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DEVELOPMENT OF THE SUPERCONDUCTING HWR CAVITIES FOR NICA PROJECT

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Abstract

Nuclotron-based Ion Collider fAcility (NICA) is an accelerator complex under construction in JINR, in which superconducting linac-injector can accelerate protons up to 20 MeV and light ions to 7.5 MeV/u. To achieve this design target, a 325 MHz, beta = 0.21 niobium half-wave resonator (HWR) called HWR1 was developed jointly by IMP and JINR. This paper optimizes the electromagnetic design of NICA cavity, designs the mechanical structure (including helium jacket) and gives the results of multi-physical studies. Simulation results show that Epk/Eacc = 5.88, Bpk/Eacc = 9.96 mT/(MV/m). In addition, the niobium cavity has been fabricated and vertically tested, the magnetic shield and helium jacket are in the process of electron beam welding, and the cryomodule will be assembled in the next 1~2 months.

INTRODUCTION

The NICA project in Russia is a major scientific initiative focused on exploring the properties of dense nuclear matter. Located at the Joint Institute for Nuclear Research (JINR) in Dubna, NICA aims to recreate conditions similar to those of the early universe by colliding heavy ions at high energies. The facility consists of a complex of accelerators, including a superconducting synchrotron and two collider rings, designed to accelerate ions and polarized protons. The primary goal of NICA is to study the phase transitions between hadronic matter and quark-gluon plasma, providing insights into the fundamental forces governing particle interactions. Through its unique capabilities, NICA will play a critical role in advancing our understanding of strong interactions and the structure of matter under extreme conditions [1-4].

The existing linear injector LU20 has been in operation for 50 years and is now considered outdated. As a result, the superconducting linear accelerator LILac has been developed as a new injector [5-6]. The Institute of Modern Physics, Chinese Academy of Sciences (IMP, CAS), optimized the electromagnetic design of the HWR1 cavities within this superconducting linac, manufactured a prototype, and tested it.

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CAVITY DESIGN

Electromagnetic Design

The design of the HWR1 seeks to achieve a balanced compromise between optimal RF performance, adequate mechanical properties, and ease of fabrication and surface preparation. The initial focus is on optimizing the RF properties of the HWR cavity, with the goal of minimizing heat load and maximizing the accelerating gradient. This is achieved by targeting a higher R/Q0 (where R is the shunt impedance and Q0 is the unloaded quality factor), a higher geometry factor (G), and lower peak surface fields (Bpk/Eacc and Epk/Eacc) to avoid field emission.

To achieve these objectives, the HWR1 is designed with a taper-shaped inner conductor and a ring-shaped drift tube, which minimizes the peak surface fields. At the same time, the outer conductor is kept cylindrical to ensure ease of fabrication. Two rinsing ports are opened on each side to facilitate post-processing of the superconducting cavity. The thicker port on the outer conductor is the coupling port of the fundamental power coupler (FPC), and the thinner port on the opposite side is the signal extraction port.

The final optimized RF parameters of the cavity are presented in Table 1. And the cavity electromagnetic field distribution are presented in Fig. 1.

Table 1: RF Parameters of HWR1

Parameters	Value	Unit
Frequency	325	MHz
β_{opt}	0.21	
Beam Aperture	30.00	mm
G	59	ohmn
R/Q	299.82	ohmn
Leff (βλ)	193.84	mm
Ep/Eacc	5.88	
Bp/Eacc	9.96	mT/(MV/m)
Cavity Diameter	194	mm
Cavity Height	471	mm

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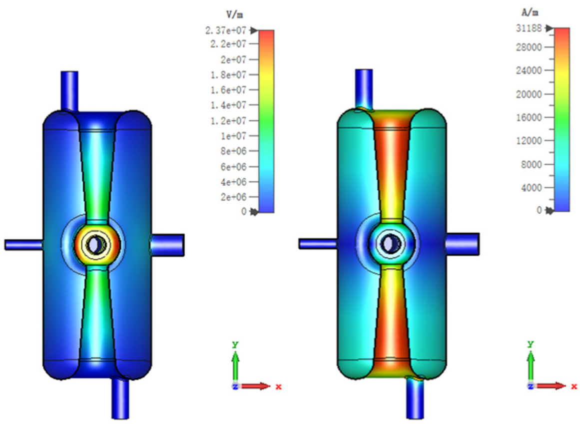

Figure 1: HWR1 electric field distribution (left) and magnetic field distribution (right) of the 325 MHz mode.

Mechanical Structure Design

Based on the vacuum model provided by the electromagnetic design, the cavity is segmented into various stamping components using established manufacturing techniques, aiming to minimize the size of each stamped part while ensuring stamping quality. The final superconducting cavity is assembled through electron beam welding. Fig. 2 illustrates the exploded view of the HWR1 cavity and its helium jacket.

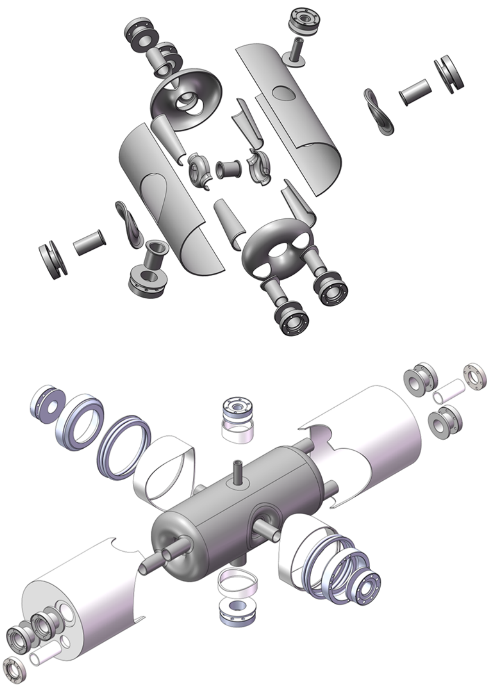

Figure 2: Exploded view of HWR1 cavity (up) and its helium jacket (down).

A superconducting cavity is a pressure vessel, and in order to ensure its safe operation, we performed safety redundancy simulation calculations on HWR1. The simulation results are shown in Fig. 3. In all parts of the superconducting cavity system, the material allowable stress was not exceeded, thus meeting the standard for safe operation. In addition, we also simulated two parameters that are of great concern in the field of superconducting cavities, which are df/dp and Lorentz frequency detuning coefficient (LFD). With a helium jacket and a tuner stiffness of 10 kN/mm, the df/dp of HWR1 is 4.96 Hz/mbar, and the LFD is -1.28 Hz/(MV/m)^2.

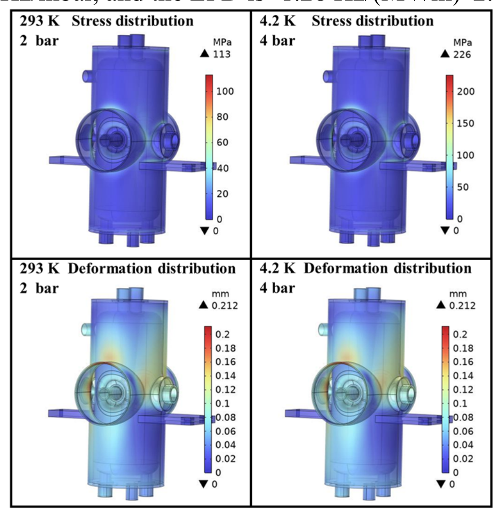

Figure 3: HWR1 safety check results.

PROTOTYPE FABRICATION

Cavity Production

The HWR1 is fabricated from high-purity niobium sheets with an RRR > 300 and has a wall thickness of 3 mm. Given the strong correlation between the RF performance of superconducting cavities and the quality of their inner surfaces, manual polishing is required to address noticeable scratches and welding spatter both before and after welding. Figure 4 shows the completed HWR1 prototypes. The IMP has produced two sample cavities. They are numbered HWR1_1 and HWR1_2.

Figure 4: HWR1 prototype before and after welding.

Before the vertical test, the prototype undergoes surface treatment as follows: 1. 150 µm BCP; 2. Annealing at 600°C for 12 hours in a vacuum environment; 3. 22 µm BCP; 4. High-pressure rinsing (HPR); 5. Cleanroom assembly.

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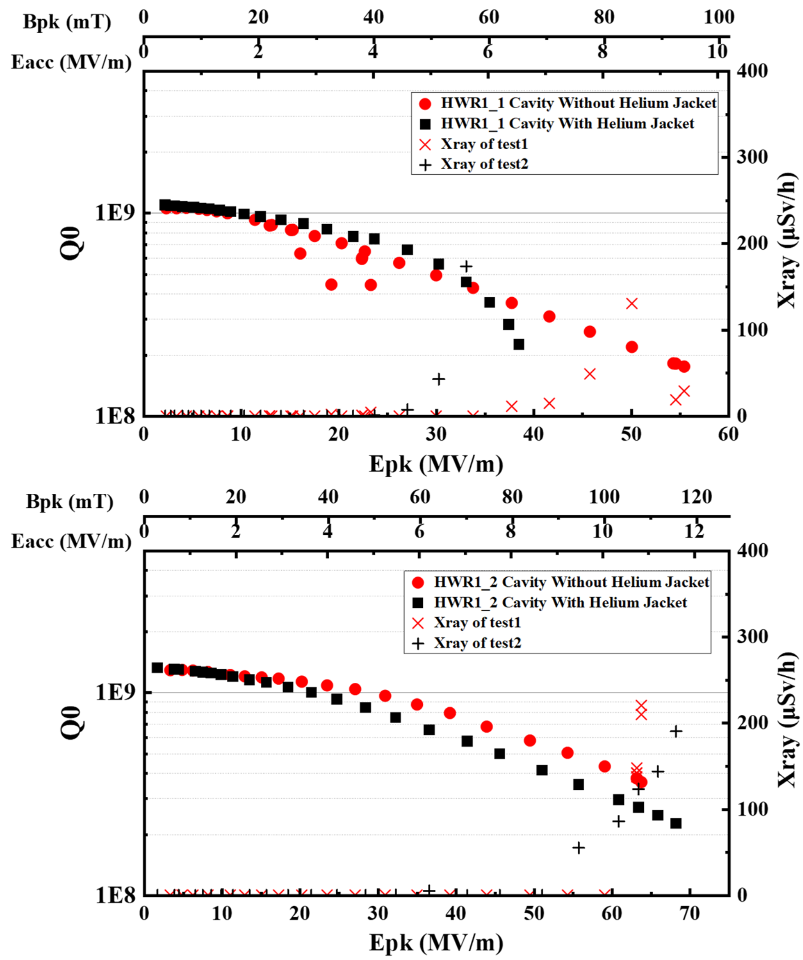

Figure 5: The red data represents the vertical test results of the bare HWR1 cavity, while the black data corresponds to the test results of the HWR1 cavity with the helium jacket. Vertical test results of HWR1_1 (up), and vertical test results of HWR1_2 (down).

Vertical Test Results

We conducted 4.2 K vertical tests on both the bare niobium HWR1s and the HWR1 prototypes after the helium jacket was welded. The test results are shown in Fig. 5. Due to the lack of ultrasonic cleaning before HPR after welding the helium jacket on HWR1_1, a significant reduction in the accelerating gradient was observed during vertical testing. In the subsequent production of HWR1_2, we improved the post-processing procedure by adding ultrasonic cleaning before HPR. As a result, the testing of HWR1_2 yielded favourable results, with the operational accelerating gradient exceeding 40 MV/m and meeting the design specifications.

CONCLUSION

The IMP has designed a 325 MHz HWR superconducting cavity with an optimal beta of 0.21 for the NICA project. The prototype has been successfully manufactured, and the vertical test results meet the required specifications. This type of superconducting cavity is planned for future use in the upgrade of the NICA linear injector.

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