Nuclear Engineering and Technology 55 (2023) 2466–2473

Contents lists available at ScienceDirect

Nuclear Engineering and Technology

journal homepage: www.elsevier.com/locate/net

Original Article

Low beta superconducting cavity system design for HIAF iLinac

Mengxin Xu [a,*], Yuan He [a,**], Shengxue Zhang [a], Lubei Liu [a], Tiancai Jiang [a], Zehua Liang [a,b], Tong Liu [a], Yue Tao [a], Chunlong Li [a], Qitong Huang [c], Fengfeng Wang [a], Hao Guo [a], Feng Bai [a], Xianbo Xu [a], Shichun Huang [a], Xiaoli Li [a,b], Zhijun Wang [a], Shenghu Zhang [a], Jiancheng Yang [a], Evgeny Zaplatin [a]

[a] Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou, 730000, China
[b] University of Chinese Academy of Sciences, Beijing, 100049, China
[c] Advanced Energy Science and Technology Guangdong Laboratory, Huizhou, China

ARTICLE INFO

Article history:
Received 5 December 2022
Received in revised form
15 March 2023
Accepted 6 April 2023
Available online 14 April 2023

Keywords:
Superconducting cavity
HIAF
iLinac
Low beta cavity
Half-wave resonator
Quarter-wave resonator

ABSTRACT

A superconducting ion-Linac (iLinac), which is supposed to work as the injector in the High Intensity heavy-ion Accelerator Facility project, is under development at the Institute of Modern Physics (IMP), Chinese Academy of Sciences. The iLinac is a superconducting heavy ion linear accelerator approximately 100 meters long and contains 96 superconducting cavities in two types of 17 cyromodules. Two types of superconducting resonators (quarter-wave resonators with a frequency of 81.25 MHz and an optimal beta $\beta = v/c = 0.07$ called QWR007 and half-wave resonators with a frequency of 162.5 MHz and an optimal beta $\beta = 0.15$ called HWR015) have been investigated. The cavity design included extensive multi-parameter electromagnetic simulations and mechanical analysis , and its results are described in details. The fundamental power coupler and cavity dynamic tuner designs are also presented in this article. The prototypes are under manufacturing and expected to be ready in 2023.

1. Introduction

Over the last half of century, heavy ion accelerator is a powerful instrument for exploring the scientific front edge in the area of nuclear physics, atomic physics, medical application and safety application. The proposed or constructed heavy ion accelerators can be sort out in two categories: High-energy facilities, the represent machine is the FAIR, which have the ability to provide intense pulsed U^{28+} beam with energy at 1.5 GeV/u [1,2]. This high energy facility's main structure relies on the circle ring, such as HIRFL [3]. The other path is high intensity accelerators. FRIB is recently accomplished heavy ion linac with a beam power of 400 kW [4]. Superconducting Radio-Frequency (SRF) cavities are employed in this linac to reach the high fields gradient and accelerating efficiency [5].

The construction of the High Intensity heavy-ion Accelerator Facility (HIAF) has been started in 2018 at Huizhou city by Institute of Modern Physics, Chinese Academy of Sciences (IMP, CAS) [6,7]. The heavy ions will be accelerated by superconducting ion-Linac (iLinac) up to the energy of 17 MeV/u. Then a Booster Ring (BRing) should be able to accumulate and accelerate beam up to 0.84 GeV/u for atomic and nuclear physic experiments. The available beam current will be 1 pμA. HIAF is designed to produce radioactive beams for nuclear reaction in cosmic and nuclei mass measurement, high-energy beams for density plasma physics research, and high charged beams for atomic physics research [8,9].

2. iLinac injector

Due to the diversity of experiments, the iLinac has been designed to operate in three modes, and the lattice will be adjusted according to each mode. Such as the injection mode, which is injecting the beam to the BRing (pulse mode, pulse length 2 ms , repetition rate 5 Hz, the charge mass ratio is 1/2–1/6.8). The continuous wave mode is used to supply beam directly for low energy terminal experiments. The time sharing mode can supply U^{48+} beam to BRing in 10 ms of one second while supplying 900ms H_3^+ beam to the terminal, with the remainder 90 ms used to adjust the lattice [10]. The iLinac layout is shown on Fig. 1.

* Corresponding author.
** Corresponding author.
E-mail addresses: xumx@impcas.ac.cn (M. Xu), hey@impcas.ac.cn (Y. He).

https://doi.org/10.1016/j.net.2023.04.010
1738-5733/

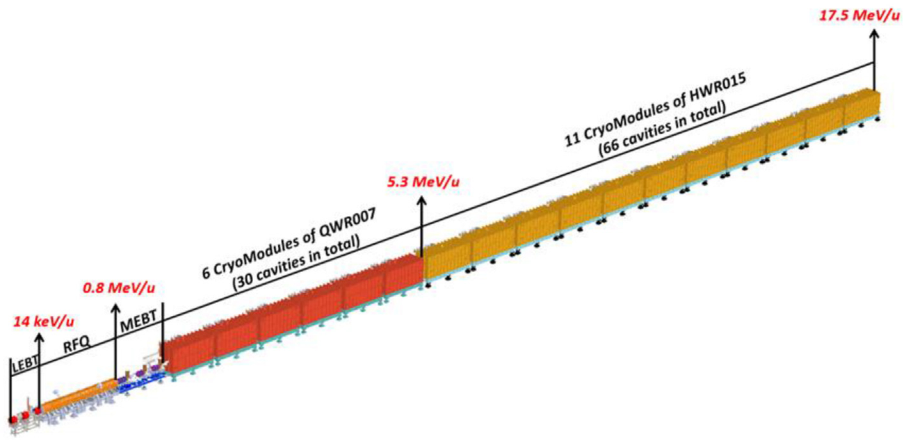


Fig. 1. Layout of the iLinac superconducting section.

In the beginning, a superconducting electron cyclotron resonance ion source (SECR) is employed for charged beam production. Then follows the front end with RF bunches and triplets for beam steering and the normal conducting RFQ cavity accelerator with the beam up to energy 0.8 MeV/u (the cavity frequency is 81.25 MHz) [11]. The Quarter Wave Resonators (QWR) and Half Wave Resonators (HWR) are used in the superconducting section for beam acceleration.

To match the upstream frequency, the QWRs have the same frequency with RFQ. The cavity's optimal beta is 0.07. The Half-Wave Resonators have the double frequency of 162.5 MHz with an optimal beta = 0.15. The HIAF linear injector tunnel is 200 meters long, which not only accommodates the current iLinac of about 100 meters, but also leaves plenty of space for future upgrades. The iLinac includes 17 cryomodules for beam acceleration. The cavities and solenoids are operated at 2 K. There are six QWR007 cryomodules with five cavities and five solenoids in each one. The eleven HWR015 cryomodules have six cavities and six solenoids in each cryomodule. The superconducting solenoids have integrated two steering dipoles inside, one for horizontal direction and other one for vertical direction.

Table 1
The RF parameters @ 2 K of low beta cavities for iLinac.

Parameters	QWR007	HWR015
Frequency (MHz)	81.25	162.5
Beam tube aperture (mm)	40	40
$\beta_{opt} = v/c$	0.07	0.15
E_{peak}/E_{acc}	4.69	4.7
B_{peak}/E_{acc} (mT/(MV/m))	8.04	6.11
V_{acc} (MV)	1.54	1.68
E_{acc} @ βopt (MV/m)	5.97	5.96
Geometric factor (Ω)	25.9	51
R/Q (Ω)	485.7	292
TTF @ β_{opt}	0.87	0.87
Q_0 @ 2 K	1.43E+09	2.8E+09

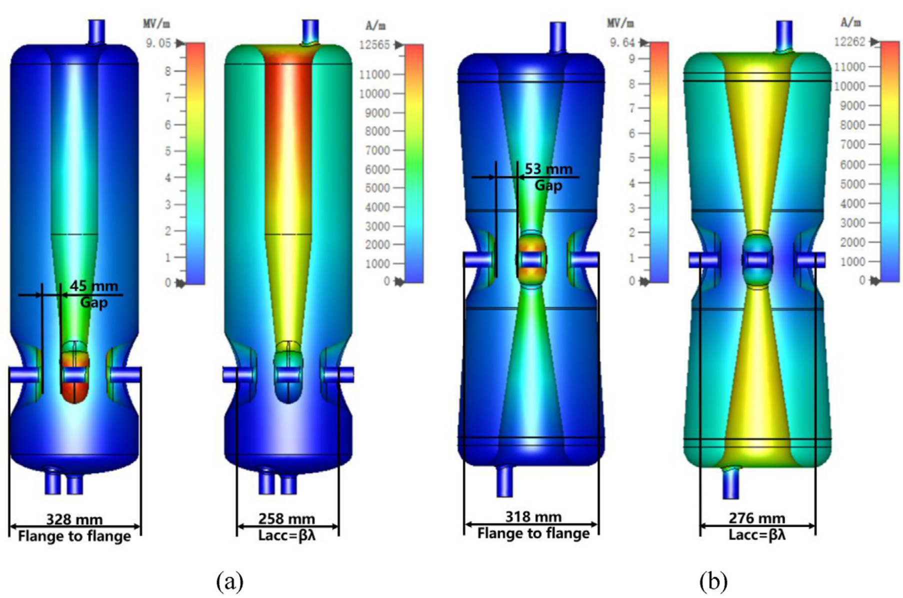


Fig. 2. Geometries and EM field distributions for (a) QWR007 and (b) HWR015. For each cavity, the left plot shows the electric field while the right one shows the magnetic field distribution.

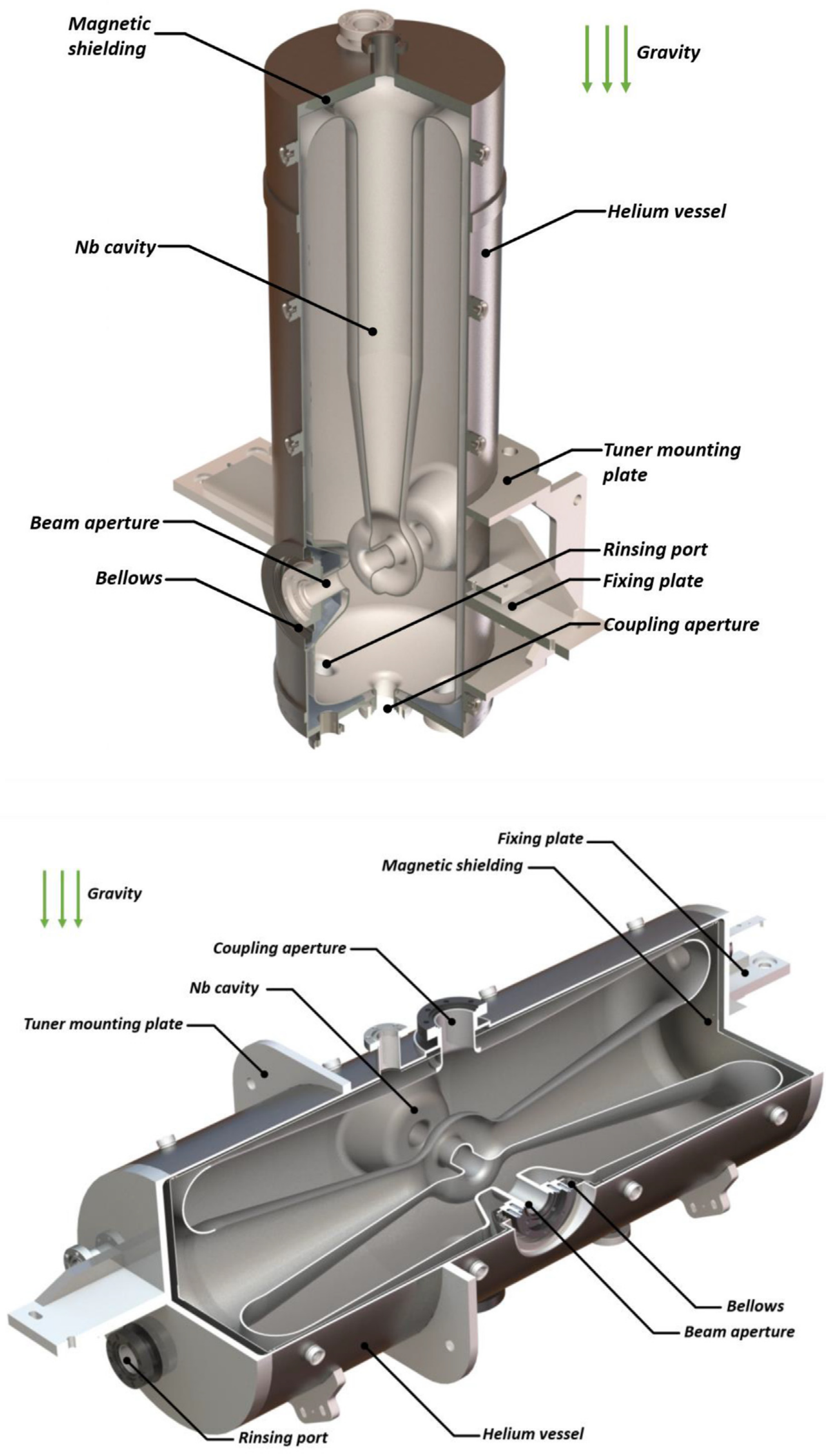


Fig. 3. The mechanical design of QWR007 and HWR015 cavities.

3. Cavities design

There are five main heavy ion superconducting linacs that have been constructed and in full operation in the world: the first one is ALPI linac, which was installed and operates at INFN-LNL. It has two types of QWRs with Nb/Cu sputtering and pure niobium technologies [12]. The second is ISAC-II at TRIUMF that consists of three types of niobium QWRs with optimal beta = 0.057, 0.07 and 0.11 respectively [13]. The third is SPIRAL2 at GANIL with the beta = 0.07 and 0.12 QWRs [14]. The forth is ATLAS linac at ANL that has QWRs with beta = 0.077 and 0.15 [15]. The fifth is a low beta section of FRIB at MSU, which is based on the beta = 0.041 and 0.085 QWRs [16].

The goal of electromagnetic optimization of superconducting

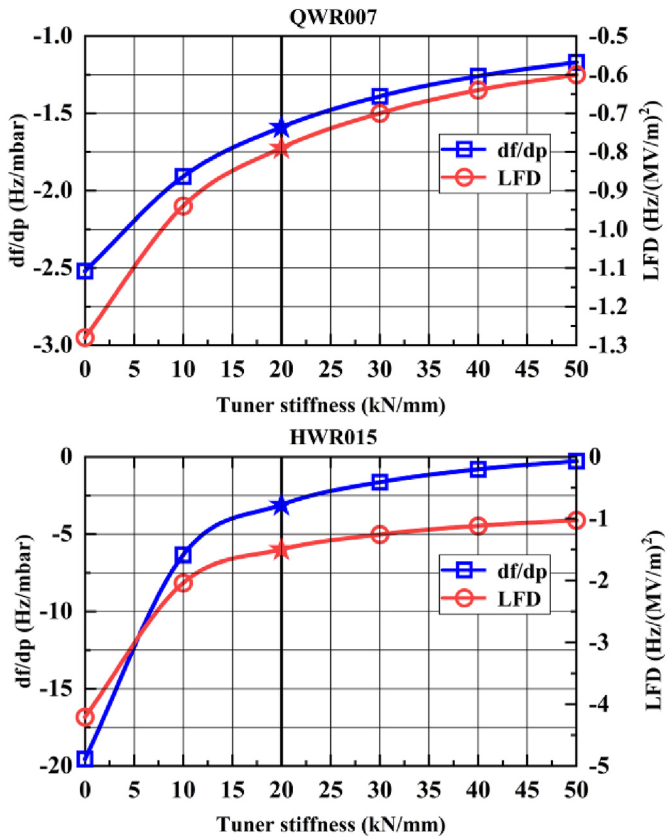


Fig. 4. The df/dp and LFD of QWR007 and HWR015.

cavities is to reduce the maximum surface field. Due to the complex structure, low beta cavities, with a BCP surface treatment, usually encounter field emission at peak electric field more than 30 MV/m instead of 50 MV/m for high beta cavity. As the peak magnetic field increases, the worse of the nonlinear BCS resistance causes the Q value of the cavity to gradually decrease. Based on the existing heavy ion superconducting cavity experience, the operating maximum peak surface magnetic and electric fields were limited by 50 mT and 30 MV/m respectively. Another goal of optimization is increasing cavity's G factor and shunting impedance for reducing the overall power dissipation. There are 23 HWRs with beta = 0.1 and 0.15 installed and operating for the CAFe linac at IMP [17]. The HIAF iLinac's resonators were designed basing on the CAFe's cavity.

The EM are performed by the software of CST Microwave Studio [18]. Fig. 2 shows the electric and magnetic field distributions in the resonators , which have optimized structures with the goal to minimize E_{peak}/E_{acc}, B_{peak}/E_{acc} and maximize (R/Q)*G.

The HWR015 cavity shares the similar structure with CAFe cavity, the high electric field region donut drift tube shape was modified to reduce the E_{peak}/E_{acc} from 4.89 to 4.7. The top section diameter of inner conductor is an enlarged tube shape (Tapper structure) to control the peak magnetic field. The QWR007 is a new design refer to the most features of SPIRAL II cavity. The diameter of the inner conductor in the straight section was optimized to 120 mm for controlling the peak magnetic field of less than 50mT. The straight section is longer for keeping the possibility to add a mechanical damper, which will be decided after the first cryomodule testing. The distance between the bottom section of the outer conductor with the beam tube was optimized to consider supplying enough coupling for the coupler and far away from the peak electric field area. The beam tube section's nose structure is the same with HWR015, and a slope angle of the nose was used for correcting the dipole components to avoid the beam steering [19]. Four rinsing ports, two on the top and two on the bottom, are designed in both cavities to ensure full cove the inner surface of cavity during high pressure rinsing. The final optimized RF parameters of the cavity are shown in Table 1.

4. Cavities mechanical design and simulation

To maintain the SRF cavity's stable operation, the HIAF iLinac helium temperature should be in the range of 1.8–2 K. And it should be keeping the possibility to operate at 4.5 K during the commissioning phase. Therefore, the cavity's mechanical design has to consider the superfluid and 4.5 K helium conditions. The cryomodule uses the same bottom-up structure as the FRIB, with the cavity supported on the rails [20]. The pressure fluctuations between cavity walls and the helium vessel will deform the cavity shape, resulting in the change of resonance frequency and accelerating field profile. It's important to minimize the frequency sensitivity to pressure change df/dp for CW operation [21]. The effects of high electromagnetic fields will cause the cavity frequency change, which comes from the Lorentz forces detuning (LFD) [22].

The cavity with the helium vessel is shown in Fig. 3. The grade 2 titanium is used to fabricate the helium vessel. It is assembled and welded with the cavity's Nb/Ti flange by tungsten inert gas (TIG) welds. To reduce the force requirement for the tuner system, the cavity both beam ports are connected with the helium vessel by titanium bellows. The cavities are assembled in cryomodules in vertical (QWR) and horizontal (HWR) positions respectively. The HWR015 cavity is mounted horizontally on the rail, rather than vertically like the QWR007 cavity, due to avoid interference between the support fixing plates and the coupler. The magnetic field shield layer is used to prevent flux entering the superconducting niobium, which will cause additional power loss. The residual magnetic field requirement for HIAF cavity is less than 15 mG. A 1 mm thickness magnetic shield fabricated by 1J79 permalloy is assembled between the cavity and helium vessel for both types of cavities.

The df/dp and LFD were simulated with software ANSYS [23]. The boundary conditions are set as follows: cavity's supporting fixing plate were fixed point. Since beam port is connected with the tuner, a varying stiffness is applied from 0 to 50 kN/mm. The coupler port is a fixed boundary too. The results of simulations are shown on Fig. 4.

The target of the tuner system's design is to reach the stiffness value better than 30 kN/mm even though considering the transmission losses. There is enough margin for tuner to meet the cavity's minimum stiffness requirement of 20 kN/mm. To enforce the QWR007 cavity's strength, two steps are used during the design: The top side have a stiffening ring connected with helium vessel, and the thickness of cavity noses surrounding beam tubes is 5 mm to increase their rigidity. The QWR007 and HWR015 have a df/dp design values -1.6 and -3 Hz/mbar respectively. The pressure fluctuations of cryogenic system are limited by less than 2 mbar during 2 K operation, which corresponds that the frequency change should be less than -3.2 and -6 Hz. Hence, there is enough margin of the RF power supply comparing with the cavity's 100 Hz half bandwidths. The two cavities' LFD values are -0.8 and -1.5 Hz/(MV/m)^2 respectively. The total frequency change for LFD is -28.16 and -57.11 Hz for operating gradient. As the HIAF iLinac cavities are operating in CW mode, this number can be compensated during the cavity's turn on stage.

The loss of insulating vacuum in cryomodule is a serious problem. The rapid heat exchange will be boiling off the liquid helium in a short time. Pressurized helium gas will cause the cavity

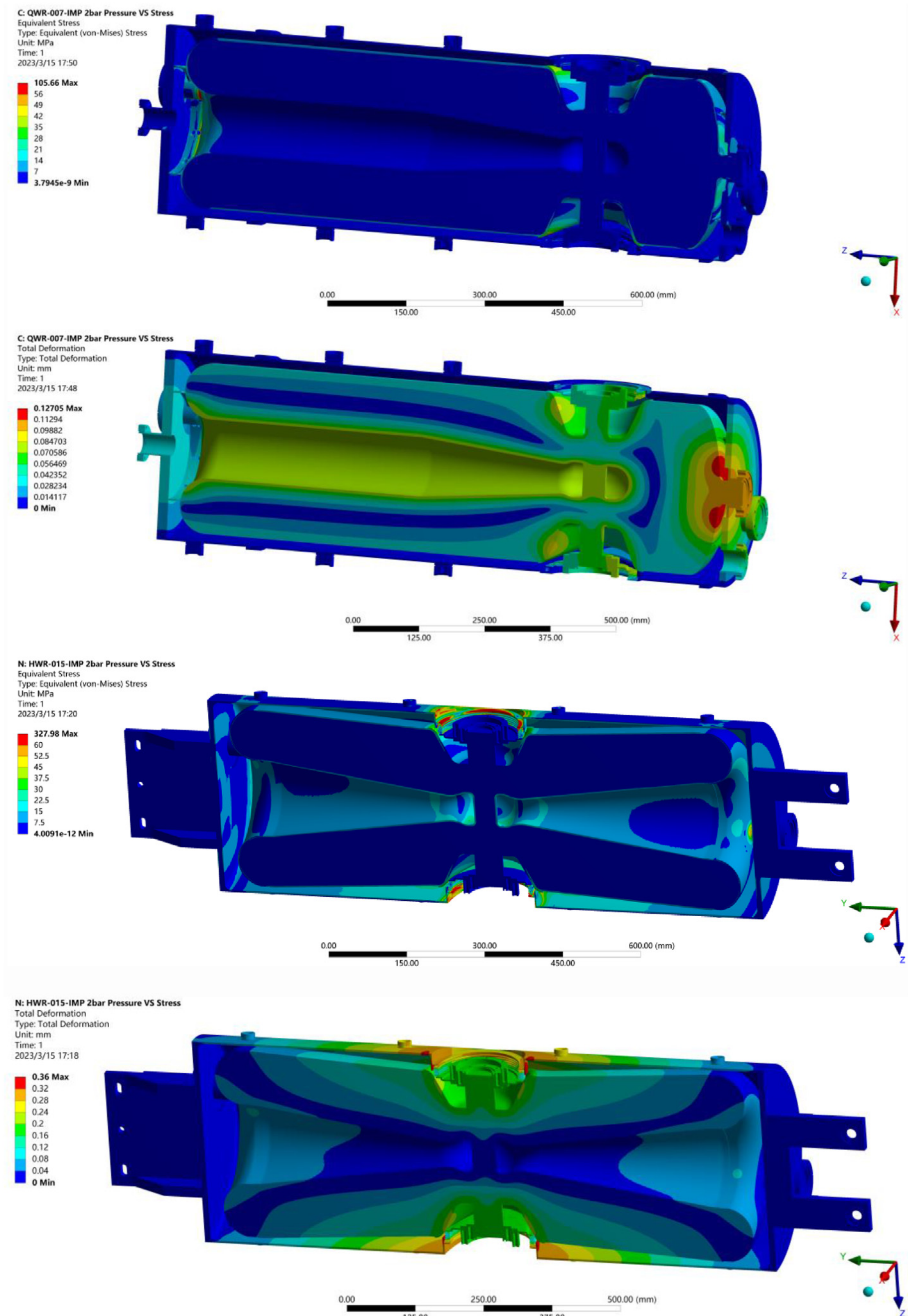
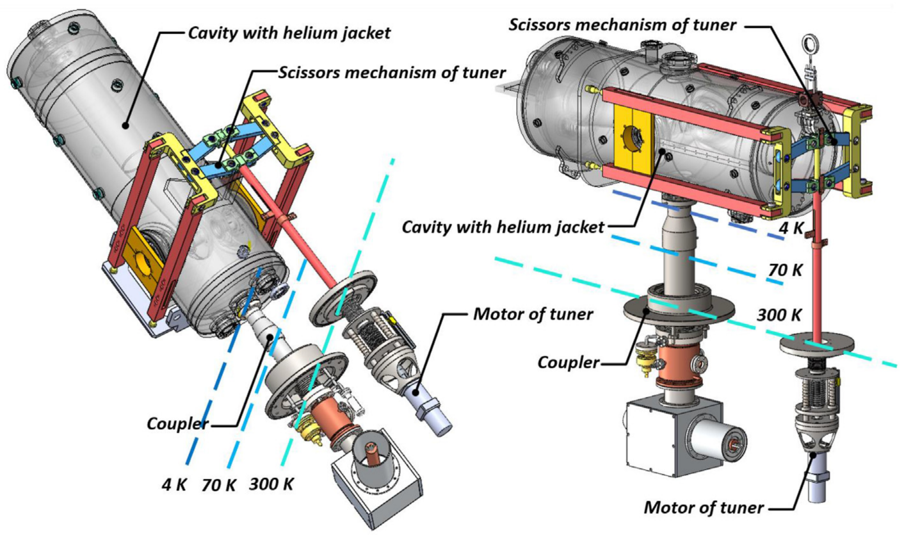


Fig. 5. The stress and deformation distribution of QWR007(Top) and HWR015(Bottom).

deformation. An explosive valve will be designed in the cryomodule to relief this high pressure, normally this valve is set to 2 bar. After the venting, the cavity will go through different temperatures. In addition, the niobium strength is varying according to the temperature. For RRR = 300 niobium, the allowable stresses are 46 (293 K) and 171 (2 K) MPa respectively [24]. The two niobium vendors of IMP show testing yield stress of 50~60 MPa. During the cavity design, two kinds of maximum allowable working pressure (MAWP) were simulated and verified, 2 bar at 293 K and 4 bar at 2 K. The two cavity's simulation results are shown on Fig. 5. These are the deformation and stress distribution at 293 K, which is a worst case comparing to the 2 K. The maximum stress of QWR007 cavity shows 56 MPa, the location is between the top ribs with cavity donut cover's EB welding seam. The maximum stress was evaluated as acceptable, because the welding 90 degrees angle behaved sharply during the simulation, and the other areas were less than 39 MPa. The maximum stress of HWR015 cavity shows 45 MPa for 2 bar @ 293 K, which is evaluated as acceptable too. The maximum deformation shows 0.127 mm and 0.42 mm for QWR007 and HWR015 cavity respectively.

5. Cavity auxiliaries

The cavity system with coupler and tuner is shown on Fig. 6.



(a) (b)

Fig. 6. Isometric views of the cavity systems: (a) QWR007; (b) HWR015.

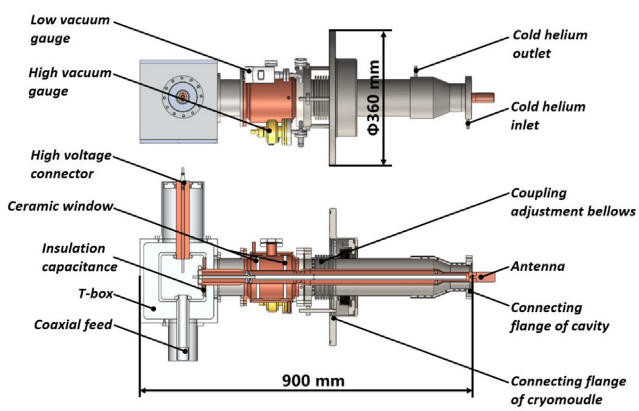


Fig. 7. The fundamental power coupler for HIAF SRF cavity.

Table 2
The coupler parameters of HIAF superconducting cavity.

Parameters	QWR007	HWR015
Frequency (MHz)	81.25	162.5
Adjusting length (mm)	~10	~6
Half Bandwidths (Hz)	100~220	100~220
Q_{ext} (10^5)	1.8~4.1	3.6~8.2
Max operation CW power (kW)	2.8	3.2
Power during condition (kW)	6	6

5.1. Fundamental power coupler design

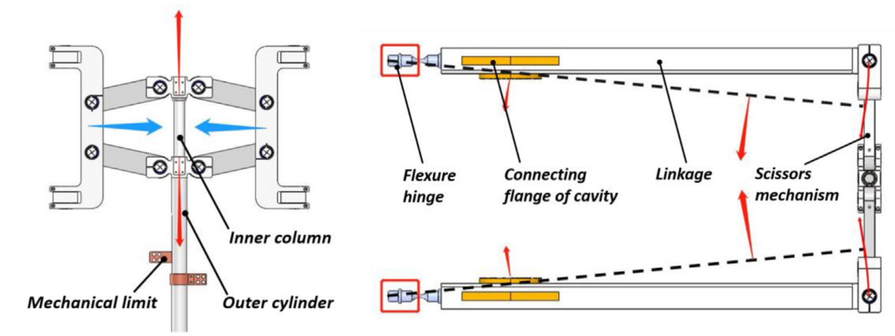
The primary function of the power coupler is to deliver RF power from RF source to SC cavity. The temperature of coupler will cross a range from room temperature to cryogenic. In addition, the other function of the coupler is to isolate atmospheric pressure from the cavity vacuum. The HIAF coupler has a coaxial geometry, which was matured structure in CAFe linac [25]. A dual-warm-ceramic window was used in the warm section to reduce the chance for breaking the vacuum by window cracking. The outer conductor has a bellow for adjusting the coupling coefficient. The coupler structure is shown on Fig. 7. To prevent a heat leaking to the cavity, a 4 K helium gas interception with helix shape was located near the flange connected with the cavity. The inner conductor keeps a cooling pipe preserving the possibility for high power upgrade. The "T" shape transition box was used for easy connection of the cooling pipe and the setup of the high voltage bias.

The coupler will transmit maximum 2.8 kW and 3.2 kW power to the QWR007 and HWR015 cavities. During the conditioning stage, the power will ramp up to 6 kW, which provides additional power to compensate mismatching and frequency fluctuations. The parameters of coupler are shown on Table 2.

The shape of the coaxial line has been optimized for power transition with S11 less than -30 dB. The stresses on ceramic window are less than 220 MPa. The window was coated with a layer of TiN to relieve the multipacting.

5.2. Tuner design

The slow tuner design for the HIAF cavity is based on the work at CAFe of the 162.5 MHz slower tuner for HWR010 cavities. The motor drives the inner rod and outer tube to form an extrusion of the arms, which eventually squeezes the cavity beam tube. Then the deformation causes the cavity frequency change. The piezo-actuator can be added to the inner rod to form a fast tuner too [26]. The schematic model of the slower tuner for the HWR015 cavity is shown on Fig. 8. The arms have a length of 630 mm, and the inner rod and outer tube is 880 mm length to through the cryomodule to connect with ambient side's actuator. The tuner will be mounted on the cavity's helium vessel and located inside the insulating vacuum space. An electromechanical actuator, which drives the coarse tuner, consists of stepper motor, a speed reducer, coupling, and a lead screw. The tuner parameters are shown in Table 3.



(a) (b)

Fig. 8. Motion diagram of tuning mechanism.

Table 3
Parameters of tuners of HIAF's SRF cavity.

Parameters	QWR007	HWR015
Course Tuning range (kHz)	100	200
Cavity tuning sensitivity (kHz/mm)	73.1	126
Cavity stiffness (kN/mm)	16.5	6
Tuner stiffness (kN/mm)	30	30
Tuning force (kN)	22.6	10.5
Resolution (Hz)	<5	<5
Backlash (Hz)	<5	<5
Accuracy of linear motion unit (μm)	<5	<5

6. Summary

The design of superconducting cavity system of HIAF project have been overviewed including the cavity, fundamental power coupler and tuner. The QWR007 and HWR015 cavities were designed according to the experience received from CAFe Linac's low beta cavity. The stiffening rings and thicker niobium sheet are used during the multi-physics optimization to decrease the frequency sensitivity to the helium pressure instability and Lorentz forces deformations. A dual-warm-ceramic window coupler and the scissor like mechanical tuner were developed for the cavity.

The production of niobium cavity is progressing on schedule by two industry companies. The first several sets of cavities, and subsystems such as FPC and tuner will be delivered in recent few months, which can be used to validate the design.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors appreciate the strong supports from the colleagues of IMP's LINAC team. This work is supported by the Large Research Infrastructures "High Intensity heavy-ion Accelerator Facility" (Grant No. 2017-000052-73-01-002107).

References

[1] O. Kester, W. Barth, O. Dolinskyy, F. Hagenbuck, K. Knie, H. Reich-Sprenger, H. Simon, P. Spiller, U. Weinrich, M. Winkler, et al., Status of the fair accelerator facility, in: Proceedings of IPAC2014, Dresden, Germany, 2014, pp. 2084–2087.
[2] I. Selyuzhenkov, Status of the FAIR facility in darmstadt, J. Phys. Conf. Ser. 1685 (1) (2020), 012020, https://doi.org/10.1088/1742-6596/1685/1/012020.
[3] L. Mao, J. Yang, W. Yang, J. Xia, Y. Yuan, P. Yuan, W. Qiao, D. Gao, G. Xiao, H. Zhao, et al., Introduction of the heavy ion research facility in lanzhou (hirfl), Journal of Instrumentation 15 (12) (2020), T12015.
[4] J. Wei, H. Ao, S. Beher, N. Bultman, F. Casagrande, C. Compton, L. Dalesio, K. Davidson, K. Dixon, A. Facco, et al., The frib superconducting linac-status and plans, in: 28th Linear Accelerator Conf.(LINAC'16), East Lansing, MI, USA, 25-30 September 2016, JACOW, Geneva, Switzerland, 2017, pp. 1–6.
[5] J. Wei, et al., FRIB Commissioning and Early Operations, JACoW IPAC2022, 2022, https://doi.org/10.18429/JACoW-IPAC2022-TUIYGD3. TUIYGD3.
[6] X. Zhou, Xiaohong, jiancheng yang, and HIAF project team., status of the high-intensity heavy-ion accelerator facility in China, AAPPS Bulletin 32 (1) (2022) 35.
[7] J. Yang, J. Xia, G. Xiao, H. Xu, H. Zhao, X. Zhou, X. Ma, Y. He, L. Ma, D. Gao, et al., High intensity heavy ion accelerator facility (hiaf) in China, Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms 317 (2013) 263–265.
[8] X. Ma, W. Wen, S. Zhang, D. Yu, R. Cheng, J. Yang, Z. Huang, H. Wang, X. Zhu, X. Cai, et al., Hiaf: new opportunities for atomic physics with highly charged heavy ions, Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms 408 (2017) 169–173.
[9] Z. Xiaohong, Physics opportunities at the new facility HIAF, Nucl. Phys. Rev. 35 (4) (2018) 339–349, https://doi.org/10.11804/NuclPhysRev.35.04.339.
[10] S. Liu, Y. He, Z. Wang, The Beam Dynamics Design of HIAF Superconducting Injector, 2018 presented at HB2018 in Daejeon, Korea, July.
[11] Z. Zhang, X. Xu, Y. He, S. Zhang, C. Wang, S. Zhang, C. Li, Y. Huang, Design of a radio frequencyquadrupole for a high intensity heavy-ion accelerator facility, Phys. Rev. Accel. Beams 25 (8) (2022), 080102, https://doi.org/10.1103/PhysRevAccelBeams.25.080102.
[12] G. Bisoffi, G. Bassato, S. Canella, D. Carlucci, A. Facco, P. Modanese, A. Pisent, A. Porcellato, P. Pósocco, et al., Alpi qwr and s-rfq operating experience, in: Proceedings of SRF2007, Peking University, Beijing, China, 2007.
[13] D. Longuevergne, C. Beard, A. Grassellino, P. Kolb, R. Laxdal, V. Zvyagintsev, RF cavity performance in the ISAC-II superconducting heavy ion linac, in: Proceedings of Linear Accelerator Conference LINAC2010, Tsukuba, Japan, 2011, p. THP044.
[14] Claude Marchand, et al., Performances of SPIRAL2 low and high beta cryomodules, in: Proc. 17th Int. Conf. On RF Superconductivity (SFR2015), 2015.
[15] P. Ostroumov, R. Pardo, SRF acceleration for heavy ions: ATLAS decadal operation and evolution, Journal of Instrumentation 12 (04) (2017), https://doi.org/10.1088/1748-0221/12/04/t04001. T04001–T04001.
[16] C. Zhang, W. Hartung, J. Popielarski, K. Saito, S. hoon Kim, W. Chang, T. Xu, Certification testing of production superconducting quarter-wave and half-wave resonators for frib, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 1014 (2021), 165675, https://doi.org/10.1016/j.nima.2021.165675.
[17] Y. He, et al., Development of accelerator driven advanced nuclear energy and nuclear fuel recycling, in: Proc. 10th International Particle Accelerator Conference (IPAC'19), Melbourne, Australia, 19-24 May 2019, No. 10 in International Particle Accelerator Conference, JACoW Publishing, Geneva, Switzerland, 2019, pp. 4389–4393, https://doi.org/10.18429/JACoW-IPAC2019-TUYPLS2.
[18] https://www.3ds.com/products-services/simulia/products/cst-studio-suite/.
[19] P.N. Ostroumov, K.W. Shepard, Correction of beam-steering effects in low-velocity superconducting quarter-wave cavities, Physical Review Special Topics-Accelerators and Beams 4 (11) (2001), 110101.
[20] F. Bai, Cryomodule development at IMP-lessons learned from operation of C-ADS and recent design for HIAF project. TTC 2021, TESLA Technology Collaboration, 19-21 January, https://indico.desy.de/event/27572/contributions/94178/, 2021.
[21] P.N. Ostroumov, et al., Elliptical superconducting RF cavities for FRIB energy upgrade, Nuclear Instruments and Methods in Physics Research Section A:

Accelerators, Spectrometers, Detectors and Associated Equipment 888 (2018) 53–63.
[22] Curt Hovater, et al., RF Control Requirements for the CEBAF Energy Upgrade Cavities. No. JLAB-ACE-00-01; DOE/ER/40150-1766, Thomas Jefferson National Accelerator Facility (TJNAF), Newport News, VA (United States), 2000.
[23] http://www.ansys.com/.
[24] Donato Passarelli, et al., Methodology for the structural design of single spoke accelerating cavities at Fermilab, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 834 (2016) 1–9.
[25] Z. Lin, T. Jiang, S. Huang, Y. Huang, Z. Gao, R. Wang, Z. Xue, Z. Yang, C. Li, M. Lu, et al., Development of a dc bias structure with reduced rf leakage for suppressing the multipacting effect in the high power coaxial couplers, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 988 (2021), 164891.
[26] G. Davis, J. Delayen, M. Drury, E. Feldl, Development and testing of a prototype tuner for the cebaf upgrade cryomodule, in: PACS2001. Proceedings of the 2001 Particle Accelerator Conference (Cat. No.01CH37268), 2, 2001, pp. 1149–1151, https://doi.org/10.1109/PAC.2001.986609.