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उच्च-तीव्रता त्वरकों के लिए अगली पीढ़ी के बीम निदान

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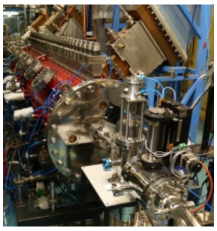

लेहिपा में एस-एफएफसी असेंबली

सारांश

यह लेख लेहिपा और मेहिपा जैसे उच्च-तीव्रता वाले प्रोटॉन त्वरकों के प्रभावी संचालन के लिए महत्वपूर्ण बीम नैदानिक उपकरणों में हाल की स्वदेशी प्रगति पर प्रकाश डालता है। जबकि पारंपरिक अवरोधक उपकरण एक मूलभूत माप रीढ़ प्रदान करते हैं, ध्यान तेजी से उच्च-रिज़ॉल्यूशन, गैर-विनाशकारी प्रौद्योगिकियों की ओर स्थानांतरित हो गया है। चर्चा किए गए प्रमुख नवाचारों में उप-नैनोसेकंड वाइड-बैंडविड्थ मॉनिटर, क्रायोजेनिक बीम पोजीशन मॉनिटर, गैर-आक्रामक गैस शीट प्रतिदीप्ति प्रोफाइलर और भौतिकी-सूचित मशीन लर्निंग फ्रेमवर्क शामिल हैं। एक साथ, ये अगली पीढ़ी के उपकरण तेजी से, डेटा-संचालित चरण अंतरिक्ष पुनर्निर्माण और अत्यधिक सटीक ऑनलाइन बीम ट्यूनिंग की सुविधा प्रदान करते हैं।

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Next-Generation Beam Diagnostics for High-Intensity Accelerators

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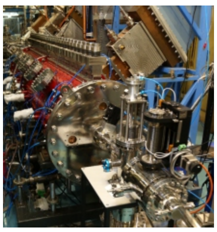

S-FFC assembly in LEHIPA

ABSTRACT

This article highlights the recent indigenous advancements in beam diagnostic instruments critical for the effective operation of high-intensity proton accelerators such as LEHIPA and MEHIPA. While traditional interceptive devices provide a foundational measurement backbone, the focus has rapidly shifted toward high-resolution, non-destructive technologies. Key innovations discussed include sub-nanosecond wide-bandwidth monitors, cryogenic beam position monitors, non-invasive gas sheet fluorescence profilers, and physics-informed machine learning frameworks. Together, these next-generation tools facilitate rapid, data-driven phase space reconstruction and highly precise online beam tuning.

KEYWORDS: *Energy High Intensity Proton Accelerator (LEHIPA), Medium Energy High Intensity Proton Accelerator (MEHIPA), High-Intensity Accelerators*

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उच्च तीव्रता वाले प्रोटॉन लीनॉकः वर्तमान स्थिति एवं भावी योजनाएं
HIGH INTENSITY PROTON LINAC : CURRENT STATUS AND WAY FORWARD

Introduction

The effective commissioning and operation of high-intensity proton accelerators, such as the Low Energy High Intensity Proton Accelerator (LEHIPA) and the Medium Energy High Intensity Proton Accelerator (MEHIPA), rely heavily on robust diagnostic instruments. While conventional tools like Faraday cups, current transformers, and wire profilers form the foundational backbone of beam measurement, new frontiers are rapidly expanding our capabilities. Recent indigenous developments have introduced wide-bandwidth devices for sub-nanosecond longitudinal profiling, specialized warm and cold beam position monitors for precise alignment in extreme environments, and non-invasive gas sheet fluorescence techniques for continuous transverse profiling. Furthermore, the integration of tomographic phase space reconstruction and physics-informed machine learning is revolutionizing the field, transitioning from traditional interceptive measurements to rapid, data-driven, and non-destructive online tuning.

The Foundation: Conventional Beam Diagnostics

Before exploring the new frontiers, it is important to recognize the foundation of conventional beam diagnostics which are deployed in LEHIPA [1]. Precise measurement of the beam current and transverse profile is crucial for optimizing accelerator performance and ensuring overall stability. For beam current measurement, interceptive devices like Faraday Cups (FCs), often utilizing water cooling and high-temperature radiation-resistant materials like tantalum or copper, are designed to safely intercept and measure the entire beam charge. Non-interceptive Current Transformers, such as DCCTs and ACCTs, are also heavily relied upon to accurately measure steady-state and fast macro pulsed beam currents without disrupting the beam path. For mapping spatial distributions, interceptive tools like wire profilers, multiwire profilers, and water-cooled slit profilers remain standard instruments, providing the high-resolution data necessary for essential beam tuning in low-intensity transport lines.

New Frontiers in Beam Diagnostics

As accelerator technologies advance, so too must the diagnostic tools used to measure them. The latest developments push the boundaries of bandwidth, non-invasive measurement, and intelligent data processing.

Wide Bandwidth Devices: Catching the Sub-Nanosecond

Capturing the high-speed dynamics of modern linac beams requires devices with extraordinary temporal resolution.

Strip-line Fast Faraday Cup (S-FFC)

Fast Faraday cups are crucial interceptive diagnostic devices used for measuring the time structure of sub-nanosecond beam bunches. For the Low Energy High Intensity Proton Accelerator (LEHIPA), a novel, wide-bandwidth strip-line fast Faraday cup (S-FFC) was successfully developed, employing a robust 3.5 mm thick strip capable of withstanding larger beam intensities and longer pulse durations [2]. With a broad operational bandwidth of approximately 7 GHz, this device accurately captures the time structure of individual micro-pulses, measuring a full width at half maximum (FWHM) of ~300 ps.

Coaxial Wall Current Monitor (C-WCM)

For continuous, online characterization of high-intensity bunches without disrupting the beam, a Coaxial Wall Current Monitor (C-WCM) was designed for LEHIPA [3]. Devoid of ferrite materials to eliminate high-frequency performance degradation, the C-WCM achieves a substantial measured bandwidth of about 6 GHz. Its eight azimuthally distributed feedthroughs equip it with both longitudinal profiling and high-performance beam position monitoring capabilities.

Warm and Cold Beam Position Monitors

Beam position monitors (BPMs) are essential for precise beam alignment and stability, conventionally utilizing four symmetrically arranged electrodes to detect beam-induced

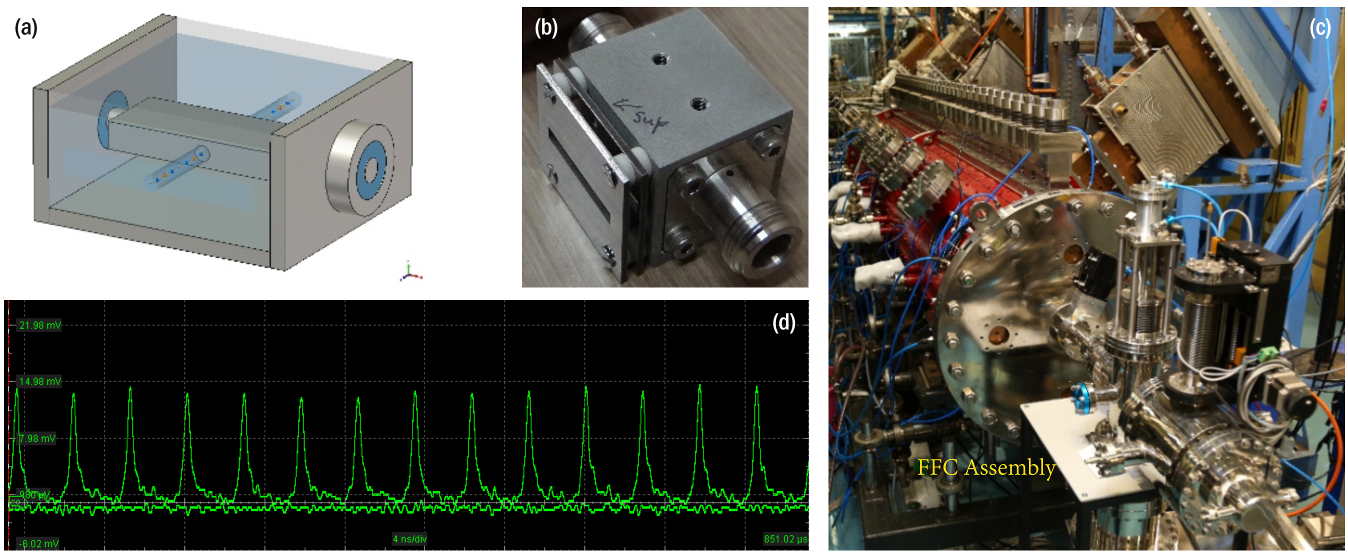

Fig.1: (a) Model and (b) picture of S-FFC; (c) S-FFC assembly in LEHIPA and (d) beam bunch train measured with S-FFC (4 ns/div).

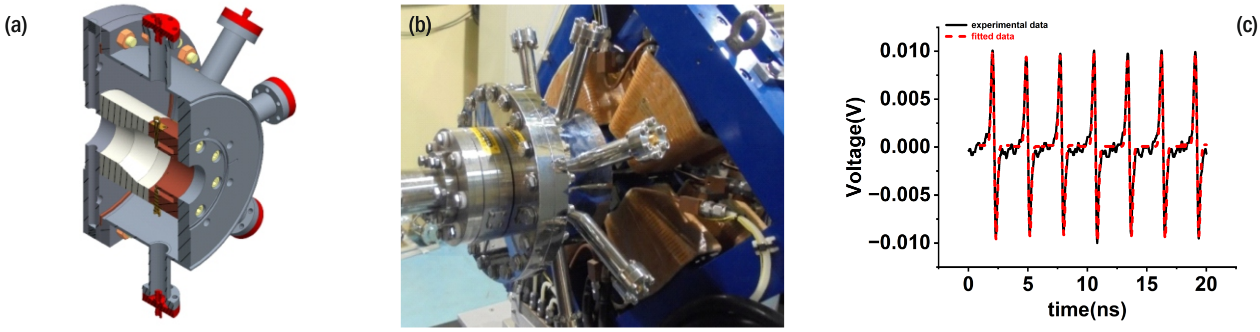

Fig.2: (a) 3D model of C-WCM final assembly, (b) C-WCM in the high energy beam transport line of LEHIPA, (c) Individual beam bunches on C-WCM with a derivative Gaussian fitting.

electric fields. For room-temperature sections of the LEHIPA accelerator, "warm" BPMs are deployed, delivering a sensitivity of 11 %/mm within a linear measurement region of ±3 mm. As beamlines push into cryogenic environments, such as the 40 MeV MEHIPA, specialized “cold” BPMs have been engineered [4]. These cold variants are fabricated from SS 316 LN stainless steel to withstand severe thermal contraction and feature uniquely curved electrodes to ensure structural integrity under cryogenic stress. Despite the extreme conditions, these cold monitors expand their sensitivity to 11 %/mm and offer a broader linear measurement region of ±4 mm, securing highly precise diagnostics.

Non-Invasive Gas Sheet Beam Profiling

To overcome the thermal and mechanical limitations of interceptive profilers, a novel dual gas sheet beam profile monitor is being developed for the LEHIPA facility [5]. This non-invasive system works by generating two thin nitrogen gas sheets at a 45-degree angle to the beam axis. When the charged particle beam intersects this gas sheet, it induces molecular excitation and subsequent fluorescence, providing a direct two-dimensional visual representation of the beam's intensity profile. Experimental testing with a 20 keV, 10 mA pulsed proton beam successfully imaged this characteristic fluorescence, making it directly visible to the eye without requiring complex image intensifiers. Crucially, the beam profile measurements obtained using this gas sheet technique showed close agreement with those from conventional solid scintillator screens. This innovative development marks the first time such an intense low-energy proton beam has been used to directly view the beam-induced fluorescence of a gas sheet.

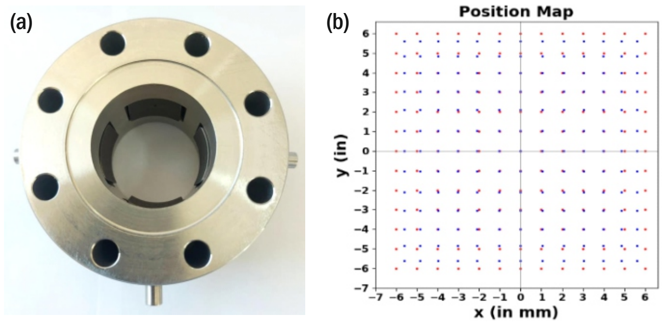

Fig.3: (a) Picture of cold BPM assembly, (b) Position map of the cold BPM with CST simulations.

Tomographic Phase Space Reconstruction

Accurate transverse phase space characterization is vital for matching beams and minimizing emittance growth in facilities like LEHIPA. A minimally interceptive Computed Tomography (CT) approach has been implemented to reconstruct the two-dimensional transverse phase space by utilizing one-dimensional spatial profiles measured across varying solenoid magnetic field strengths [6]. An essential feature of the custom Python-based reconstruction program is its ability to digitally filter out secondary molecular species (like H_{2+} and H_{3+}) from the composite profiles. By choosing the Simultaneous Algebraic Reconstruction Technique (SART) over Filtered Back-Projection, this method provides superior reconstruction accuracy, guiding the successful re-optimization of beamline parameters.

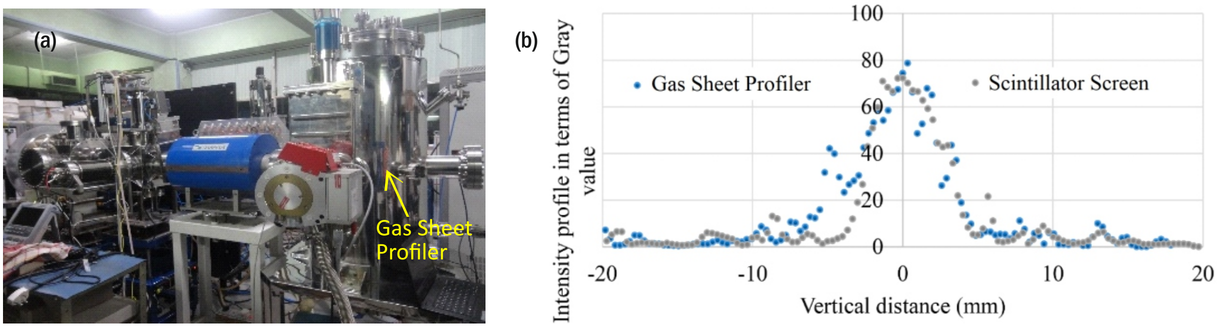

Fig.4: (a) Photograph of the gas sheet generator setup in test bench (b) Beam profile acquired by the gas sheet profiler and scintillator screen.

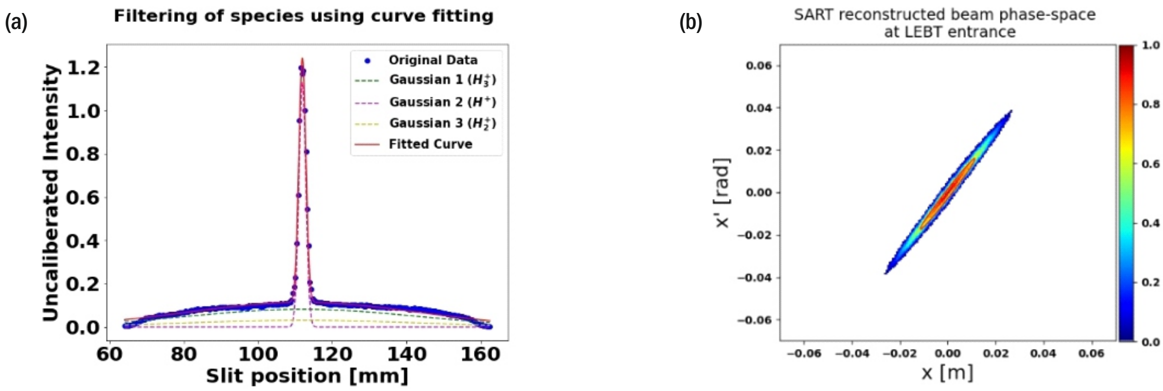

Fig.5: (a) 3-species curve fitting of a measured beam profile. (b) SART reconstructed beam phase space distribution in x-x'.

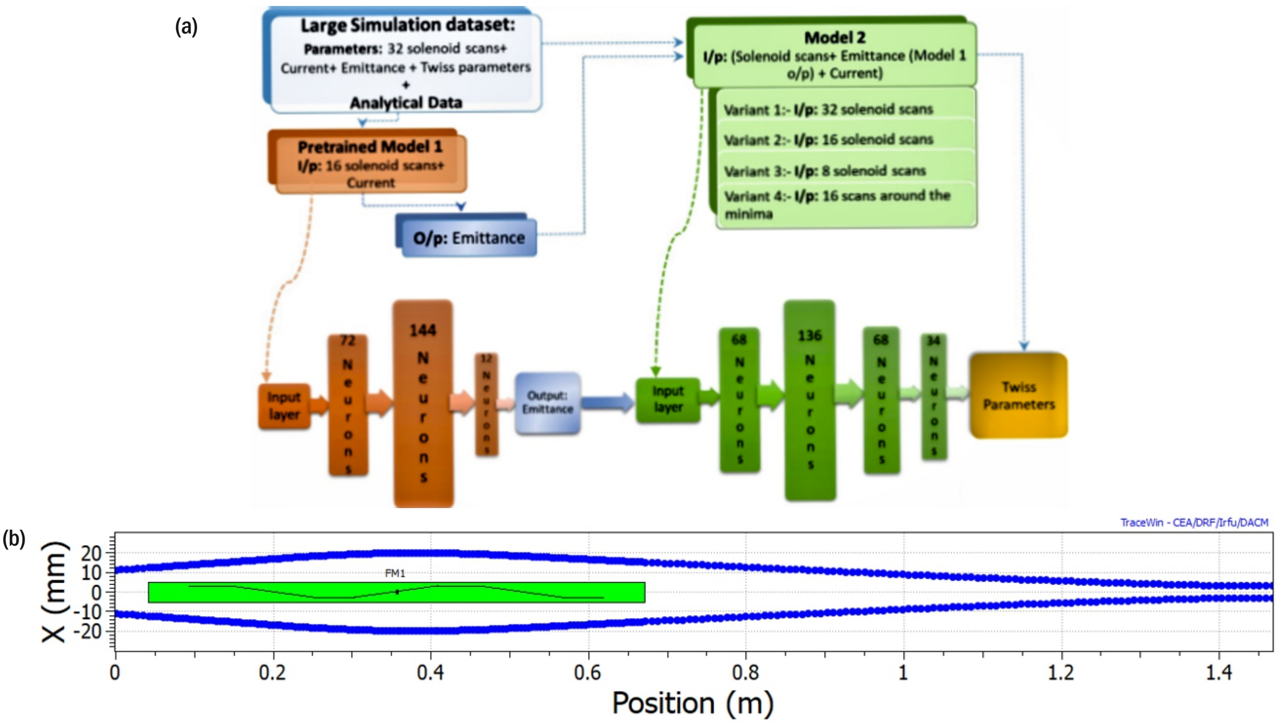

Fig.6: (a) Architecture of the two-stage cascaded neural network framework. (b) PIC beam envelope simulation result for LEHIPA parameters predicted by Two-stage NN model.

The AI Revolution: Machine Learning in Diagnostics

The integration of machine learning (ML) marks a paradigm shift toward rapid, data-driven beam diagnostics, overcoming the computational and noise-sensitivity limitations of traditional methods.

Physics-Informed ML for Phase Space Reconstruction

A novel dual-network machine learning framework has been developed for the LEHIPA facility to effectively overcome the noise sensitivity and computational overhead of traditional solenoid scans [7]. This cascaded architecture features an initial model that predicts transverse beam emittance from RMS beam size data and current, which then feeds into a secondary model alongside additional RMS measurements to accurately deduce the Twiss parameters. By employing physics-informed pre-training based on analytical envelope equations and subsequent fine-tuning with TraceWin simulations, this approach successfully embeds fundamental beam physics constraints, drastically reducing the reliance on expensive simulation datasets while delivering highly accurate, real-time predictions for automated accelerator tuning.

Transverse Profile Reconstruction

To expand non-invasive diagnostic capabilities, advanced machine learning techniques are now being applied to reconstruct detailed transverse beam profiles from multi-electrode monitors such as the C-WCM. This approach utilizes a newly developed hybrid computational framework that pairs a Neural Network (NN) with Differential Evolution (DE) optimization. Within this architecture, the NN serves as a high-speed predictive surrogate model, instantly mapping

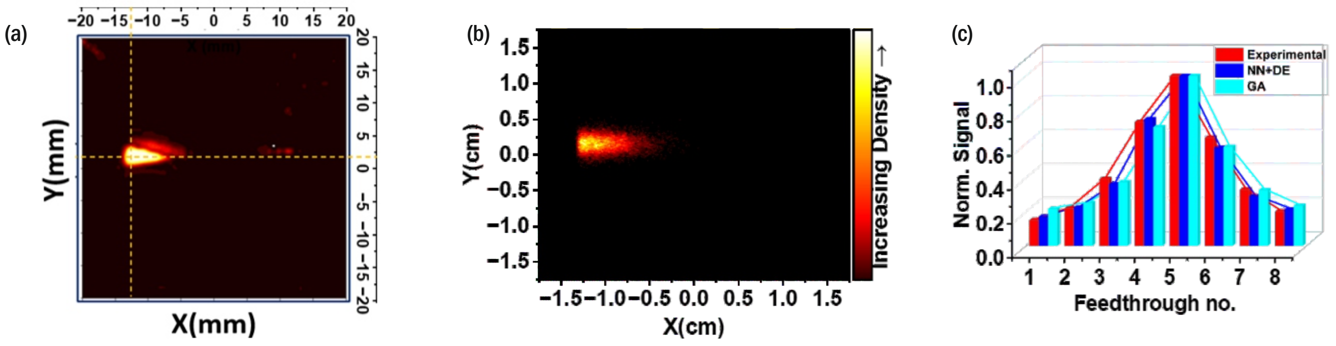

Fig.7: (a) Beam profile recorded at scintillator screen; (b) C-WCM based reconstructed beam profile; (c) comparison of experimental and simulated feedthrough signals.

fundamental beam parameters to corresponding electrode responses. Simultaneously, the DE algorithm efficiently minimizes the discrepancy between these predicted outputs and the actual measured signals, ensuring rapid and highly accurate profile reconstruction.

Conclusions

The continuous evolution of beam diagnostic tools is imperative to safely and efficiently meet the rigorous demands of modern high-intensity particle accelerators. By integrating wide-bandwidth devices and non-invasive profiling techniques like gas sheet fluorescence, the thermal and mechanical limitations of conventional interceptive monitors are effectively mitigated. Moreover, the application of tomographic phase space reconstruction and physics-informed machine learning heralds a new era of rapid, automated, and highly accurate beam characterization. Ultimately, these state-of-the-art indigenous developments secure the operational stability, alignment, and optimized performance of advanced facilities like LEHIPA and MEHIPA.

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