

Design, fabrication, and test of a parallel-coupled slow-wave high-gradient structure for short input power pulses

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Tsinghua University has designed an X-band (11.424 GHz) slow-wave parallel-coupled ten-cell standing-wave accelerator structure, operated it at a high gradient with 40-ns-long rf pulses. Unexpected bead-pull results were observed during the cold testing, which we attribute to intercavity coupling. To explain these results, a multicell coupling circuit model was developed and used to analyze the data. High-power testing was conducted on the TPOT-X platform, achieving a highest gradient of 130 MV/m after 1.1×10^7 conditioning pulses. Compared to conventional multicavity high-gradient structures, the distributed power feeding system offers a shorter conditioning period and demonstrates the potential to achieve higher accelerating gradients under short-pulse operation.

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I. INTRODUCTION

Conventional linear electric accelerators are extensively used in medical and industrial applications [1,2], underscoring the importance of compact high-gradient accelerating structures. As a leading approach for generating high-energy electrons, high-gradient normal-conducting structures have been actively developed for use in colliders and light source facilities [3–5]. For instance, CERN has designed a multicavity structure achieving a gradient of 120 MV/m for the Compact Linear Collider (CLIC) [6]. Additionally, the main accelerating sections of free-electron lasers (FELs) [7] and VIGAS [8] employ multiple linacs operating across different frequency bands.

Despite ongoing advancements, the achievable accelerating gradient is fundamentally constrained by rf breakdown during the conditioning process [9–14]. Empirical data from CLIC experiments indicate that, at a fixed accelerating gradient, the breakdown rate (BDR) is proportional to the fifth power of the input pulse width [15]. Therefore, shorter pulses are conducive to achieving higher accelerating gradients. Previous studies in the short-pulse regime have primarily focused on single cavities or high-frequency (30 GHz) experiments. Recently, an X-band traveling wave (TW) cavity structure tested at Argonne

National Laboratory (ANL) demonstrated operation at gradients up to 313 MV/m with a pulse full width at half maximum (FWHM) of 6 ns [16]. For a 30 GHz TW structure, accelerating gradients of 140, 100, and 70 MV/m were reached with pulse widths of 4, 8, and 16 ns, respectively, at CLIC [17,18].

In conventional high-gradient linear accelerating structures, power is typically coupled axially through the beam aperture or coupling holes, constraining input pulse widths to the structure's filling time [19]. To obtain higher gradients, X-band traveling wave structures operate with a pulse width of more than 100 ns [20,21]. Consequently, multicell structures designed to operate under short pulses are expected to further enhance accelerating gradients.

Increasing the cell coupling coefficient can effectively reduce the filling time, enabling short-pulse input in over-coupled standing-wave accelerating structures. Based on this principle, the parallel-coupled accelerating structure was proposed as a topological configuration for linear accelerators. In this design, power is coupled into each cell independently through an external power distribution network [22–24]. Since rf power propagates through waveguides or coaxial lines near the speed of light, the electromagnetic fields in all cells are established simultaneously. This power distribution scheme demonstrates the potential for achieving high-gradient acceleration in multicell structures with short-input power pulses. It also provides greater flexibility in the geometric optimization of the cavity design [25]. In 2018, SLAC developed the first high-gradient parallel-coupled 20-cell structure [26]. This structure operates at 11.424 GHz and achieves an accelerating gradient of 140 MV/m under an input power

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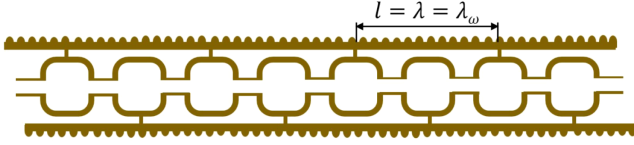


FIG. 1. The slow-wave parallel-coupled accelerating structure designed by Tsinghua University.

of 33 MW with a 400 ns pulse width. However, this structure has not yet been further tested under short-pulse conditions.

Tsinghua University has conducted research on the circuit design of parallel-coupled system networks and developed a short-pulse parallel-coupled accelerator structure [27], as shown in Fig. 1. In vacuum waveguides, the rf phase velocity exceeds the speed of light. To address this, periodic slots are employed as a slow-wave structure, ensuring proper phase matching for each cavity. Additionally, the phase advance is set to 0° or 180° , ensuring equal power distribution across the cells. The entire structure is intentionally overcoupled to achieve a short filling time, with an effective coupling coefficient of approximately $\beta' = 26$. Theoretically, with a 10-ns pulse input at 1.1 GW, an average accelerating gradient of 200 MV/m can be achieved. This predicted result is derived from CLIC's experimental findings and established empirical formulas.

To obtain valuable experimental data, this structure was planned for high-power testing on Tsinghua University's X-band high-power testing platform, TPOT-X [28]. TPOT-X operates at 11.424 GHz and employs a klystron as its power source. The platform can output up to 50 MW with a 1.5 μ s microwave pulse at a maximum repetition rate of 40 Hz. With the assistance of a pulse compressor, TPOT-X is capable of generating microwave pulses with peak power in the hundreds of MW and pulse widths in the hundred-nanosecond range. However, the platform's shortest achievable pulse width is approximately 40 ns because of limitations imposed by the pulse rise time and the need to maintain the performance of the pulse compressor. Therefore, the original 10-ns structure was modified to satisfy the 40-ns pulse requirement.

In this paper, we discuss the redesign, fabrication, and testing of an X-band short-pulse parallel-coupled accelerating structure with ten cells, based on previous research and within the limits of experimental conditions. In Sec. II, we present the rf design of the parallel-coupled accelerating structure and calculate the real-time field distribution of the structure. Section III describes the fabrication process and the results of the low-power tests. Section IV reports on the high-power experimental results of the structure under short-pulse conditions. Finally, Sec. V provides a summary.

II. PHYSICS DESIGN AND ANALYSIS

Three subsections are presented in this section to describe the structure in detail. The first part focuses on

the rf design of the slow-wave structure. In the second part, we describe the geometry of the accelerating cell. This includes an analysis of the single-cell design as well as the coupling coefficients of the entire structure. Finally, in the third part, we calculate the real-time distribution of the electromagnetic field in the parallel-coupled structure.

A. Distribution waveguide design

The phase shift between two adjacent feeding ports is set to 0 or π to ensure that each identical cell receives an equal amount of rf power. For electrons traveling at the speed of light within the structure, the rf phase velocity must be matched to the speed of light to achieve phase synchronization and maintain continuous acceleration. A smooth waveguide structure is unsuitable for this purpose because the guided wavelength, λ_g , exceeds the free-space wavelength, λ . To address this, periodic slots were introduced as a slow-wave structure, as shown in Fig. 1. This design incorporates multiple feeding waveguides, offering greater design flexibility for the waveguide coupler but also increasing the complexity of manufacturing. To achieve a symmetric structure, the device was fabricated by assembling two milled halves of the structure [6]. Two transmission waveguides were placed on opposite sides of the cell to alternately feed the accelerating cavities, with the coupler waveguide connected to the broad wall of the transmission waveguide (E-plane).

The rf phase velocity is primarily determined by the cross-sectional dimensions of the main waveguide and the corrugation parameters of the slow-wave structure (Fig. 3). It can be observed that adding more slots in the T-junction unit improves field uniformity. However, this improvement is limited by the precision of the machining tools. Based on these considerations, we selected a slot number of $n = 4$ and adjusted the slot depth wh for a specific slot width wd so that the phase advance per corrugation period is approximately $\pi/2$. To balance the impact on the maximum surface E-field (as shown in Fig. 2) and the feasible

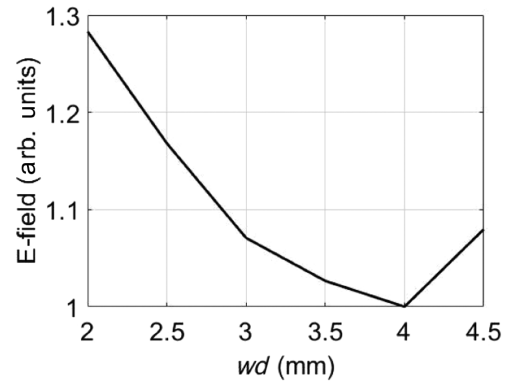


FIG. 2. The relative maximum surface E-field at different corrugation intervals wd .

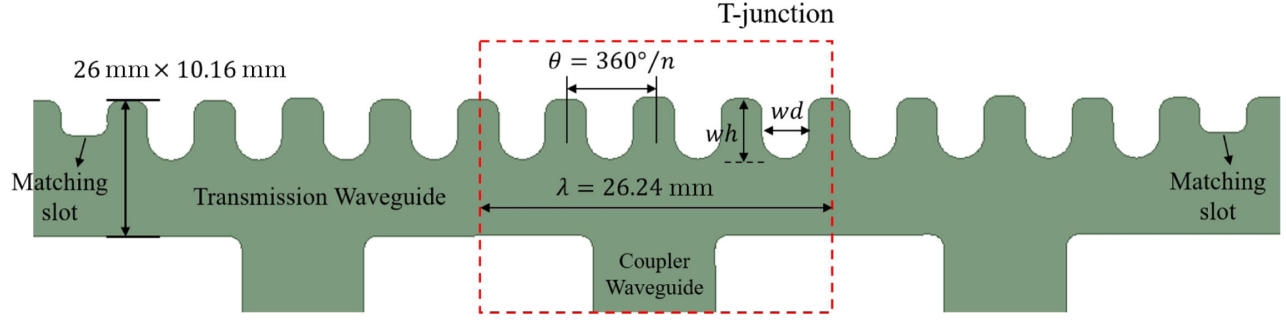


FIG. 3. The HFSS design of waveguide power feedline: the red dashed box includes a single slow-wave transmission unit.

machining range, wd was set to 3.5 mm. Matching sections were added at both ends of the transmission waveguide to ensure impedance matching with the smooth waveguide. The scattering matrix of the T-junction can be written as

$$S_3 = \begin{bmatrix} 0.18 & 0.82 & 0.54j \\ 0.82 & 0.18 & -0.54j \\ 0.54j & -0.54j & -0.64 \end{bmatrix}, \quad (1)$$

where port 1 is the power input port on the left in Fig. 3, port 2 connects to the subsequent T-junction, and port 3 feeds power to the accelerating cavity.

Compared to the smooth waveguide, the corrugated structure causes a significant change in the impedance for microwaves. The use of matching slots ensures that microwave power is fed into the network with minimal reflection.

B. Accelerating cavity design

The geometric design of the accelerating cavity is based on the racetrack-shaped cells of the CLIC-G-OPEN,

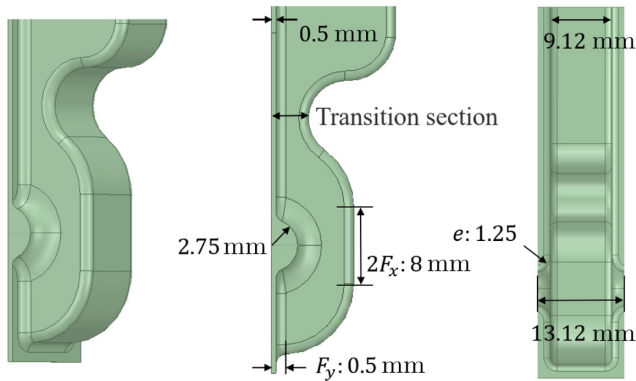


FIG. 4. The HFSS design of the accelerating cavity with coupler waveguide: elliptical fillets are used at the connection between beam iris and cavity to reduce the surface electric field. The length of the straight line sections in the cell geometries, F_x and F_y , are 4 and 1.2 mm, respectively.

which are well optimized and suitable for halves fabrication. Because of limitations in machining accuracy, the cavity shape with nose cones and high shunt impedance was not selected. Figure 4 shows the HFSS model of the identical cell with a coupler waveguide. The accelerating cell is connected to the rectangular waveguide through an arc section. The main parameters are presented in Table I.

The coupling coefficient is adjusted by the size of the transition section opening, where the peak magnetic field appears, as shown in Fig. 5. The peak electric field and modified Poynting vector (S_c) are concentrated near the beam hole, consistent with axis-coupled calculation results. Furthermore, based on previous test results showing no noticeable increase in BDR for side-coupled cells compared to axis-coupled ones [29], this cell type is suitable for high-gradient parallel-coupled structures. During the design process, we observed that the amplitude of the electric field in each cavity is unequal when the resonant frequency of all cells is kept the same. The size of the beam aperture in this design is comparable to that of the CLIC-G-OPEN TW structure, making the intercavity coupling non-negligible. To address this issue, simulations were performed to optimize the resonant frequency difference between the end cells (1 and 10) and the middle cells (2–9), which was set to 9 MHz to ensure an equal-amplitude E-field distribution at the single resonance frequency of the structure.

TABLE I. RFRf parameters of a parallel-coupled single cell. Field values are for an average accelerating gradient of 200 MV/m.

Parameter	Value
Frequency	11.424 GHz
Iris radius	2.75 mm
Q_0	8200
Shunt impedance	89 MΩ/m
Peak surface E	257 MV/m
Peak surface H with transition section	0.57 MA/m
Maximum S_c	32 MW/mm ²

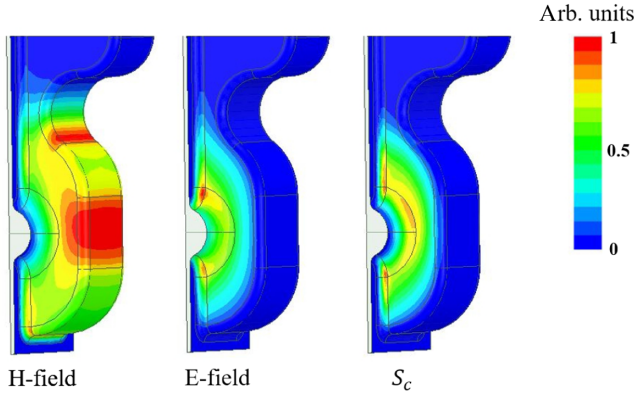


FIG. 5. Surface field plot of the accelerating cell with transition waveguide.

C. Design and analysis of the structure

With short-pulse input, the stored energy in the cells does not reach a steady state during the filling time. For constant power input, the filling efficiency η can be written as

$$\eta = \frac{U(t)}{P_0 t}, \quad (2)$$

where U represents the stored energy in the cavity, P_0 denotes the input power, and t is time. The time at which the filling efficiency reaches its maximum value is defined as the optimal filling time. Similar to the optimization of the filling time for traveling-wave accelerating structures [30], we calculated the optimal filling time for the parallel-coupled structure, expressed as

$$t_f \simeq \frac{2.512 Q_0}{\omega(1 + \beta')}. \quad (3)$$

At an input pulse width of 40 ns, the optimized coupling coefficient of the structure (β') and the single cell β were determined to be $\beta' \approx 6.2$ and $\beta \approx 4$ [27]. The structure is fed by two input ports as shown in Fig. 6: the power in each port is equal but the phase differs by 180° . A regular waveguide with a relatively short broadwall length was

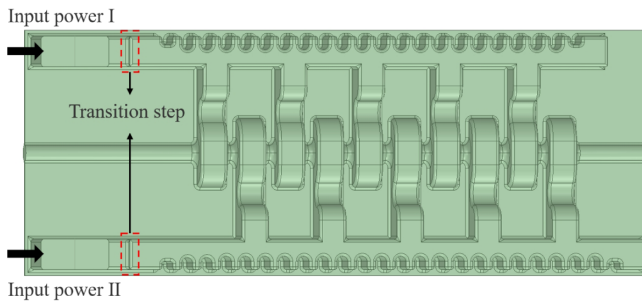


FIG. 6. Half geometric design of the slow-wave parallel-coupled accelerating structure with ten cells. A transition step is used to connect waveguides of different broadwall sizes.

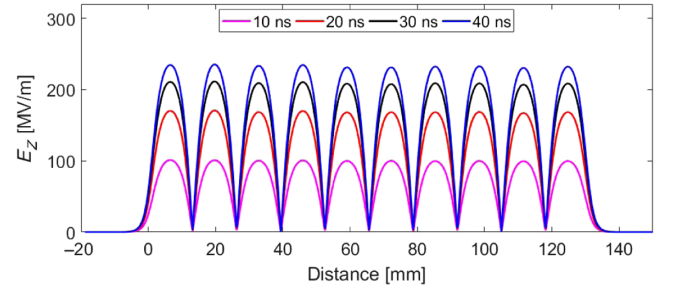


FIG. 7. The electric field distribution along the axis at different times, with a pulse of 100 MW.

adopted to inject power into the corrugated waveguide network, avoiding the growth of undesired microwave modes and minimizing efficiency loss.

For short-pulse accelerating structures, time-domain analysis tools are essential to simulate the real-time distribution of the electromagnetic field. A method based on the fast Fourier transform was developed and validated to provide accurate real-time field data [27]. Using this method, we analyzed the filling process of the designed parallel-coupled structure. With an input pulse of 100 MW, a 40-ns pulse length, and a 1-ns rise time, the simulation results showed that power begins filling each cell simultaneously at $t = 4$ ns, and the cell E-fields increase at the same rates over time. Figures 7 and 8 show the E_z field profile along the axis and the average accelerating gradient versus time, respectively. The parallel-coupled structure was designed for single-bunch input, making it compatible with pulses of different shapes.

III. FABRICATION, TUNING, AND LOW POWER TEST ANALYSIS

Based on the rf design of the parallel-coupled structure, we provide a detailed description of the fabrication process in the first subsection below. The second subsection presents the cold test and tuning results of the structure.

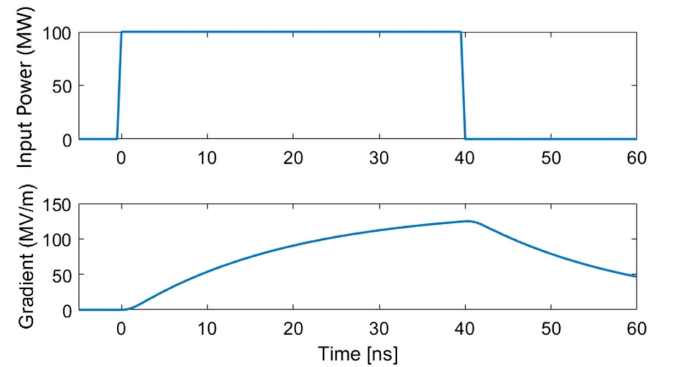


FIG. 8. The temporal average gradient of the structure with a pulse of 100 MW and 40 ns of length. The rise time and fall time was set to be 1 ns.

Because of the power coupling between adjacent cavities through the beam holes, amplitude distribution measurements of the electric field are challenging. However, for structures operating under short pulses, the accuracy of the single-cavity frequency is more meaningful than the steady-state electric field distribution when considering the effects of high-power testing. In the third subsection, we present a coupled circuit model for the parallel-coupled structure, explaining that the bead-pull results do not correspond to the true on-axis electric field distribution within the structure.

A. Fabrication

The mechanical design of the slow-wave parallel-coupled structure consists of upper and lower copper blocks as shown in Fig. 9. Each part is machined according to the half structure split by the middle cross section along the long dimension of the slow-wave waveguide. The use of two halves welded together effectively reduces the complexity of fabrication but imposes high requirements on positioning accuracy. Therefore, four alignment holes are provided on each side of the copper block for alignment during welding, and tuning holes are located on the side walls and top.

To simplify the fabrication process, no water-cooling channels were incorporated within the structure. Temperature regulation and stabilization of the structure were achieved through externally attached water-cooling strips during high-power testing. The maximum error for the transmission waveguide dimensions was -0.01 mm, corresponding to a phase shift of 4° . On the other hand, the error for the accelerating cavity was -0.015 mm, corresponding to a frequency deviation of approximately 15 MHz.

B. Tuning and low-power test

The structure was tested under low-power input conditions, and the measurements include cavity frequency,

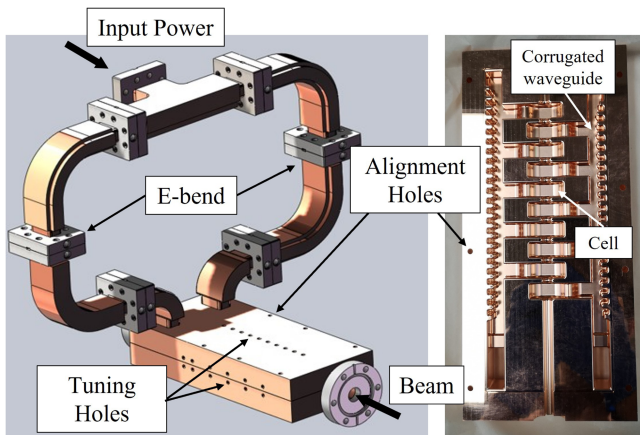


FIG. 9. Illustration of the mechanical design of the parallel-coupled structure with E-bend waveguide and power splitter.

overall S -parameters of the structure, and field distribution. To minimize errors between the two ports of the vector network analyzer, the final structure was connected to a power splitter for single-port testing, as shown in Fig. 9.

Unlike conventional multicavity accelerating structures, the fields in the cells of the parallel-coupled structure are excited by coupling with distributed waveguides rather than through cell-to-cell coupling. Consequently, the S -parameter curve of the structure is expected to exhibit a single peak. Figure 10(a) shows the single-cavity frequencies before and after tuning. Before tuning, the single-cavity frequency of the structure exhibits a distribution from low to high, because of the counterweight being placed closer to the downstream end during welding, resulting in tighter contact surfaces. To achieve field flatness, the frequency difference between the end cells and the middle cells needs to be accurately tuned to the design value.

Tuning was accomplished by shorting all cells except the one under test using two conductive bars inserted from opposite sides of the iris. The overall frequency of the structure was tuned to 11.424 GHz, with a frequency difference of less than 40 kHz between the middle cells. For the first and last cavities, different resonance frequencies were necessary to ensure the S -parameter curve exhibited a single peak. It should be noted that the discrepancy between the measured results and the design value is attributed to machining errors in the beam apertures, which also highlights that the cavities cannot be considered completely isolated from one another. The S -parameter of the structure [Fig. 10(b)] was measured using a power splitter, which indicated that the coupling

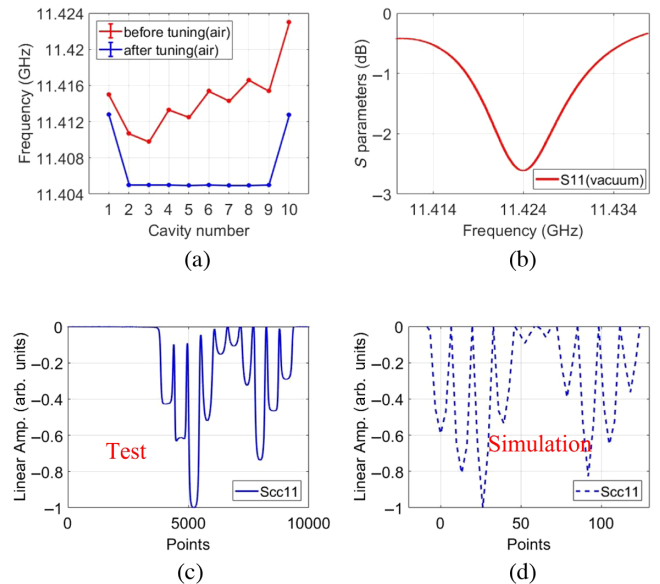


FIG. 10. Tuning results of the slow-wave parallel-coupled structure. (a) and (b) show the resonant frequencies of the tuned cells and the structure, respectively. (c) and (d) are the test and simulation bead-pull data of the structure.

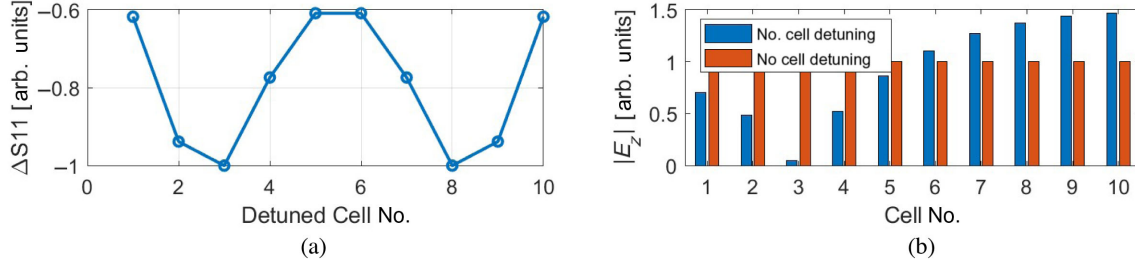


FIG. 11. Theoretical calculation results of the circuit model for the parallel-coupled structure. (a) The normalized variation of S_{11} vs position of perturbation. (b) On-axis normalized E-field amplitude.

coefficient of the structure is approximately 6.7, meeting the design specifications for operation with short pulses.

We used the nonresonant perturbation bead-pull method [31] to measure the on-axis field. In this case, a metal bead induces a disturbance to the electric field at its location, which leads to a change in the reflection coefficient of the structure. When moving the bead at a constant speed along the structure, we obtained an unexpected curve of the relative change in the reflection coefficient versus the bead position, as shown in Fig. 10(c). In HFSS, a copper sphere with a diameter of 1 mm was placed and simulated at different positions along the structure, which is illustrated in Fig. 10(d). Theoretically, the cavities working in π mode are considered to be isolated from each other, resulting in an equivalent change in the reflection coefficient when the single cell is detuned. However, a nonflat amplitude distribution was observed in both tests and simulations, indicating that the bead-pull method is unsuitable for field measurement in this case. We attribute these results to intercavity coupling and developed a circuit model of the

parallel-coupled structure for further analysis. The detailed calculation is presented in the Appendix.

Choosing the input signal $a_0 = 1$, we can derive the variation curve of the reflected coefficient as the detuned cell varies, which shows a high degree of similarity with the experimental results in Fig. 11(a). The normalized E-field distributions in the parallel-coupled structure, with no cell and one cell detuning, were illustrated in Fig. 11(b). Intercavity coupling plays an equally important role in rf excitation compared to the feeder waveguide coupling, which will be reduced further by adopting a smaller beam aperture.

IV. HIGH-POWER TEST

The slow-wave parallel-coupled accelerating structure was tested at the Tsinghua high-power test stand for X-band (TPOT-X). Figure 12 depicts the layout of the high-power test platform, with the main test section inside the shield room and the power supply system

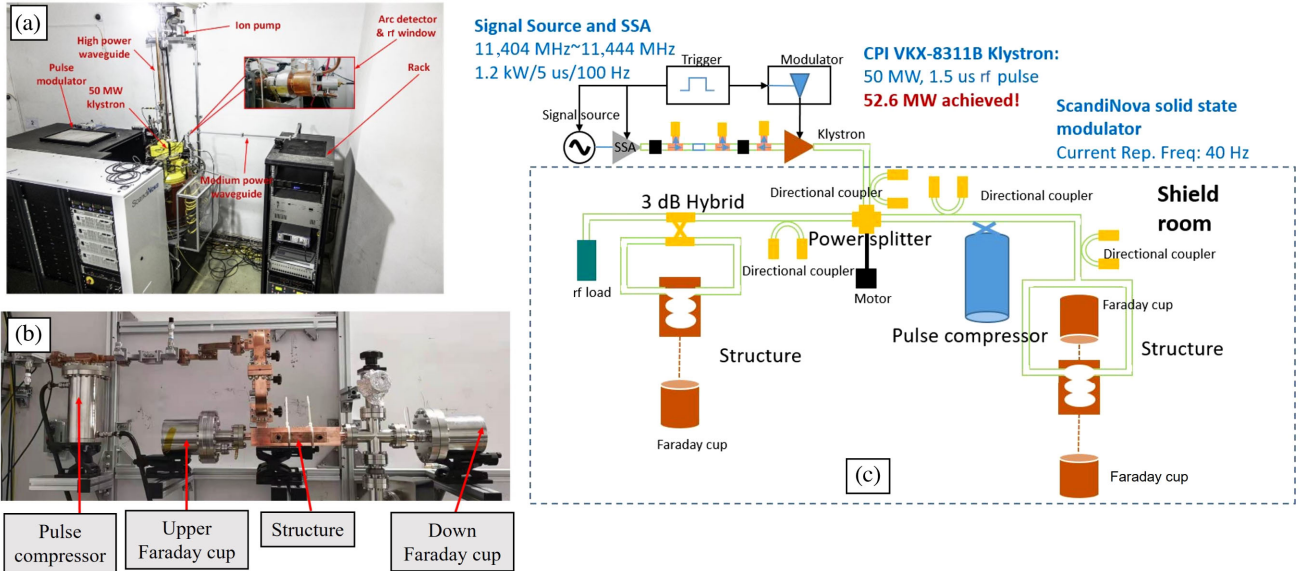


FIG. 12. Setup of high-power test platform. (a) Power supply system outside the shield room. (b) Main test section of structure. (c) The layout figure of TPOT-X.

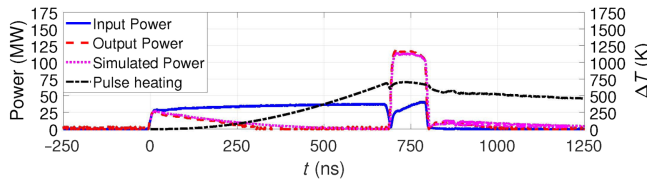


FIG. 13. SLED pulse waveforms (in color) and the average temperature rise on the inner surface of the compressor because of pulsed heating (in black). After amplitude modulation, the output of pulse compressor is approximated as a square pulse of 100 ns.

outside. We used a pulse compressor after the klystron to generate ultrashort pulses that exceed the klystron limit. Smooth or corrugated spherical or cylindrical resonant cavities with a quality factor $Q_0 > 100,000$ are commonly used as pulse compressors [32–34]. Consequently, we designed and fabricated an X-band corrugated cylinder pulse compressor, with the quality factor $Q_0 \simeq 117,000$ and coupling coefficient $\beta \simeq 3.67$. Figure 13 shows the typical compressed square pulse waveform with an adjustable width and a power level of 120 MW that could be stably generated by the compressor.

During the high-power rf conditioning, the input and output power waveforms of the structure are recorded to calculate the accelerating gradient, which has been proven to be accurate. Power waveforms at waveguide network joints were acquired and diagnosed by installing directional couplers and crystal detectors, allowing measurement of the incident and reflected rf signals. A typical waveform during the test is shown in Fig. 14.

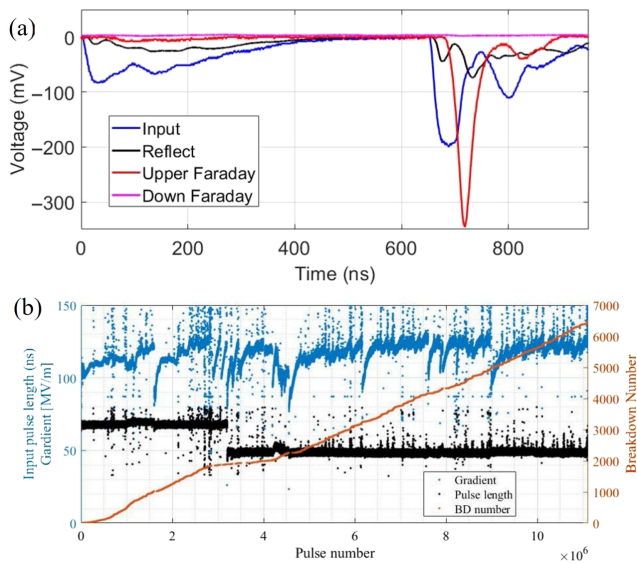


FIG. 14. (a) Signals measured during operation including the dark current signals in the upstream and downstream Faraday cups. The reflected signal increases during the pulse as expected. (b) The high-power test history of the parallel-coupled structure.

Dark current signals from the upstream Faraday cup were used as the criterion for rf breakdown events, which typically occur at the end of input pulses. A threshold detector on rf signals in the real-time measurement system was used to trigger and collect the breakdown event data. The power was increased step by step with a 30-s wait period, during which the power level remained constant. If no breakdown occurred during the wait period, the power was increased by 0.5 MW. Otherwise, the microwave input was turned off for 30 s, and the power level decreased by 0.2 MW at the start of the next period.

The final high-power test history of the parallel-coupled structure is illustrated in Fig. 14, which displays the total breakdown number versus pulse number. In the early stages of the experiment, the pulse length was set to 70 ns to speed up the processing, with a total of 3×10^6 pulses, achieving an accelerating gradient of 120 MV/m. The width of the subsequent 8×10^6 pulses was adjusted to the design value, with the tested gradient reaching 130 MV/m for short input power pulses. The estimated breakdown rate was 5×10^{-4} and 1×10^{-3} , for pulse widths of 47 ns and 70 ns, respectively.

By the end of high-power testing, the parallel-coupled slow-wave structure had undergone 1.1×10^7 pulses, which is fewer than most high-gradient accelerating structures. As illustrated in the experimental microwave layout in Fig. 12, the reflected power flows through the pulse compressor to the klystron power system, rather than being directed to the rf load. Once the structure's gradient reached 100 MV/m, reflected power exceeding 10 MW could potentially cause cumulative damage to the power source system as conditioning continued. Therefore, considering the safety and longevity of the power source, we did not conduct extended high-power testing on the parallel-coupled structure. In future plans, a 3 dB directional coupler will be used to combine and transmit the reflected signals from two identical structures to a steel load, while a two-stage compressor will generate pulses exceeding 200 MW power.

Table II shows the high-power test results of four different X-band accelerating structures. The fabrication methods of the Tsinghua ten-cell structure and CLIC-G-OPEN are similar to that of the parallel-coupled slow-wave structure, but the width of the high-power input pulses differs. Compared to the single-cell structure, the parallel-coupled design achieves a comparable accelerating gradient within the same high-power test duration and therefore can be considered equivalent to conditioning ten single cavities simultaneously. Additionally, among the three multicell structures, the potential to reach higher gradients is validated under short-pulse input operation.

The S-parameters were remeasured to evaluate the effect on the rf properties because of the high-power

TABLE II. High-power test results of four X-band accelerating structures.

Structure	Pulse width (ns)	Gradient (MV/m) ^a	Maximum gradient (MV/m) ^b	BDR ^c
Parallel-coupled slow-wave structure	47	120	130	5×10^{-4}
Tsinghua TW single-cell structure	50	110	123	3×10^{-4}
Tsinghua TW 12-cell structure [35]	90	80	93	2×10^{-5}
CLIC-G-OPEN TW 24-cell structure	200	50	100	6×10^{-6}

^aThe accelerating gradient of four structures during 1×10^7 conditioning pulses.

^bThe final achieved accelerating gradient. The total high-power pulse number for CLIC-G is 1×10^8 and the total pulse number for structures from top to bottom in the table are $1.1/2.5/3.2 \times 10^7$, respectively.

^cThe breakdown rate per pulse at the maximum gradient.

testing, with no significant changes observed. Subsequently, an endoscope was used to inspect the breakdown sites inside the tested structure, with white spots shown in Fig. 15 marking the breakdown locations. In contrast to most other high-gradient structures, the normalized cumulative breakdown number shown in Fig. 15 demonstrates a uniform breakdown distribution along the parallel-coupled structure, which confirms a similar distribution of electric field strength. The spot densities of the two opposing iris areas were found to be similar after comparing different side images. Breakdowns primarily occurred near the beam hole and central gap plane, consistent with the distribution of the maximum surface modified Poynting vector (S_c).

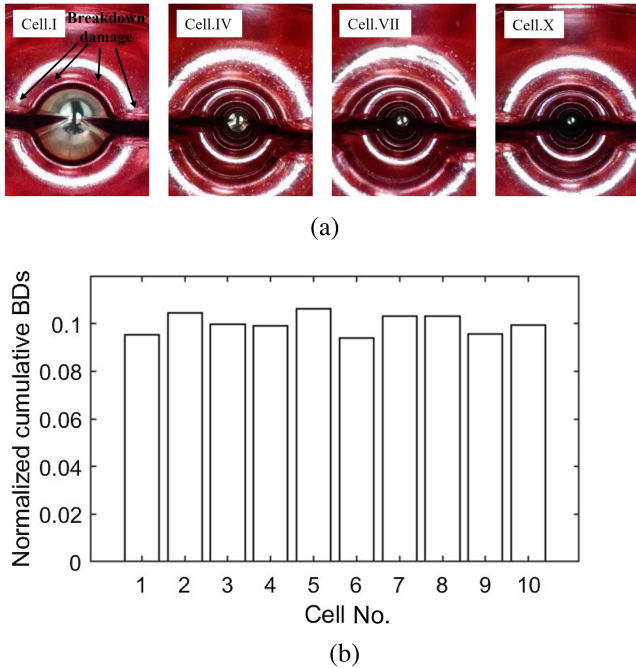


FIG. 15. Endoscopic images and breakdown distribution inside the structure. (a) Endoscopic images of the right side of cells at different positions of the structure. (b) Breakdown induced spotty damage distribution along the structure.

V. CONCLUSION

The design, fabrication, and testing of the first X-band short-pulse slow-wave parallel-coupled accelerating structure were reviewed. To ensure phase synchronization, we selected a corrugated waveguide as the power distribution network to reduce the phase velocity. The structure, which delivers power simultaneously and independently to each cavity, helps to effectively reduce the field rise time, thus enabling short-pulse operation. Simulation results show that the structure can operate with ultrashort pulses of 40 ns, with electric field amplitude variations in each cell changing synchronously and equally. This demonstrates its potential for high-gradient operation. Because of the structural complexity, we used a manufacturing technique where two copper blocks were used to machine half of the structure, which were then joined together. We also described the cold testing and tuning results of the structure, where we found that beam-hole coupling still existed and affected the overall reflection coefficient. Nonresonant perturbation methods could not be used to measure the actual electric field amplitude distribution in the structure. Instead, a multicell coupling circuit for the parallel-feeding structure was developed and its accuracy was verified by comparing predictions to data. Finally, we conducted the high-power test on the TPOT-X platform, which is based on a corrugated cylinder pulse compressor, and achieved an accelerating gradient of 120 MV/m with 47 ns long pulses and a BDR level of 5×10^{-4} . After conditioning, endoscopic images revealed no significant damage to the structure, and the field strength across the cavities was uniform. In conclusion, the parallel-coupled structure is a promising choice for multicavity short-pulse accelerators and provides an effective solution for future high-gradient short-pulse applications.

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DATA AVAILABILITY

The data that support the findings of this article are openly available [6,16,28,35].

APPENDIX: COUPLING CIRCUIT MODEL OF THE PARALLEL-COUPLED STRUCTURE

According to the circuit model of a resonant cavity [36], the generator voltage I_n can be expressed as a function of the steady-state cavity voltage V_n :

$$I_n = V_n \frac{1+\beta}{2\beta} \left(1 + j \frac{2Q_L \Delta\omega}{\omega_0} \right), \quad (\text{A1})$$

where ω_0 , $\Delta\omega$, Q_L , and β are the angular frequency of input

rf power, frequency difference between the input signal and the resonant frequency, loaded quality factor, and coupling coefficient, respectively. To analyze the relationship between the coupling constant and the detuning frequency, we rewrite Eq. (A1) as

$$j \frac{\omega_0}{2Q_L} I_n = V_n \frac{1+\beta}{2\beta} \left(-\Delta\omega + j \frac{\omega_0}{2Q_L} \right). \quad (\text{A2})$$

The reflected signal, because of the impedance mismatch between the input waveguide and the cavity resonant circuit, can be expressed as

$$R_n = V_n - I_n. \quad (\text{A3})$$

Considering the coupling behavior between adjacent cells in the parallel-coupled structure, an equation is established that reflects the coupling mechanism between the multicells and waveguides:

$$\frac{1+\beta}{2\beta} \begin{bmatrix} -\frac{\Delta\omega_1}{\omega_0} + j \frac{1}{2Q_L} & k & \cdots & 0 \\ k & -\frac{\Delta\omega_2}{\omega_0} + j \frac{1}{2Q_L} & k & \vdots \\ \vdots & \cdots & \ddots & k \\ 0 & \cdots & k & -\frac{\Delta\omega_n}{\omega_0} + j \frac{1}{2Q_L} \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \\ \vdots \\ V_n \end{bmatrix} = j \frac{1}{2Q_L} \begin{bmatrix} I_1 \\ I_2 \\ \vdots \\ I_n \end{bmatrix} \quad (\text{A4})$$

where k is the coupling constant. In the coupling model of a conventional SW accelerator, the constant satisfies the condition that one of the eigenvectors of the coupling matrix aligns with the distribution of electric field amplitude at the π mode. Equation (A4) allows us to calculate the theoretical frequency difference between the end cavities and the middle cavities, ensuring uniform electric field amplitude.

For the parallel-fed power distribution network, the reflected power flows back into the network and affects other cells when they are not critically coupled. In conjunction with the scattering matrix of the rf feed system [27], the incident signal of all cells could be calculated as

$$S_{n+1} \begin{bmatrix} a_0 \\ R_1 \\ \vdots \\ R_n \end{bmatrix} = \begin{bmatrix} b_0 \\ I_1 \\ \vdots \\ I_n \end{bmatrix}, \quad (\text{A5})$$

where a_0 is the amplitude of the input signal, b_0 is the reflected one, and S_{n+1} represents the scattering matrix of the network with N ports for cells and one port for the power source. The vector $[V_1, V_2, \dots, V_n]^T$ representing the field distribution in the parallel-coupled structure can be obtained by solving Eqs. (A3)–(A5).

DATA AVAILABILITY

The data that support the findings of this article are openly available [6, 16, 28, 32].

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