Simulation and Optimization of Helium Pressure Sensitivity Coefficient for HWR019 Superconducting Cavity

Authors: Li Xiaoli, Xu Mengxin, He Yuan, Liang Zehua, Zhang Shengxue, Li Chunlong, Liu Lubei, Huang Qitong, Liu Tong, Jiyu Wang, Liu Guochang, Wang Zhi, Jiang Tiancai, Xiang Pingan, Wang Zhijun, Yang Yangyang, Xu Mengxin

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Abstract

China Initiative Accelerator Driven System (CiADS) operates its superconducting linear accelerator section in continuous wave mode, where 4K liquid helium pressure fluctuations causing deformation and detuning of superconducting cavities represent a critical factor affecting the stable operation of low-β cavities. To address the operational instability of half-wave superconducting resonator cavities due to helium pressure fluctuations, this study employs numerical simulation methods to investigate the relationship between liquid helium pressure fluctuations and frequency variation characteristics of the cavity, using the β=0.19 half-wave superconducting resonator (HWR019) in the CiADS superconducting linear section as a case study. Through computational analysis of the relationships among the cavity-liquid helium contact region, cavity wall thickness, liquid helium cooling channel geometry, and the cavity helium pressure sensitivity coefficient (KPress), the KPress value of the HWR019 superconducting cavity was successfully reduced to near zero. Simultaneously, through thermodynamic calculations of the cavity, corresponding enhanced heat transfer schemes were provided, effectively reducing the maximum temperature of the superconducting cavity during operation and meeting the stable operation requirements for superconducting cavities in the CiADS facility. The analysis and optimization methodology also holds reference value for similar types of low-β superconducting cavities.

Full Text

Preamble

Simulation and Optimization of Helium Pressure Sensitivity Coefficient in the HWR019 Superconducting Cavity

Xiaoli Li[12], Mengxin Xu[13,*], Yuan He[13], Zehua Liang[12], Shengxue Zhang[1], Chunlong Li[1], Lubei Liu[1], Qitong Huang[3], Tong Liu[1], Jiyu Wang[1], Guochang Liu[12], Zhi Wang[34], Tiancai Jiang[1], Pinan Xiang[3], Zhijun Wang[13], Yangyang Yang[1]

[1] Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, China
[2] School of Nuclear Science and Technology, University of Chinese Academy of Sciences, Beijing 100049, China
[3] Guangdong Academy of Sciences, Guangzhou 510650, China
[4] School of Materials and Energy, Guangdong University of Technology, Guangzhou 510006, China

Abstract

For the superconducting linac section of the Chinese Accelerator Driven Transmutation Research Facility (CiADS) operating in continuous wave mode, cavity detuning caused by fluctuations in liquid helium pressure represents a critical factor affecting the stable operation of low-β cavities. Addressing the operational instability of half-wave superconducting resonators due to helium pressure fluctuations, this study takes the 162.5 MHz, β=0.19 half-wave resonator (HWR019) used in the CiADS superconducting linac as a case study. Using numerical simulation methods, we investigate the relationship between liquid helium pressure fluctuations and cavity frequency variations. By systematically analyzing the correlations among the helium contact region on the cavity, wall thickness, cooling channel geometry, and the helium pressure sensitivity coefficient (KPress), we successfully reduce the KPress value of the HWR019 superconducting cavity to near zero. Simultaneously, thermodynamic calculations provide enhanced heat transfer solutions that effectively lower the maximum operating temperature of the superconducting cavity, ensuring stable operation for CiADS. The analytical and optimization methodology developed herein also offers valuable insights for similar low-β superconducting cavities.

Keywords: RF superconductivity; half-wave resonator; helium pressure sensitivity coefficient; CiADS

2. Mechanism of Helium Pressure Fluctuation Effects on HWR Superconducting Cavities

At the operating temperature of 4.2 K, liquid helium exhibits significantly greater pressure fluctuations than in the 2 K superfluid state. These pressure variations act on the outer surface of superconducting cavities, causing time-dependent deformations that lead to frequency detuning exceeding the cavity bandwidth and resulting in operational instability. Due to structural stiffness differences between the electric and magnetic field regions in HWR RF superconducting cavities, distinct frequency responses to helium pressure fluctuations emerge in different cavity zones. The HWR superconducting cavity can be modeled as an RLC parallel resonant circuit with an open middle section and shorted ends, as illustrated in the equivalent circuit shown in [Figure 1: see original paper], where l represents the equivalent inductance, c the equivalent capacitance, and f the cavity' s characteristic frequency.

For the HWR019 cavity with β=0.19, the small acceleration gap implies a large capacitance change rate per unit length. According to equivalent parallel resonant circuit theory, minute deformations in the strong electric field region cause significant capacitance variations, leading to frequency detuning. Consequently, low-β superconducting cavities exhibit heightened sensitivity to helium pressure fluctuations in their strong electric field regions. The pressure force from liquid helium always acts normal to the cavity surface, directed inward. In strong electric field regions, helium pressure-induced deformation increases equivalent capacitance and decreases resonant frequency, whereas in strong magnetic field regions, deformation decreases equivalent inductance and increases frequency. These opposing effects partially cancel each other, though the net detuning magnitude requires quantitative analysis.

The impact of helium pressure fluctuations on HWR cavities primarily depends on the response sensitivity of different cavity regions and the overall structural rigidity. The helium pressure sensitivity coefficient (KPress) quantifies this response, defined as the linear ratio between the characteristic frequency shift (Δf) and the pressure change (ΔP).

3. Computational Model and Settings

[Figure 2: see original paper] presents the top view of the computational model for the 162.5 MHz HWR019 cavity in the CiADS facility. The cavity features two cleaning ports at both ends, four symmetrically distributed support plates along the beam port axis, and two coupler ports arranged perpendicular to the beam pipe. The textured region represents the vacuum area obtained by shelling the inner cavity walls. Boundary conditions are configured as shown in [Figure 3: see original paper], with the four support plates fixed and elastic constraints (stiffness K) applied at both beam pipe ends, where K is determined from the cavity' s tuning sensitivity. The cavity outer surface contacts liquid helium for cooling, while the inner surface experiences Lorentz forces. The model is discretized using tetrahedral unstructured meshes, with mesh independence verified to ensure simulation reliability. The characteristic frequency f serves as the observation parameter, and its variation with the minimum mesh limit M is examined. As shown in [Figure 4: see original paper], when M exceeds 140, the characteristic frequency achieves excellent convergence. Therefore, the minimum mesh limit is set to 160, yielding approximately 12 million tetrahedral elements for the entire cavity. With meshing, boundary conditions, and material parameters established, the model is ready for computation.

4.1 Impact of Helium Fluctuations on Different Regions

To investigate helium fluctuation effects on various HWR019 cavity regions, we analyzed three common cooling configurations: full cavity immersion, end-cap plus inner conductor cooling, and inner conductor-only cooling. The helium distribution for each case is depicted in [Figure 5: see original paper]. The underlying principle relates the helium contact area to KPress: full immersion covers both strong electric and magnetic field regions; end-cap plus inner conductor cooling covers partial magnetic and electric field regions; and inner conductor-only cooling covers the strong electric field region and part of the magnetic field region. When helium pressure fluctuations cause a deformation ΔV in a microscopic surface element ΔS, the resulting frequency shift $\Delta f = f$ - f_0 (where f is the deformed cavity frequency and f_0 is the original frequency) is calculated by Formula 1:

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Here, W represents the energy stored in the undeformed cavity, ΔW denotes the change in magnetic energy storage after deformation (ΔW = $_0$), and ΔW represents the change in electric energy storage (ΔW = $_0$). This simplifies to Formula 2:

Δ $-\Delta$

Since helium pressure perturbations act inward along the surface normal, $\Delta V > 0$ and thus $\Delta W > 0$. Perturbations in strong magnetic field regions produce relatively small ΔW compared to ΔW, yielding $\Delta f > 0$ (frequency increase). Conversely, perturbations in strong electric field regions produce smaller ΔW relative to ΔW, resulting in $\Delta f < 0$ (frequency decrease).

As shown in , full cavity immersion yields KPress < 0, indicating that magnetic region detuning is completely offset and electric field response dominates. End-cap plus inner conductor cooling gives KPress > 0, showing electric field detuning is offset with magnetic region effects prevailing. Both cases demonstrate insufficient compensation between regions, leading to significant operational impact. Inner conductor-only cooling dramatically reduces KPress to 0.0081 Hz/Pa, indicating excellent cancellation between electric and magnetic region detuning effects. Since the primary heating zone in HWR cavities is located in the inner conductor's strong magnetic field region, this cooling approach simultaneously optimizes heat transfer performance and mechanical stability.

4.2 Relationship Between Cavity Wall Thickness and KPress

[Figure 6: see original paper] (left) illustrates the relationship among HWR019 cavity wall thickness, helium contact area, and KPress, where K represents the elastic constraint stiffness at the beam ports. The x-axis shows wall thickness, y-axis indicates the cooling configuration group from the previous section, and z-axis displays KPress values. As wall thickness increases from 0 to 8 mm and constraint stiffness K grows from 5 kN/mm to 50 kN/mm, KPress decreases consistently. However, beyond 5 mm thickness, the rate of KPress reduction diminishes significantly—increasing thickness from 5 mm to 10 mm yields less than 0.005 Hz/Pa improvement. Based on previous results, inner conductor-only cooling should produce even lower KPress values. [Figure 6: see original paper] (right) shows KPress versus wall thickness for this configuration, revealing KPress = 0.0087 Hz/Pa at 5 mm thickness with negligible change beyond this point. Therefore, 5 mm wall thickness provides an optimal balance between mechanical stability and material efficiency.

4.3 Relationship Between Outer Wall Geometry and KPress

Building on previous results, we determined optimal wall thickness and cooling configuration for the HWR019 cavity. For the 5 mm thick cavity with inner conductor-only cooling, residual helium pressure effects persist, prompting further investigation of inner conductor outer geometry. The inner conductor cooling region divides into two sections: the central sphere near the beam tube (strong electric field region) and the end-region strong magnetic field zone. The central sphere’ s complex geometry makes modification difficult, and since it’ s not the primary heating region, filling this area solid eliminates helium contact and reduces electric field region sensitivity. For the magnetic field region, we compared conical and cylindrical helium channel geometries, as shown in [Figure 7: see original paper].

The cylindrical channel yields KPress = 0.0000397 Hz/Pa, substantially lower than alternative geometries, indicating that cylindrical structures provide superior resistance to lateral helium pressure deformation compared to conical designs. Additionally, as shown in , the cylindrical channel reduces the Lorentz detuning coefficient (K). We subsequently varied the cylindrical channel diameter from 44 mm to 60 mm (maximum allowed by electromagnetic design) in 2 mm increments. [Figure 8: see original paper] demonstrates that KPress decreases monotonically with increasing diameter, suggesting progressively better cancellation between capacitive and inductive effects in the equivalent circuit. The final design employs a 60 mm diameter cylindrical channel, achieving KPress = 0.0000279 Hz/Pa—effectively eliminating helium pressure impact on HWR019 cavity stability.

4.4 Thermal Analysis of Cavity Heat Transfer

To ensure high stability during 4.2 K operation, the HWR019 cavity employs localized inner conductor cooling. Given niobium’ s low thermal conductivity at cryogenic temperatures, thermodynamic analysis of the optimized structure is essential to prevent thermal quenching. [Figure 9: see original paper]a shows the temperature distribution for a pure niobium cavity (5 mm Nb) operating at peak surface electric field E = 28 MV/m (accelerating gradient E = 6.7 MV/m), revealing a maximum temperature of 9.44 K—exceeding niobium’ s superconducting transition temperature. Two enhancement strategies are proposed:

1. **Adding helium cooling pipes to the outer conductor**: Six uniformly distributed cooling pipes strengthen heat transfer, reducing the maximum temperature to 4.28 K at E = 6.7 MV/m—a 5.16 K improvement that satisfies stable operation requirements.

2. **Composite cavity construction**: To reduce fabrication costs, a niobium-aluminum composite cavity leverages high-conductivity outer materials. Using 4N aluminum (RRR = 10^4, thermal conductivity = 240.4 W/(m·K) at 4.2 K), a 2 mm Nb/3 mm Al composite cavity reaches only 4.75 K at E = 6.7 MV/m, as shown in [Figure 10: see original paper]. Combining composite construction with outer conductor pipe cooling further reduces the peak temperature to 4.27 K ([Figure 11: see original paper]), meeting all operational requirements.

5. Conclusions

This study systematically investigated the helium pressure response of the HWR019 superconducting cavity, analyzed regional sensitivity to liquid helium pressure fluctuations, and examined the influence of wall thickness on KPress. By optimizing the inner conductor outer geometry, we reduced the 4.2 K KPress value below 0.001 Hz/Pa, ensuring stable cavity operation. Thermodynamic analysis yielded two viable cooling solutions—pipe cooling or high-conductivity composite cavities—both capable of maintaining stable operation. These methods provide valuable references for analyzing and optimizing helium pressure sensitivity in similar low-β superconducting cavities.

Key findings include:

1. **Regional response simulation** demonstrates that the overall KPress depends on the compensation degree between electric and magnetic field region responses. Full cavity immersion and end-cap plus inner conductor cooling fail to achieve adequate cancellation. Inner conductor-only cooling yields low KPress while simultaneously cooling the primary heating zone (strong magnetic field region), providing both effective heat removal and high mechanical stability.

2. **Wall thickness analysis** shows KPress decreases with increasing thickness, but the improvement rate diminishes significantly beyond 5 mm. This indicates that while thicker walls reduce helium pressure effects, a threshold exists beyond which additional thickness provides minimal benefit. The 5 mm thickness optimally balances thermal performance and mechanical stability.
3. **Inner conductor geometry optimization** reveals that cylindrical cooling channels produce lower KPress than conical channels, demonstrating superior structural strength against lateral pressure. Furthermore, as magnetic and electric region deformations partially compensate, KPress decreases with increasing cylindrical channel diameter.
4. **Thermal calculations** confirm that pure niobium cavities with outer conductor cooling pipes maintain maximum temperatures of 4.28 K at operational gradients. Cost-effective niobium-aluminum composite cavities with pipe cooling achieve similar performance (4.27 K maximum), preventing thermal quench in both configurations.

References

[1] LIU S H, WANG Z J, JIA H, et al. Physics design of the CIADS 25MeV demo facility [J]. Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 2017, 843: 11-7. doi: https://doi.org/10.1016/j.nima.2016.10.055

[2] WANG Z J, WANG F F, HUANG G R, et al. The Status of CiADS Superconducting LINAC, IPAC2019[C]. Melbourne, Australia, 2019:994-997. doi: 10.18429/JACOW-IPAC2019-MOPTS059

[3] XU M X, GUO H, HE Y, et al. CiADS and HIAF Superconducting Cavity Development Status and the Transition to Production Stage [Z]. JACoW SRF2021 (2022) MOPCAV008. doi: 10.18429/JACoW-SRF2021-MOPCAV008

[4] MA Jin Ying. Study on the Ponderomotive and Microphonics instability of the Superconducting cavities [D]. Institute of Modern Physics, Chinese Academy of Sciences, 2022:55.

[5] AMBERG M, AULENBACHER K, BUSCH M, et al. STRUCTURAL MECHANICAL ANALYSIS OF SUPERCONDUCTING CH CAVITIES [C]. Proceedings of SRF 2011, Chicago, IL USA , 2011:35.

[6] LIU Nai Quan, LIN Yu Zheng, LIU Guo Zhi, et al. Accelerator Theory[M]. Beijing: Tsinghua University Press, 2004: 162-168.

[7] PADAMSEE H, KNOBLOCH J, HAYS T, et al. RF Superconductivity for Accelerators [J]. Physics Today, 1999, 52(7): 54. doi: 10.1063/1.882759

[8] HE Shou Bo. Study of Mechanical Stability and Frequency Tuning for Low beta Superconducting Half-wave Resonator in High Intensity Proton Linac for

China ADS [D]. Institute of Modern Physics, Chinese Academy of Sciences, 2014:48-51.

[9] GE Ming Qi, ZHAO Sheng Chu. Lorentz Force Detuning Analysis of 700MHz Single-cell Superconducting Cavity[J]. High Energy Physics and Nuclear Physics, 2005(04):413-417.

[10] FU Shi Nian, FANG Shou Xian, GUAN Xia Ling, et al. The Key Physics and Technology Issues in the Intense-beam Proton Accelerators[R]. China Nuclear Science and Technology Report, CNNC-0003, 2001.06.15.

[11] YUE Wei Ming. Research on the key technologies of the Taper type half wavelength superconducting resonator[D]. Lanzhou University, 2021:36-39.

[12] GASSOT H. Mechanical Stability of the RF superconducting Cavities [C]. Proceedings of EPAC 2002, Paris, France, 2002: 2235-2237.

[13] POSEN S, LIEPE M. Mechanical optimization of superconducting cavities in continuous wave operation [J]. Physical Review Special Topics - Accelerators and Beams, 2012, 15(2): 022002. doi: https://doi.org/10.1103/PhysRevSTAB.15.022002

[14] LI Bo, LIU Hua Chang, WANG Yun, et al. Detuning Analysis of the Superconducting Elliptical Cavity for CSNS-II Linac[J]. Nuclear Physics Review, 2020, 37(2): 186-190. doi: 10.11804/NuclPhysRev.37.2020013

[15] MA Yan Wei. Superconducting Materials Science and Technology[M]. Beijing: Science Press, 2022.

[16] BALLANTINI R, CHINCARINI A, GEMME G, et al. Pipe cooling perspectives for superconducting accelerating cavities [J]. Physical Review Special Topics - Accelerators and Beams, 2003, 6(8): 083201. doi: https://doi.org/10.1103/PhysRevSTAB.6.083201

[17] XU M X, GUO H, HE Y, et al. Status and Challenges of Nb/Cu SRF Cavities for Superconducting Linac [R]. Proceedings of the 31st International Linear Accelerator Conference, England, 2022.

[18] ZHANG A L, LI Y X. Thermal Conductivity of Aluminum Alloys—A Review [J]. Materials, 2023, 16: 2972. doi: https://doi.org/10.3390/ma16082972

Note: Figure translations are in progress. See original paper for figures.