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Editorial

Advances in Particle Acceleration: Novel Techniques, Instruments and Applications

Sergey V. Kutsaev

RadiaBeam Technologies, LLC, 1735 Stewart st., Santa Monica, CA 90404, USA; kutsaev@radiabeam.com

1. Introduction

In the last decade, there have been significant advancements in accelerator technologies, driven by both fundamental research and practical applications in various fields, including X-ray science, medical treatments, and industrial processes [1]. This progress owes much to the emergence of new technologies for accelerators [2], such as new materials, including superconductors, fabrication techniques, novel acceleration methods as well as measurement and simulation tools [3]. Moreover, new technologies enable novel applications of particle accelerators that were not possible before.

One of the brightest examples of the emerging accelerator technologies are the novel radiotherapy methods that have advanced over the past decade, significantly improving the precision, effectiveness, and safety of cancer treatments [4]. These innovations focus on minimizing damage to healthy tissues while delivering high doses of radiation to tumors. For example, FLASH radiotherapy is a technique that delivers a radiation dose so quickly that it spares healthy tissues while effectively damaging cancerous cells. Early studies have shown that FLASH therapy can reduce side effects and improve the therapeutic ratio [5]. However, the clinical application of FLASH therapy requires the development of accelerators with unprecedented parameters, while maintaining their commercial viability [6]. The challenges of building such accelerators include low penetration depth of electron beams and poor electron-to-photon conversion efficiency for X-ray machines.

The other direction of accelerator-based radiotherapy development is the use of hadron accelerators instead of electrons or X-rays to treat cancer [7]. The key advantage is the ability to precisely control the proton beam's energy, allowing it to stop at a specific depth in the tissue (known as the Bragg peak), minimizing damage to surrounding healthy tissues. However, hadron therapy availability is currently limited due to the complexity and cost of the accelerators and other equipment.

Boron Neutron Capture Therapy (BNCT) is another technique that requires hadron accelerators [8]. During BNCT, patients are first injected with a boron-containing compound that selectively accumulates in cancer cells. The tumor is then exposed to low-energy neutrons, which interact with the boron to produce high-energy alpha particles that destroy the cancer cells. Accelerator-based neutron sources have become a critical component of modern BNCT due to their advantages over traditional reactor-based neutron sources. Research and development in accelerator technologies for BNCT are ongoing, with several facilities worldwide working on improving the efficiency, cost-effectiveness, and clinical outcomes of these systems.

The principle of BNCT resembles the principle of radioisotope therapy, also known as radionuclide therapy or targeted radionuclide therapy that involves the use of radioactive substances to treat various types of cancer and other medical conditions. This therapy relies on the ability of radioisotopes to deliver targeted radiation to diseased tissues, minimizing damage to the surrounding healthy tissues. Recent advancements in radioisotope therapy includes the development of theranostic isotopes used in a combined approach to both diagnose and treat diseases, particularly cancers [9]. In this approach, the same or similar

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isotopes are used for both imaging (diagnostic) and treatment (therapeutic) purposes. This allows for a more personalized and precise treatment strategy, as diagnostic imaging helps to identify the location and extent of the disease, while the therapeutic component targets and treats the affected areas. Advances in radioisotope therapy are enabled due to innovations in accelerator (particularly, cyclotron) technology that have improved the production and availability of medical isotopes, reducing dependence on older reactors and increasing access to newer isotopes like Ac-225, Tc-99 m, and others [10].

Another emerging area of accelerator development is a pursuit for a compact light source, which represents a significant advancement in making high-intensity, high-brightness radiation sources more accessible for a broad range of scientific and industrial applications. The most important of which is the investigation of the material properties at the atomic and molecular levels, including studies of crystal structures, phase transitions, and defects [11]. For example, the semiconductor industry requires advanced light sources for processes like photolithography, inspection, and metrology. Such light sources must be designed to be smaller and more efficient than traditional large-scale systems. Recently, among others, significant progress was made in the development of compact Free Electron Lasers (FEL) and Inverse Compton Sources (ICS) for industrial material science applications [12,13].

The advances of these and other emerging accelerator-based applications were achieved thanks to the development of novel accelerator technologies that enabled enhanced miniaturization, power capacity, reliability, sustainability and cost-efficiency of modern applied accelerators. One of the key directions in technology research is the increase in the accelerating gradient of the accelerators [14]. High-gradient acceleration allows for shorter accelerators, which can achieve the same energy as longer, lower-gradient systems.

Achieving high gradients is being approached in several different directions. For example, traditional RF cavities, which use radiofrequency (RF) electromagnetic fields to accelerate particles, have seen significant improvements in gradient capabilities. These include the advances in material science and cavity design have allowed copper RF cavities to achieve gradients of up to 120 MV/m in X-band systems [15] and >200 MV/m in mm-wave systems [16], with innovations in surface treatments and cooling to manage power loss and prevent breakdown.

Another promising method for enhancing accelerating gradients involves operating accelerator structures at cryogenic temperatures (below 77 K). At these low temperatures, copper exhibits increased durability and a lower coefficient of thermal expansion, which helps reduce mechanical stresses and deformations caused by pulsed heating from RF fields. Recent research indicates that 250 MV/m gradients can be achieved in X-band structures when cooled to temperatures below 45 K [17].

Superconducting RF (SRF) cavities use superconducting materials to generate high accelerating fields with low power dissipation, making them ideal for continuous-wave (CW) operation and high-power accelerators [18]. Advances in cavity design and surface treatments have led to SRF cavities with higher quality factors, allowing for higher gradients with reduced cryogenic cooling requirements. Techniques like nitrogen doping of niobium cavities have significantly improved the performance of SRF cavities, enabling gradients of 35–50 MV/m. Importantly, the use of novel superconducting materials such as Niobium-tin (Nb_3Sn) is a crucial development for SRF accelerators due to its ability to operate at higher temperatures with the same RF losses compared to bulk niobium cavities [19].

Finally, the development of novel acceleration techniques such as plasma wakefield acceleration (PWFA) is a promising and rapidly developing direction in high gradient accelerators. This method involves using a beam of charged particles or a laser to create a wake in plasma, which can then accelerate subsequent particles to very high energies over short distances. Gradients in the range of tens to hundreds of GV/m have been achieved, far exceeding the capabilities of traditional radiofrequency (RF) accelerators [20]. PWFA has the potential to significantly reduce the size and cost of future linear colliders for particle physics and compact accelerators for medical and industrial applications.

2. An Overview of Published Articles

This Special Issue entitled "Advances in Particle Acceleration: Novel Techniques, Instruments and Applications" covers recent advances in the above-mentioned areas by collecting nine research contributions that represent the current state of the art of accelerator technology and offer inventive solutions and novel perspectives. The papers in this overview have been reordered from their original sequence of publication and are now grouped according to the discussed applications.

In the first contribution, titled "Transformative Technology for FLASH Radiation Therapy", Prof. Reinhard Schulte from Loma Linda University (USA) and his colleagues from other US universities, laboratories and industrial companies provide a detailed review of the advancements in FLASH radiation therapy, a novel approach in cancer treatment that has shown promising results due to its potential to deliver ultra-high dose rates with minimal damage to surrounding healthy tissues. This paper highlights the recent advancements in accelerator technology that enable the generation of the high dose rates required for FLASH therapy. These include developments in linac-based systems and compact particle accelerators capable of achieving the necessary performance. Advances in imaging and dosimetry are also discussed in-depth as being crucial for the accurate delivery of FLASH therapy. Improved imaging techniques allow for the precise targeting of tumors, while dosimetry innovations ensure the accurate measurement and control of the radiation dose.

The second paper, titled "Characterization of a Modified Clinical Linear Accelerator for Ultra-High Dose Rate Beam Delivery", by Dr. Umberto Deut from INFN (Italy) and his colleagues, focuses on the modifications and performance evaluation of a clinical linear accelerator (linac) adapted for ultra-high dose rate beam delivery, which is crucial for applications such as FLASH radiation therapy. The primary goal of this study was to adapt a standard linac including changes to the electron gun, RF components, and beam delivery systems to produce ultra-high dose rates.

The third paper, titled "Design of a Miniaturized Electron Cyclotron Resonance Ion Source for High-Voltage Proton Accelerator", by Dr. Hua-Fei Yu from Shanghai University (China) and his colleagues, describes the design and development of a compact electron cyclotron resonance (ECR) ion source specifically tailored for use in high-voltage proton accelerators for proton irradiation, BNCT, and as injectors for proton medical accelerators. This paper details the design of the magnetic field configuration and microwave system required to achieve efficient ionization and beam production in the miniaturized ECR ion source. This paper provides a viable solution for compact, efficient proton beam generation, with promising performance characteristics.

Advanced ion accelerators require modern software for beam dynamics simulation. In the fourth paper, titled "DYNAMION—A Powerful Beam Dynamics Software Package for the Development of Ion Linear Accelerators and Decelerators", Dr. Stepan Yaramyshev from GSI (Germany) and his colleagues present DYNAMION, a comprehensive beam dynamics software package developed to support the design, optimization, and analysis of ion linacs used for scientific, medical, and industrial applications. The software helps in designing efficient and effective linac systems. The authors discuss the ongoing efforts to enhance the software's capabilities, including the addition of new features, improved algorithms, and expanded support for different types of accelerators.

The fifth paper, titled "Research and Design of the RF Cavity for an 11 MeV Superconducting Cyclotron", by Dr. Yue Wu from ShanghaiTech University (China) and his colleagues, focuses on the development and optimization of the RF cavity used in an 11 MeV superconducting cyclotron for positron-emitting isotope production. The RF cavity is a crucial component in cyclotrons, as it provides the electromagnetic fields necessary to accelerate charged particles to high energies. The authors discuss the selection of appropriate RF frequencies and the geometric design of the cavity to match the requirements of the superconducting cyclotron. The use of superconducting materials allows for lower power losses and higher performance compared to conventional conductors. This paper discusses the challenges encountered during the design process, such as achieving the necessary field strength and managing thermal loads.

The development of novel SRF materials is further discussed in the sixth paper titled "Nb_3Sn Cavities Coated by Tin Vapor Diffusion Method at Peking University" by Prof. Gai Wang from Peking University (China) and his team. This study explores the development and application of a tin vapor diffusion method for coating niobium (Nb) cavities with niobium-tin (Nb_3Sn). This coating process is aimed at improving the performance of superconducting RF (radiofrequency) cavities used in particle accelerators. This paper discusses some challenges associated with the tin vapor diffusion method, such as achieving uniform coating and controlling the coating process to avoid defects. Recommendations for future work include optimizing the coating process further, exploring the application of the technique to other types of cavities, and conducting long-term performance studies. This study concludes that the tin vapor diffusion method is a promising approach for coating niobium cavities with Nb_3Sn, offering improvements in superconducting properties and potential benefits for accelerator applications.

The seventh paper, titled "X-ray Free Electron Laser Accelerator Lattice Design Using Laser-Assisted Bunch Compression", by Dr. Haoran Xu from LANL (USA) and his colleagues, brings us into the realm of X-ray FELs. This study aims to design an efficient accelerator lattice for X-ray Free Electron Lasers. The focus is on incorporating laser-assisted bunch compression techniques to enhance the performance of the accelerator and improve the characteristics of the generated X-ray pulses. The improved lattice design and bunch compression techniques are intended for use in X-ray FEL facilities, which are used for generating high-intensity, short-wavelength X-ray pulses for scientific research, materials science, and imaging applications.

Novel plasma acceleration techniques are discussed in the eighth paper titled "Plasma Accelerator Utilizing the Medium of Near-Earth Space for Orbital Transfer Vehicles" by Prof. A.R. Karimov from National Research Nuclear University MEPhI (Russia) and his colleagues. This paper explores the concept and design of a plasma accelerator that leverages the medium of near-Earth space to facilitate orbital transfer vehicles. This approach aims to develop efficient propulsion methods for spacecraft operating in the vicinity of Earth. It has the potential to significantly enhance the capabilities of orbital transfer vehicles and support advanced space missions.

The space applications of the accelerators are also discussed in the ninth paper titled "Upgrades of a Small Electrostatic Dust Accelerator at the University of Stuttgart" by Dr. Yanwei Li and his team from the University of Stuttgart (Germany). The paper focuses on the recent improvements and modifications made to a small electrostatic dust accelerator employed in experiments related to space science, plasma physics, and materials research. The authors detail specific upgrades made to the accelerator, such as enhancements to the electric field generation, improvements in particle injection systems, and refinements in beam diagnostics. The implemented upgrades have successfully enhanced the performance of the dust accelerator and its capabilities, providing valuable tools for ongoing and future research.

3. Conclusions

In conclusion, this Special Issue titled "Advances in Particle Acceleration: Novel Techniques, Instruments and Applications" focuses on the latest advancements and developments in the field of particle acceleration and includes a collection of articles that covers a range of topics that represent areas of interest for the accelerator physicists, engineers, developers, and users.

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