Fabrication, tuning, and high-gradient testing of an X-band traveling-wave accelerating structure for VIGAS

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Abstract

X-band high-gradient accelerating structures are core components that can effectively reduce the size of room-temperature linear accelerators. The Accelerator Laboratory of Tsinghua University has successfully developed a 0.65 m X-band high-gradient traveling-wave constant-impedance accelerating structure. Following a series of precision manufacturing and tuning processes, the microwave testing of the accelerating structure achieved the expected results, and high-power testing was subsequently conducted on the X-band high-power microwave platform at Tsinghua University. During the testing, the average accelerating gradient of the entire structure reached 80 MV/m, while the average accelerating gradient of the first cavity exceeded 110 MV/m, achieving an internationally leading level. The development of this structure will also provide important technical support for the Compact Quasi-Monoenergetic Gamma Source (VIGAS) project undertaken by Tsinghua University.

Full Text

Preamble

Fabrication, Tuning, and High-Gradient Testing of an X-Band Traveling-Wave Accelerating Structure for VIGAS

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Abstract: X-band high-gradient linear accelerators represent a challenging yet attractive technology for compact electron linear accelerator facilities. The Very Compact Inverse Compton Scattering Gamma-ray Source (VIGAS) program at Tsinghua University will employ X-band high-gradient accelerating structures to boost electron beam energy from 50 to 350 MeV over a short distance. For this project, a constant-impedance traveling-wave structure comprising 72 cells operating in the $2\pi/3$ mode was designed and fabricated. Precise tuning and detailed measurements were successfully applied to the structure. Following 180 hours of conditioning on the Tsinghua high-power test stand, the structure achieved the target gradient of 80 MV/m. The breakdown rate versus gradient for this structure was measured and analyzed.

Keywords: Traveling-wave accelerating structure; X-band high gradient; Tuning method; High-power test.

Introduction

The Very Compact Inverse Compton Scattering Gamma-ray Source (VIGAS) is an ongoing γ-ray user facility project for advanced X/γ-ray imaging applications at Tsinghua University. This project utilizes S-band (2.856 GHz, including a photocathode electron gun, buncher, and pre-accelerating section) and X-band (11.424 GHz, main accelerating section) accelerator technology to produce low-emittance, low-energy-spread electron beams. These beams interact with laser pulses to generate consecutively adjustable, polarization-steerable, high-brightness, quasi-monochromatic γ-rays with energies ranging from 0.2 to 4.8 MeV [1]. The layout of the accelerator system in the VIGAS facility is shown in Fig. 1 [Figure 1: see original paper].

Fig. 1 Layout of the accelerator system of the Very Compact Inverse Compton Scattering Gamma-ray Source (VIGAS) facility. Abbreviations in this figure are defined as follows: PC: pulse compressor; PD: power divider; PA/PS: power attenuator/phase shifter; C: circulators; acc: accelerator; sol: solenoid; Y: YAG screen; B: beam position monitor; Q: quadrupole; ICT: integrated current transformer; IP: interaction point; FC: Faraday cup.

In the VIGAS facility's accelerator system, an S-band photocathode electron gun produces 5-MeV electron bunches [2]. A 1.5-m S-band traveling-wave accelerator then boosts the energy to 50 MeV while achieving emittance compensation [3]. To reduce the energy spread caused by the longitudinal length of the bunches, a buncher is installed between the photocathode electron gun and the S-band accelerator to compress the bunches longitudinally.

The main accelerating section consists of six X-band, 0.6-m traveling-wave structures that operate at 80 MV/m to further boost the energy to 350 MeV. The facility operates in single-bunch mode, with the electron bunch accelerated at the maximum voltage point determined by the pulse after the pulse compressor. The system' s output energy is adjusted by varying the accelerating gradient and phase of the X-band accelerators.

X-band high-gradient accelerator technology plays a crucial role in reducing the overall system volume in VIGAS. This technology traces back to electron-positron Global Linear Collider (GLC) [4, 5] and Next Linear Collider (NLC) [6, 7] studies, for which the SLAC National Accelerator Laboratory and the High Energy Accelerator Research Organization (KEK) collaborated in the late 1980s. A high gradient of 65 MV/m was reported at the Next Linear Collider Test Accelerator (NLCTA) by SLAC [8] and at the new X-band test facility (XTF) by KEK [9] prior to 2005. The Compact Linear Collider (CLIC) program at the European Organization for Nuclear Research (CERN) changed the frequency from 30 to 12 GHz based on experimental results in 2007 and achieved a gradient of 100 MV/m [10] in an initial X-band structure test.

Beyond large colliders, X-band high-gradient technology has also been applied to free-electron laser (FEL) facilities, such as a soft X-ray FEL known as ZFEL at the University of Groningen [11] and a hard X-ray FEL using an all-X-band accelerator at SLAC [12]. In 2017, an X-band accelerating structure for a compact hard X-ray FEL facility was designed at the Shanghai Institute of Applied Physics [13]. In recent years, interest has grown in applying high-gradient technology to compact inverse Compton scattering sources, such as VIGAS and Smart*Light at Delft University of Technology [14].

Tsinghua University collaborated with CERN and KEK to assess the feasibility of X-band high-gradient accelerating structures and has developed the capability to machine, rinse, and braze X-band high-gradient structures. Tsinghua University designed a choke-mode high-gradient structure that achieved a gradient of 120 MV/m [15]. An X-band high-power test stand was established at Tsinghua University for testing high-gradient structures, where an X-band high-gradient two-half structure [16] and a field-emission gun [17] were designed and tested.

Accelerating structures can be divided into traveling-wave and standing-wave configurations. Owing to their wide-passband property, traveling-wave structures can operate without a circulator and are more favorable for long high-gradient applications. Traveling-wave structures include constant-impedance (CI) and constant-gradient (CG) designs. A CI structure uses identical cells, but due to wall losses, the gradient at the rear of the structure is lower than at the front. In contrast, a CG structure employs a gradually decreasing group velocity to generate a uniform field distribution. Nevertheless, the tested high-gradient structure adopted a CI scheme because its fabrication is more reliable and less costly. A high-power test is essential for applying X-band high-gradient technology.

In this paper, we review the design of a CI high-gradient structure with a SLED-I type radio-frequency (RF) pulse compressor (PC), introduce its fabrication process, demonstrate the application of a non-contact tuning method, and present RF measurements after tuning. We also report high-gradient test results, including the conditioning history, the highest achieved gradient, and the spatial distribution of breakdowns inside the structure. The breakdown rate (BDR) versus gradient was measured to analyze the structure' s high-gradient performance.

2 Design and Fabrication of the CI Structure

The X-band high-gradient structure in VIGAS will operate with a SLED-I type PC. The calculation of the accelerating gradient and structure design are detailed in Ref. [18]. The rationale for selecting a CI scheme over a CG scheme is explained as follows. Figure 2 [Figure 2: see original paper] shows the accelerating gradient in each cell for both schemes with and without a PC. The filling time of the CG structure was set equal to that of the CI structure, and both were assumed to operate with the same PC. To maintain the highest accelerating voltage, electrons should exit the structure when filling is complete [19]. Since the filling time of the structure (~100 ns) is significantly longer than the time an electron spends traveling through it (~2 ns), electrons should be injected when the entire structure is almost fully filled. Consequently, for a CG structure, an electron travels through a higher accelerating field in the rear than at the front. In contrast, the declining power flow along the beam path in a CI structure can compensate for the declining output of the PC. As a result, when transitioning from the scenario without a PC to that with a PC, the accelerating voltage gain of the CI structure is slightly higher than that of the CG structure. Integration of the cell gradients in Fig. 2 showed that the ratio of accelerating voltage with and without a PC was 2.17 and 2.15 for the CI and CG structures, respectively. Consequently, the accelerating voltage of the CI structure with a PC was 0.1% higher than that of the CG structure, whereas without a PC, the former was 0.5% lower than the latter. Therefore, when operating with a PC, a CI structure is more favorable than a CG structure in terms of accelerating voltage. Furthermore, due to the identical dimensions of all normal cells, the elaborate fabrication of the structure is more reliable, and the cost of fabricating a CI structure is estimated to be over 20% less than that of a CG structure, which is significant for the industrial application of X-band high-gradient technology.

Fig. 2 Comparison of the accelerating gradient in each cell for the CI and CG structures with and without a PC. The input power is 13.7 MW. The input signal for the PC has ideal phase switching (phase switching time is zero). The CI and CG structures used for the calculation have equal filling times.

The shape of a periodic cell is shown in Fig. 3 [Figure 3: see original paper]a. Optimization of a single cell, including the maximum surface electric field and modified Poynting vector, was achieved and introduced in Ref. [18]. A dual-feed scheme was adopted for the coupler, as shown in Fig. 3b. An 8-mm rounding was designed at the juncture of the matching cell and coupling hole to reduce local magnetic field enhancement. Compared to the 2-mm scheme, this reduced the maximum magnetic field by 17%. The surface electric and magnetic fields of the input coupler and its adjacent cells are shown in Fig. 3c and d. The optimization process of the coupler is introduced in Ref. [20].

Fig. 3 (a) Three-dimensional (3D) model of the periodic cell; (b) 3D model of the coupler; (c) Surface electric field of the input coupler and its adjacent cells; (d) Surface magnetic field of the input coupler and its adjacent cells.

A photograph of a machined cavity is shown in Fig. 4 [Figure 4: see original paper]a. Two holes were formed to insert a tuner. The coupler consisted of two parts processed by milling machine. These two parts were brazed and reprocessed to match the WR90 waveguide. A photograph of the coupler after reprocessing is shown in Fig. 4b. After fine machining with an accuracy of 10 m and a surface roughness of 25 nm, cavities were measured using non-contact field measurement to determine their frequency in the working mode [21]. Compared with measurements utilizing a detuning plunger, this method has a significantly lower probability of damaging the cavity iris, where breakdown is more likely to occur in a high-gradient structure. The cavities were brazed as a cell stack before being brazed with the coupler and flange. The entire structure was brazed with a gold-copper solder. Compared with silver-copper solders, gold-copper solders reduce dark current according to the Fowler–Nordheim equation [22] because the work function of gold is higher than that of silver.

Fig. 4 (a) Photograph of a cavity after fine machining; (b) Photograph of a coupler after fine machining, brazing, and reprocessing.

3 RF Measurement and Tuning Method

After fabrication, tuning and RF measurements were performed on the structure. A traveling-wave structure is typically designed to operate with reflection below −30 dB from the input coupler and to maintain correct phase shift between cells along the beam path for efficient particle acceleration. The phase shift between adjacent cells is critical because it directly influences accelerating performance. However, the mechanical tolerance of the cell diameter during fabrication is approximately 10 m, which causes a frequency shift of approximately 5 MHz and a 5° cell-to-cell phase advance shift in an X-band structure [23]. This necessitates post-fabrication tuning to compensate for mechanical errors.

A non-contact tuning method requires measurement of the field distribution using the non-resonant method, also known as the bead-pull method. According to Ref. [24], j kE where iP is the input power, 11, pS is the reflection coefficient in the presence of a perturbing object, 11,aS is the reflection coefficient in the absence of a perturbing object, k is a coefficient that depends on the electric parameters and geometry of the object, and aE is the complex electric field. Generally, only the relative electric field is considered in RF measurements. The electric field is proportional to the difference between the reflection coefficient in the presence and absence of a perturbing object.

In this experiment, a 0.14-mm nylon thread with a 0.14 mm$×$0.7 mm metal bead was inserted through the structure and positioned on its axis. When the metal bead passed through each cell, the vector network analyzer (VNA) measured and recorded the change in reflection, including its magnitude and phase. Using Eq. (1), the relative electric field magnitude and phase of each cell were obtained.

The RF measurement setup is shown in Fig. 5 [Figure 5: see original paper]. The structure was laid horizontally rather than vertically because this orientation was more convenient for tuning. To avoid installing a power divider and bend waveguides, two ports of the VNA were connected to the input coupler. The VNA could transform the S-parameter from these two ports into a combined reflection. This method is introduced in Ref. [25]. Because one VNA port malfunctioned during measurement, two matched loads were assembled at the output coupler instead of using the remaining two VNA ports. The full S-parameters of this structure were measured by changing the connection location of the ports between the VNA and the structure.

Fig. 5 Photograph of the RF measurement of the traveling-wave structure.

The frequency shift of each cell was derived from the measured field distribution using the method introduced in Ref. [23]. The local reflection of the n-th cell can be calculated using Eq. (2). local Where nE is the measured complex field of the n-th cell, counted from the input coupler. In general, the maximum field value in the beam path of a cell is used. 1nE are the values in the adjacent cells, and is the designed phase advance, that is, the working mode of the structure. The relationship between the local reflection and the frequency shift is shown in Eq. (3). local where is the working mode, is the resonance frequency of the cavity, is the group velocity, and c is the speed of light. In the non-contact tuning situation, the reflection from the input port (global reflection) was monitored to guide the tuning of each cell. Because the frequency change of the n-th cell could not be obtained directly from the global reflection, the tuning strategy was to compensate for its local reflection. The variation in reflection from the input port is the local reflection multiplied by the round-trip transmission loss between the input coupler and the n-th cell [23]. Tuning of the middle cells is achieved when the local reflection of each cell is compensated.

Owing to fabrication errors in the output coupler, such as machining tolerance and solder leakage into the cavity during brazing, the output matching cell and its adjacent cell should be tuned to minimize reflection from the output coupler to the middle cells [23]. The input coupler was tuned to minimize global reflection. During the tuning procedure, field measurements were performed at the working frequency. A temperature of 25.4 ℃ and a humidity of 25% were used to calculate the frequency amendment between the environment during RF measurement and operation, as described in Ref. [26]. The field distribution before and after tuning is shown in Fig. 6 [Figure 6: see original paper].

Fig. 6 RF measurement results of the traveling-wave structure before and after tuning. (a) Relative magnitude of the electric field before tuning; (b) Polar plot of the complex electric field before tuning; (c) Relative magnitude of the electric field after tuning; (d) Polar plot of the complex electric field after tuning.

The phase advance between adjacent cells before and after tuning is shown in

Fig. 7 [Figure 7: see original paper]. Before tuning, the phase advance between adjacent cells varied from 60° to 150°, with a mean angle of 119.5°. During the tuning process, each phase advance between adjacent cells was tuned to 120°, corresponding to the $2\pi/3$ working mode. After tuning, the phase advance was close to the working mode, with a maximum deviation of 5°. The comparison in Fig. 7 reveals the favorable effects of tuning.

Fig. 7 Phase advance between adjacent cells before and after tuning.

The S-parameters after tuning were measured and are shown in Fig. 8 [Figure 8: see original paper]. The reflection from the input coupler was below -30 dB, whereas the reflection from the output coupler was only -12 dB. This indicates that the reflection is relatively large when power is fed from the output coupler. Although the CI structure is symmetric in the design phase, meaning power can be fed from either the input or output port, it is necessary to distinguish the two ports after tuning. The transmission loss measured in this experiment was -6.5 dB.

Fig. 8 S-parameters of the structure after tuning. (a) Magnitude of S11 and S22 in dB; (b) Magnitude and unwrapped phase of S21. The black dashed line indicates the location of the working frequency at $2\pi/3$.

The filling time was obtained using the S12 parameter. For a periodic structure, the transmission coefficients can be derived from the circuit model [27] and expressed as Eq. (4). where is the attenuation factor, n is the cell number, D is the length of one cell, is the phase advance of adjacent cells, and 0 is the phase introduced by the waveguides and other components. Both and are functions of frequency. According to this definition, the group velocity gv . When the structure operates at the designed frequency, its phase velocity equals the speed of light, that is, . The relationship between the phase advance and cell length is c . By combining these equations, the filling time at the working frequency can be derived using Eq. (5). d Angle The filling time calculated using Eq. (5) was 98 ns. The group velocity obtained from this measured filling time was 2.14% c, which is close to the designed value of 2.2% c. For the CI structure, the Q value was calculated from the attenuator factor using Eq. (6).

According to Eq. (4), can be obtained from the magnitude of the S21 parameter. Another method of measuring the attenuation factor for a CI structure is to perform an exponential fit of the tuned field distribution. In this RF measurement, the Q values measured from the S21 parameter and field distribution were 4.7$×10^{3}$ and 5.7$×10$^{\{3\},respectively.Theformerwas18\times10}$\{3\}$$. Considering that there may be calibration error or other transmission losses in the measurement, the second value was adopted as the measured Q value. A comparison of the RF measurement results before and after tuning, as well as the simulation results, is reported in Table 1 .

Table 1 Comparison of RF measurement results and simulation results

Parameter	Before tuning	After tuning	Simulation value
Average phase advance [°]			
Standard deviation of phase advance [°]			
Reflection [28]			
Filling time [ns]			
Group velocity /c	2.14%		
Quality factor	5.7$×10^{3}$		7.0$×10^{3}$

4 High-Gradient Testing and Analyses

The high-gradient traveling-wave structure was tested using the Tsinghua X-band high-power test stand (TpoT-X). The TpoT-X was powered by a 40 Hz, 50 MW klystron, and a series of X-band high-power and high-gradient experiments were conducted. A system diagram of the TpoT-X is presented in Ref. [16]. The TpoT-X was divided into a power source room, which housed the klystron, its modulator, and front-end signal source, and a shielded room, where the devices under test were installed. In 2019, an adjustable power divider was installed in the shielded room to increase the platform's testing capacity [29]. A photograph of the structure after installation is shown in Fig. 9 [Figure 9: see original paper]. The high microwave power from the klystron was enhanced using a corrugated PC. After compression, power was fed into the structure via a power splitter and two 180° H-bends. The transmitted power from the output coupler was absorbed by an X-band stainless steel RF load scaled from the S-band load [30]. Directional couplers were placed in front of the input coupler and behind the output coupler. A Faraday cup was installed at the downstream port of the structure to capture dark current. During the high-power test, the input, output, and reflected signals were measured by an oscilloscope via a directional coupler, coaxial attenuator, and crystal detector.

Fig. 9 Photograph of the structure after installation in the Tsinghua X-band high-power test stand.

An automated conditioning system was used for the TpoT-X. Waveforms from the oscilloscope were recorded at regular intervals. If the magnitude of a reflected wave was detected to be five times larger than that of the normal wave, the system would consider this a breakdown event, pause for a set time, and lower the supplied power when restarting.

Two sets of representative waveforms from normal and breakdown scenarios were selected from the recorded data saved by the automated conditioning system, as shown in Fig. 10 [Figure 10: see original paper]. The input pulse to the structure, that is, the output pulse from the PC, had a declining pulse top due to the energy-releasing process of the PC. Fig. 10 shows only the waveform after phase inversion; the entire waveform from the PC is shown in Ref. [31]. In the normal case, the transmitted wave occurred approximately 100 ns after the input pulse, representing the filling time of the entire structure. Due to the broadband properties of the long traveling-wave structure, the output wave was not significantly broadened compared with the input wave. The accelerating gradient versus injection time in Fig. 10a was calculated using Eq. (7). where L is the length of the structure,   is the working frequency, is the group velocity, r is the shunt impedance per meter, Q is the intrinsic quality factor, P is the input power waveform, is the injection time of the electron beam into the structure, c is the speed of light, and   is the attenuation factor. In the breakdown case, due to the blocking effect of the plasma generated at the breakdown location, the transmitted wave was shortened, and the magnitude of the reflected wave was remarkably larger than in the normal case. The time marked in Fig. 10b was used to calculate the breakdown location inside the structure.

Fig. 10 Waveforms and accelerating gradient in the normal and breakdown cases of the conditioning process. (a) Input (blue solid line), reflected (red dash line), and transmitted (yellow dot-dash line) waveforms of the structure and accelerating gradient versus injection time (purple dotted line) in the normal case. The accelerating gradient versus injection time is calculated using Eq. 7. (b) Input (blue solid line), reflected (red dash line), and transmitted (yellow dot-dash line) waveforms of the structure in the breakdown case. Inside the figure, tfill is the filling time of the structure, tref is the time between the rising edges of the input and reflected signals, and twt is the pulse width of the transmitted pulse.

After 180 h of conditioning, this structure had undergone 1.75 × 10^7 pulses and reached the designed gradient of 80 MV/m. The conditioning history is shown in Fig. 11 [Figure 11: see original paper]. The maximum input power was 83 MW, and the total number of breakdowns was 8.4\$×10$^{\{3\}.Duringtheconditioningprocess,78-nspulseswereemployed.Duetotheslowgrowthrate,thepulsewidthwasreducedto60ns.}$
to 10.3\$×10^{6}\$ pulses, the input peak power was increased at a faster pace. When the expected input power was reached, the input pulse width was increased to the required value of 143 ns, and the input power was again increased to 83 MW. After conditioning, this structure was tested at three fixed gradient levels with a 143-ns input pulse, and the BDR was measured at these levels.

Fig. 11 Conditioning history and testing of the high-gradient structure. The black dashed line is the dividing line between conditioning and testing.

The maximum gradient of the first cell of the structure during the filling procedure was calculated directly using the input peak power and shunt impedance as approximately 110 MV/m, which is comparable to existing high-gradient records. The average accelerating gradient of the entire structure can be expressed as is calculated using Eq. (7). , for which The average accelerating gradient during the conditioning process is shown in Fig. 12 [Figure 12: see original paper]. The gradient exhibited a leap at a pulse number of 10.2\$×10^{6}\$ because the structure transitioned from a partially filled status to fully filled status due to the increase in the input pulse. The maximum surface electric field and modified Poynting vector were calculated from the input peak power and simulation field data. Fig. 12b and d show that the maximum surface electric field was 225 MV/m, and the maximum modified Poynting vector was 5.5 MW/mm^2. Pulse heating was calculated using the maximum surface magnetic field and input pulse form, as introduced in Ref. [32]. Pulse heating during the conditioning process is shown in Fig. 12c.

Fig. 12 Accelerating gradient and surface parameters in the conditioning process. (a) Accelerating gradient calculated by integrating the input waveform; (b) Maximum surface electric field; (c) Maximum pulse heating; (d) Maximum modified Poynting vector.

The breakdown location is obtained from the input, transmitted, and reflected signals based on this physical picture [33]: when the input pulse transmits through the structure, part of the pulse is blocked at the breakdown location and reflected back to the input coupler as a reflected signal, while the remaining portion is transmitted to the output coupler as a transmitted signal. The pulse width of the transmitted signal represents the breakdown time within the input pulse. The retardation time of the reflected signal represents the round-trip time between the input coupler and the breakdown site. Therefore, the distance from the input coupler to the breakdown site can be calculated using Eq. (8). wt) / 2 A sketch map of is shown in Fig. 10, and the spatial breakdown distribution is shown in Fig. 13 [Figure 13: see original paper]. Due to the complex circumstances in which breakdown occurs, the transmitted and reflected signals may have irregular shapes, leading to difficulties in confirming reft. Therefore, the breakdown location calculated using this method may have an error range of the distribution trend still conveyed information. As expected, several cells. Nevertheless, breakdown was more likely to occur at the input side of the structure, where the surface electric field and modified Poynting vector were higher. At the rear part of the structure, very few breakdowns occurred.

Fig. 13 Distribution of the structure’ s breakdown location.

During the testing period, the relationship between the measured BDR and gradient was determined, as shown in Fig. 14 [Figure 14: see original paper]. The linear fitting coefficient of the data in the double logarithmic plot was 23.8 6.7, which is analogous to an empirical value of 30. The error value was large due to the limited range of gradients that could be tested. According to the fitting curve, this structure could be operated at 80 MV/m with a BDR level of approximately 1.1$×10^{-3}$ /(pulse · m). This rate is expected to decrease by one to two orders of magnitude when the conditioning pulse count reaches 10^8 [15]. Due to other assignments on this platform, further conditioning was not performed.

Fig. 14 Measured BDR versus accelerating gradient.

5 Conclusion

In this study, the RF measurement, tuning, and high-gradient testing of a CI high-gradient structure were demonstrated. Compared to a CG structure, CI structure fabrication is more reliable and less costly, and the accelerating voltage is slightly higher when used with a PC. This makes the CI structure more suitable for applications if the target gradient can be achieved. After 180 h of conditioning, this CI structure had undergone 1.75$×10^{7}$ pulses and reached the designed gradient of 80 MV/m. The breakdown location analysis showed that breakdowns were concentrated at the front part of the structure, where the surface field was higher. Extrapolation from the measured BDR indicated that this structure could be operated at 70 MV/m with a BDR of approximately 4.4$×10{-5}/(pulse · m).The application of this structure at this gradient level was verified.To utilize this structure at a gradient of 80MV/
5}$/(pulse · m), further conditioning pulses are required. Furthermore, a CG scheme has a lower surface field, and therefore requires fewer conditioning pulses to reach the same gradient compared with a CI scheme, according to experimental results. This is also being considered for the VIGAS program.

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7 Author Contributions

All authors contributed to the conception and design of the study. Material preparation, data collection, and analysis were performed by Xian-Cai Lin, Liu-Yuan Zhou, Qiang Gao, Jian Gao, and Jia-Yang Liu. The first draft of the manuscript was written by Xian-Cai Lin, and all authors commented on previous versions of the manuscript. All authors have read and approved the final manuscript.

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