

## Future facilities and instrumentation

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**Abstract.** Explorations in nuclear physics over the past forty years have significantly advanced our understanding of matter under extreme conditions. Studies at various energy scales, from the AGS to the LHC, have not only confirmed the existence of QGP but also initiated its detailed and meticulous characterization. Progress in detector technology has been pivotal, from streamer chambers to TPCs and cutting-edge silicon detectors, which have enabled precise tracking and particle identification. Despite these advancements, many questions about the QGP properties and the QCD phase diagram remain unanswered. Making progress in these areas provides motivation for continued research utilizing both existing and upcoming accelerator facilities and experimental setups. This paper provides a succinct summary of the present state of accelerator and detector facilities, the progress of ongoing projects, and a perspective on future facilities and detector projects in this domain.

### 1 Introduction

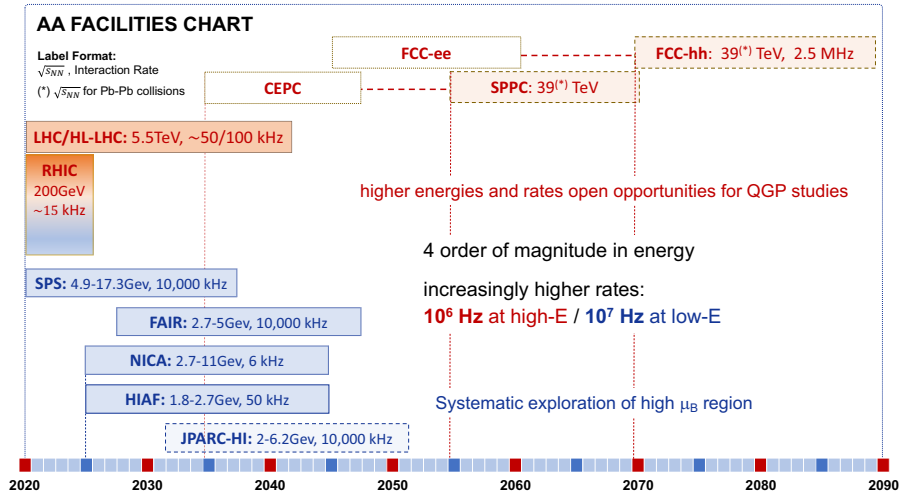
Over the last four decades, the study of nuclear interactions at relativistic energies has significantly deepened our understanding of the properties of matter under extreme conditions of temperature and pressure. The study of collisions between nuclei from a variety of light and heavy elements, conducted at center-of-mass energies spanning three orders of magnitude – from a few GeV per nucleon at the AGS to several TeV at the LHC – and at interaction rates ranging from a few hundred to several tens of thousands per second, led to the first evidence for a deconfined state of quarks and gluons at the SPS and to the observation of its nature as a strongly coupled medium at RHIC. The QGP's properties are meticulously investigated at both RHIC and the LHC, where new phenomena have been observed.

A diverse array of experiments, employing a comprehensive suite of detector technologies, has been deployed to explore this domain. These efforts have ranged from the early use of streamer chambers, such as NA35 at the CERN SPS, to the deployment of large Time Projection Chambers (TPCs) in almost all dedicated heavy-ion experiments, and the implementation of the most advanced silicon detectors for precise decay vertex and trajectory reconstructions. Additionally, sophisticated techniques for the identification of individual hadrons, electrons, muons, and photons have been developed, demonstrating the breadth and depth of the detector technology advancements within this field.

Despite these significant advances, many questions about the quark-gluon plasma (QGP) remain unanswered. Critical issues include precision measurements of the QGP properties, elucidation of how these properties emerge from the dynamics of its constituent particles,

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**Figure 1.** Key accelerator facilities and their operational timelines.

and a deeper understanding of the phase structure of QCD matter. These unresolved questions provide the motivation for continued research in this area, utilizing both existing and upcoming accelerator facilities and experimental setups.

Figure 1 summarizes the key accelerator facilities and their operational timelines. At high energies, RHIC is set to conclude its journey in 2025, while the LHC will continue with the high-luminosity phase (HL-LHC) until 2041. Charting the far future is more challenging, yet groundbreaking facilities are already in the planning stages. CERN is exploring the feasibility of a future hadron collider with proton collisions at a center-of-mass energy of at least 100 TeV, preceded by an electron-positron Higgs and electroweak factory starting in the 2040s with FCC-ee [1], and followed at a later stage, in the 2070s, by FCC-hh [2]. Similar plans are proposed in China with the CEPC [3] followed by the SPPC [4], which could commence earlier. The A–A program at these high-energy facilities aims to further investigate the QGP properties, their dependence on the system size, and their relationship to the dynamics of its internal constituents. Additionally, it seeks to develop a unified understanding of QCD particle production across varying system sizes.

At lower energies, the Beam Energy Scan (BES) at RHIC was completed in 2021, while the heavy-ion program continues at the SPS, extending at least until 2025 with NA61 [5], and potentially beyond with the proposed NA60+ [6]. Additionally, the construction of new facilities like FAIR [7] in Darmstadt, NICA[8] in Dubna, and HIAF [9] in Hichou, which are expected to start operation by the end of this decade, along with Japan’s consideration of JPARC-HI [10], underscores the global effort to explore the high baryon chemical potential region of the QCD phase diagram. These efforts aim to delineate the onset of deconfinement, observe the first-order phase transition directly, and locate the critical endpoint.

Furthermore, the development of electron-ion facilities provide a unique perspective on investigating cold QCD matter. Notably, the EIC [11] in the United States has made significant progress in the approval process and is set to enter operation in 2030. This facility presents a remarkable opportunity towards exploring the QCD landscape over a wide range of resolution ( $Q^2$ ) and densities (Bjorken  $x$ ).

## 2 High Energy Facilities

The RHIC will continue its high-energy program, incorporating the newly installed sPHENIX detector [12] alongside enhancements to the STAR detector [13], until 2025. Concurrently, the LHC and its forthcoming high-luminosity phase (HL-LHC) are expected to extend the heavy-ion programs across all four experiments until 2041 [14]. Significant upgrades are underway for the ATLAS [15] and CMS [16] detectors in preparation for Run 4 (2029 – 2032) and subsequent operations, while entirely new detectors are planned for ALICE [17] and LHCb [18] for Runs 5 and 6 (2035 and beyond). Furthermore, future hadron colliders at CERN and in China are anticipated to include heavy-ion programs [19], achieving center-of-mass energies up to 40 TeV per nucleon, possibly incorporating dedicated heavy-ion detectors.

The sPHENIX detector [12], whose installation was completed in early 2023, is equipped with excellent vertexing capabilities, thanks to a MAPS-based vertex detector, high-performance tracking in a 1.4 T magnetic field with a combination of silicon detectors and a Time Projection Chamber (TPC), and electromagnetic and hadronic calorimeters covering the full azimuthal angle. sPHENIX has adopted free streaming readout systems, as other recent experiments involving nuclear beams (ALICE, CBM, EPIC).

The LHC has entered in Run 3 (2022 – 2025) a new high-luminosity phase for heavy ions, featuring a sixfold increase in luminosity and extensive refurbishments of the ALICE [20] and LHCb [21] detectors. Preparations for Run 4 include further enhancements to both the accelerator and experiments, aiming to a fivefold increase in pp instantaneous luminosity. The ATLAS and CMS experiments are undergoing significant renovations [15, 16] to address the challenges posed by this increased luminosity in LS4 (2026 – 2028), with minor upgrades also planned for ALICE [22, 23] and LHCb. Furthermore, the ALICE and LHCb collaborations have proposed completely new detectors [17, 18] for Runs 5 and 6, which are currently in the planning phase, marking a promising prospect for heavy-ion physics.

As collision rates at particle accelerators rise, the demands on particle detectors become increasingly stringent, requiring innovative solutions and advanced capabilities. The HL-LHC will produce pp collisions at rates of  $8 \times 10^9 \text{ s}^{-1}$ , resulting in a pile-up of up to 200 and particle rates of up to  $3 \text{ GHz/cm}^2$  in the innermost detector layers. These conditions require detectors with higher granularity, spatial and time resolution (4D tracking), and radiation-hard technologies to withstand radiation levels up to  $10^{16} \text{ 1 MeV N}_{\text{eq}}/\text{cm}^{-2}$ . Additionally, reading out and processing the vast amount of data produced necessitates more sophisticated triggers, data readout, and processing systems.

The increase in luminosity prompted significant upgrades to the ATLAS and CMS detectors [15, 16]. These enhancements not only improved their existing rate capabilities but also provided an opportunity to further expand their functionality and performance. Central to the heavy-ion program are the new silicon trackers, which have increased acceptance, and the timing detectors designed for pile-up rejection. These detectors provide Time-Of-Flight (TOF) Particle Identification (PID) capabilities, particularly for CMS with the barrel TOF. Additionally, significant enhancements have been made to the Trigger and Data Acquisition (DAQ) systems. The enhancements to the CMS readout capabilities for minimum bias events are notable, enabling the storage of all Pb-Pb collisions in Run 4, mirroring what ALICE has already achieved in Run 3.

LHCb is proposing a completely new detector [18] for installation in LS4 to record pp collisions at a tenfold higher luminosity, targeting the same performance as in Run 3 but with a pile-up of about 40. Key features include enhanced granularity, fast timing (a few tens of ps), and radiation hardness (up to a few times  $10^{16} \text{ 1 MeV N}_{\text{eq}}/\text{cm}^{-2}$ ). While motivated by

the flavor physics program, this upgrade will also enable LHCb to become a general-purpose heavy-ion experiment at forward rapidity, without limitations on event centrality inspection.

ALICE has been operational since 2022 with a fully refurbished detector [20], significantly improving its readout and vertexing capabilities. For the upcoming heavy-ion run, the new setup is capable of reading out and recording all collisions at peak rates of about 50 kHz. For Run 4, two further upgrades are in progress: the ITS3 [22] and the FoCal [23]. Looking ahead to Runs 5 and 6, a completely novel detector, ALICE 3 [17], is under development. This series of subsequent upgrades will enhance the ALICE rate capabilities by nearly three orders of magnitude and its pointing resolution by a factor of 30 with respect to the original detector installed in 2008.

ALICE 3 is optimized for high-efficiency reconstruction of multi-heavy flavor hadrons and low-mass dileptons. It features vertexing inside the beampipe with an unprecedentedly low material budget, achieving a precision of  $10\ \mu\text{m}$  for 200 MeV particles, and offers large acceptance covering eight rapidity units, particle identification for photons, electrons, muons, and hadrons, capable of reading out AA collisions up to 1 MHz and pp collisions up to 25 MHz.

### 3 High Baryon Density Facilities

Several cutting-edge facilities are being developed to explore the QCD phase diagram with unprecedented precision, offering insights into different regions.

FAIR (Facility for Antiproton and Ion Research), currently under construction, will supply beams of all chemical elements, including antiprotons. Designed for energies up to 11 GeV per nucleon and intensities reaching  $10^9$  particles per second, FAIR features a superconducting ring accelerator with a 1,100-meter circumference, complemented by storage rings and several experimental stations. Utilizing GSI's existing accelerator as an injector, FAIR is structured around four main research pillars: APPA, NUSTAR, PANDA, and CBM, with the latter one specifically focusing on studies of compressed baryonic matter. FAIR's implementation is being phased through a "modularized start version", aiming for a scaled achievement of its scientific objectives by 2028, including the CBM experiment within the First Science+ stage.

CBM [24] (Compressed Baryonic Matter Experiment) aims to conduct high-rate measurements (up to 10 MHz) of hadrons, multi-strange hyperons, charmed particles, and dileptonic decays of vector mesons. It requires fast, radiation-hard detectors, free-streaming readout electronics, and robust computing for real-time event selection. The detector system is equipped with high-precision vertexing using CMOS pixel detectors and silicon-strip sensor tracking within a superconducting dipole magnet, alongside advanced PID capabilities for hadrons and electrons using TOF, RICH, and TRD detectors, and a dedicated muon ID detector.

NA60+ [6] extends the design of its predecessor, NA60, incorporating advanced detector technologies for a beam energy scan between 6.3 to 17.3 GeV. It aims to measure hard processes, including charm production, and electromagnetic probes. The experiment features a high-precision vertex detector employing CMOS sensor technology, the same developed for the ALICE ITS3, and a muon spectrometer with MPGD stations. Following positive feedback on its Letter of Intent, a technical proposal is scheduled for 2024-2025, with construction and installation in 2026-2028, and data collection starting in 2029.

A new high-intensity ion facility [9] is under construction in Hizhou, Guangdong, based on a low-energy, high-intensity synchrotron booster and the CEE detector, focusing on event-by-event fluctuations, correlations, hadron production, and flow.

Lastly, the JPAC-HI [10] project uses the existing 30 GeV proton synchrotron, incorporating a heavy-ion injector and a new hadron experimental facility. This setup will enable a beam energy scan from 2 to 7 GeV at very high rates, allowing for the investigation of multiple probes in high-baryon density regions.

## 4 Electron Ion Collider

The Electron Ion Collider [11] (EIC) represents a significant advancement in nuclear physics research, using the existing infrastructure of the Relativistic Heavy Ion Collider (RHIC) and augmenting it with the addition of an electron storage ring. This enhancement allows for electron energies ranging from 4 to 18 GeV, incorporating cooling mechanisms within the existing RHIC tunnel and an electron injector. The EIC is designed to perform collisions across a wide center-of-mass energy (CME) range from 29 GeV to 140 GeV, with highly polarized electron and proton beams, along with a variety of ion species. This setup will feed into two detectors, aiming to start the science phase in 2035.

The EPIC detector, selected in 2022 as the reference design for one of the EIC's primary detectors, features a large rapidity coverage and employs a new 1.7 T magnet for high-precision tracking, utilizing CMOS pixel sensors, the same ones developed for the ALICE ITS3, and Micro-Pattern Gas Detectors (MPGD) for its tracking systems. For PID at the track level, EPIC incorporates a suite of detectors including Time-of-Flight (TOF), pFRICH, dual-RICH, and high-performance Detection of Internally Reflected Cherenkov light (DIRC) across different pseudorapidity regions. The detector's design also includes finely segmented electromagnetic and hadronic calorimetry on the hadron-going side and an imaging calorimeter equipped with Monolithic Active Pixel Sensors (MAPS) in the barrel region, ensuring robust measurement capabilities across the full spectrum of anticipated experimental conditions.

## 5 Novel technology

The advancement of detector technologies for relativistic nuclear collisions constitutes a dynamic area of research. These technologies incorporate a broad spectrum of particle detection methods, primarily to fulfill the demands of particle identification. This process necessitates highly accurate timing for time-of-flight measurements and efficient, high-granularity photon detectors for RICH applications. The field has seen numerous innovative contributions. Due to space limitations, this article highlights just one pivotal advancement: the development of Monolithic Active Pixel Sensors (MAPS), which marked a significant milestone in particle physics instrumentation. In the preceding discussion, we have highlighted a number of experiments that incorporate vertex detectors equipped with MAPS, specifically CMOS Active Pixel Sensors. This technology first came to prominence in the domain of heavy-ion physics, with the first deployment of a CMOS-based vertex detector in the STAR experiment in 2014 [25]. The subsequent development efforts, particularly by the ALICE collaboration with ALPIDE [26] for its Inner Tracking System upgrade (ITS2), have advanced this technology to a degree of sophistication where CMOS sensors are now becoming foundational components in the construction of vertex detectors for all forthcoming experiments.

A further refinement of the technology process was implemented aiming to create fully depleted sensors [27]. These sensors rely exclusively on drift for charge collection, occurring within tens of picoseconds, thereby increasing their radiation tolerance and permitting operation at room temperature after exposure to radiation doses up to  $10^{15}$  n/cm<sup>2</sup> [28].

The fabrication of cylindrical sensors that can be situated as close to the interaction point as the beam aperture allows is being pioneered by the ALICE ITS3 [22]. These sensors can

be produced with a minimal thickness of roughly  $40\ \mu\text{m}$  and shaped around the beam pipe, thereby creating an ideal detector with a cylindrical geometry that includes only the sensitive silicon within the acceptance. Moreover, the envisioned design for the ALICE 3 [17] vertex detector allows for the positioning of the first detection layer at an unprecedented proximity of just 5 mm from the beamline, inside the vacuum chamber.

## 6 Conclusions

This paper has highlighted significant progress in the study of the QGP and the broader field of QCD, enabled by advances in accelerator and detector technologies. The forthcoming era is characterized by the HL-LHC program at high energies and the introduction of new high-intensity facilities like FAIR, NICA, HIAF, and JPARC–HI, along with the continuation of the SPS program at lower energies. Coupled with the evolution of increasingly sophisticated, fast, and precise detector technologies, these advances signal a promising future for nuclear physics. Looking ahead, the potential to extend studies to higher energies with projects like the FCC and SPPC, and the unique perspectives on cold QCD matter offered by electron–ion facilities, underscore the field’s vibrant and long-term prospects.

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