Analysis of the State-of-art Proposals for Advanced Accelerator

Mu Qin*

Department of Physics, University College of London, London, the United Kingdom

*Corresponding author: zcapmqi@ucl.ac.uk

Abstract. As a matter of fact, accelerators are a common facility for particle physics research contemporarily. This study provides a comprehensive overview of the latest advancements and experimental proposals in the field of particle accelerators. Particle accelerators have been instrumental in major breakthroughs in modern physics, such as the discovery of the Higgs boson, and are continually evolving to address unsolved questions in fundamental physics, including dark matter and beyond the Standard Model phenomena. The review focuses on cutting-edge technologies such as the Future Circular Collider (FCC) and advancements in high-intensity radiation sources, like X-ray free-electron lasers. Despite the impressive contributions of current facilities, significant challenges remain regarding their size, cost, and energy requirements. Addressing these limitations, emerging innovations such as plasma wakefield accelerators and spin-polarized beams show promise in making future accelerators more compact, cost-effective, and accessible. The paper aims to bridge current technological progress with the future potential of particle accelerators, offering insights into how they might continue to advance the understanding of the universe while overcoming their inherent challenges.

Keywords: Particle accelerators; Higgs Boson; dark matter; high-Intensity light sources.

1. Introduction

Particle accelerator have driven some of the most profound discoveries in modern physics, helping physicist understand the fundamental particles and forces. Since the first linear accelerators in the 1930s, accelerator has progressed from single purpose machines to massive, multi-functional facilities that enable highenergy experiments at unprecedented scales [1]. The prime role of these machines has expanded from particle collision experiment to applications in medical physics, materials science and nuclear research, demonstrating the utility of accelerators and what accelerator technology can achieve in terms of energy and precision [2].

Over the last few decades, research in particle accelerators has accelerated, with significant breakthroughs in high energy(HE) physics. Projects such as Large Hadron Collider (LHC) have enable the discovery of the Higgs boson, affirming the Standard Model and opening new avenues for research into dark matter and unexplained phenomena [3]. More recently, proposals like the Future Circular Collider(FCC) aiming to look deeper into particle interaction with unprecedented precision and energy. These essential advancement addresses lingering question in physics, especially for scientists exploring the ’dark sector’ and other aspect of physics beyond the Standard Model [4]. The recent developments in high-intensity radiation sources, in both X-ray and EUV free-electron lasers, has also increased the applications of accelerators creating new opportunities for materials science and medical imaging [5].

The main point for this study is to examine these state of the art advancements and experimental proposals that might help the future of particle accelerators. However, Despite the groundbreaking contributions, current accelerators still face limitations, such as its size, cost, and power consumptions that will limit their scalability and accessibility [6]. Addressing these challenges requires a new framework for accelerator research such that the it can balances technological innovation with economic feasibility, ensuring that future machines can be cheaper and more powerful.

In the first section this paper will provides a brief overview of the accelerator’s components and principles, detailing the global facilities of accelerator. Followed by examinations of some of the most advanced experimental proposals in the filed, focusing on applications for the higgs bosons, dark matter, and high intensity light sources. Then recent results from high-energy experiments are analyzed and expore how they contribute to the understanding of fundamental physics. Finally, the limitations inherent to current accelerator and provide an outlook on possible advancements for a miniaturized, cost effective models.

2. Descriptions of Accelerators

Particle accelerators are as the name implied are designed to accelerate charged particles to a high velocity, allowing scientist to explore the fundament properties of matters. The basic structure of particle accelerator generally comprises two main components: an electron/ion gun and an acceleration module. With the electron or the ion gun being the source, generating charged particles by applying a high electric field to a conductive material, which liberates electrons or ions for acceleration. These particles are then injected to the acceleration module, where they are successive stages of electromagnetic fields. Fig. 1 gives a basic diagram of a particle accelerators The most common accelerator is linear or circular [7].

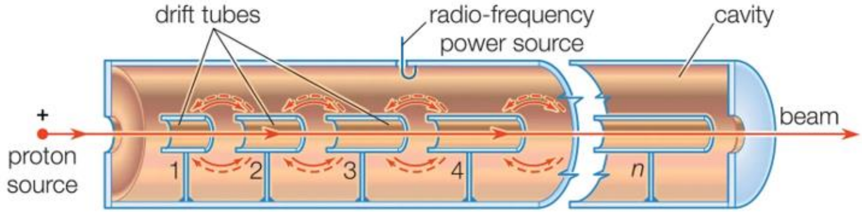

Fig. 1 Schematic of a basic particle accelerator setup [7].

Linear Accelerator employ a straight path for particle accelerations, enabling it to achieve high energy without synchrotron radiation losses. The circular accelerator such as synchrotrons and cyclotrons, will lead the particle in a circular path, allowing for multiple passes through the same accelerating fields and thus reaching high energy level. However, circular accelerator due tend to lead to synchrotrons radiation losses at high energy, thus limiting their efficiency [8]. Across the globe, a wide array of there is a wide array of particle accelerator at use. The Large Hadron Collider (LHC) at CERN for instance enabled the discovery of Higgs boson, a breakthrough that confirmed essential elements of the standard model of particle physics [9]. Another significant facility, in the United state renowned for its work in X-ray free electron laser, and the Japan Proton Accelerator Research Complex (J-PARC), which supports both particle and nuclear physics research [10].

3. Advance Proposal for Accelerators

In recent years, advancement in particle accelerator had led to proposals for new experimental setups and designs that push the boundary of high energy physics. These proposals are aimed at exploring the fundamental particles and forces, investigating dark matter, and improving high-intensity radiation sources for a variety of applications. As mentioned above, the LHC discovered the Higgs boson, for which researchers are looking to explore more of the properties of this particle. The Future Circular Collider (FCC) proposed by CERN, aim to achieve higher collision energies than the LHC thus leading to a more precise measurement of Higgs boson properties. The FCC designs inculdes a collider ring with a circumference of 100 km, far surpassing the 27 km circumference of the LHC [11]. Fig. 2 shows a schematic of the FCC [12].

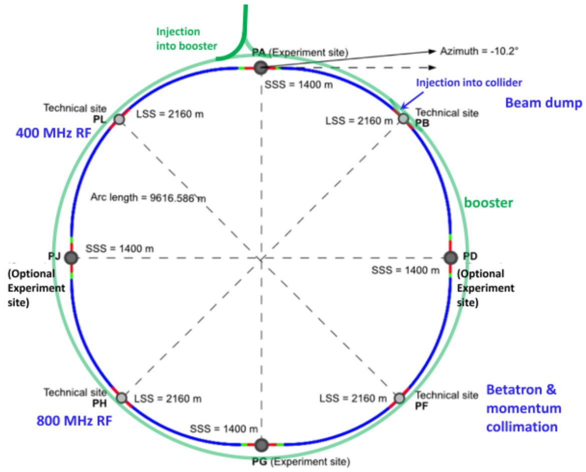

Fig. 2 Proposed experimental setup for studying Higgs boson interactions at the Future Circular Collider [12].

One of the major unsolved questions in modern physics is the nature of dark matter, which is a form of matter that does not emit, absorb, or reflect light thus detectable only through gravitational effects. Proposed experiments aim to use high-energy accelerators to probe the "dark sector," potentially revealing new particles or forces that could account for dark matter.

The NA64 experiment at CERN utilizes high-engry electron and muon beams to search for dark sector particles, such as dark photons.Additionally, the LUXZEPLIN (LZ) experiment, which uses a dual-phase xenon time projection chamber, has been instrumental in the search for weakly interacting massive particles (WIMPs)The International Linear Collider(ILC) and Compact Linear Collider (CLIC) are also being considered for dark matter searches, with designs that allow for high precision in particle collision measurement [4, 13]. Fig. 3 shows a Schematic of a dark matter detection [13].

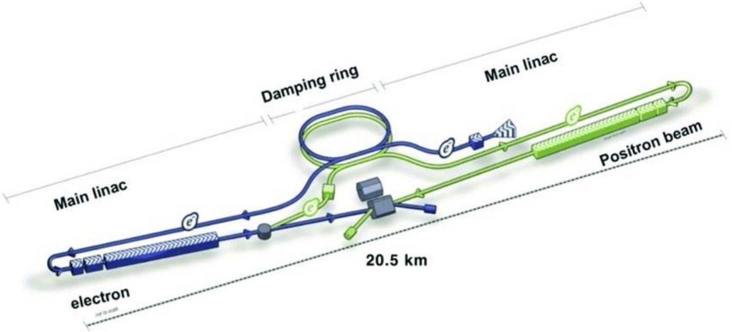

Fig. 3 Schematic of a dark matter detection experiment in the ILC [13].

X-ray and extreme Ultraviolet (EUV) free electron lasers (FEL), are accelerators driven light source that have becomes indispensable tools in fields like materials science and medical imaging. Recent advancement in FEL technology have focued on increasing the brightness and coherence of the emitted radiations. The SLAC National Accelerator Laboratory, for instance, has made substantial progress in deveoping advanced EUV and X-ray FELS, which are expected to produce more intents beams that can be use for ultrafast imaging and spectroscope [14].

4. State-of-art Results

Recent experiment at the Large Hadron Collider (LHC) have refined measurement of the Higgs boson 's mass, decay channels and interactions with other particles. A significant focus in Hisggs boson has been understanding the shape of the Higgs potential V (ϕ) and its sensitivy to quantum corrections. The potential for the scalar field ϕ with a mass parameter μ2 < 0, where symmetry breaking occurs along any point at the bottom of the potential. When quantum correction is applied, they can alter the Higgs potential. In the Standard Model, the vacuum state lies at ϕ = |v| with v = 246GeV. However the quantum corrections to the model's coupling can create a secondary minimum suggesting vacuum metastability. Which raises the question about whether the current vacuum is absolutely stable. Fig. 4 displayed the relationship and the quantum corrections [15].

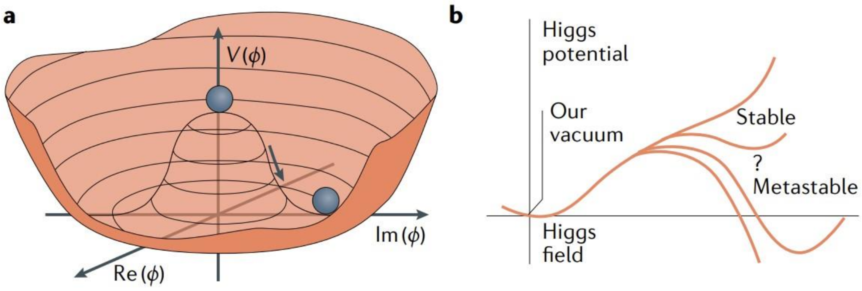

Fig. 4 (a) The Higgs potential V (ϕ) with μ2 < 0; (b) Quantum corrections lead to a secondary minimum [15].

One of the key goals of high-energy accelerators is to detect particles that could constitute dark matter. In a recent study, NA64 employed a high-energy muon beam to look for a new particles interacting primarily with muons. While it did not detect any new particle, it did establish a limit on the existence of dark photon and other dark matter candidates [16]. For the LZ experiment, in its initial run no significant excess over the expected background, however it did place one of the most sensitive constraints to date on WIMP-nucleon spin-independent interactions [17]. Result that was obtain is shown in Fig. 5 [18].

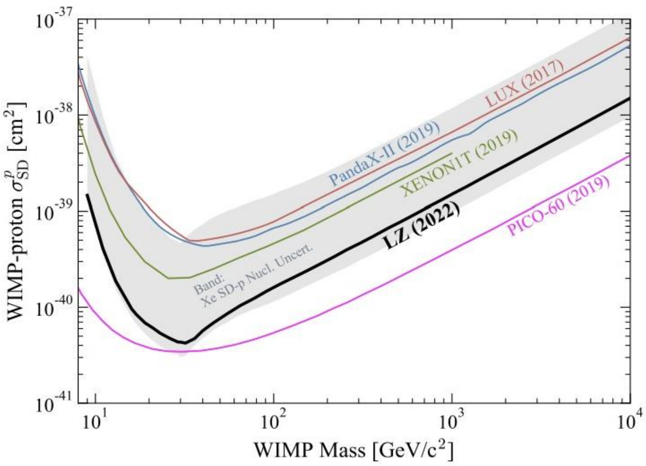

Fig. 5 The 90% confidence limits (black line) on the spin-dependent WIMPproton cross section versus WIMP mass, including uncertainty bands (gray) due to xenon nuclear correction factors [18].

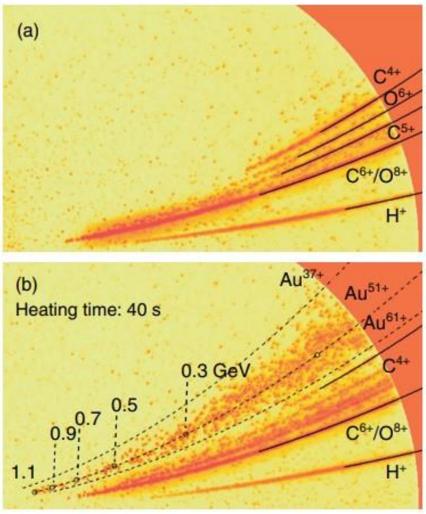

Fig. 6 Raw data measured By the TPS [20].

Researchers at the Linac Coherent Light source (LCLC) achieved a substantial increase in FEL power, exceeding 300 % of previous limits, while reducing photon pulse length to 10 femtosecond (1 femtosecond = 1 quadrillionth of a second). These ultrashort, high-intensity X-ray pulses allow scientists to observe rapid atomic and molecular processes [19]. Laser-driven acceleration has reached a new level as it is possible to accelerate super-heavy ions, such as gold to energies up to 1.2 GEV by using ultra thin targets and extremely high intensity. These heavy ions has been ionized to remove many electrons, carry immense energy. For which the ions were detected by a Thomson parabola spectrometer (TPS) as given in Fig. 6 [20].

5. Limitations and Prospects

One of the most challenges about accelerators is their sheer size. High-energy accelerators like the Large Hardon Collider require a extensive infrastructure, with large circular tunnels stretching over kilometers to achieve energy needed for particle collision. The size are not only difficult to build, it also pose a challenge to where it can be build geographically, as it requires a land that is larger and stable enough to construct.Time is also a factor that needed to be consider, as constructing and operating these accelerators involves coordination and a long timeline spanning decades at a time.This will lead to a fewer number of facilities worldwide, resulting in a concentrated reliance on only a few limited accelerators [21].

The other limitation is the expensive maintains of the building and operating these large scale accelerators. The main expense is the construction, tunnels,cooling systems and power facilities are costly to build. The power consumption require to maintain a high-energy particle accelerator is also not cheap as it require continuous power to generate the intense magnetic and electric fields necessary to accelerate particles. For example, the Future Circular Collider(FCC) and the Compact Linear Collider (CLIC) are estimated to cost several billion dollars [22].

To address these limitations, scientist has explored new technologies that could lead to a more compact and cost-effective accelerators. One of the more promising development is the plasma Wakefield accelerators, which generate high energies over shorter distances by harnessing electric fields in plasma. Therefore making it more feasible for construction and operation in various location[23]. Another development is on the spin-polarized accelerators, it utilize polarized particle beams to enhance collision efficiency and sensitivity in experiments. Aligning the spins of particle within the beam, the spin-polarized accelerator can achieve a higher interaction rate, thus improving the effectiveness of experiment and potentially reduce the size of the facility of the accelerator due to a fewer particle require to achieve the same outcome [23].

6. Conclusion

In conclusion, particle accelerators have significantly advance the understanding of fundamental particles, but current limitations such as size,cost and energy consumption must be addressed for future progress. Recent proposals and experiments focusing on the bosons and exploring the dark sector displayed great potential for providing a deeper insight into fundamental physic. High-intensity light source and advanced technologies improving the equipment for medical imaging and materials science expanding their practical applications. To overcome the limitation of high cost and large size, innovations such as plasma wakefield accelerators and spin-polarized beams offers solutions to a more compact and efficient design. To make the future accelerators more partial and efficient, researches need to balance the technological improvements with cost considerations. By optimizing design on cost-effective solutions, it could be more accessible to a broader range of research institutions.

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