HIGH-LEVEL APPLICATIONS FOR LINAC COMMISSIONING AT ELI-NP*

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Abstract

The ELI-NP (Extreme Light Infrastructure – Nuclear Physics) Gamma-ray Beam System (ELI-GBS), currently under construction, employs an 800 MeV linear accelerator (LINAC) to generate high-brightness gamma rays through laser–electron interactions. Its control system is designed as a distributed, EPICS-based architecture, where engineering-level control is provided for devices such as LLRF, modulators, magnets, profile monitors, and current monitors. A set of high-level application tools is required for LINAC beam commissioning, tuning, and the measurement of key accelerator parameters. To meet the beam diagnostic capabilities and performance requirements of the commissioning process, we have developed Python-based high-level application software to support essential commissioning tasks, including gun phase scans, emittance measurements, and beam energy measurements. The software uses the pyepics package to interface with engineering-level device IOCs. To support visualization and offline simulation, a set of Python soft IOCs has also been implemented, enabling realistic emulation of device behavior and data acquisition workflows. The online measurement capabilities of the system will be validated during the upcoming RF Gun commissioning and the subsequent LINAC commissioning phases. This paper focuses on the implementation and offline simulation aspects, which are of practical value for facilities in the commissioning stage.

INTRODUCTION

The Gamma-ray Beam System (GBS) at Extreme Light Infrastructure - Nuclear Physics (ELI-NP) delivers gamma-ray beams via inverse Compton scattering, employing an 800 MeV linear accelerator (LINAC) and a high-finesse optical cavity at the interaction point [1, 2]. The LINAC consists of five acceleration modules, each capable of up to 160 MeV, with quadrupole magnets for beam focusing and beam position monitors for orbit diagnostics. The layout is shown in Figs. 1, 2, and 3. The control system is based on EPICS, which provides distributed process variables PVs for device control and monitoring via Input/Output Controllers (IOCs). A similar system has been implemented for the gamma beam profile station at ELI-NP [3].

For LINAC commissioning, high-level applications are essential to perform beam physics calculations and measure key parameters. This paper presents Python-based high-level applications for LINAC commissioning at ELI-NP, including gun phase scans, emittance measurements, and beam energy measurements. The applications interface with EPICS via pyepics and leverage simulated soft IOCs for offline validation. Implementation details and simulation results are discussed in the following sections.

While similar high-level applications have been demonstrated at other facilities [6], the specific contribution of this work lies in the integration of soft IOCs for offline validation prior to hardware availability. This approach enables consistent simulation of device responses within the EPICS environment and facilitates comparison between simulated and measured data during commissioning.

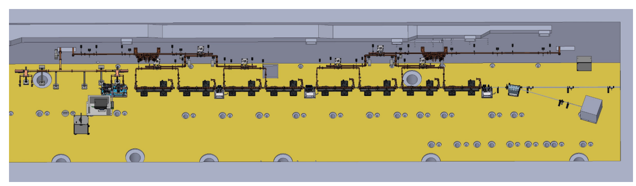

Figure 1: The first half of the ELI-NP linac.

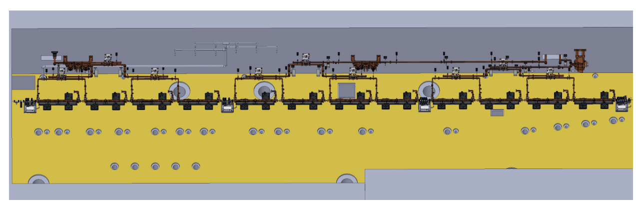

Figure 2: The second half of the ELI-NP linac.

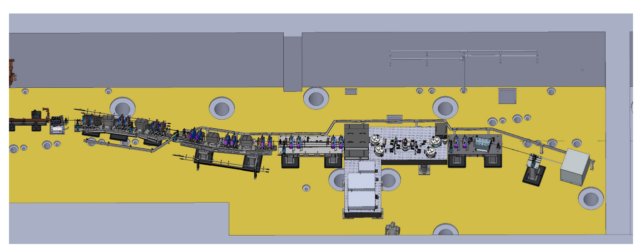

Figure 3: The transport line and the interaction section of the ELI-NP GBS.

IMPLEMENTED HIGH-LEVEL APPLICATIONS

The overall EPICS-based control architecture for the GBS LINAC is shown in Fig. 4. The system consists of device-level IOCs that interface with hardware, a centralized archiver for data logging, and an alarm system for monitoring operational status. High-level applications interact with these components via Channel Access (CA) or PVAccess protocols. To achieve the goals of the commissioning

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process, we have developed Python-based high-level application software to support essential commissioning tasks, including gun phase scans, emittance measurements, beam energy measurements, and beam trajectory correction. The applications utilize key packages such as pyepics and matplotlib, and interface with soft IOCs created for simulation purposes. Simulation is an important step in the commissioning process, as it helps anticipate how RF phase adjustments affect beam charge and timing, reduces the need for extensive experimentation on the actual accelerator, and allows identification of optimal parameters prior to hardware testing. For the high-level physics applications, a simulated soft IOC was created, consisting of multiple databases for gun phase scans to access RF phase and other important parameters from the simulated LINAC components. The use of soft IOCs ensures that simulated data follow the same EPICS interface as real devices, allowing a consistent workflow between simulation and operation.

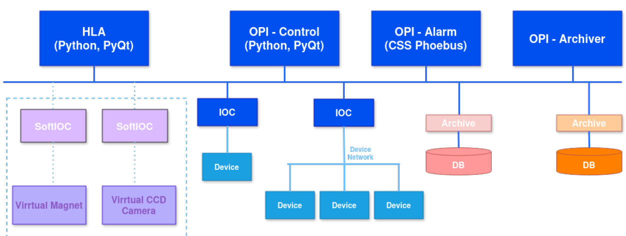

Figure 4: The architecture including EPICS Control, Archiving and Alarm for the ELI-GBS LINAC

Gun Phase Scans

Simulating the RF gun beam pulse is essential for understanding how the injection phase affects beam charge and for identifying the optimal operating point prior to hardware commissioning. The phase scan procedure enables determination of the optimum injection phase, where the beam charge is maximized and the energy spread is minimized. The interface, shown in Fig. 5, consists of a control panel and a measurement display. From the control panel, the user can initiate and stop phase scan measurements, and select the phase angle range and the number of scan points. The measurement display plots the beam charge measured by two integrating current transformers (ICTs) as a function of RF phase. In the simulation, a linear phase array is generated using NumPy's `linspace` function, creating equally spaced phase values across the user-specified range. The RF phase is read from the simulated soft IOC. The beam charge as a function of phase is modeled using a super-Gaussian distribution centered at the optimum phase ϕ_0:

$$Q(\phi) = Q_0 \cdot \exp\left(-\frac{|\phi - \phi_0|^n}{2\sigma_\phi^2}\right), \tag{1}$$

where $n \geq 2$ is the super-Gaussian order, Q_0 is the maximum charge, and σ_ϕ characterizes the phase acceptance width. For typical RF guns, $n \approx 4$–6 provides a flat-top region around the optimum phase ϕ_0, which more accurately represents the beam charge response compared to a simple Gaussian ($n = 2$) [5]. This super-Gaussian model captures the typical flat-top behavior observed in high-gradient RF guns, where the charge remains near maximum over a finite phase range before decreasing sharply at the edges [4, 5]. The order n can be adjusted to match measured data during commissioning. The RF phase scan algorithm starts when the user clicks Start. The system reads the RF phase from the simulated soft IOC and generates beam charge values according to Eq. 1. The data are formatted as waveform records and sent to EPICS. A safety interlock check is performed after each step; if clear, the results are displayed. If not, the system waits 10 seconds before retrying. Upon completion, the button resets. To generate realistic ICT waveforms, for each phase setting we simulate a current pulse with a Gaussian profile, add Gaussian noise (0.01 V standard deviation), and generate 4000 voltage samples per detector. The total charge is extracted via integration. The resulting charge values are plotted against RF phase, allowing identification of the optimum injection phase and assessment of the RF gun phase acceptance.

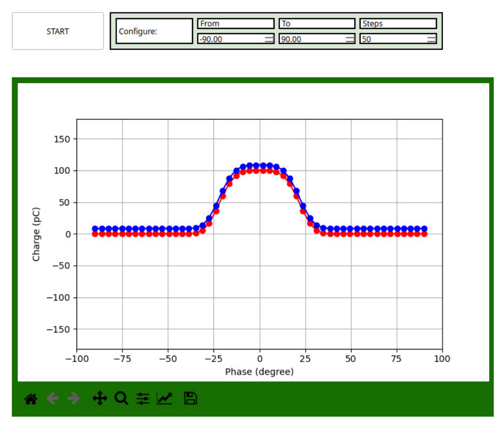

Figure 5: RF phase scans simulation results

Emittance Measurement

Emittance is a fundamental property of a charged particle beam, quantifying the average spread of particles in position-and-momentum phase space, typically expressed in mm·mrad. A lower emittance indicates higher beam quality. We adopt the quadrupole scan method to measure the emittance. The measurement setup consists of a quadrupole magnet followed by a drift space and a profile monitor. By varying the quadrupole strength k and measuring the corresponding beam size σ_x at the screen, the beam matrix at the quadrupole entrance can be reconstructed. For a quadrupole modeled as a thin lens with focal length $f = 1/(k \cdot l_{\text{quad}})$, the transfer matrix from the quadrupole entrance to the screen is:

$$R(k) = \begin{pmatrix} 1 & L \\ 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} 1 & 0 \\ -1/f & 1 \end{pmatrix} = \begin{pmatrix} 1 - L/f & L \\ -1/f & 1 \end{pmatrix}. \tag{2}$$

where L is the drift length. The beam size at the screen is given by:

$$\sigma_x^2(k) = C(k)^2\sigma_{0,11} + 2C(k)S(k)\sigma_{0,12} + S(k)^2\sigma_{0,22}. \quad (3)$$

where $C(k) = 1 - L/f$, $S(k) = L$, and σ_0 is the beam matrix at the quadrupole entrance. By performing measurements at $n \geq 3$ different quadrupole strengths, the unknown beam matrix elements are obtained via least-squares fitting:

$$\begin{pmatrix} \sigma_{0,11} \\ \sigma_{0,12} \\ \sigma_{0,22} \end{pmatrix} = \left(\mathcal{M}^T \mathcal{M}\right)^{-1} \mathcal{M}^T \begin{pmatrix} \sigma_{x,1}^2 \\ \sigma_{x,2}^2 \\ \vdots \\ \sigma_{x,n}^2 \end{pmatrix}. \quad (4)$$

where $\mathcal{M}$ is the $n \times 3$ matrix with rows $[C_i^2,\ 2C_iS_i,\ S_i^2]$. The emittance is then calculated as:

$$\epsilon = \sqrt{\sigma_{0,11}\sigma_{0,22} - \sigma_{0,12}^2}. \quad (5)$$

The beam emittance measurement system is implemented as an interactive Python simulation using PySide6 for the GUI framework and Matplotlib for data visualization. The simulation allows users to perform quadrupole scans and calculate emittance. The Twiss parameters are also derived, with consistency verified by the Courant-Snyder invariant $\beta\gamma - \alpha^2 = 1$.

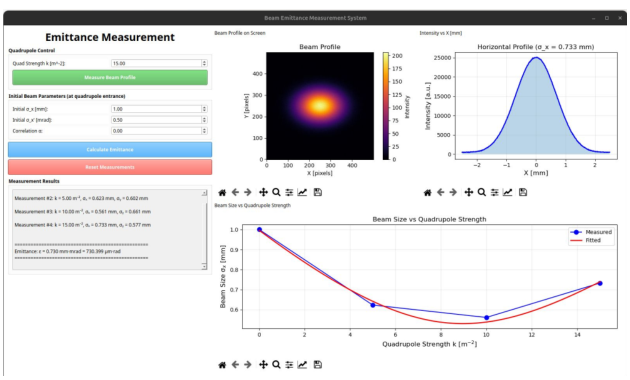

Figure 6: Emittance measurement GUI and simulation results.

In Fig. 6, the measured emittance is $\epsilon = 0.730$ mm · mrad, indicating a well-focused beam. This method provides essential tools for beam quality characterization and optimization [7].

Beam Energy Measurements

Precise beam energy measurement is essential for LINAC commissioning. We will implement a dipole-based magnetic spectrometer, utilizing a bending magnet and a downstream profile monitor. When a relativistic electron beam traverses a dipole magnet with field B, the Lorentz force bends the trajectory with radius ρ governed by $B\rho = p/e$, where p is the electron momentum. For relativistic electrons, the beam energy is $E \approx ecB\rho$. A dipole magnet with effective length l_{eff} imparts a deflection angle $\theta \approx l_{\text{eff}}/\rho$. For small deflection angles ($|\theta| \ll 1$, which is satisfied for typical beam energies $\gtrsim$ 100 MeV and dipole fields $\lesssim$ 1 T), the paraxial approximation holds, and the transverse displacement measured by a profile monitor at distance L downstream is $x = L \cdot \tan\theta \approx L \cdot \theta$. This yields:

$$E = ecB \cdot \frac{Ll_{\text{eff}}}{x}. \quad (6)$$

Note that this expression assumes $|\theta| \ll 1$; a full trigonometric correction can be applied if necessary during high-precision calibration.

The magnetic spectrometer is implemented as a Python-based soft IOC for offline simulation and commissioning preparation. The virtual IOC simulates the response of a dipole magnet and a downstream profile monitor (YAG screen). Given a user-specified beam energy E_0 and relative energy spread σ_E/E_0, the code calculates the expected centroid displacement $x_0 = ecB \cdot Ll_{\text{eff}}/E_0$ and the beam size at the screen $\sigma_x = L \cdot (\sigma_E/E_0) \cdot \rho$, where ρ is the bending radius. Gaussian noise with a signal-to-noise ratio of 20 dB is added to simulate realistic detector readout. The profile waveform is generated as a Gaussian distribution with mean x_0 and standard deviation σ_x, sampled at 512 pixels. The user can vary the magnet current (proportional to B) and observe the corresponding change in x_0. The system then performs a least-squares fit of x_0 vs. $1/B$ to extract the energy. This virtual IOC enables validation of the energy measurement algorithm before hardware is available.

By measuring the beam centroid displacement at a fixed magnetic field, the beam energy can be determined with high precision. The beam energy spread is also reflected in the broadening of the profile distribution. This method will be implemented as a key diagnostic tool during LINAC commissioning [8].

CONCLUSION

A set of Python-based high-level applications has been developed for LINAC commissioning at ELI-NP, providing essential diagnostic capabilities for gun phase scans, emittance measurements, and beam energy measurements. The tools interface with EPICS via pyepics and utilize simulated soft IOCs for offline validation. The gun phase scan enables injection optimization, the quadrupole scan-based emittance measurement characterizes beam quality, and the magnetic spectrometer provides high-precision energy determination. These applications will be validated during the upcoming commissioning phases, contributing to the reliable operation of the Gamma-ray Beam System at ELI-NP. The use of soft IOCs also provides a consistent interface between simulated and real machine data, supporting more efficient interpretation of measurement results during commissioning.

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