

High-power test of the single-periodic magnetically coupled standing-wave accelerating structure for a proton therapy linac

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A single-periodic magnetically coupled standing-wave accelerating structure prototype operating at 3 GHz for low phase velocity particles has been designed as the first tank of the 30–230 MeV accelerating section for the compact proton therapy linac developed by the Institute of Modern Physics, Chinese Academy of Sciences. Fabrication and rf measurement of the prototype have been completed. High-power test of the prototype was performed. The cavity could operate stably at the effective input power of around 5.7 MW, corresponding to the accelerating gradient of 38 MV/m at the pulse length of 5 μ s and the repetition rate of 70 Hz. Further increasing the duty factor to 0.1%, the accelerating gradient decreased to 24 MV/m due to the uneven cooling of each single cell. The details of the high-power test setup and preparation, the process of rf conditioning, and the high-power test results are described in this paper. Limiting factors for higher accelerating gradients with high duty factors are discussed, and two novel cooling channel schemes are described.

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I. INTRODUCTION

Compact proton therapy linacs with high accelerating gradients and high frequencies have been widely studied and developed in recent years. The Intensity Modulated Proton Linear Accelerator for Radiotherapy (TOP-IMPLART) proton linac, developed by ENEA Frascati Research Center, was successfully operated at a beam energy of 63 MeV, and the last module of the fourth section has already been installed, increasing the beam energy to 71 MeV [1–4]. The first commercial high-frequency linac-based proton therapy accelerator system is the Linac for Image Guided Hadron Therapy (LIGHT) system, which was promoted by Applications of Detectors and Accelerators to Medicine, CERN spin-off (ADAM) [5,6]. All major subsystems of the LIGHT system have been integrated, and the LIGHT system reached the maximum treatment energy of 230 MeV on September 26, 2022 [7,8]. An all-linac solution for the Turning Linac for Proton therapy project (TULIP) was proposed by TERA Foundation in 2013 [9,10]. TERA launched a high gradient research campaign in collaboration

with CERN. An S-band high gradient backward traveling wave accelerating structure for $\beta = 0.38$ was designed and tested [11–14]. A new compact, ultrahigh dose rate (FLASH) radiotherapy proton therapy linac was also proposed in Shanghai, China, and the design of the all-linac proton therapy facility scheme was completed [15,16].

Fast and effective modulation of the output beam energy could be achieved since the output energy of the linac could be actively changed by switching off some of the tanks and adjusting the incident power level [4,17]. Besides, proton therapy linacs can be single-room facilities by using accelerating structures with high frequencies and high gradients. A compact proton therapy linac has been developed at the Institute of Modern Physics, Chinese Academy of Sciences (IMP, CAS) [18,19], as shown in Fig. 1. The compact proton therapy linac configuration consists of four sections: 750 MHz RFQ and 750 MHz IH-DTL that cover the first 10 MeV energy range well, followed by two S-band SCDTLs that accelerate protons from 10 to 30 MeV; then S-band high-gradient accelerating structures are used to boost the proton energy to 230 MeV.

The 30–230 MeV accelerating section includes 24 tanks, with 11 accelerating cells in each tank, corresponding to the particle velocity ranging from 0.26 to 0.56 c and an effective accelerating gradient ranging from 30 to 37 MV/m.

A single-periodic magnetically coupled standing-wave accelerating structure prototype operating at 3 GHz for the

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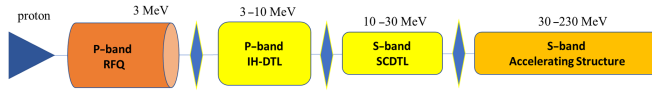


FIG. 1. Layout of proton therapy linac scheme.

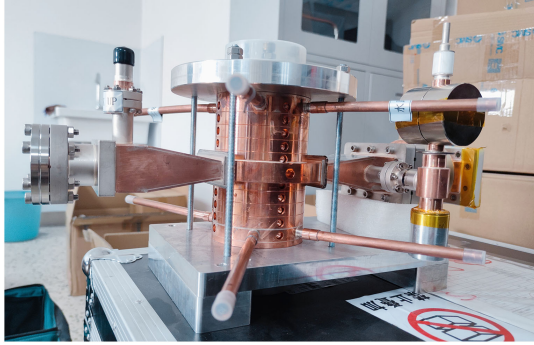


FIG. 2. Overall view of the completed prototype.

low phase velocity of 0.26 c , as shown in Fig. 2, has been designed, fabricated, and rf measured. The active length of the prototype cavity is 143 mm, consisting of 10 regular cells and a matching cell, and the matching cell is in the middle of the cavity to improve mode separation. The field flatness of the prototype is less than 5% after tuning. More detailed process of the rf design, optimization, and fabrication for the prototype was described in Ref. [18]. In this paper, the high-power test of the single-periodic magnetically coupled standing-wave accelerating structure prototype is introduced, and limiting factors for higher accelerating gradients with high duty factors are discussed and analyzed.

II. HIGH-POWER TEST SETUP AND PREPARATION

The high-power test of the first single-periodic magnetically coupled standing-wave accelerating structure prototype was performed at IMP. The high-power test setup consists of three systems, as shown in Fig. 3: the power source system, the accelerating structure prototype and its accessory measuring equipment system, and the low-level radio frequency (LLRF) system. All these systems must be ready before the high-power test.

A. Power source system

The accelerating structure was powered by a 6 MW S-band klystron, which delivered rf pulses with a maximum length of 20 μ s at a repetition rate of 100 Hz, or rf pulses with a length of 10 μ s at a maximum repetition rate of 200 Hz. The klystron is driven by a preamplifier stage consisting of a 1200 W solid-state amplifier with 60 dB gain. The excitation signal of the klystron is provided by the LLRF system based on the signal generated by the arbitrary waveform generator.

The klystron is connected to the structure via N_2 -filled WR-284 waveguides, followed by a 3 GHz ceramic window to isolate the vacuum, and is protected against reflected power by a high-power circulator. The power source system needs to be tested with matched load first to verify the availability of the klystron and the high-power circulator before the high-power test. The test station consists of the klystron, two directional couplers, one high-power circulator, and a water-cooled load at the end of the test station to absorb incident power, as shown in Fig. 4. Two directional couplers are located before and after the high-power

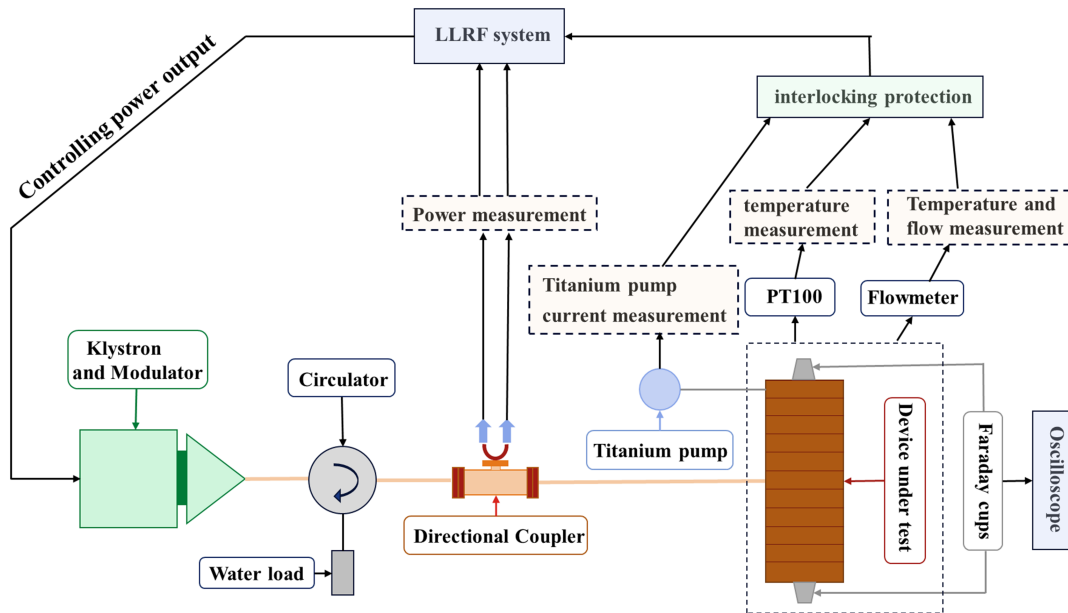


FIG. 3. Schematic diagram of the high-power test system.

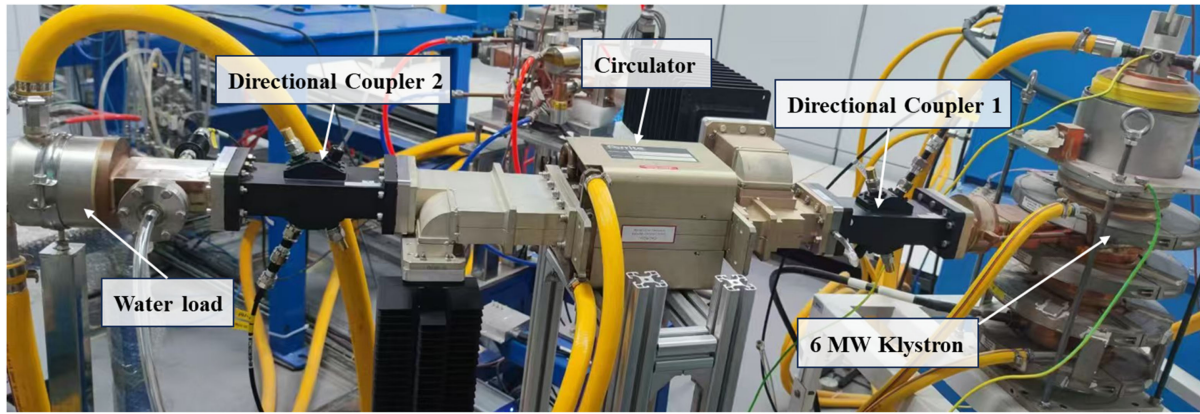


FIG. 4. Drawing of test setup for the power source system.

circulator: one measures the output power of the klystron, and the other measures the transmitted power after the circulator to evaluate whether rf breakdown (BD) events have occurred in the circulator. Pickup on the rf water load was equipped to measure the incident power.

The high-power circulator and waveguide were filled with nitrogen gas (N_2) to prevent rf breakdown by resisting ionization. First, when the N_2 pressure was 0.2 MPa, the transmitted power measured by directional coupler 2 and the pickup on the water load no longer increased with increasing klystron output power once it exceeded 3.1 MW, which proves that the circulator cannot operate stably at high klystron output power. Increasing the N_2 pressure to 0.4 MPa, the problem was solved. The test result of the power source system showed that the power generated by the klystron to the accelerating structure through the circulator and directional couplers was 5.74 MW, which meets the high-power test requirements.

B. Accelerating structure prototype and its accessory measuring equipment system

To match the output waveguide port of the klystron, the accelerating structure under test is placed vertically. The high-power test setup is shown in Fig. 5. A 3 GHz ceramic window separates the N_2 from the accelerating structure vacuum. Two titanium windows are placed in the beam ports to isolate the cavity vacuum, with the capability for dark current measurement when equipped with Faraday cups. Then, helium leak testing was performed on all interfaces, and the leakage rate was lower than 1×10^{-10} mbar. L/s, which satisfied the cavity vacuum sealing requirements. Before the high-power test, high-temperature baking and venting of the cavity were performed to realize a high vacuum in the accelerating structure, which helps to avoid rf breakdown in strong electromagnetic fields due to the residual gases inside the cavity. Besides, baking is helpful to reduce the rf conditioning time. The vacuum inside the cavity

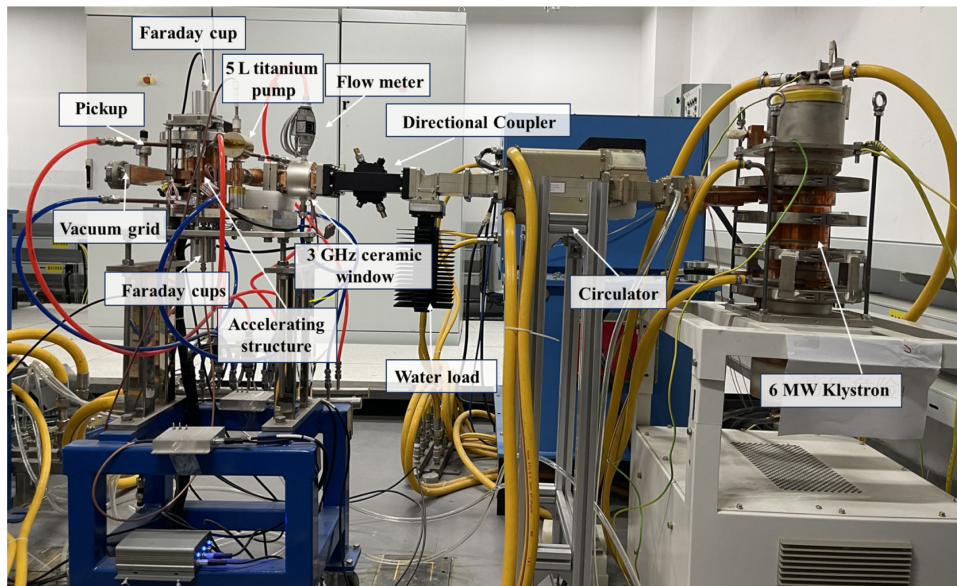


FIG. 5. High-power test setup.

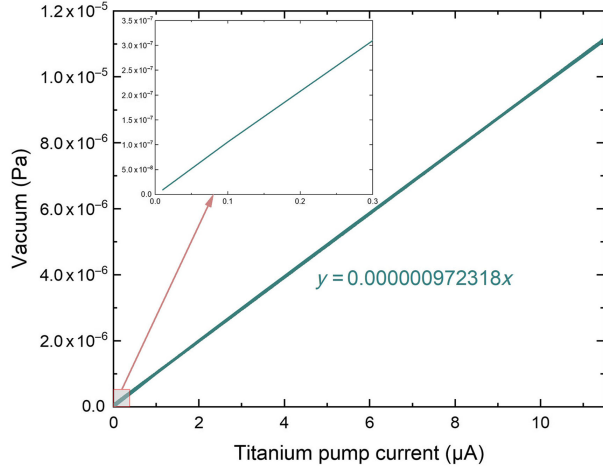


FIG. 6. Relationship between the titanium pump current and the vacuum of the structure.

reached 2.6×10^{-8} Pa after high-temperature baking and venting. A 5 L titanium pump is installed on the waveguide of the power coupler through an rf pumping port to keep the ultrahigh vacuum in the cavity. Titanium pump current is read in real time to monitor the vacuum of the cavity. Figure 6 shows the relationship between the titanium pump current and the vacuum of the structure.

Two Faraday cups, placed at the titanium windows, are used to measure dark current and detect breakdown events. A directional coupler is placed at the input of the cavity to measure the incident and reflected rf power signals. A pickup located at the waveguide with the vacuum grid is used to measure the effective transmitted power into the cavity.

The ambient temperature for the device under test is maintained at 20 °C. The temperature of the inlet cooling water is maintained at 22.5 ± 1 °C. A four-channel bottom-to-top cooling water flow direction is used to avoid air bubble accumulation, thus increasing the cooling effect of the structure. Four flow meters are installed on the cooling channels to monitor the flow and temperature of the cooling water. Sixteen temperature sensors are attached to the same relative positions on the 11 rf cells, the upper and lower end caps, the two waveguides, and the ceramic window to monitor the temperature of each rf cell and prevent overheating.

An area radiation monitor is mounted on the wall of the test room to monitor the dose of γ -rays and neutrons around the accelerating structure under test.

C. LLRF system

The interfaces of the LLRF system and the klystron-modulator's independent interlock system are used for rf conditioning. The LLRF system has several functions in the high-power test, including (1) Controlling the pulse length and incident power level of the accelerating structure. Note

TABLE I. Interlocking conditions for high power testing.

Interlocking conditions	
Temperature sensor's temperature	>45 °C
Cooling water flow	<3 L/min
Titanium pump current (vacuum of cavity)	>5 μ A ($<4.9 \times 10^{-6}$ Pa)

that the power-level channels are calibrated before measuring the power signals with the LLRF system. (2) Performing data acquisition of rf power signals and detecting BD events by monitoring sudden increases in reflected power or abrupt decreases in pickup power 2 μ s after the pulse starts. (3) Receiving the interlock signal and cutting off the incident power immediately if any interlock condition is triggered. The interlock conditions for the high-power test are summarized in Table I.

The klystron-modulator is equipped with an independent interlock, which ensures personal safety (none can enter the testing room while in operation) and machine safety.

III. HIGH-POWER TEST PROCESS AND RESULTS ANALYSIS

A. Calibration of power signals

To obtain the accelerating gradient of the structure, it is necessary to measure the effective power fed into the cavity accurately during high-power tests. The incident, reflected, and pickup power signals were transmitted by three 32-m-long coaxial cables from the directional coupler and the pickup of the cavity to the LLRF system, and the attenuations along the three signal lines were measured before the high-power test. The measurement results are summarized in Table II. The maximum incident, reflected, and pickup power during the test was around 5.74 MW, which is more conveniently expressed in dBm. It can be converted between dBm and mW using Eq. (1).

$$Y[\text{dBm}] = 10 \log_{10} \frac{X[\text{mW}]}{1 [\text{mW}]} \quad (1)$$

Here X is the power in mW, and Y is the corresponding power in dBm. Therefore, the maximum incident, reflected, and pickup power was 97.589 dBm. However, the maximum power value that can be accepted by the LLRF system is 10 dBm, so two -20 dB attenuators were added to the incident and reflected power signal transmission lines, respectively, and a -30 dB attenuator was positioned on the pickup power signal transmission line to avoid damaging the electronic circuits due to excessive power coupled into the LLRF system, and the LLRF system can measure a minimum power level of -35 dBm, which meets the requirements of high-power testing. Then the power signal of the cavity can be obtained directly through the LLRF

TABLE II. Measured attenuations and maximum/minimum power coupled to the LLRF system.

	Incident power signal transmission lines	Reflected power signal transmission lines	Pickup power signal transmission lines
Maximum incident power (dBm)	97.589	97.589	97.589
Minimum incident power (dBm)	66.99	66.99	66.99
Bidirectional coupler (measure) (dB)	-59.361	-59.064	
rf cables (measure) (dB)	-15.313	-15.216	-15.391
Attenuator (measure) (dB)	-19.814	-19.911	-29.838
Pickup port coupling (measure) (dB)			-49.2
Total attenuation of the transmission line (dBm)	-94.488	-94.191	-94.429
Maximum output power coupled to the LLRF system (dBm)	3.101	3.398	3.16
Minimum output power coupled to the LLRF system (dBm)	-27.498	-27.201	-27.439

system after correlating the measured attenuation with the corresponding power-level channels of the LLRF system.

The LLRF system under different pulse lengths and repetition rates was calibrated by the peak power meter (8990B KEYSIGHT) to verify the accuracy of the power measurements. The results of the power signal with 9 μ s pulse length and 10 Hz repetition rate measured by the peak power meter and the LLRF system are shown in Figs. 7 and 8, respectively. Figure 7(a) shows both the incident and pickup power signals and Fig. 7(b) shows both the pickup and reflected power signals. From the figures, the power waveforms measured by the peak power meter and the LLRF system are similar. The mean incident power measured by the peak power meter is 96.21 dBm, i.e., 4.18 MW, which is basically consistent with that measured by the LLRF system of about 4200 kW. An additional N to SMA coaxial coupler was added on the power transmission line to measure the power signal with the peak power meter. Here the attenuation through the coaxial coupler was not calibrated, so the power amplitude measured by the peak power meter is slightly lower than that measured by the LLRF system; however, the results are within the allowable error range. The later peak of the reflected power waveform is higher than the former peak, indicating that the accelerating structure is overcoupled, which is consistent with

the results of cold rf measurement [18]. The sampling rate of the LLRF system is 12.5 MHz, so the pulse length measured by the LLRF system is consistent with that measured by the peak power meter. Therefore, the power signals measured by the LLRF system were considered accurate based on the calibration results, so all results and analyses of the high-power test were based on the LLRF system.

B. High-power test process and rf conditioning logic

The delay time of the arbitrary waveform generator was adjusted first to synchronize the excitation signal of the klystron with the high-voltage pulse signal of the modulator before the high-power test, as shown in Fig. 9.

The cavity resonance frequency was different from that obtained in cold rf measurement [18] due to the effect of cooling water and room temperature change. Therefore, the cavity resonant frequency was captured first from the reflected power signal where the reflected power is minimum; then the phase-locking function of the LLRF system was switched on to track the resonant frequency of the cavity as the incident power changes.

The rf conditioning began with a low repetition rate of 10 Hz and a pulse length of 2 μ s to avoid damage to the cavity. With the titanium pump current level below an

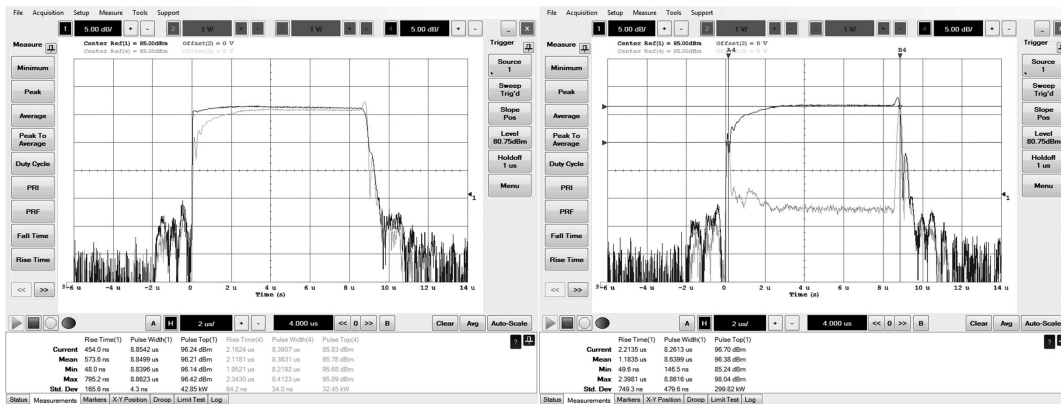


FIG. 7. Power signals measured by the peak power meter.

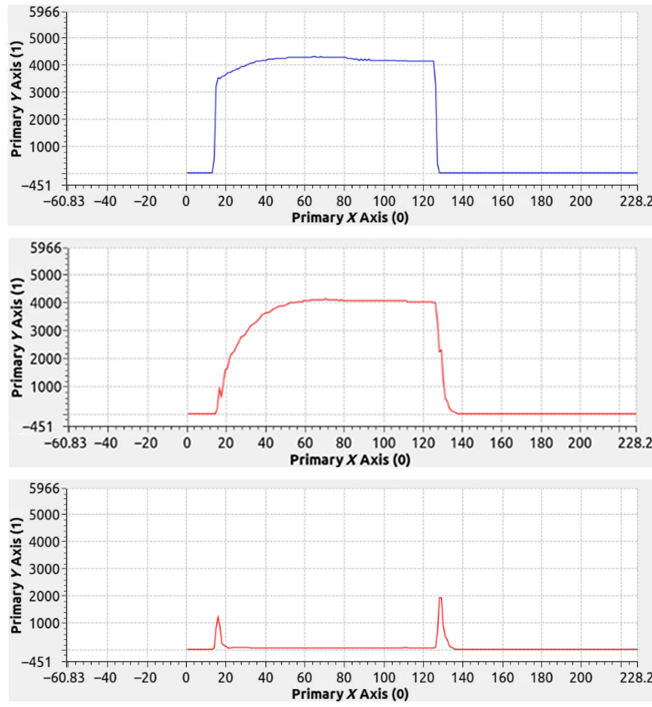


FIG. 8. Power signals measured by the LLRF system.

acceptable threshold, typically $2 \mu\text{A}$, corresponding to 2×10^{-6} Pa, and with no BD events for a long time, the incident power was increased in certain steps until the effective input power into the cavity reached the target value. Then, the incident power was reduced by about 20%, and the pulse length was incremented by $0.5 \mu\text{s}$. When the effective input power into the cavity exceeded the target value, the process was repeated with a longer pulse. The pulse length was progressively increased up to $5 \mu\text{s}$. Then, with the pulse length of $5 \mu\text{s}$, the repetition rate was gradually increased in steps of 10 Hz, similar to the process of increasing the pulse length.

The titanium pump current was in the nA range with no incident power, indicating that the cavity vacuum was well maintained. The titanium pump current slightly increased

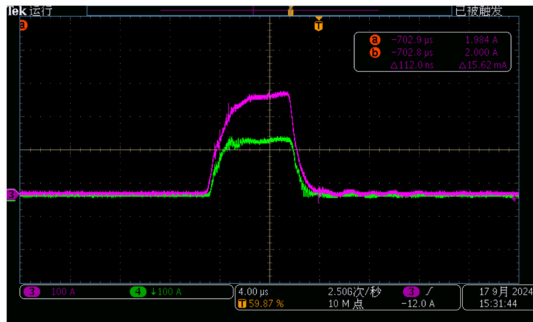


FIG. 9. Synchronization of the excitation signal of the klystron with the high-voltage pulse signal of the modulator.

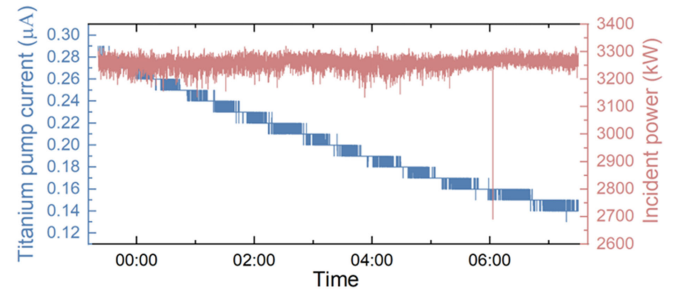


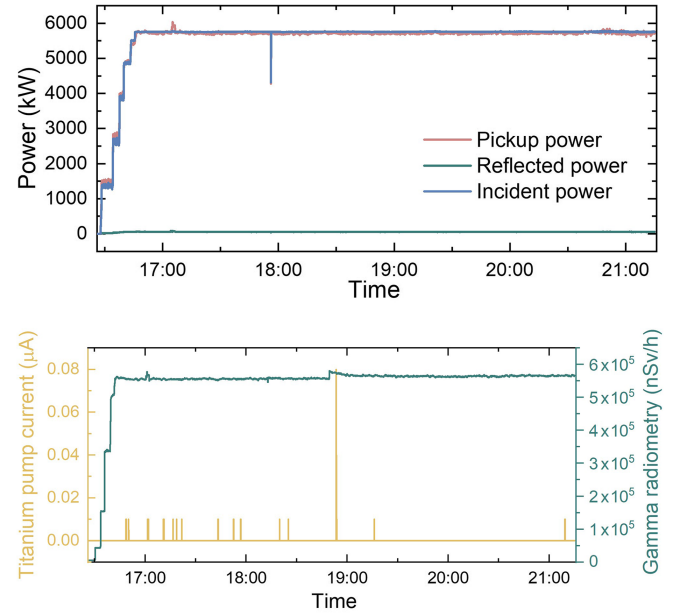
FIG. 10. Titanium pump current over time as the incident power remains constant.

after the incident power was fed into the structure, and then gradually decreased as the incident power remained constant, which was a process of gradual recovery of the vacuum in the cavity, as shown in Fig. 10. The breakdown rate (BDR) of the structure was always less than 1×10^{-6} bpp/m during the progress of rf conditioning.

C. High-power test results analysis

After the rf conditioning, the cavity could operate stably at effective input powers exceeding 5.7 MW, with a maximum incident power of 5.74 MW generated by the klystron through the circulator and directional coupler, a pulse length of $5 \mu\text{s}$, and a repetition rate of 70 Hz. Figure 11 shows the variations in incident, reflected, and pickup power, titanium pump current, and generated γ -rays radiometry over time.

The effective accelerating gradient of the cavity can be calculated by Eq. (2):

FIG. 11. Incident, reflected, and pickup power of the cavity (up), titanium pump current, and γ -rays radiometry (down) over time with the pulse length of $5 \mu\text{s}$ and the repetition rate of 70 Hz.

$$E_{\text{acc}}^2 = ZTT \left(\frac{P_{\text{cav}}}{L} \right). \quad (2)$$

Here E_{acc} is the effective accelerating gradient of the cavity, ZTT is the effective shunt impedance in unit length, P_{cav} is the effective dissipated power of the structure, equal to the incident power P_{in} minus the reflected power P_{ref} , and L is the structure length, which is 142.85 mm.

The reflected power measured by the directional coupler may have some isolation error, so Eq. (3) was used to calculate the P_{ref} [20]:

$$P_{\text{ref}} = P_{\text{in}} \left(\frac{\text{SWR} - 1}{\text{SWR} + 1} \right)^2. \quad (3)$$

Here SWR is the standing wave ratio of the cavity, which is 1.1345 and was obtained in the cold rf measurement [18]. The reflected power was small because the coupling of the cavity was close to the critical coupling, and the reflected power was only in the order of kW, with the incident power being in the order of MW. Therefore, the effective input power of the structure P_{cav} was essentially equal to the incident power, which means $P_{\text{cav}} = P_{\text{in}} - P_{\text{ref}} \approx P_{\text{in}}$.

The effective shunt impedance ZTT can be calculated by the Eq. (4):

$$ZTT = GQ_0. \quad (4)$$

Here G is the geometric factor of the cavity in unit length, which is a structural parameter that is independent of the cavity material; thus, the actual geometric factor of the accelerating structure is equal to the simulation value, which is 6233 Ω/m [18]. According to the cold rf measurement results [18], the actual Q_0 is 95.8% of the

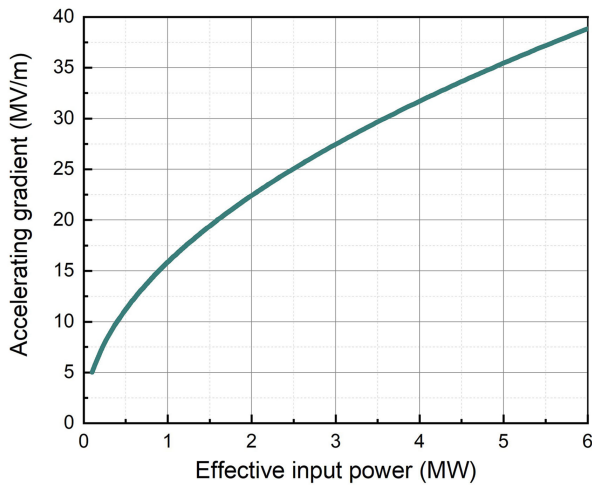


FIG. 12. Relationship between the accelerating gradient and the effective input power of the accelerating structure.

simulation value. Therefore, the actual shunt impedance ZTT of the cavity is 35.9 $\text{M}\Omega/\text{m}$.

Based on the above analysis, the relationship between the accelerating gradient and the effective input power of the accelerating structure is obtained, as shown in Fig. 12.

The accelerating structure prototype can operate stably at 5.7 MW with a duty factor of 0.035%, achieving an effective accelerating gradient of 38 MV/m. Furthermore, the BDR of the accelerating structure remained below 1×10^{-6} bpp/m, indicating the potential for this prototype to achieve even higher accelerating gradient.

IV. STUDY ON HIGH DUTY FACTOR

LIGHT, the first linear accelerator used for proton cancer treatment worldwide, can vary the beam energy 200 times per second, with a treatment pulse length ranging from 0.5–5 μs , depending on the depth of the tumour layer [8,21]; the linear accelerator operates at a maximum duty factor of 0.1%. The single-periodic magnetically coupled standing-wave accelerating structure prototype was also investigated under high duty factors conditions to explore its operational stability.

The surface resistance of the normal-conducting accelerating structure is calculated by Eq. (5):

$$R_s = \sqrt{\frac{\mu_0 \omega}{2\sigma}}. \quad (5)$$

Here σ is the electrical conductivity of the structural materials and ω is the angular frequency. In normal-conducting accelerating structures, the rf power dissipation scales with the operating frequency, leading to more pronounced heating at higher frequencies. Similarly, achieving a high gradient requires higher rf power to establish the field. The combination of these two effects results in a large heat flux density, limiting high-frequency and high-gradient structures to low-duty-factor operation [14,16].

When the accelerating structure prototype operates at a high duty factor, the heat flux density increases, leading to a greater heat load on the cooling water. If the water flow rate remains constant, the coolant temperature increases significantly as it flows through the structure, which may lead to instability in the series-cooled accelerating structure shown in Fig. 13. In this section, the structural stability of the cavity prototype is investigated under high duty factor conditions with the repetition rate of 200 Hz and the pulse length of 5 μs .

A. Coolant flow direction

A four-channel bottom-to-top cooling water flow direction is used first to avoid air bubble accumulation. The cavity can operate stably at 1.8 MW with a repetition rate of 200 Hz and pulse length of 5 μs . As the incident power

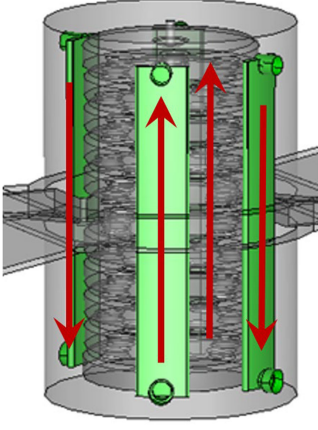


FIG. 13. Cooling channels of each accelerating cell are connected in series.

increased further, the pickup power no longer increased, and the reflected power remained essentially unchanged. The cavity's incident, reflected, and pickup power waveforms remained normal. At the same time, the dark current and titanium pump current did not increase significantly. Besides, the temperature rises monitored by the temperature sensors attached to the upper side rf cells were higher than those of the lower side rf cells. This temperature gradient increased with incident power. The lower part of the structure is cooled better due to the four-channel cooling water flow from bottom-to-top. Varying temperatures across cells caused differing elastic deformations, altering the field distribution and resulting in nonuniform cavity voltages.

To cool the structure more evenly, the four-channel bottom-to-top cooling water flow direction was changed to a staggered arrangement of two bottom-to-top and two top-to-bottom cooling water flow directions. The achievable pickup power then increased to 2.4 MW, corresponding to an accelerating gradient of 24 MV/m. The variations in the incident, reflected, and pickup power, titanium pump current, and generated γ -rays radiometry over time are shown in Fig. 14. From the figure, cavity outgassing was occasionally observed, and the vacuum recovered quickly. It was obvious that the accelerating structure could operate at a higher power through improved cooling uniformity.

The accelerating structure could not operate stably after the incident power exceeded 2.4 MW even with the improved cooling scheme. Figure 15 shows the temperature distribution of each rf cell monitored by the temperature sensors, and the 11 cells of the cavity were defined in top-to-bottom order as cell 1, cell 2, ..., and cell 11. From the figure, cooling efficiency on the lower side of the structure was still better than the upper side.

The heat carried away by the cooling water was derived to calculate the effective input power of the cavity. As the electromagnetic field was established after power was fed into the cavity, free electrons in the conductor moved in the electromagnetic field to form a conduction current,

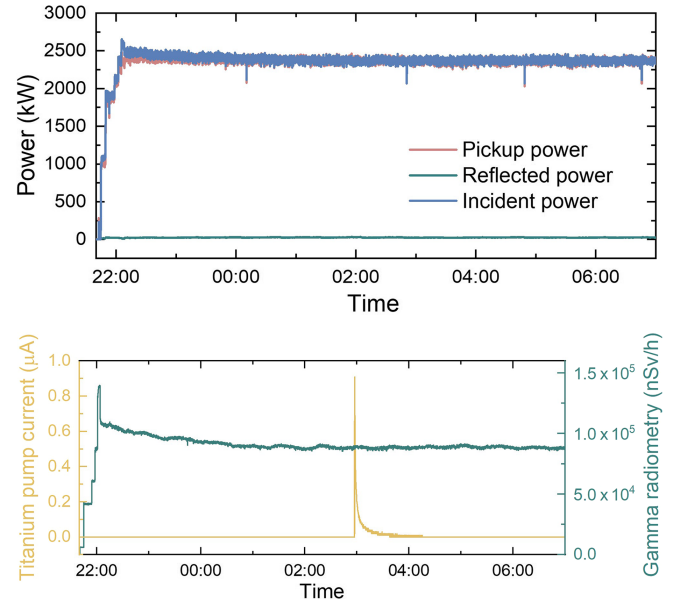


FIG. 14. Incident, reflected, and pickup power of the cavity (up), titanium pump current, and γ -rays radiometry (down) over time with the pulse length of 5 μ s and the repetition rate of 200 Hz.

generating Joule heat that was mainly removed by the cooling water. The heat Q carried away by the cooling water can be calculated by Eq. (6).

$$Q = cm\Delta T. \quad (6)$$

Here c is the specific heat capacity of water, which is 4200 J/(kg. $^{\circ}$ C), m is the mass of water, which can be calculated using the formula $m = \rho V$ based on the flow rate monitored by the flow meters, ΔT is the temperature rise of

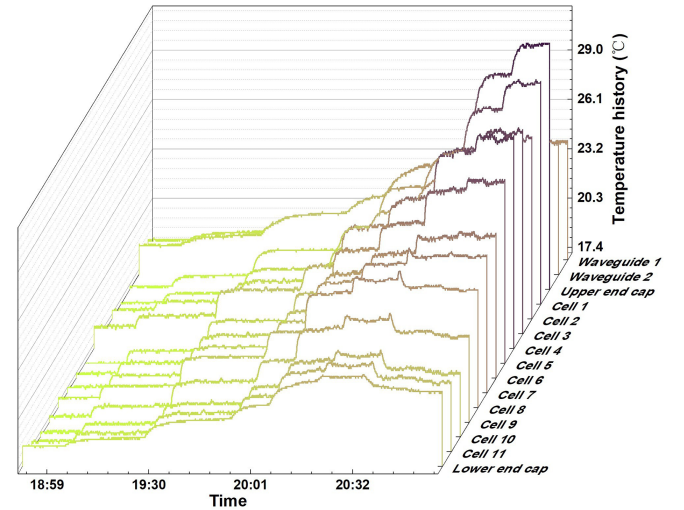


FIG. 15. Temperature variations in all rf cells, end caps, and waveguides when the cooling water pipes were arranged in two bottom-to-top and two top-to-bottom staggered cooling water flow directions.

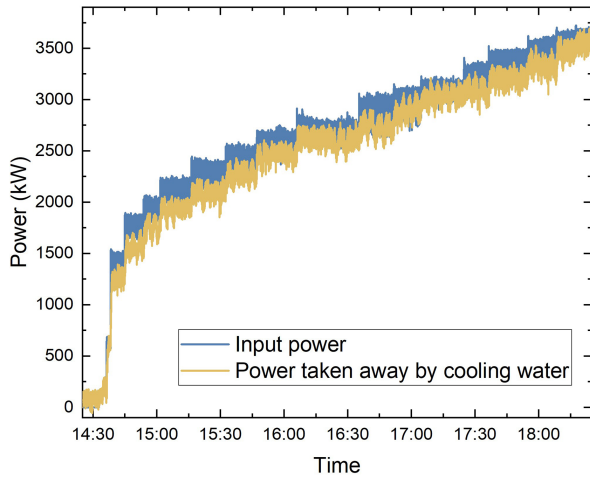


FIG. 16. Average power of the cavity with duty factor of 0.1%.

the cooling water flowing through the accelerating structure, which can be calculated based on the water temperature monitored by the flow meters in real-time minus the water temperature with no power feeding into the cavity. There are four cooling water channels on the accelerating structure, the flow and temperature of each channel can be individually monitored, and the total heat taken away by the cooling water is the sum of the heat taken away by each channel.

The average power fed into the cavity can be calculated from the heat taken away by the cooling water per unit time, which is 1/1000 of the effective input power of the cavity with a pulse length of 5 μ s and a repetition rate of 200 Hz.

Figure 16 shows the power taken away by the cooling water varies with the average incident power. From Fig. 16, the effective input power of the cavity, calculated from the heat removed by the cooling water per unit time, still increased with increasing incident power after the incident power exceeded 2.4 MW. The power removed by the cooling water per unit time was slightly less than the incident power, indicating that almost all of the incident power had been fed into the accelerating structure. From Figs. 14 and 15, it can be inferred that the incident power was almost totally fed into the accelerating structure, but the cavity voltage of each rf cell was not consistent after the incident power exceeded 2.4 MW.

At high power level, the temperature distribution of the accelerating structure was not uniform. A full-cavity thermal analysis, based on the temperature data in Fig. 15 and yielding a 3D deformation distribution, was performed. First, the heat flux for each accelerating cell was calculated inversely from its experimentally measured temperature shown in Fig. 15. This calculated heat flux was then imported into Ansys Fluent [22] and defined as the heat source to simulate the temperature distribution of the accelerating structure. The simulated results agreed well with the experimentally measured temperature distribution provided in Fig. 15. With this simulated temperature distribution, thermal stress

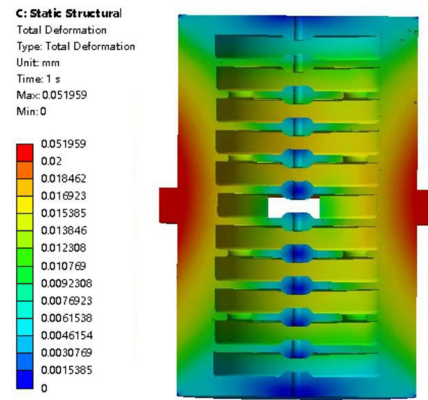


FIG. 17. 3D deformation distribution of the structure.

analysis was performed in the structure solver with proper physical constraints. The 3D deformation distribution of the structure is shown in Fig. 17.

The on-axis electric field was simulated based on the 3D deformation distribution of the structure, as shown in Fig. 18, and the flatness of the on-axis electric field was deteriorated. Because the lower side of the structure was cooled better than the upper side, the temperature on the upper side was higher, and the upper side rf cells had larger deformation due to the higher temperature rises, resulting in higher field amplitudes in the upper side rf cells, which further caused higher temperature rises. Thus, as the incident power was further increased, the electric field flatness on the axis would be worse.

In order to further improve the cooling effect of the upper side, the water flow of one cooling channel was switched to top-to-bottom; then the cooling scheme became three top-to-bottom flows and one bottom-to-top flow. The temperatures of each rf cell displayed opposite trends, i.e., the temperature rises of the upper side rf cells were lower than that of the lower side rf cells, as shown in Fig. 19. This proves that the flow direction of the cooling water has a

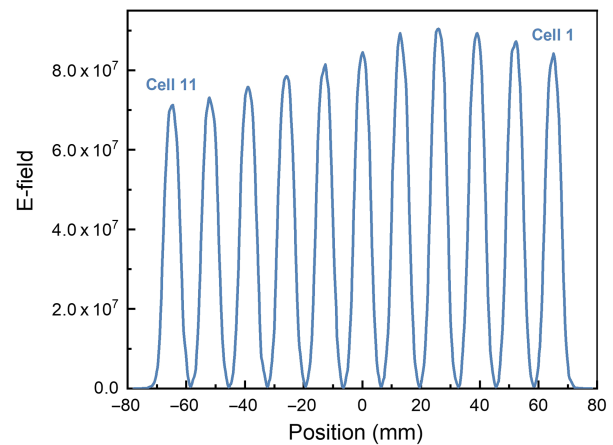


FIG. 18. On-axis electric field simulated by the temperature rise.

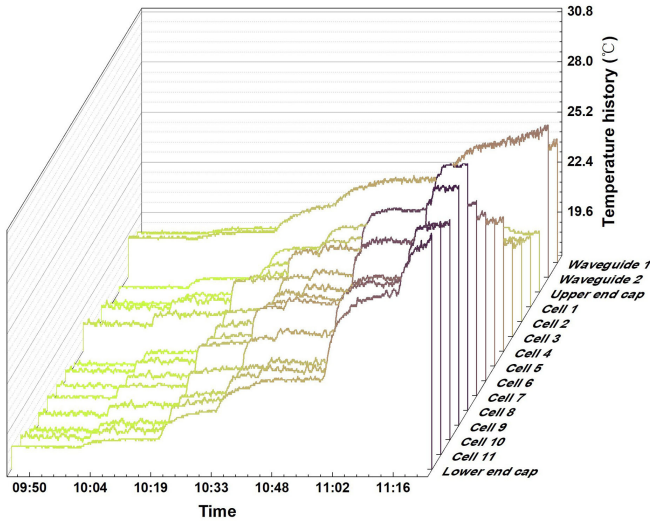


FIG. 19. Temperature distribution of all rf cells, end caps, and waveguides with one bottom-to-top and three top-to-bottom cooling water flow directions.

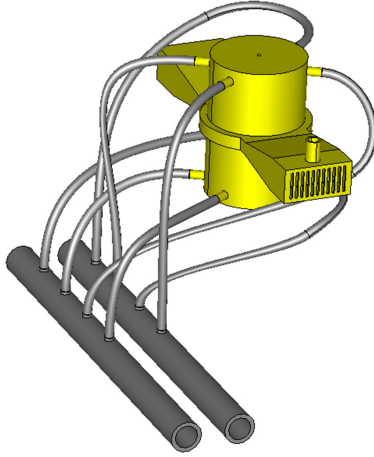


FIG. 20. Model for the fluid simulation based on the actual construction of the cooling water channels.

great influence on the cooling uniformity. However, the structure still could not operate stably when the incident power exceeded 2.4 MW.

B. Cooling water flow rate

To further improve the cooling uniformity of the cavity, Ansys CFX software [23] was used to perform fluid simulation and analysis. Figure 20 shows the model for the fluid simulation based on the actual cooling water channels. The curvature and length of each cooling water pipe in the model cannot be guaranteed to be consistent with the actual situation because the external water pipes are PU pipes. The simulation results are slightly different from the real situation, but are enough for guiding the cooling water flow adjustment. The boundary conditions for the fluid simulation were set according to the actual state, i.e., 0.5 MPa pressure was set at the inlet of the manifold, and the flow rates were set separately at the outlet of each pipe according to the flow rate values monitored by the flow meter. The simulation results are shown in Fig. 21, and only the temperature distributions of the upper and lower end caps are shown to compare the temperature difference of the upper and lower sides of the accelerating structure more intuitively. The simulation result was consistent with the temperature distribution of the actual measurements, the temperature of the upper end cap was higher when the water pipes were two bottom-to-top and two top-to-bottom staggered water flow directions, and the temperature of the upper end cap was lower when the water pipes were one bottom-to-top and three top-to-bottom cooling water flow directions.

Reducing the flow rate of certain cooling channels was attempted to achieve a more uniform temperature distribution of the structure. For the one bottom-to-top and three top-to-bottom cooling water flow cases, first, keeping the inlet pressure constant at 0.5 MPa, the flow rates of the three water pipes with top-to-bottom cooling water flow directions were gradually reduced, and the simulation

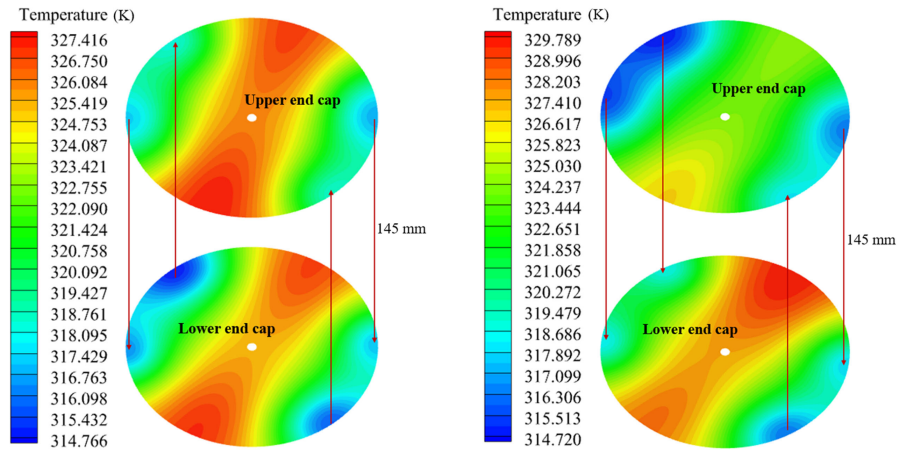


FIG. 21. Simulation results of two bottom-to-top and two top-to-bottom staggered cooling water flow directions (left) and one bottom-to-top and three top-to-bottom cooling water flow directions (right).

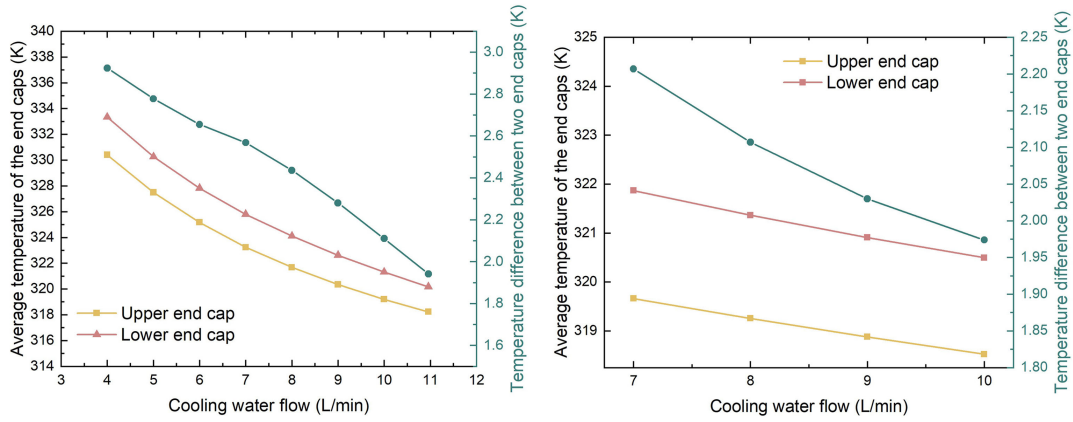


FIG. 22. Temperature variation with cooling water flow rate. Changing the flow rate of three cooling water pipes from top-to-bottom (left); changing the flow rate of one cooling water pipe from bottom-to-top (right).

results are shown in Fig. 22 (left). As can be seen from the figure, the uneven cooling of the structure cannot be improved by reducing the flow rate of the three pipes with top-to-bottom cooling water flows, which was also consistent with the actual test results. The reason may be that after reducing the flow rate of the three top-to-bottom cooling water flow pipes, the temperature rise of the cooling water flowing through the accelerating structure becomes larger, so the cooling effect on the lower side of the structure becomes worse, leading to a further increase in the temperature difference between the upper and lower sides of the structure. Conversely, the flow rate of one bottom-to-top cooling water pipe was gradually reduced while keeping the flow rates of the three top-to-bottom pipes constant. The simulation results are shown in Fig. 22 (right), and the temperature difference still increased as the flow rate decreased. Therefore, the uneven cooling of the accelerating structure cannot be improved by reducing the flow rate of certain cooling pipes, because both the flow rate and the temperature rise of the cooling water will have different cooling effects on different parts of the structure.

Higher cooling water flow rates seem helpful to reduce the temperature rise of the cooling water flowing through the accelerating structure, thus improving the cooling uniformity. However, the cooling water flow could not be further increased due to the limitation of the available thermostatic water machine in our test station.

C. Electric field stabilization analysis

Figure 23 shows the variation in the maximum effective input power as a function of the duty factor. The structure operated at a lower effective input power as the repetition rate increased, while the pulse length was maintained at 5 μ s. Furthermore, the average power (peak power multiplied by duty factor) remained basically within the range of 2.1–2.4 kW across different duty factors. This result confirms the stable operation of the single-periodic

magnetically-coupled standing-wave accelerating structure prototype at average powers below 2 kW.

When the average power fed into the accelerating structure exceeds 2 kW, uneven thermal deformation of the accelerating structure significantly impacts the field distribution. Therefore, the cavity's ability to maintain field uniformity under perturbations was analyzed. For the single-period magnetically-coupled standing-wave accelerating structure, the end cells have the greatest impact on the electric field flatness of the cavity. Figure 24 shows the variation of the on-axis electric field within the accelerating structure under different levels of perturbation applied to end cell 11. From the figure, with only a 0.23 MHz increase in the frequency of cell 11, the on-axis electric field flatness deteriorates by 8.92%. The flatness would further deteriorate if other cells were also subject to perturbations. This means that the operational stability of the structure can be enhanced by improving the field stabilization.

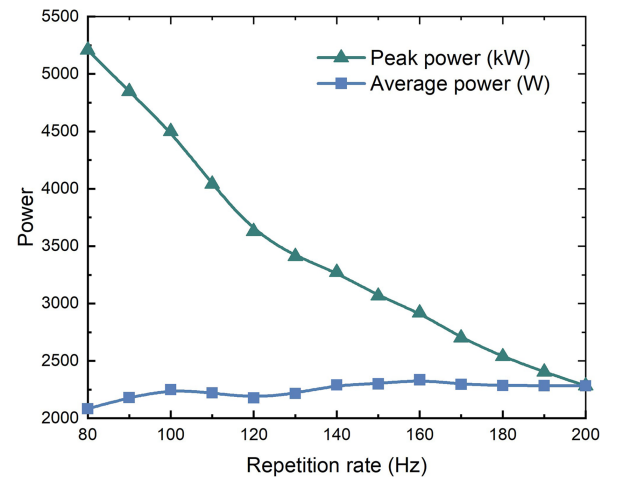


FIG. 23. Maximum pickup power and average power of the cavity at different repetition rates.

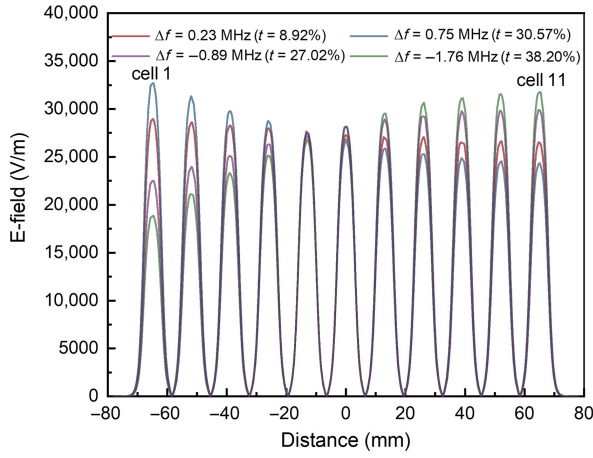


FIG. 24. Field stabilization analysis. The symbol Δf denotes the frequency deviation of cell 11, and t denotes the flatness of the on-axis electric field.

For future designs of single-period magnetically-coupled standing-wave accelerating structures, the structural stability can be enhanced by increasing the cell-to-cell coupling.

V. FURTHER IMPROVEMENTS IN COOLING SCHEMES

In standard treatments, the average beam current is usually in the range of tens to hundreds of nA, corresponding to a low rf duty cycle. For FLASH irradiation, high instantaneous dose rates are required, but high average duty operation is not required. Therefore, the performance of the current single-period magnetically-coupled standing-wave accelerating structure already meets and exceeds the required level for proton therapy applications.

To expand the utility of the proton linac into fields like isotope production, the accelerating structure must operate at a higher duty factor. Therefore, two novel cooling channel schemes were designed.

The first cooling channel scheme uses separate outside cooling for each rf cell, as shown in Fig. 25. Cooling channels with small diameters are located on the outside of the disk to leave enough space for dimple tuners. The flow

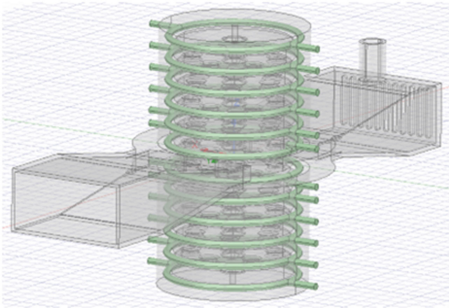


FIG. 25. Diagram of each rf cell with separate outside cooling channel.

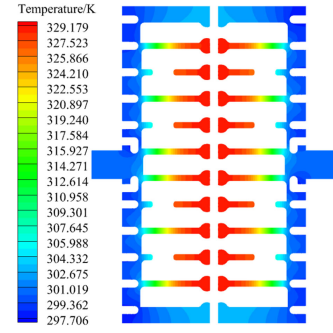


FIG. 26. Simulation result of each rf cell with separate outside cooling channel.

rate of each cooling channel can be individually adjusted to ensure that the accelerating structure is cooled evenly. Figure 26 shows the simulation results, the accelerating structure is cooled uniformly and the cooling effect of this cooling scheme is superior to the current cooling scheme of four longitudinal waist-shaped water channels for the same total flow rate.

Another cooling scheme allows the cooling water flow into the middle of the disk, and each rf cell is cooled separately, as shown in Fig. 27. The temperature rise of the structure is only 4 K with the duty factor of 0.1%, as shown in Fig. 28, which makes it possible for higher duty cycle

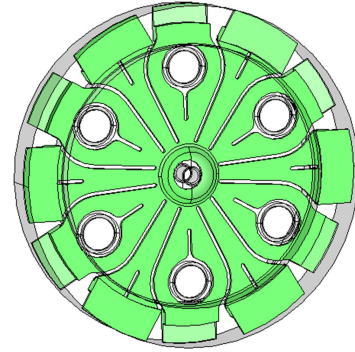


FIG. 27. Model of the cooling channel in the middle of the disk.

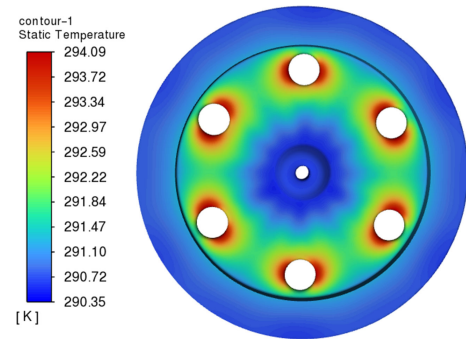


FIG. 28. Temperature distribution of a rf cell at 0.1% duty factor.

and longer rf pulse operation and provides a wider application scenario for the high frequency and high-gradient accelerating structure. This novel structure can be fabricated using diffusion welding technology. The power prototype is currently under construction, with the cavity rf cold test scheduled for September 2026.

VI. SUMMARY

A single-periodic magnetically coupled standing-wave accelerating structure prototype operating at 3 GHz for low phase velocity (0.26) particles has been high-power tested. The rf conditioning process went well at low duty factor, and a short time was spent to extend the pulse length to 5 μ s and increase the repetition rate to 70 Hz, with the cavity operating stably at 5.7 MW, corresponding to an accelerating gradient of 38 MV/m. The analysis was then conducted for a high duty factor of 0.1%. The results indicated that the accelerating gradient of the cavity decreased to 24 MV/m due to the uneven cooling of each single cell. The maximum average effective input power of the cavity remained basically in the range of 2.1–2.4 kW at different duty factors. This confirmed that the performance of the single-period magnetically-coupled standing-wave accelerating structure prototype meets and exceeds the required level for proton therapy applications.

To extend the application of the proton linac into fields like isotope production, two novel cooling channel schemes were designed to provide more uniform cooling and improve the cooling efficiency of the accelerating structure.

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DATA AVAILABILITY

The data that support the findings of this article are not publicly available. The data are available from the authors upon reasonable request.

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