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Analysis of the Principle and State-of-art Facilities for Collider

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Abstract:

As a matter of fact, the particle accelerator plays an extremely important role in physics and other fields, and makes a contribution that cannot be ignored in promoting the progress of human science in recent years. With this in mind, this study focuses on the current situation and principle of particle accelerator. To be specific, some advanced facilities such as large Hadron Collider, Shanghai Light Source and Relativistic heavy Ion Collider are introduced in detail, which have achieved fruitful research results based on the state-of-art facilities. This study introduces the current challenges faced by the Collider and the broad prospects for its future development. At the same time, this research also provides a basis for the construction and improvement of advanced facilities and contributes to the progress of science and technology according to the analysis. Overall, these results shed light on guiding further exploration of colliders and offer a guideline for particle physics.

Keywords: Particle accelerators; collider; light source.

1. Introduction

Accelerators have played a crucial role in humanity's exploration of matter and the microscopic world. Its history can be traced back to the end of the 19th century when people began to explore charged particles in the microscopic world and study their properties and interactions. At that time, accelerators were only used as experimental tools for researching particle physics. However, since 1990, as a device with diverse uses, its role has become increasingly significant [1]. With the passage of time, the technology of accelerators has continued to evolve, and multiple types of accelerators have been invented and utilized. Different accelerators have different performances and technological principles. They compete while also complementing each other, constantly being improved and corrected. The combination and connection of different types of accelerators constitute many large-scale accelerator instruments in the world [2].

In the past 20 years, the construction and operation of accelerators have achieved remarkable achievements worldwide. The construction of the world-renowned Large Hadron Collider (LHC) enables scientists to better study particle control experiments at high energies and also promotes the research on the Higgs boson. In China, in addition to the construction of facilities such as the Super Collider CEPC, China has also made leapfrog progress in theory and is at the forefront internationally [3]. These achievements not only promote the research and development of physics theories but also contribute to the understanding of the essence of things. In the past half-century, collider technology has continued to develop and has made significant progress in multiple aspects.

In terms of energy enhancement, new acceleration technologies and design concepts continue to emerge. Scientists are pursuing higher-energy collisions. For example, more advanced laser focusing technologies and superconducting technologies are adopted. Stronger laser focusing intensity can endow particles with higher energy, enabling them to reach a higher energy state during collisions, which helps people study and understand physical phenomena at high energies. Around 1990, the Chirped Pulse Amplification (CPA) technology was invented, increasing the laser intensity for accelerating particles from 10^{13} W/cm^2 to 10^{22} W/cm^2. At the same time, the theory of excitation acceleration has also been enriched. Many new acceleration methods have been created by people [4]. This can effectively improve the efficiency and energy limit of particle acceleration.

There have also been many unprecedented innovative designs in the design of accelerators. For example, during the exploration of the Higgs boson, Chinese scientists conceived of the Circular Electron-Positron Collider (CEPC) in September 2019 to facilitate further research on the Higgs boson. The blueprint of this scheme was completed in November 2017 and is currently in the planning and construction stage [5]. At the same time, there are many collider projects under construction and design internationally, such as the Electron-Ion Collider (EIC) in the United States, which the US Department of Energy has chosen to build at Brookhaven National Laboratory. The expected cost is between 1.6 and 2.6 billion US dollars and is expected to be completed within the next decade. Once completed, it will conduct in-depth research on the strong interaction force that binds quarks together. There is also the Future Circular Collider (FCC) in Europe, which Europe plans to build an approximately 91-kilometer circular tunnel underground at the border between France and Switzerland. Its goals include studying the Higgs boson in more detail and exploring new physical phenomena beyond the Standard Model. These designs continue to improve and innovate in technology, laying the foundation and paving the way for humanity‘s exploration of particle physics.

With the rapid development of science, physics is also constantly progressing. As an advanced instrument always at the research frontier, software helps people reveal, verify, and develop microscopic physics, further study the current situation and principles of collisions to find their shortcomings and make improvements. It is of great significance for the progress of physics. This article aims to expound on the current situation of accelerators and understand their principles, and provide research basis for the development of new equipment in the future through the study of different accelerators. This study will briefly introduce the definition, classification, and current situation of colliders in Sec. 2. In Sec. 3, the principle of colliders will be introduced. Sec. 4 will explore some of the most cutting-edge colliders existing internationally and briefly describe the current limitations of this technology and possible future development trends at the end of the article.

2. Descriptions

The Collider is a large device that accelerates particles and collides with each other. The phenomena and products of particle collision are observed and detected. People can understand the basic structural properties and interactions of particles. Take the large Hadron Collider LHC as an example, which uses ultra-high energy hadrons (e.g., protons and protons) to collide, and scientists also discover the parity non-conservation of some particles of the Higgs boson. There are many kinds of colliders, which can be classified in 10 ways. For example, from the point of view of the types of accelerated particles, there are electron accelerators, light ion accelerators, heavy ion accelerators and particle cluster accelerators; if they are divided according to the ideal motion orbit shape of the central particles, there are linear accelerators and non-circular accelerators; they can also be distinguished according to the types of accelerating electric fields, such as high voltage electrostatic field accelerators, time-varying electromagnetic field accelerators and so on. Hence the difficulty of classifying accelerators clearly is large [6].

There are many colliders around the world. LHC is currently the world‘s largest and highest-energy particle accelerator, which is located in a 27-kilometer-long tunnel near Geneva, while Japan‘s International Linear Collider (ILC) is considered to be a supplement to LHC. China‘s Beijing Electron Positron Collider BEPC is the only high-energy particle collider in the world that can operate at 2 billion to 5 billion electron volts. In addition, many colliders are in the preparatory construction stage or closed. These also promote the development of particle physics.

3. Principle

Taking the more common linear accelerator as an example, its structure mainly includes acceleration structure data stream transmission system and collision zone. The acceleration structure uses a superconducting cavity in

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which the electric field is at a low temperature. Through the superconducting radio frequency acceleration technology, the charged particles are accelerated to close to the speed of light, the principle of acceleration follows Newton's second law and the law of conservation of energy in classical electrodynamics. The energy obtained by particles is related to the intensity of accelerating electric field E and acceleration distance L, and the specific formula is W = qEL, where W is the energy obtained by particles and Q is the charge of particles. They can accurately move along the orbit and collide in the collision zone, which usually depends on the motion of the particles constrained by the magnet system. In the process of collision, according to the law of conservation of energy and momentum in relativity, the total energy and momentum of the two particles remain unchanged before and after the collision. The energy produced by the collision can be calculated by the formula $E=\sqrt{2E1E2\left(1-cos\theta\right)}$, where E is the Center-of-mass energy, E1 and E2 are the energies of two beams of particles, and θ is the angle between the two beams of particles. During the high-speed impact of particles, huge amounts of energy can be converted into the mass of particles and other new particles are generated, and the data of these particles will be recorded and studied [7].

4. State-of-art facilities

There are many top accelerators in the world. Among them, as shown in Fig.1, the Shanghai Synchrotron Radiation Facility, as one of the world's leading third-generation synchrotron radiation sources, has made significant contributions to scientific research and industrial R&D in China. The Shanghai facility was completed on December 24, 2007. It consists of a linear accelerator for generating and accelerating electron beams, a synchrotron used as a booster and a storage ring, and two beam transport lines [7]. The energy of the storage buffer can reach 3.5GeV, which is the highest in the medium energy region. After optimization, its performance is in the most widely used X-ray energy region. With the new breakthrough of insert technology in recent years, it can not only produce synchrotron radiation when the photon energy is at 1-5keV, and the brightness of this kind of light is the highest, but also produce high-brightness hard X-ray in the spectral range of 5-20keV. The performance of this kind of light is close to that produced by 6-8GeV high-energy light source [8].

Fig. 1 A view of Shanghai Synchrotron Radiation Facility [7].

The beamline project of Shanghai Synchrotron Radiation Facility also has many highlights. In July 2023, the beamline project of Shanghai Synchrotron Radiation Facility was completed, and 16 new beamlines and experimental stations with wide application and advanced technology were built, Fig 2 shows the layout of Line Station of Shanghai Synchrotron Radiation Facility. Among them, the fast X-ray imaging station successfully achieved 60ps resolution X-ray single-pulse imaging on the medium-energy synchrotron radiation facility. The time required for X-ray imaging was greatly reduced, and this technology is leading internationally. The 3D nano-imaging vertical line can be used to image the internal structure at the nanoscale, and the TXM station achieved a spatial resolution of 20nm for the first time using the bending magnet source [9].

The Shanghai Synchrotron Radiation Facility has been operating stably for more than 10 years. It uses electrons accelerated to near the speed of light in the accelerator. When they do circular motion in the storage ring, they emit radiation light along the tangent. Through advanced means, the emitted light can range from infrared to hard X-rays, covering extremely wide research fields. It has also strongly promoted the development of related fields and achieved influential research results, such as the discovery of new quantum materials and the analysis of biomolecular structures.

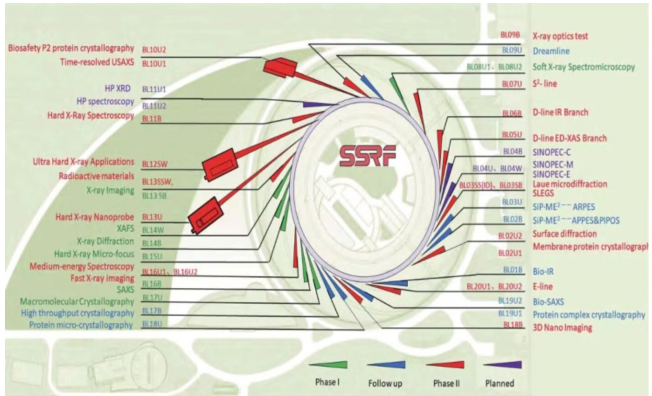

Fig. 2 The layout of Line Station of Shanghai Synchrotron Radiation Facility [7].

The total length of the LHC is about 27 kilometers, with 9593 superconducting magnets inside. As the world's largest particle, the accelerator was built in 1998 and officially put into operation in 2008. The principle is to ionize hydrogen gas to obtain protons, and use an electric field to move the protons in a vacuum pipeline. After being accelerated by a series of measures such as a synchrotron, the protons enter a circular orbit. When passing through an injector, the number of protons collides at the intersection of the pipeline. Fig. 3 shows the powering layout of the eight arc cryostats. At full power operation, there are trillions of protons per second, which is greater than 99% of the speed of light and travels around the accelerator ring tens of thousands of times [10]. Scientists can simulate the early state of the universe by colliding particles at ultra-high energies. Studying the properties of matter and energy, this collider also provides technical support in the exploration of dark matter and dark energy. Neutrinos produced by LHC were first detected in CERN in 2023. They are the highest energy neutrinos ever produced in the laboratory, similar to the neutrinos found when deep space particles cause violent particle showers in the earth's atmosphere, helping to reveal the mysteries of the deep space of the universe.

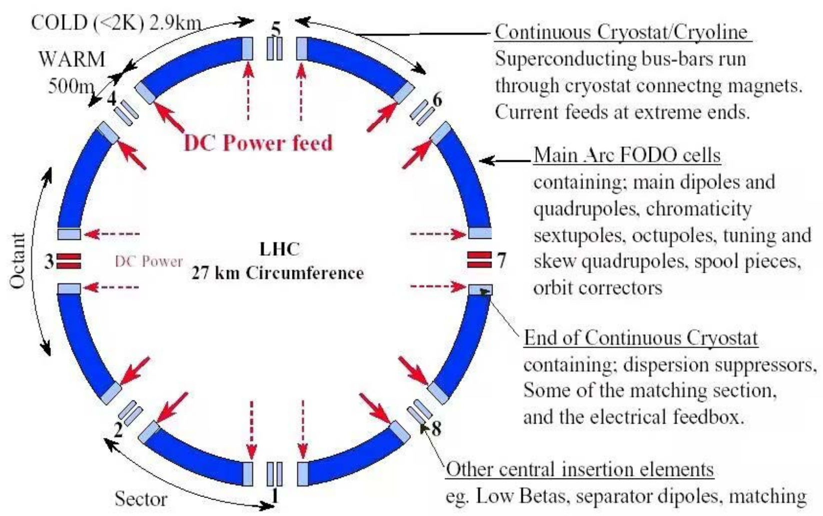

Fig. 3 Powering of the eight arc cryostats [10].

The relativistic heavy ion collider (RHIC) located in New York, USA, is the only collider in the world capable of heavy ion pairing. RHIC was operated in 2000 and its accelerator consists of two independent rings, responsible for clockwise and counterclockwise beam flow respectively. The six positions on the circumference of these two rings intersect with each other, and each ring consists of six lakes approximately 356 meters long and six insertion segments approximately 277 meters long with collision points. This collider can circulate ions in opposite directions and freely select ions for collision [11]. It can achieve a high energy of 100 GeV per nucleus for hydrogen ion flow, creating a high-temperature and high-density environment similar to the early Big Bang. In 2010, according to published measurement results, the collision temperature of gold ions had exceeded 345 MeV, forming liquid like elementary particles. Fig. 4 illustrates the acceleration system for RHIC. In 2024, researchers

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from the Institute of Modern Physics of the Chinese Academy of Sciences used RHIC to observe a new antimatter hypernucleus-anti-hyperhydrogen-4, which is the heaviest antimatter hypernucleus ever found in experiments, and verified the symmetry of positive and antimatter properties [12].

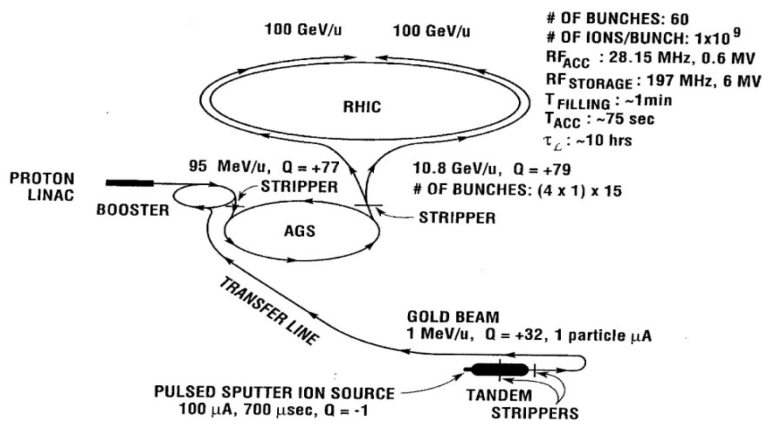

Fig. 4 The diagram of RHIC acceleration for Au beams [12]

5. Limitations and Prospects

However, at present, the research of Collider still faces many challenges. In terms of capital, the cost of construction and maintenance of the Collider is extremely high. Take the large Hadron Collider in Europe as an example, its construction cost is as high as 1 billion US dollars, and the annual operation and maintenance costs cannot be ignored. Therefore, the funding limits the wide application of the collider and the construction of the existing collider in terms of energy. the energy of the existing collider is still insufficient to provide an environment for some functional phenomena, for example, in the study of the grand unified theory, the energy of the collider is not enough to verify some of the theories, resulting in many problems in the theory that have not been solved.

In addition, the detection accuracy of the detector also makes some experiments impossible to be carried out successfully. As a variety of different experiments need to be completed by the collider. There are higher requirements for the accuracy of detectors. Today‘s detectors sometimes find it difficult to accurately detect cases where the signal is weak or the existence time is very short in a large number of examples. For example, the Higgs boson is not discovered by direct detection, but is confirmed by the calculation of its decay products and other particles. It can be seen that if the accuracy of the detector can be improved, many experiments and theories will be directly confirmed.

Although the Collider faces many challenges and problems, it still has broad prospects and development opportunities. The construction of many new types of colliders has been put on the agenda, such as China‘s CEPC. The construction of these new machines is expected to help human beings discover new examples and phenomena, further fill the gaps in the scientific community and improve theories, and the collider experiments are not limited to physics, but also provide technical support for materials, astronomy, chemistry and other fields. The more and more advanced Collider technology will also lead to progress in many fields and accelerate the development of human science and technology.

6. Conclusion

To sum up, this study analyzes the principles, uses and advanced equipment of the Collider. The Collider is based on accelerating particles and causing them to collide to explore the basic principles of the properties of microscopic things. The important position of particle collider in today‘s scientific community and the advanced technology and achievements of some advanced facilities in particle acceleration and detection are described in detail. Looking at the past, it is clear that the Collider still has some shortcomings and limitations in some aspects, and is now facing challenges. Looking forward to the future, it is expected that the Collider will continue to innovate in technology and be able to build more advanced facilities to further explore deeper phenomena and theories. This study is of great significance, which not only deepens the understanding of the collider, but also provides an important reference for researchers to further improve the technology and carry out new research experiments.

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