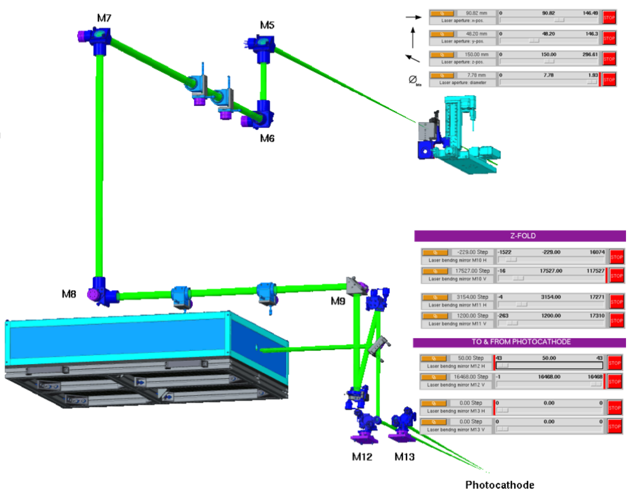

Figure 9: Example of GUI for the laser beam transfer line from the predecessor GunLab, the former diagnostic beamline for bERLinPro gun tests [16].

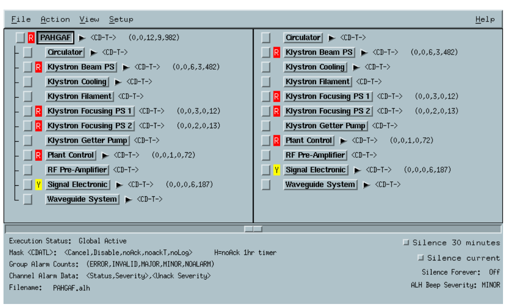

Figure 10: Alarm Handler *alh*.

Program launchpad (see Fig. 11) and machine operation parameter save/restore/compare are already adapted from the BESSY instances and is extended with ongoing installation and commissioning of components.

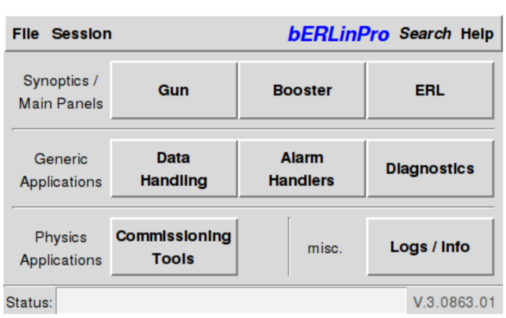

Figure 11: Program launchpad featuring dynamic menu updates and versatile app process control options.

BERLinPro is not planned as a user-facility and hence is not operated by the BESSY/MLS operator crew. The main "users" of the bERLinPro control-room will be scientists and engineers commissioning the machine and pursuing new goals in accelerator physics. Therefor, the typical routine tasks performed at a production user facility are not applicable to bERLinPro.

Novel Developments from the Community

For controls and applications, this is a unique chance to evaluate and establish newer tools and techniques like

EPICS version 7 - a major upgrade to the EPICS version 3 control system suite currently in use at BESSY and MLS. After several years of development, the most recent development branch of EPICS V3 and the new development (used to be named EPICS V4) merged into what is now named EPICS 7. The new communication protocol *pvAccess* together with the underlying *pvDatabase* or any other 3rd party service layer, enables the transition from a controls framework to a physics framework [17].

CSS/phoebus is following the paradigm of the eclipse-based Control System Studio [18] but with a streamlined lightweight implementation [19]. CSS/phoebus will, once integrated into the operator environment, provide operator displays, alarm monitoring and retrieval and plotting of archived as well as live data.

PyDM, caQtDm, … For day one, all operator displays will be created with the same tools that have already been in use at BESSY and MLS for many years. Since the aging display managers *dm2k* and *edm* are both well established, they are nevertheless based on outdated software environments and not easily portable to other system platforms. Establishing a replacement display manager like PyDM or caQtDm requires a transition in user experience as well as deployment strategy and hence takes time and will be started when bERLinPro has entered the commissioning phase.

Until then, small steps could be performed by using edmq, TChart and Talh. These are implementations of edm, StripTool and alh, that are compatible in use, but are implemented on top of Qt5 instead of Motif and hence offer a more modern interface capable of displaying Unicode characters. Development of these was initiated at TRIUMF and has been presented at the 2019 EPICS collaboration meeting at ITER [20].

Commissioning Software Environment

Commissioning will further be supported by several scripting environments (MATLAB, Jupyter notebook, etc.) as well as by a number of software stacks (Bluesky/ophyd [21], ocelot, transitions...) to provide a uniform testbed and production environment for developers and scientists.

Simulation programs (elegant, OPAL) get their configuration files from a reference database. In a later phase the project will certainly benefit from the OPAL capabilities to describe space charge effects and take advantage of machine learning procedures [22].

To loosen potential dependencies to and/or conflicts within the operating system environment of the operator consoles, all these supported application will be deployed in dedicated software ans OS environments using Singularity [23] containers.

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SUMMARY

Setting up bERLinPro as a test facility has numerous consequences for controls. It has to be very flexible and easy to adapt. Temporary units like the MESA LINAC module or components on development path like the SRF gun variants are demanding w.r.t. timely installation and replacement.

On the other hand requirements to availability, reliability and maintainability of the controls installation are relaxed compared to a light source in production. Software tools and automation inventory need not to be operator ready.

These relaxed requirements open the possibility to also experiment with novel software and establish new systems that, at a later time, could also broaden and renovate the control room computing environment at BESSY and MLS.

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