OPERATIONAL STATUS AND FAULT ANALYSIS OF THE CSNS VACUUM SYSTEM AND DEVELOPMENT PROGRESS OF THE CSNS-II VACUUM SYSTEM

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Abstract

Since the China Spallation Neutron Source (CSNS) was officially commissioned in 2018, its operational performance has been continuously improved. To date, the beam power has reached 185 kW, which is 85% higher than the design value, with a stable annual beam delivery time of more than 5000 hours and good overall operational reliability. The vacuum system serves as the core support for stable beam transport, mainly consisting of the Linear Accelerator (LINAC), Rapid Cycling Synchrotron (RCS), Low Energy Beam Transfer Line (LRBT), and High Energy Beam Transfer Line (RTBT). In addition, supporting vacuum systems for application beamlines such as APEP and Back n have been developed, with operating vacuum pressures ranging from 10^{-3} Pa to 10^{-7} Pa.The first phase vacuum system is equipped with 294 ion pumps, 64 cold cathode gauges, 12 turbo molecular pumps, and more than 600 vacuum pipelines. After nearly ten years of operation, the vacuum system has remained stable overall; however, typical faults such as DTL leakage, bellows corrosion, vacuum gauge fluctuation, and vacuum chain fracture have occurred. Based on practical operational experience, this paper systematically summarizes fault characteristics, analyzes fault mechanisms, and proposes corresponding countermeasures, providing a reference for the stable operation of vacuum systems in similar accelerators.The CSNS II project was officially launched in 2024 to meet the 500 kW high power requirement, with a five year construction plan focusing on superconducting cavities, high energy proton beamlines, and a muon beamline. The vacuum system has been comprehensively upgraded based on the first phase configuration. Meanwhile, this paper presents the latest development progress of the CSNS II vacuum system.

1. INTRODUCTION

The China Spallation Neutron Source (CSNS) is a major national scientific and technological infrastructure in China. Since its commissioning in 2018, key indicators including beam power, operational stability, and beam delivery duration have been continuously improved, providing a high level research platform for materials science, new energy, life sciences, and other fields. For accelerators, vacuum is essential for stable operation. Poor vacuum conditions cause beam loss, high voltage arcing, and equipment contamination, directly affecting operational efficiency and safety. The first phase CSNS vacuum system covers the entire beam path from the ion source to the front of the target station, featuring a wide range of vacuum levels, a large number of components, and complex operating conditions. Over nearly ten years of operation, typical vacuum faults have occurred due to equipment aging, high radiation, high power operation, and material outgassing, affecting vacuum stability and beam continuity. To further increase beam power and expand research capabilities, the CSNS II project was officially launched in 2024 with a five year construction plan. The core upgrades include introducing superconducting cavities, constructing new spectrometers, and adding high energy proton beamlines and a muon beamline. The vacuum system requires comprehensive upgrades based on the first phase design to meet higher vacuum requirements and enhanced stability. High radiation induced corrosion and seal failure are common challenges for high power accelerator vacuum systems. This paper systematically summarizes typical faults, analyzes mechanisms, proposes mitigation strategies, and presents the latest CSNS II upgrade progress, providing a valuable reference for peer institutions.

2. OVERVIEW OF THE CSNS VACUUM SYSTEM

2.1 System Composition and Vacuum Specifications

The first-phase vacuum system comprises four core sections:The vacuum system of the Linear Accelerator (LINAC), LINAC to RCS Beam Transfer Line (LRBT), Rapid Cycling Synchrotron (RCS), and RCS to Target Beam Transfer Line (RTBT), along with supporting vacuum systems for application beamlines such as the Associated Proton Experimental Platform (APEP) and the Back streaming White Neutron Source (Back-n), which together form a complete gradient vacuum network. Strict vacuum specifications are defined for each section: the ion source and low energy beam transport section (IS&LEBT) requires a pressure below 5×10^{-3} Pa, the radio frequency quadrupole to drift tube linac section (RFQ–DTL), LRBT and RTBT demand a pressure less than 1×10^{-5} Pa, the Rapid Cycling Synchrotron (RCS) requires a vacuum pressure below 5×10^{-6} Pa, and the proton

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beam window (PBW) needs a pressure lower than 1×10^{-4} Pa [?, ?].

2.2 Equipment Configuration

The first phase vacuum system is fully equipped with: 294 ion pumps, 64 cold cathode gauges, 12 turbo molecular pumps, and more than 600 vacuum pipelines, enabling optimized pumping, real time monitoring, and interlock protection to ensure stable vacuum conditions along the entire beam path. Figure?? shows the layout of the CSNS vacuum system. At present, the vacuum level in each region exceeds the design requirements, achieving stable operation.

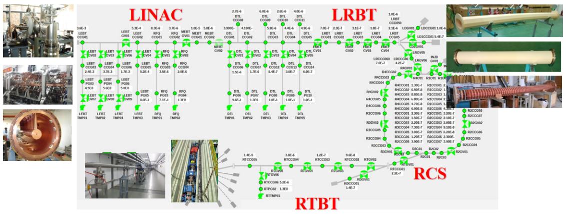

Figure 1: Layout of the CSNS Vacuum System

3. TYPICAL VACUUM FAULTS AND MITIGATION MEASURES FOR THE VACUUM SYSTEM

3.1 DTL Vacuum Leakage

Due to the complex structure and densely arranged pipelines of the drift tube linac (DTL) at CSNS, it is characterized by difficult leak detection, slow fault response, and challenging localization of leakage points; once a leak occurs, it will lead to a significant increase in vacuum pressure and a notable rise in beam loss. The main causes of this fault include longterm operational vibration, seal degradation, residual welding stress, and internal contamination caused by cooling water leakage. In response to the aforementioned fault and its causes, the ion pump current method is adopted to rapidly narrow down the leakage range based on the linear correlation between ion pump current and vacuum pressure; meanwhile, a residual gas analyzer (RGA) is installed in the DTL cavity, which can quickly identify water or gas leakage by comparing the spectral signatures under normal and abnormal operating conditions, thereby substantially reducing the leak detection period. Figure **??** shows the variation in the number of DTL leakage incidents in recent years. With accumulated experience in handling such vacuum leaks, the vacuum leakage rate of each DTL cavity has gradually decreased.

3.2 Electrochemical Corrosion Leakage of Bellows

Bellows installed in the RCS ring are exposed to a high radiation environment, where a leakage rate of 5×10^{-4} mbar·L/s was observed in 2025 accompanied by a remarkable decrease in vacuum pressure; the root cause is electrochemical corrosion induced by intense radiation that penetrated the bellows wall and formed micro pinholes, with

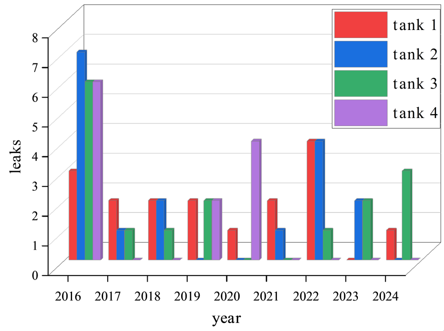

Figure 2: Statistics of DTL Leakage Occurrences

hot spot labels and residual adhesive identified at the leakage site [?]. Since immediate component replacement is impractical in high radiation zones, Vacseal vacuum sealant was adopted for temporary sealing despite its limited effectiveness for bellows — the first sealing lasted 17 days, the second 10 days, and the third application has remained effective until now to date to ensure continuous facility operation, while a full bellows replacement is scheduled during the next shutdown maintenance to fundamentally address the corrosion induced leakage. Fig. **??** presents the pressure variation curve of leakage caused by electrochemical corrosion of the bellows.

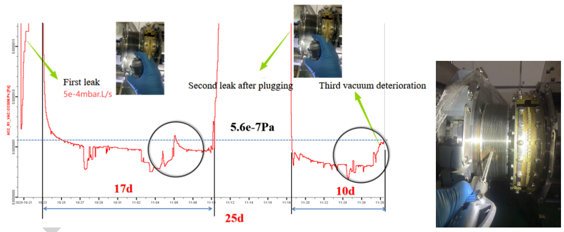

Figure 3: Pressure Variation Curve of Bellows Electrochemical Corrosion Leakage

3.3 Periodic Fluctuation of Vacuum Gauge Readings

The cold cathode vacuum gauge LDCCG01, located upstream of the beam dump in the LRBT, exhibits periodic reading fluctuations with pressure oscillating between 10^{-6} Pa and 10^{-5} Pa, which interferes with vacuum condition evaluation. This anomaly is potentially attributed to prolonged operation of the ion pump leading to argon instability, which causes cathode erosion and gas re-emission, resulting in abnormal gauge readings. Therefore, targeted measures including replacing aged vacuum gauges, optimizing ion pump operating parameters, and replacing new three-pole ion pumps are implemented to eliminate the influence of argon instability and guarantee accurate and reliable vacuum data.

3.4 Vacuum Chain Fracture

Isolated vacuum chain fractures occurred in the RCS region, leading to local vacuum isolation failure and abnormal pressure; such damage arises from reduced mechanical strength of the chains caused by long term vibration, stress fatigue and material aging, so all fractured chains, especially those with threaded blocks, were replaced, with no further chain fracture faults observed in subsequent operation.

4. UPGRADE PROGRESS OF THE CSNS II VACUUM SYSTEM

4.1 Upgrade of the Front End Vacuum System

With the increased hydrogen gas load from the LINAC ion source, the pumping speed of the original first phase pump sets became insufficient to meet the high load operational requirements. Through investigating the pumping speed curves of pump sets from multiple manufacturers and conducting multiple rounds of testing and verification, new pump sets matching the high hydrogen load conditions were selected, and the pumping layout was optimized to ensure that the vacuum in the low energy section remains stably below 1×10^{-5} Pa [**?**, **?**].

4.2 Development of the New Superconducting Cavity Vacuum System

Superconducting cavities impose extremely stringent vacuum requirements, demanding a pressure reduction from 1×10^{-5} Pa to 1×10^{-7} Pa. To meet the ultra high vacuum requirements for superconducting cavity operation, two differential pumping systems, namely the Low Energy Differential Pumping (LEDP) and High Energy Differential Pumping (HEDP) systems, were deployed to establish multi stage vacuum gradients upstream and downstream of the superconducting cavities. Additionally, room temperature section vacuum and thermal insulation vacuum for the superconducting cavities were newly constructed, forming an integrated adiabatic vacuum protection system to prevent superconducting cavity quenching.

4.3 Innovative Design of the RABT Vacuum System

The vacuum chamber for the pulsed magnet SW2 must simultaneously satisfy the requirements of low eddy current, corrosion resistance, and high vacuum sealing. An innovative design adopting a variable size double hole ceramic vacuum chamber with a vitrified bonding process was proposed, which effectively suppresses eddy current heating and mitigates corrosion induced leakage. A 0.1 mm Inconel/TC4 metal cladding scheme was retained as a redundant backup to enhance system reliability.

4.4 Key Breakthroughs in the Muon Source Vacuum System

The muon source vacuum system presents significant challenges, requiring the vacuum level to be reduced from the kilopascal (kPa) range to 1×10^{-4} Pa across seven orders of magnitude; conventional Kapton windows are prone to damage and fail to block the diffusion of radioactive materials. A combined isolation scheme integrating valves and $3\mu m/100\mu m$ Kapton windows was implemented to prevent tritium and other radioactive substances from flowing downstream. Five sets of 1200 L/s turbo molecular pump units were configured to ensure that the vacuum in the muon beamline is better than 1×10^{-4} Pa, thereby addressing the critical challenge of high to low vacuum isolation.

5. CONCLUSION

After nearly ten years of operation, the first-phase vacuum system of the China Spallation Neutron Source (CSNS) has maintained overall stability and reliability, supporting a beam power of 185 kW and an annual beam delivery duration exceeding 5,000 hours with excellent operational performance. Typical faults encountered during operation, including DTL leakage, bellows corrosion, vacuum gauge fluctuation, and vacuum chain fracture, have been effectively resolved through practical and targeted measures, accumulating valuable operational experience. The CSNS-II project introduces superconducting cavities, high-energy proton beamlines, and a muon beam-line, with the vacuum system comprehensively upgraded based on the first-phase configuration. Key technologies such as differential pumping, ceramic vacuum chambers, and Kapton window isolation have achieved significant breakthroughs, substantially improving vacuum specifications and system stability. Subsequent efforts will focus on reliability verification in high-radiation environments, system integration and commissioning, and intelligent operation and maintenance optimization, providing strong support for the smooth progress and longterm stable operation of the project

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