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A SNAPSHOT OF CERN BEAM INSTRUMENTATION R&D ACTIVITIES

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Abstract

The CERN accelerator complex stands out as unique scientific tool, distinguished by its scale and remarkable diversity. Its capacity to explore a vast range of beam parameters is truly unparalleled, spanning from the minute energies of around a few keV and microampere antiproton beams, decelerated within the CERN antimatter factory, to the 6.8 TeV high-intensity proton beams that race through the Large Hadron Collider (LHC). The Super Proton Synchrotron (SPS) ring plays also a crucial role by slowly extracting protons at 400 GeV. These proton currents are then directed toward various targets, generating all sorts of secondary particle beams. These beams, in turn, become the foundation of a diverse fixed-target research program, enabling scientific exploration across a wide spectrum. Moreover, as CERN looks ahead to future studies involving electron-positron colliders, the development of cutting-edge diagnostics for low emittance and short electron pulses is also underway. This contribution serves as a snapshot, shedding light on the main R&D initiatives currently underway at CERN in the field of beam instrumentation.

INTRODUCTION

The CERN accelerator complex is a dynamic and continually evolving system. Over a decade ago, an ambitious global initiative was launched to enhance the collision capabilities of the Large Hadron Collider (LHC). This initiative aims to achieve higher collision rates and is executed in phases. The initial phase focused on the LHC Injector Upgrade program [1], which successfully generated higher brightness beams within the CERN injector complex. Building on this achievement, the subsequent stage of the high Luminosity LHC upgrade (HL-LHC) [2] is scheduled for implementation from 2026 to 2028. This phase aims to further elevate beam intensities and reduce emittance, introducing novel challenges to beam instrumentation. These instruments must adapt to unprecedented beam densities while maintaining the highest reliability and precision.

Beyond its contributions to the LHC and its physics endeavors, CERN has embarked on a comprehensive consolidation of the fixed target physics program in the 'North Area' of the Super Proton Synchrotron (SPS). This undertaking necessitates a complete overhaul of the instrumentation employed for extracting continuous beams from the SPS. These beams are subsequently directed towards various targets and experimental zones.

Anticipating the completion of the LHC's scientific program, the scientific community's aspirations encompass the exploration of $e^- - e^+$ collisions at up to 380 GeV center of mass energies. While the Compact Linear Collider (CLIC) [3] has been under scrutiny for decades, CERN is currently engaged in assessing the feasibility of the 91-kilometer-long Future Circular Collider (FCC). The FCC would initially focus on lepton collisions [4] and potentially accommodate 100 TeV proton collisions in subsequent phases, using the same infrastructure. Although linear and circular colliders differ in their design and implementation, there are notable similarities in terms of beam properties, beam energy, intensity, transverse and longitudinal sizes, as well as the demand for a high level of radiation tolerance within the tunnel. This suggests the prospect of adapting technologies initially developed for CLIC for use in the FCC-ee.

In this paper, we provide a comprehensive overview of the ongoing R&D endeavors at CERN in the realm of beam instrumentation. This encompasses a spectrum of activities, including the design of innovative electromagnetic pick-ups, the refinement of techniques for measuring transverse profiles of high power density beams, advancements in short longitudinal beam profiling, the optimisation of high dynamic range particle detectors and the latest strides in read-out electronics and digital acquisition systems. By shedding light on these R&D activities, we aim to present the essence of CERN's pursuit of cutting-edge instrumentation techniques.

COMPLEX DESIGN OF ELECTROMAGNETIC PICK-UPS

Within the scope of the HL-LHC program, the demand for large-aperture, high-field quadrupole magnets has surged to compress proton beam sizes during collisions to unprecedentedly minuscule dimensions. This new configuration requires novel cryogenic directional stripline beam position monitors [5], enabling the measurement of counter-propagating beams with a precision surpassing a mere micron. This intricate design encompasses Tungsten alloy inserts, strategically positioned to absorb collision debris and curtail radiation doses to neighboring magnets. Furthermore, these monitors are coated with copper and NEG (Non-Evaporable Getter) coatings, a dual-layer approach that minimizes beam impedance and paves the way for attaining ultra-high vacuum conditions.

Amid recent advancements, beam position monitors (BPMs) with heightened frequency bandwidth have garnered substantial interest. This is not only pertinent to short electron bunches but also to furnish intrabunch monitoring with fast time response for high-intensity proton beams. A range of technologies is presently under exploration, featuring electro-optical (EO) crystals [6] and dielectric pick-ups [7,8].

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EO BPMs promise to replicate the beam's electrical field optically, encompassing a bandwidth spanning from direct current to multi-tens of gigahertz. On the other hand, dielectric pick-ups leverage the phenomenon of charged particles generating coherent Cherenkov diffraction radiation, achieving even greater bandwidth capabilities—on the order of several hundreds of gigahertz in our case. Notably, this technology exhibits potential for extension into the visible wavelength range, offering a well-suited solution for femtosecond-long bunches. The deployment of these innovative technologies is currently under rigorous scrutiny for potential integration into LHC and their performance will be compared to the ones of more traditional high-frequency RF button pick-ups.

MEASURING THE TRANSVERSE PROFILE OF HIGH POWER DENSITY BEAMS

State-of-the-art Interceptive Diagnostics

Optical Transition Radiation (OTR) imaging system a widely adopted tool in linacs and transfer lines, has exhibited great achievement in measuring remarkably small beams, surpassing the realm of a mere micron in spot size [9, 10]. Even if these systems have withstood high charge densities while employing thermally robust material like glassy carbon, OTR imaging systems would get inevitably damaged when encountering beam densities above a certain threshold. In the domain of hadron synchrotron rings, Wire scanners (WS) offer an avenue for swift movement, reaching speeds of up to 20 meters per second [11]. However, they encounter analogous challenges and limitations as carbon wires cannot endure the full beam intensity in numerous machines, such as the SPS and LHC.

In a bid to overcome these hurdles, a pioneering research and development initiative has recently been launched, focusing on low-density materials. Preliminary trials at CERN involved Carbon nanotube wires and screens, although the outcomes have not yet unearthed superior alternatives, the potential they hold is monumental [12]. The existing limitations observed in these tests can be attributed to the material's purity, intertwined with the intricacies of the production process, leaving room for improvement in this aspect. As research continues to unfold, the pursuit of optimal low-density materials for advanced beam instrumentation remains an essential endeavor. By refining these materials and production methods, CERN seeks to break new ground, ushering in a new era of instrumentation capable of withstanding and accurately measuring high-intensity beams in diverse particle physics contexts.

Non-invasive Beam Size Monitoring

Non-invasive instruments hold the potential to address all of these limitations, making them the ultimate solution to the persistent challenges associated with measuring increasingly higher beam intensities.

Monitors utilizing gas ionization or gas fluorescence principles exhibit versatility by operating effectively at low gas pressures. These approaches present an attractive non-invasive solution suitable for high-intensity and relatively low-energy beams. Gas ionization monitors equipped with advanced hybrid pixel detectors equipped have enabled bunch-by-bunch transverse profile measurements with rapid read-out speeds on the order of a few nanoseconds, employing gas pressures ranging from 10^{-7} to 10^{-8} Torr [13]. Gas fluorescence, despite its smaller cross-section compared to ionization, has shown promise by utilizing supersonic gas jets and potentially extended integration times to provide non-intrusive beam imaging capabilities [14]. Ongoing systematic investigations at the CERN accelerator complex are dedicated to comprehensively exploring the performance of both gas ionization and gas-jet fluorescence monitors.

An alternative avenue entails utilizing Optical Diffraction Radiation (ODR) emanating from slits, or Optical Cherenkov Diffraction Radiation (OChDR) emitted within dielectric materials [15]. Methodical studies involving ODR [16] have successfully demonstrated the ability to measure beam sizes as minute as 5 microns in the VUV range. Furthermore, an imaging system employing OChDR, offering enhanced photon yield and simplified detector configuration, exhibited success in previous tests [17]. However, the measured beam sizes were relatively large and prevented a comprehensive assessment of detector resolution and limitations. Both techniques rely on incoherent radiation and are best suited for ultra-relativistic beams with γ values surpassing 10^3 that would be available in future $e^- - e^+$ collider.

For ultra-high energy synchrotrons like the SPS, LHC, 3rd Generation light sources, FCC-ee, and FCC-hh, the emission of synchrotron radiation from bending magnets or undulators emerges as a natural source for beam diagnostics. However, the diffraction limit of the radiation source poses a primary challenge for synchrotron radiation (SR) based transverse beam profile imaging systems, often necessitating operation in the X-ray domain to achieve beam size accuracy at the micron level. To overcome this limitation, alternative methods such as interferometry in the optical [18] and subsequently X-ray range [19] are under investigation.

MEASURING THE LONGITUDINAL PROFILE OF SHORT BUNCHES

Proton bunches coursing through the CERN accelerator complex often span relatively extended durations, typically 1 to 2 nanoseconds (FWHM). However, as bunch charges escalate, the likelihood of encountering instabilities amplifies, intensifying the imperative to meticulously characterize the longitudinal bunch profile with heightened time resolution—on the order of tens of picoseconds. This requirement parallels the upcoming FCC-ee project, where electron and positron bunches of 5 to 30 picoseconds in length are expected to collide.

To tackle this challenge, techniques originally developed for the characterization of short electron bunches in contexts like Free-Electron Lasers or linac colliders have emerged as relevant solutions. Optical monitors employing Streak cameras were already in use as early as the 1990s. Even today, they remain indispensable tools, offering straightforward operation and furnishing time resolutions within the picosecond realm [20, 21].

Recently, remarkable strides have been achieved through the integration of electro-optical methods. This synergy has enabled the measurement of turn-by-turn (at a few MHz) picosecond-long bunch profiles [22]. These techniques have evolved in a benchmark tool for longitudinal bunch profile monitoring [23], and are considered as good candidate for bunch-by-bunch (66 MHz) longitudinal profile monitors in the context of the FCC-ee project [24].

Meanwhile, instruments focused on capturing the bunch spectrum at elevated frequencies through the emission of coherent radiation [25, 26] present a simpler and cost-effective alternative to optical or electro-optical methodologies. Advanced non-invasive monitors founded on coherent Cherenkov diffraction radiation [27] are presently undergoing design and development, with applications spanning both hadron and lepton accelerators.

DEVELOPING PARTICLE DETECTOR FOR BEAM LOSS MONITORING

Beam loss monitoring (BLM) in the LHC demands measurements with an extraordinarily high dynamic range, spanning approximately 9 orders of magnitude. This is facilitated by ionization chambers [28], working in conjunction with precision electronic systems. Together, they enable measurements reaching down to the picoampere range within integration times of few seconds.

For the observation of rapid beam losses on the nanosecond timescale, Diamond detectors [29] have been strategically positioned at critical locations throughout the accelerator complex, including injection and extraction regions, as well as collimation region. In a continuing evolution, BLMs built on the foundation of Hybrid pixel detector technology developed at CERN are now under development. These novel detectors promise elevated sensitivity, radiation tolerance, and an impressive temporal resolution of 1.2 nanoseconds.

In scenarios demanding extended coverage across substantial distances, such as the FCC-ee or SPS slow-extraction contexts, BLMs that remain insensitive to X-rays while capitalizing on Cherenkov emission are currently under development. These optical monitors leverage radiation-hard optical fibers [30] to fulfill their monitoring roles effectively, showcasing the continuous innovation and adaptation occurring within the field of beam loss monitoring technology.

STATE-OF-THE-ART ELECTRONIC DEVELOPMENT

The CERN Beam Instrumentation group manages an impressive network of approximately 10,000 monitors dispersed throughout the entire accelerator complex. This extensive infrastructure may even expand further (more than double) in the future, especially considering the potential operations of FCC-ee. Managing such extensive systems efficiently has led to a focus on standardization, enabling cost-effective development and streamlined maintenance. Over recent years, the group has developed custom VME-based digital acquisition boards with FMC (FPGA Mezzanine Card) carriers [31]. These boards have played a pivotal role in the upgrades of numerous systems, including SPS BPMs [32], LHC BLMs, luminosity monitors, Wirescanners, and beam current transformers. Impressively, a total of 1,200 of these boards have been produced. The group is currently exploring the optimal form factor for a new DAQ (Data Acquisition) platform.

In the case of large distributed systems like BPMs and BLMs, the electronic acquisition chain typically consists of two parts. The front-end, situated close to the beam line instruments within the machine, acquires data locally and then transmits this information via optical fiber to a back-end system located several kilometers away in non-radioactive galleries or surface buildings. Given the challenging radiation environments within the LHC and SPS, where the electronics must withstand integrated radiation doses of 1 kGy and 10 kGy, respectively, radiation-tolerant to radiation-hard components are crucial. The BI group often employs ASICs and optical transceivers developed by the CERN micro-electronic group for these applications. The FCC-ee tunnel, with its even higher expected radiation levels due to strong synchrotron radiation, necessitates a similar approach for the design of the read-out electronic chain.

With increased beam intensities and a higher number of bunches, the demand for bunch-by-bunch measurements has become pervasive. The group's most recent developments explore the capabilities of RF System-on-Chip (RFSoC) technology, which allows for rapid digitization at multi-gigasamples per second (GSa/s) rates, along with substantial computing performance. Additionally, R&D efforts are underway to investigate ultrafast sampling techniques using electro-optical modulators and time-stretch techniques. These endeavors aim to enable measurements of shorter bunches and shorter bunch spacing.

CONCLUSION

The Beam Instrumentation group at CERN is engaged in an ambitious R&D program. Our goal is to measure lower emittance, higher intensity beams while continually advancing instruments to achieve the highest levels of accuracy and resolution, both in terms of spatial and temporal dimensions. A significant emphasis is placed on the development of non-invasive diagnostic techniques, representing the technology of the future. CERN's forward-looking perspective extends to its long-term future, with a particular focus on high-energy, short electron bunches in the context of $e^- - e^+$ colliders. It's important to note that this contribution does not encompass all of our activities. Our teams are also actively involved in the measurement of very low-intensity beams, which will be covered in a future presentation.

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