ISBN: 978-3-95450-238-7 ISSN: 2226-0358 doi:10.18429/JACoW-ICALEPCS2023-TU1BC005

MODEL DRIVEN RECONFIGURATION OF LANSCE TUNING METHODS*

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Abstract

This work presents a review of the shift in tuning methods employed at the Los Alamos Neutron Science Center (LANSCE). We explore the tuning categories and methods employed in four key sections of the accelerator, namely the Low-Energy Beam Transport (LEBT), the Drift Tube Linac (DTL), the side-Coupled Cavity Linac (CCL), and the High-Energy Beam Transport (HEBT). The study additionally presents the findings of employing novel software tools and algorithms to enhance each domain's beam quality and performance. This study showcases the efficacy of integrating model-driven and model-independent tuning techniques, along with acceptance and adaptive tuning strategies, to enhance the optimization of beam delivery to experimental facilities. The research additionally addresses the prospective strategies for augmenting the control system and diagnostics of LANSCE.

INTRODUCTION

The Los Alamos Neutron Science Center is a renowned scientific establishment located at the Los Alamos National Laboratory (LANL) in New Mexico. This proton linear accelerator is globally recognized for its ability to accelerate protons up to 800 MeV at high power. LANSCE effectively sustains a dynamic program focused on fundamental scientific research by offering the scientific community with high-intensity sources of neutrons and protons. These sources are utilized for conducting experiments that contribute to both government and civilian research endeavors [1] and for the production of isotopes used in medical and research applications [2]. The scattering science research employs a high-powered proton and spallation neutron source with short-pulse characteristics, operating at a capacity of 100 kilowatts. These studies are conducted at multiple beamlines, enabling concurrent research across various topics. The experimental setup comprises the Coherent CAPTAIN-Mills (CCM) detector, a 10-ton liquid argon detector positioned at 20 meters from the high-intensity neutron/neutrino source. Its primary objective is to investigate the existence of sterile neutrinos and light-dark matter [3].

The control system of LANSCE uses the Experimental Physics and Industrial Control System (EPICS), developed at LANL [4]. This infrastructure is currently being used many accelerator facilities for performing data acquisition, supervisory control, closed-loop control, sequential control, and operational optimization. The EPICS architecture was developed through a collaborative effort between experts in both physics and industrial control. The LINAC encompasses five state-of-the-art research facilities that operate simultaneously: Lujan Center, Weapons Neutron Research, Proton Radiography, Isotope Production Facility, and Ultracold Neutrons. The intricate control system employed in LANSCE facilitates the concurrent execution of numerous experiments, making it a versatile instrument for enhancing scientific research. The control system of LANSCE is regarded as an impressive engineering achievement, as it operates its LINAC control system using technology that has been in use for almost three decades [5]. Over the course of time, there have been many modifications to peripheral components. However, it is anticipated that significant enhancements will be made to the control system in the future, with the aim of achieving optimal beam delivery to the experimental facilities.

* This work was supported by the U.S. Department of Energy through the Los Alamos National Laboratory. Los Alamos National Laboratory is operated by Triad National Security, LLC, for the National Nuclear Security Administration of U.S. Department of Energy (Contract No. 89233218CNA000001). †cetaylor@lanl.gov, LA-UR-2023-##

THE LANSCE ACCELERATOR CONFIGURATION

Figure 1 shows the four basic areas to tune in the LANSCE accelerator, each with their own set of diagnostics and control systems. Two species of beam (H^+ and H^-) are generated in the 1) *Low-Energy Beam Transport* (LEBT) at 750 keV and merged into the same beamline before entry into the 2) *Drift Tube Linac* (DTL). This first accelerator increases the beam energy of the beam up to 100 MeV. From there, the beam is transported through the transition region (TR) into the 3) *side-Coupled Cavity Linac* (CCL) for final acceleration up to 800 MeV. The beam is then transported to the experimental facilities through the 4) *High-Energy Beam Transport* (HEBT). The methods of control and tuning vary significantly within each region. To better understand the requirements of these areas, we will try to break the tuning processes down into two categories and two methods. The *categories* indicates if the tuning uses a model or is dependent solely on parameter minimization. The *method* describes if the control lies with the input parameters or the control elements (steering, focusing, etc.).

TUNING CATAGORIES

In the conventional practice of operating accelerator facilities, the establishment of beam transport and acceleration is often initiated using a physics model. Diagnostics, such as emittance stations, beam position monitors, and wire scanners, are employed to quantify the beams'

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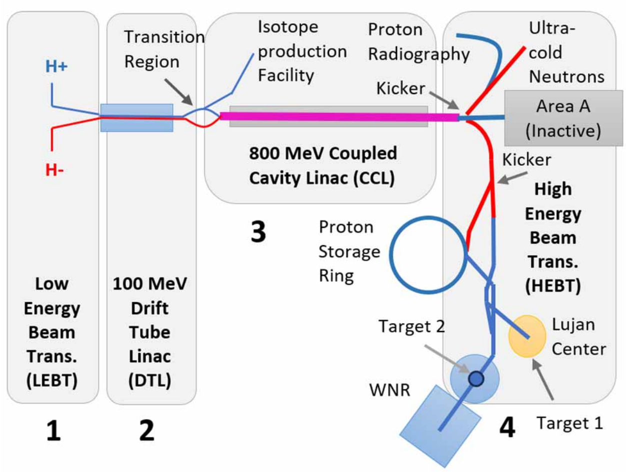

Figure 1: Diagram of the primary tuning areas. Each area has a different philosophy for tuning. The 1) LEBT is dominated with transverse diagnostics with magnet corrections and varies the most from year-to-year operation. 2) DTL tuning is the simplest, with a model driven focus. The 3) CCL is model dominate and ideally should not require much optimization. 4) The HEBT current is not very well grounded in a physics model and mostly uses optimization of the upstream sections.

response to the control elements, such as magnets or radiofrequency systems. This phenomenon is commonly known as *model-driven tuning*. Once the beam has reached the end of each tuning region optimally, the next step involves optimizing the transport and capture of the beam, which effectively requires a *model-independent tuning* procedure. In this particular stage, utilizing a tangible model is unnecessary. Rather, beam loss and current monitors are employed to inform and facilitate adjustments made to the control elements. A proficient accelerator operator can effectively implement both tuning categories by employing meticulously crafted routines and including historical offset corrections. More recent facilities have made more strides in automating their processes.

BEAM TUNING METHODS

The tuning methods employed are predominantly contingent upon the dependability and replicability of the input beam. To ensure consistency across multiple years, the recommended approach for tuning is to employ a kind of *acceptance tuning*. In this context, it is presumed that the upstream beam ought to be adjusted to align with the desired entry values of the current region. Consequently, the transportation and/or acceleration process will be carried out without any modifications to the design values of the current areas or the setpoints from the previous year. In the event that beam loss is detected within the tuning region, adjustments are made to the input beam in to enhance its compatibility. To illustrate this concept, let us imagine the process of passenger loading on a roller-coaster within a theme park. The cars are affixed to a set of tracks. To ensure the safe traversal of passengers from the commencement to the conclusion of the journey without any untoward incidents, it is imperative that the passengers possess the appropriate weight and height attributes.

Alternatively, in cases when the input beam exhibits inconsistency between run cycles, employing an *adaptive tuning* strategy is deemed more favorable. In this methodology, the control elements are adjusted inside the tuning zone to rectify the current configuration of the input beam. In this context, a suitable analogy may be drawn between the adjustment process of a laser beam on an optics table. Mirrors have the capability to be adjusted in tilt, while refractive lenses can be changed, which adapts for differences in the input laser profile and power.

LOW-ENERGY BEAM TRANSPORT (LEBT) TUNING

The transportation of the beam through the low-energy area of LANSCE has consistently exhibited the lowest level of stability across different run cycles. Although the H^+ source has a reasonable level of reliability, the H^- source exhibits variability both over its operating lifespan and between recycling processes. The stability of ion acceleration has been seen to decrease further with the Cockcroft-Walton accelerator age. A more adaptable methodology is necessary for optimizing the beam transport tuning.

The transverse matching process from the source to the DTL entry is facilitated by the LEBT tuning procedure, which incorporates the use of cTrace code (developed at LANSCE). The approach utilized in this study is *a model-driven, adaptive tuning* strategy, as depicted in Fig. 2. In order to assess both the vertical and horizontal beam profiles, a combination of two slit and collector actuator pairs is employed. The disassembled beam allows for the reconstruction of the bunch emittance. The cTrace program then uses the local measurement and current quadrupole characteristics to predict the beam envelope along the transport line. The adjustment of the quadrupole and steering magnets is determined by the fit to the incoming beam shape, aiming to achieve the required focusing and prevent particle losses through the apertures of the component.

The cTrace program is a software application written in the C++ code, based on the recent SciTrace software. In turn, the SciTrace coding was based on the original Trace2D and Trace3D programs used in the 1980's [6]. In the year 2022, an evaluation was conducted on the cTrace code, which revealed a significant increase in speed by four orders of magnitude. A novel wrapper program, referred to as RMatrix, has been recently developed to enhance the accessibility of cTrace.

Extremum seeking (ES) is a robust model-independent feedback control algorithm which has been implemented at LANSCE for va ious beam optimization and beam loss minimization tasks [7]. In addition, an innovative approach was devised to mitigate beam loss in the Low Energy Beam Transport (LEBT) region by employing a modified version of extremum searching (ES) known as Safe ES. This

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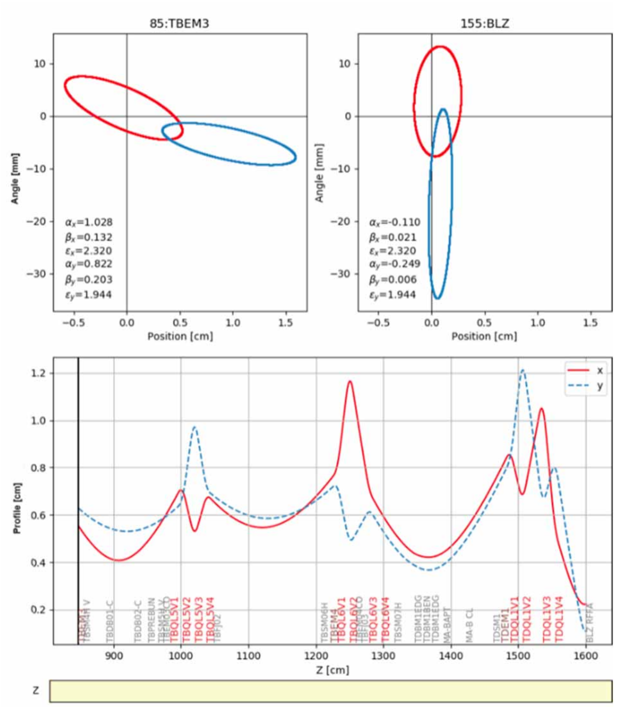

Figure 2: Beam envelope of the H- beam transport using cTrace code. The red trace shows the horizontal beam size and the blue is the vertical. Here the beam is focused into wastes at the pre-buncher (920 cm), the ground level deflector (~1150 cm) and the main buncher (~1350 cm). Finally, the beam is matched into the drift tube linac. This is C++ code runs the simulation at orders of magnitude faster than the previous SciLab application.

modified technique is capable of effectively addressing un known restrictions [8]. The algorithm employed in this study utilizes gradient-based estimating techniques in conjunction with a safety filter mechanism. The primary purpose of the program is to minimize an objective function that is currently unknown, while simultaneously ensuring that a safety measure remains positive throughout the optimization process. Through the utilization of this algorithm, we successfully enhanced the efficiency of the Low Energy Beam Transport in a dynamic manner, accommodating for intricacy and deviation within the system. Furthermore, we prioritized the preservation of operational safety, thereby mitigating the risk of harm and radiation exposure. As depicted in Fig. 3, the outcome of this *model-independent, adaptive tuning* method is a clear decrease in beam loss and an enhancement in the performance of the accelerator.

DRIFT TUBE LINAC (DTL) TUNING

In the preceding Low Energy Beam Transport section, both positively charged (H+) and negatively charged (H-) beams are subjected to acceleration up to 750 keV, with a direct current structure derived from the Cockcroft-Waltons system. A pre-buncher is employed to modulate the beam, while a primary buncher is used to match the beam into the drift tube linac. Hence, the calibration process for these LEBT radio frequency (RF) modules

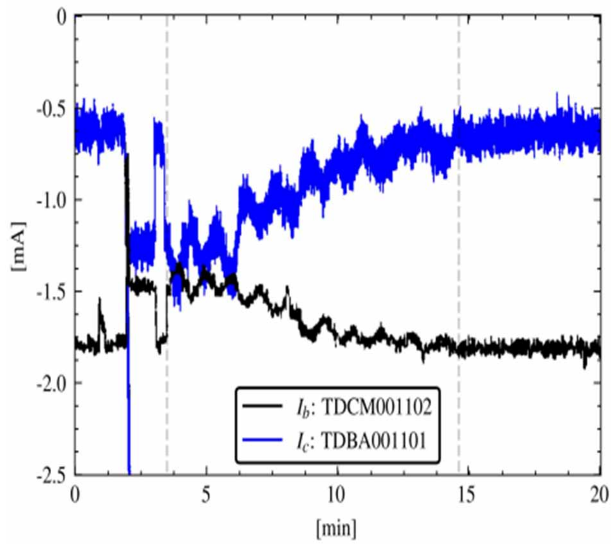

Figure 3: Here we show the saft ES adaptive tuning at work. The primary data source for the plot of I_b and I_c is derived from the LANSCE control room monitor, which provides real-time information on process variables. The initial vertical line with dots denotes the commencement of the algorithm.

begins within the subsequent DTL section. Absorber-collector pairs are employed for the purpose of quantifying the phase beam acceptance of all four DTL acceleration modules. The matching of the LEBT bunchers begins with the first absorber's measured intensity as they are shifted through their respective phase ranges. Following this, the DTL modules can then be tuned to their ideal phase and power for beam acceleration. This process can be characterized as a *model-driven procedure*, incorporating *both acceptance* and *adaptive tuning* techniques.

Recently, we have applied our new High-Performance Simulation (HPSim) software [9] for particle transport and tracking through the LEBT, DTL, and ultimately the transport to the Isotope Production Facility (IPF). HPSim is a computational program that utilizes GPU processing power to do multi-particle simulations. It is designed to provide essential six-dimensional beam distributions for various user facilities and beam configurations. The foundation of this approach lies in the utilization of established physics models, which have been extensively employed in PARMILA [10], a founding accelerator simulation code developed at LANL. HPSim is characterized by its high speed, precision, and user-friendly interface. The virtual diagnostic tool has the capability to function as a valuable resource for LANSCE, aiding in the optimization of beam parameters across various user facilities. Furthermore, it has the potential to be utilized in the evaluation and refinement of machine-learning algorithms pertaining to beam alignment and optimization.

The data corresponding to the phase scan of H^+/H^- was collected during the run cycle of 2022. Equipped with High Power Simulation (HPSim) technology, the system incorporates six radio frequency (RF) cavities, namely the pre

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buncher, main buncher, and Modules 1-4 in the Drift Tube Linac (DTL). The simulation was conducted using HPSim for a duration of 23 days, with a time interval of 1 minute, prior to the phase scan. The process of mean energy drifting was shown to be consistent with the observed variations in beam phase. Figure 4 shows how HPSim was used to accurately predict the energy distribution to the IPF target. An online model was developed and afterward shared with the LANSCE operating team to facilitate real-time prediction. Additionally, the model was utilized to analyze archived data while awaiting the arrival of the H+ beam in 2023.

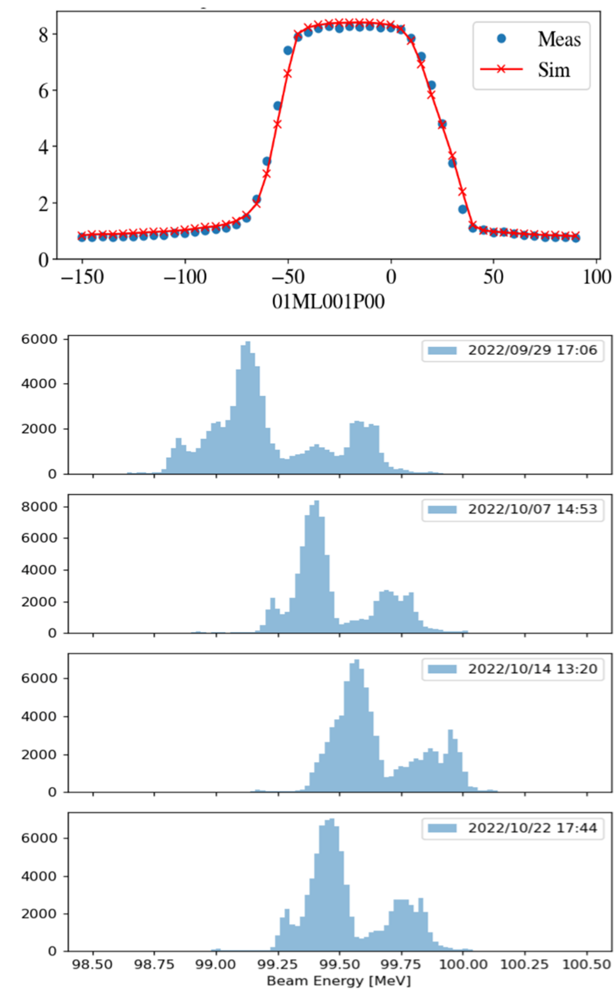

Figure 4: HPSim was calibrated with the measured phase scans of the drift tube linac and used to predict the energy distribution of the proton beam at the isotope production target. These predictions were consistent with loss and current measurements along the IPF line. The energy was verified with downstream beam position monitor measurement.

SIDE-COUPLED CAVITY (CCL) TUNING

The Side Coupled-Cavity (CCL) linear accelerator was initially calibrated utilizing the Delta-T (ΔT) technique [11]. This methodology involves the comparison of the test particle's time-of-flight discrepancy between the module's active and inactive accelerating states, which is measured at two downstream detectors. The ΔT software optimizes the module amplitude and phase with iterative measurements using linearized matrices. This necessitates the proximity of the initial phase and amplitude to the prescribed design values. Unfortunately, this method did not record data for further analysis.

In the early 1990's, an alternate phase scan method, known as Phase Scan Signature Matching (PSSM), was proposed at LANL [12]. Like the prior ΔT method, PSSM is a *model-driven, adaptive tuning* method. Now this process used at several facilities, such as the Spallation Neutron Source (SNS)[13], Fermilab [14], European Spallation Source (ESS) [15], China Spallation Neutron Source [16] and J-PARC [17]. In 2021, we applied the PSSM to LANSCE, with the goal to enhance the precision and resilience of our previous tuning procedure [18]. In our version we still rely on a time-of-flight comparison between two phase measurement loops. Therefore, we refer to this version as the phase-deltaT (PSDT) method. The PSDT method involves the collection of beam phases at two places downstream while systematically varying the phase across the full module range (Fig. 5). Subsequently, the data is fitted with a model that makes predictions regarding the time-of-flight and energy gain for every point within this phase range. Afterwards, the computer ascertains the most favorable phase setpoint (PSP) and amplitude setpoint (ASP) by minimizing the discrepancy between the data and the model. The improved PSDT system has an expanded capacity to capture and store a greater volume of data and information, hence facilitating future studies and diagnoses.

HIGH-ENERGY BEAM TRANSPORT (HEBT) TUNING

At present, the transportation of the beam through the High Energy Beam Transport system exhibits minimal reliance on a physics model and instead heavily relies on the optimization of the upstream beam in to ensure the provision of high-quality delivery to the user facilities. Multiple models of beamlines exist, however, their primary purpose is to investigate the losses that occur after the establishment of the tune. This method is deemed fair, given the anticipated level of reproducibility exhibited by the accelerator. Over the course of fifty years, the functioning of LANSCE has demonstrated a high level of reliability. In recent years, there has been a growing need to employ adaptive tuning approaches to minimize losses and optimize the number of protons reaching the target. Implementing the PSDT approach within the CCL has effectively addressed certain inconsistencies identified in previous operational cycles. Nevertheless, it is evident that substantial adjustments are required for both the CCL RF controls and the HEBT steering and quadrupole magnet setpoints.

Ideally, it is preferable to maintain the high-energy transports in an acceptance tuning regime. However, in cases

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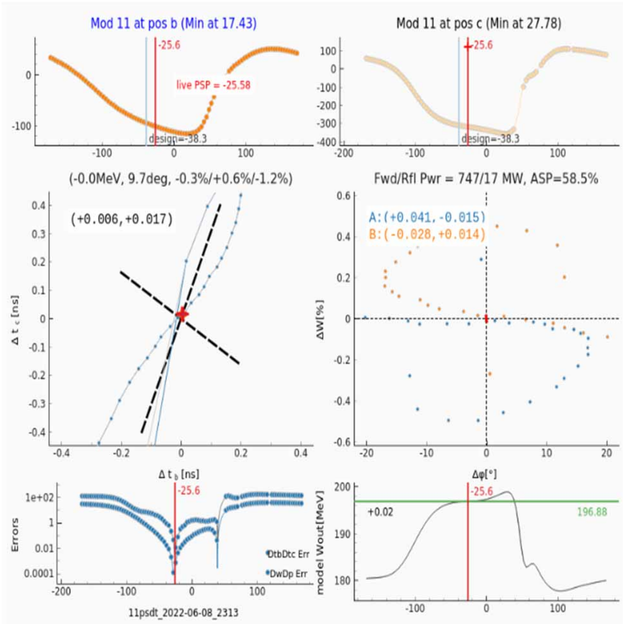

Figure 5. The Phase DeltaT (PSDT) program used to tune the acceleration of protons through the side-Coupled Cavity Linac (CCL). The top plot shows the measured phase from the first (left) and second (right) phase loops. The second row shows the difference time-of-flight (TOF) calculations for each loop (left) and the change of energy entering (blue) and exiting (orange) with respect to the phase of the beam(right). The bottom row shows the fit errors (left) and the modules total energy gain verses phase (right).

with heightened irregularities with the input beam, adopting a method akin to the Low Energy Beam Transport (LEBT) system may be required. Currently, two approaches are being developed to offer this capacity. The HPSim tool, which is utilized in conjunction with the LEBT and DTL, is now undergoing preparations for both the CCL and HEBT configurations. This will enable the utilization of particle tracking techniques to provide a qualitative assessment of the origin of beam instabilities. Additionally, a novel operations software named RMatrix (see Fig. 6) is being developed. This program utilizes a conventional beam optics transport code to provide visual representations of the modifications in beam size and position resulting from fluctuations in the setpoints of the accelerator control system. The present study aims to initiate the testing of these two technologies during the upcoming run cycle, with the ultimate goal of implementing them in the run cycle of 2024.

CONCLUSION

This study provides an overview of the existing status and prospective strategies for the LANSCE accelerator tuning techniques. We comprehensively describe the many tuning categories and corresponding procedures employed for each portion of the accelerator, ranging from the low-energy beam transport to the high-energy beam transport.

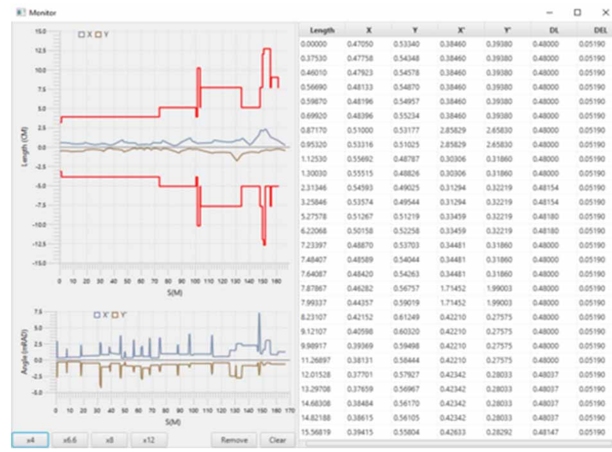

Figure 6: The RMatrix program uses the latest transport models of the high-energy transport beamlines to provide live feedback to the LANSCE operators. The top plot shows the beam RMS size, where the profile in the horizontal axis (blue) is plotted in the positive direction and the vertical (brown) is in the negative. The red lines indicate the diameter of the beampipe along the flight path.

The authors additionally include coverage of new advancements and implementations of diverse software tools, including cTrace, HPSim, RMatrix, and PSDT, which facilitate the utilization of model-driven and adaptive tuning procedures. The study showcases the advantages of utilizing these technologies in enhancing the quality, stability, and efficiency of the beam, while also aiding in data analysis and diagnostics. In the near future, we intend to expand on these advancements with the integration of machine learning techniques.

ACKNOWLEDGMENT

We would like to acknowledge the hard work and dedication of the LANSCE operations team as they help navigate the many challenges associated with tuning an aging accelerator. Additionally, the hard work from the diagnostics and control system engineers has proven instrumental in the modernization of the instrumentation upgrades and new control software.

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