Measurement and Simulation of the Beam-Coupling Impedance of a Movable Collimator in BRing at HIAF

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Abstract

The dynamic vacuum effect is the primary constraint on beam intensity in high-intensity heavy-ion synchrotrons. In the Booster Ring (BRing) of HIAF, the dynamic vacuum effect induced by charge-exchange beam losses significantly limits the ion intensity and beam lifetime. A collimator is a critical and indispensable component for mitigating the dynamic vacuum effect in high-intensity heavy-ion circular accelerators. Accordingly, a dedicated collimation system has been designed for BRing to reduce ion-induced gas desorption and suppress the dynamic vacuum effect.

However, this intercepting structure may introduce longitudinal and transverse beam-coupling impedances in BRing. In this study, comprehensive investigations were carried out to characterize the beam-coupling impedance of a movable collimator. We systematically present the results of single-wire and two-wire bench transmission measurements, together with numerical simulations. Satisfactory agreement is obtained between the numerical simulations and the wire transmission bench measurements. The power of heat deposition on each part of the collimator due to the longitudinal impedance is evaluated. A total of 24 movable collimators have been fabricated and have entered the online installation stage in the Booster Ring.

Full Text

Preamble

Beam-Coupling Impedance Measurement and Simulation of a Movable Collimator in BRing at HIAF

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The dynamic vacuum effect is the primary constraint on beam intensity in high-intensity heavy-ion synchrotrons. The dynamic vacuum effect induced by charge-exchange beam loss significantly limits the ion intensity and beam lifetime in the booster ring (BRing) of HIAF. The collimator is a critical and indispensable component for mitigating the dynamic vacuum effect in high-intensity heavy-ion circular accelerators.

A dedicated collimation system was designed for BRing to decrease ion-induced gas desorption and suppress the dynamic vacuum effect. Nevertheless, this intercepting structure may introduce longitudinal and transverse beam-coupling impedances in BRing. In this study, comprehensive investigations were conducted to characterize the beam-coupling impedance of a movable collimator. Furthermore, we systematically describe the results of single- and two-wire bench transmission measurements and numerical simulations. Satisfactory agreement was obtained between the numerical simulations and wire transmission bench measurements. The heat deposition power on each part of the collimator due to the longitudinal impedance was evaluated. The 24 movable collimators were processed and entered the online installation stage of the Booster Ring.

Keywords: Booster Ring (BRing) • collimator • longitudinal impedance • transverse impedance • wire transmission method • impedance bench measurement

Introduction

The High-Intensity Heavy Ion Accelerator Facility (HIAF) project [1] was proposed by the Institute of Modern Physics (IMP) of the Chinese Academy of Sciences in 2009 and builds upon the successful construction and operation of the Heavy Ion Research Facility in Lanzhou-Cooling Storage Ring (HIRFL-CSR) [2, 3]. As one of the 16 priority national projects for science and technology for China’ s 12th Five-Year Plan [4], the HIAF project began construction in early 2019 in Guangdong Province. The first beam in the booster ring of HIAF is expected to be delivered by the end of 2024 [5]. The facility will provide intense primary and radioactive ion beams for nuclear, atomic, and applied research sciences [6, 7]. The HIAF complex consists of a superconducting electron cyclotron resonance ion source (SECR) [8–10], an ion linac [11–15], a booster ring (BRing) [16–19], a high-energy radioactive beamline (high-energy fragment separator (HFRS) [20]), a spectrometer ring (SRing) [21–23], and several experimental terminals. A general layout of the HIAF complex is shown in Fig. 1 [Figure 1: see original paper].

As the main accelerator in the HIAF complex and a key piece of equipment, the BRing can accumulate and accelerate a $^{238}\mathrm{U}^{35+}$ beam from 17 MeV/u to an energy of 835 MeV/u. The designed beam intensity of BRing is 1×10^{11} ($^{238}\mathrm{U}^{35+}$). The dynamic vacuum effect induced by charge-exchange beam loss significantly limits the ion intensity and beam lifetime in the BRing of HIAF [24–26]. A dedicated collimation system was designed to decrease ion-induced gas desorption and suppress the dynamic vacuum effect. Simultaneously, a vacuum chamber was designed to install the collimator, and three types of pumps were installed in this chamber.

In Phase I, 24 movable intercepting collimators with water cooling were evenly distributed and installed on the BRing. An additional 24 opposite collimators in the horizontal plane will be installed in a future HIAF Phase II upgrade project. However, this intercepting structure may introduce longitudinal and transverse beam-coupling impedances in BRing. The longitudinal beam-coupling impedance may cause trouble, for example, by stimulating longitudinal beam instabilities in the BRing [27, 28]. In addition, the transverse beam-coupling impedance is the main source of transverse mode-coupling instability. The instability caused by transverse impedance can have many detrimental effects on the beam in high-intensity accelerators, such as beam offset, displacement, or emittance growth, resulting in beam loss [30, 31]. Therefore, an accurate evaluation of the longitudinal and transverse beam-coupling impedances of the movable collimator is crucial for analyzing mode-coupling instability. To ensure good beam quality and stable operation, the impedance of the components should be strictly limited during BRing commissioning. Consequently, detailed impedance simulations of movable intercepting collimators must be performed, and bench impedance measurements should be conducted to verify these simulations. The bunch length (root-mean-square, rms) of BRing is larger than 10 m, and the most interesting frequency of the beam-coupling impedance is lower than 300 MHz [32–34].

The remainder of this paper is organized as follows: Section II describes the mechanical structure of the movable collimator, including the choice of structural dimensions and water cooling. In Section III, the beam-coupling impedance of an arbitrary accelerator device is explained. Another CST simulation is conducted to obtain the cutoff frequency of the DUT. Then, the longitudinal and transverse beam-coupling impedance simulations of the movable collimator using CST software, including Particle Studio and Microwave Studio, are illustrated. Next, the longitudinal and transverse beam-coupling impedances from CST-Wakefield solver simulations and numerical measurement simulations are compared. Section IV presents the coaxial wire measurement setup in detail, the calculation of the characteristic impedance with CST Microwave Studio, the longitudinal and transverse beam-coupling impedance measurements and comparisons, and the relationship between the beam-coupling impedance and distance D, which is defined from the beam center to the collimator block edge. In Section V, the heat deposition power of the collimator is evaluated. Summary and concluding remarks are provided in Section VI.

II. Mechanical Structure of the Movable Collimator

Depending on the beam aperture size, the horizontal and vertical lengths of the collimator block were chosen to be 112 mm and 120 mm, respectively. The collimator thickness along the beam direction is 20 mm. The block material was coated with gold to reduce secondary electron emission. Each collimator block was controlled in a horizontal position within a maximum stroke of 170 mm, and the position resolution was less than 0.3 mm. Water cooling was adopted for the collimator block because of the high-intensity beam. Beckhoff servomotors are operated in a closed-loop control scheme to move the collimator block located at the edge of the beam. The collimator block was isolated from the ground using AlN ceramic to monitor the halo beam signals. The induced signal is amplified using IV electronics. To improve the signal-to-noise ratio, IV electronics were mounted on the backplane of the collimator. Because the vacuum pressure of the booster ring must be extremely high and less than 5×10^{-12} mbar, the collimator chamber is equipped with ion, molecular, and titanium pumps. The diameter of the collimator chamber was 300 mm. The collimators were installed in the horizontal plane and in the inner part of the booster ring. The mechanical design of the collimator is illustrated in Fig. 2 [Figure 2: see original paper].

III. Longitudinal and Transverse Impedance Simulations

A. Beam Coupling Impedance

Assuming that a bunched beam with total charge q_1 travels through a structure with offset $\vec{r}_1$ parallel to the z-axis with speed $v\vec{e}_z$, the longitudinal and transverse wake potentials are defined as follows [36] (see Eq. (1) and Eq. (2)):

$$W_{\parallel}(\vec{r}_1, s) = \int_{-\infty}^{+\infty} \left[\vec{E}(\vec{r}_1, z, t) + v\vec{e}_z \times \vec{B}(\vec{r}_1, z, t)\right] \cdot v\vec{e}_z \, dz$$

$$W_{\perp}(\vec{r}_1, s) = \int_{-\infty}^{+\infty} \left[\vec{E}(\vec{r}_1, z, t) + v\vec{e}_z \times \vec{B}(\vec{r}_1, z, t)\right] \cdot \vec{e}_x \, dz$$

where $t = (s + z)/c$ and s is the distance between the test charge q_2 and the head of the excitation bunch in the direction opposite to the speed $v\vec{e}_z$, as shown in Fig. 3 [Figure 3: see original paper]. The longitudinal and transverse impedances $Z_{\parallel}(\omega)$ and $Z_{\perp}(\omega)$ in the CST software can be calculated from the wake potentials $W_{\parallel}(\vec{r}_1, s)$ and $W_{\perp}(\vec{r}_1, s)$ using a Fourier transformation as follows [37] (Eq. (3) and Eq. (4)):

$$Z_{\parallel}(\omega) = -\frac{\int_{-\infty}^{+\infty} W_{\parallel}(\vec{r}_1, s) e^{-i\omega s} ds}{\int_{-\infty}^{+\infty} \lambda(s) e^{-i\omega s} ds}$$

$$Z_{\perp}(\omega) = i\frac{\int_{-\infty}^{+\infty} W_{\perp}(\vec{r}_1, s) e^{-i\omega s} ds}{\int_{-\infty}^{+\infty} \lambda(s) e^{-i\omega s} ds}$$

where $\lambda(s)$ is the longitudinal distribution of the bunch q_1.

B. Simulation Model and Results

The collimator is installed in a vacuum chamber equipped with ion, molecular, and Ti pumps. A simplified model of the mechanical structure was used to accelerate the simulation process. The bellows and servomotor of the collimator were deleted because they did not significantly affect the beams. The ion pump, molecular pump, and titanium pump were not considered to improve simulation efficiency because the internal structure of the vacuum pumps was highly intricate. A simplified structure of the collimator installed in a chamber with only three pump ports is shown in Fig. 4 [Figure 4: see original paper].

To study the beam-coupling impedance behavior, we performed a detailed simulation of the collimator, as shown in Fig. 4, using the wakefield method. The wakefield solver of Particle Studio solves Maxwell' s equations in the time domain using a particle bunch to excite the electromagnetic fields. A test charge was used to sample the fields and compute the wake fields and impedances. The wakefields were tracked over 50 m behind the bunch. We also used the Transient Solver of CST Microwave Studio to simulate the wire measurements. The main output of the simulation, which is a physically measurable quantity, is the scattering parameter $S_{21,\mathrm{DUT}}$. Hence, we used the scattering parameter S_{21} for both the Device Under Test (DUT) and reference (the collimator block outside the chamber). In the wire simulation, the collimators were perfectly matched at both ends. The longitudinal impedance is calculated from $S_{21,\mathrm{DUT}}$ and $S_{21,\mathrm{ref}}$ using the standard log formula [37] (Eq. (5)):

$$Z_{\parallel} = 2Z_{\mathrm{ch}} \log\left(\frac{S_{21,\mathrm{DUT}}}{S_{21,\mathrm{ref}}}\right)$$

where $S_{21,\mathrm{ref}}$ is the reference defined as the collimator block outside the chamber and Z_{ch} is the characteristic impedance of the coaxial line formed by the wire and the DUT wall. Z_{ch} is the simulation output; then, we can calculate and cross-check the beam-coupling impedance. The main parameters of the CST Particle Studio and CST Microwave Studio simulations are summarized in Tab. 1 .

Simultaneously, all 24 collimator chambers were installed near the quadrupole magnet and connected to racetrack-type quadrupole magnet vacuum chambers, as shown in Fig. 5 Figure 5: see original paper. The first mode of the rectangular waveguide is TE10 mode, and the cutoff frequency is as follows (Eq. (6)):

$$f_c = \frac{c}{2a} = 0.6521 \text{ GHz}$$

where a is the length of the rectangular waveguide cross-section and is approximately 230 mm, and c is the speed of light.

To obtain an accurate cutoff frequency value, we conducted another simulation using CST Microwave Studio. As shown in Fig. 5(a), one incident wave was set up to pass through a PEC tube with the same cross-section as the quadrupole magnet vacuum chamber. The frequency of the incident wave was changed from DC to 1 GHz, and the dependence of the S-parameter on the frequency was calculated, as shown in Fig. 5(b). The S_{21} curve simulated by CST illustrates that the cutoff frequency is 0.6549 GHz. The approximate analytical solution and the simulated results were consistent with each other. Because the cutoff frequency of the quadrupole-magnet vacuum chamber, which is connected to the collimator chamber, is approximately 0.65 GHz, the real and imaginary parts of the longitudinal and transverse impedances are displayed up to 0.65 GHz.

Figure 6 [Figure 6: see original paper] shows a comparison of the longitudinal beam-coupling impedance from CST-Wakefield solver simulations and the wire simulation. Evidently, it is mainly a narrow-band impedance, and the longitudinal impedances at the first and second frequencies are approximately 360 MHz and 528 MHz, respectively. The longitudinal beam-coupling impedances from CST-Wakefield solver simulations and numerical measurement simulations were in good agreement.

Because all collimators were installed in the horizontal plane, we mainly performed and focused on the horizontal simulation of the transverse impedance. In addition, the CST Particle Studio wakefield solver allowed us to define the positions of the source beam and test particle (as the observation or computation point). Therefore, we can separately calculate the transverse dipolar and quadrupolar terms [38]. Transverse dipolar kicks were obtained by displacing the beam’ s transverse location to $(x, y) = (10 \text{ mm}, 0)$ for a horizontal wake. Figure 7 [Figure 7: see original paper] shows a comparison of the transverse dipolar beam-coupling impedance in the horizontal plane from CST-Wakefield solver simulations and the wire simulation. Very good agreement was observed for the broadband behavior, as shown in Fig. 7. Comparable to the longitudinal case, the horizontal dipolar impedance at the first and second frequencies was also approximately 360 MHz and 528 MHz, respectively.

IV. Beam-Coupling Impedance Measurement and Comparison

A. Longitudinal Impedance Measurement

A measurement campaign on one of the movable collimators was launched in 2023 at IMP. Longitudinal measurements are straightforward. A single wire was inserted into the Device Under Test (DUT) with matching resistors at both ends of the collimator chamber, and the signal transmission (S_{21}) was measured using a VNA, from which the longitudinal impedance was calculated according to Eq. (5). The VNA and connecting cables had a characteristic impedance (Z_{ch}) of 50 Ω. A TEM line composed of a single wire and a DUT generally has a higher line impedance Z_L. To perform the measurements, a coaxial line composed of the wire and beam pipe must be adapted to the 50 Ω impedance of the VNA cables. This can be achieved using a matching network. As a simple and practical solution, we consider a single resistor $Z_m = Z_L - 50\ \Omega$ before and after the DUT, as shown in Fig. 8 [Figure 8: see original paper]. To match the 50 Ω cables, we set $Z_m = Z_L - 50\ \Omega$.

For a circular beam pipe and wire, the line impedance is given by the well-known expression (Eq. (7)):

$$Z_L = 60 \ln\left(\frac{D}{d}\right)$$

where D is the beam pipe diameter and d is the wire diameter. We chose the wire diameter $d = 0.62$ mm and the diameter of the collimator chamber $D = 300$ mm. According to Eq. (7), we calculate $Z_L = 370\ \Omega$. Finally, the series-matching resistor $Z_m = Z_L - 50\ \Omega = 320\ \Omega$ was calculated. We chose a radio frequency (RF) carbon resistor for our matching network, which has low inductance, making it ideal for high-frequency applications. We chose $A = 6$ dB attenuators before and after the DUT for the matching network to reduce port reflection. The S-parameters were measured using the Rohde and Schwarz (R&S) ZVN-20 2-port VNA, which has a frequency range of 100 kHz to 20 GHz. The transmission S_{21} was measured at a step size of 100 Hz with 5000 sweep points, and the input power was set to 0 dBm. N-type female adaptors were selected for the input and output of the DUT and were connected to the sucobox from Huber+Suhner, which contained the matching resistor. Figure 8 shows the collimator installation and RF measurements for the longitudinal impedance schematic setup.

The simulation and measurement results are in good agreement (Fig. 9 [Figure 9: see original paper]). In addition, the real and imaginary parts of the longitudinal impedance are extremely small below 300 MHz, which is the most interesting frequency for BRing because the bunch length in the BRing exceeds 10 m, as mentioned before. The longitudinal-impedance measurement results for the movable collimator are shown in Fig. 10 [Figure 10: see original paper] for

$D = 40$ mm, 50 mm, and 60 mm. The measurement results show that the longitudinal impedance is inversely proportional to the distance D, which is defined as the distance from the beam center to the collimator block edge. This indicates that the longitudinal impedance does not affect beam stability in the BRing of HIAF.

B. Transverse Impedance Measurement

The experience obtained using wire transmission methods for longitudinal impedance measurements has motivated the search for a similar technique for transverse measurements. Hence, direct wire transmission measurements were also performed for transverse impedance. The transverse impedance measurement consists of two wires driven by opposite phases. A dipolar field was excited in the DUT and interacted only with the fringe field. In practice, the phase opposition between the two wires can be obtained by splitting the input signal into a 180° hybrid and recombining it in the same manner to obtain the DUT output signal. The 180° microwave hybrid H-183-4 was obtained from MACOM company, and the entire operating bandwidth ranged from 0.03 GHz to 3 GHz with a seven-octave frequency range. The 180° microwave hybrid could suppress the unwanted "0" mode very well owing to its excellent isolation, which is greater than 30 dB below 1 GHz. The maximum insertion loss was less than 0.4 dB, and the phase imbalance was better than $±$7.5° for the entire operating frequency range.

For resistive matching after a 180°-microwave hybrid, each 50 Ω hybrid output must be matched to half of the difference-mode line impedance Z_L. If matching is performed with single-series resistors R_m for each wire, the value of each resistor is set as $R_m = Z_L/2 - 50\ \Omega$. Figure 11 [Figure 11: see original paper] shows the collimator installation and RF measurements for the transverse impedance schematic setup.

To precisely measure the transverse impedance using the direct wire transmission method, one of the key points is to calculate the precise matching resistor. In this study, we utilized CST Microwave Studio to calculate the line impedance of double wires. The diameter of each wire was 0.62 mm, and the center distance between the two wires was 35.75 mm. The CST simulation model is illustrated in Fig. 12 [Figure 12: see original paper]. A waveguide port and differential mode excitation were adopted to simulate the line impedance of the double wires, as shown in Fig. 12. The simulation results indicate that the line impedance Z_L was 585 Ω, as shown in Fig. 13 [Figure 13: see original paper]. Finally, $R_m = Z_L/2 - 50\ \Omega = 242.5\ \Omega$. In our measurements, we soldered an RF carbon-matching resistor between the copper wire and an N-type connector pin with tin, and used sucobox to cover the enamelled copper wire, as shown in Fig. 14 [Figure 14: see original paper].

The beam-coupling impedance $Z_{\|}$ was measured using a vector network analyzer via the double-wire transmission method and calculated as shown in the longitudinal case. Subsequently, the transverse impedance in the horizontal plane is determined using [38, 39] (Eq. (8)):

$$Z_\perp = \frac{2c^2}{\omega^2 \Delta^2} Z_\parallel$$

where c denotes the speed of light, Δ denotes the center distance between the two wires, and $\omega = 2\pi f$. According to Eq. (8), the transverse dipolar impedance is finally calculated.

Figure 15 [Figure 15: see original paper] shows a photograph of the double-wire transmission measurement setup of the movable collimator. Ports 1 and 2 are the VNA ports used for transmission measurements of the DUT. Figure 16 [Figure 16: see original paper] compares the transverse dipolar impedance, including the real and imaginary parts, with CST wire simulation and the measurement results for the movable collimator when $D = 40$ mm. Good agreement is also observed between the simulated and measured results for the horizontal impedance of the movable collimator when $D = 40$ mm, as shown in Fig. 16. The transverse dipolar impedance measurement results of the movable collimator are shown in Fig. 16 when $D = 50$ mm and 60 mm, respectively.

The measurement results illustrate that the transverse dipolar impedance is inversely proportional to distance D, which is similar to the longitudinal behavior. Evidently, the measured result has four narrow-band transverse dipolar impedances below 300 MHz approximately at 69 MHz, 99 MHz, 124 MHz, and 169 MHz, respectively. Nevertheless, narrowband impedances, including the real and imaginary parts below 300 MHz, are not observed in the CST numerical simulation possibly because the water-cooling pipe, signal wire, and screws on the collimator block are not considered; alternatively, this result was obtained possibly because the feed-through, ion pump, molecular pump, and titanium pump were not considered in the simplified simulation model.

The total real and imaginary parts of the horizontal dipolar impedance for the 24 movable collimators are approximately 120 kΩ m^{-1} and 43 kΩ m^{-1} at 124 MHz, respectively, which are significantly lower than the threshold impedance for the transverse mode-coupling instability. The transverse beam-coupling impedance may stimulate transverse mode-coupling instability when it exceeds a specific threshold. DELPHI (discrete expansion over Laguerre polynomials and Head-tail modes for instabilities) was used to calculate the beam stability for a typical ^{78}Kr^{19+} heavy-ion beam of the booster ring. In the DELPHI simulation, all structures, including the movable collimator for BRing, were included in the weighting of their local betatron functions. The simulation results showed that wideband impedances and other structures, including collimators, are not expected to have a significant impact on the beam stability in the BRing of HIAF [33, 40].

V. Heat Deposition Evaluation on the Collimator

As the beam passes through the collimator, it loses a certain amount of energy. To obtain the heat deposition power on each part of the collimator owing to the longitudinal impedance, a module called the time-frequency power loss monitor in CST PARTICLESTUDIOSUITE was used. In the wakefield simulation, the longer the bunch length, the lower the calculated impedance frequency. Assuming that the bunch length is 150 mm, the calculated frequency of the beam impedance is approximately 650 MHz, which is the cutoff frequency.

In the simulation, we assumed that the bunch charge, bunch rms length, and wakefield tracking length were 1 nC, 150 mm, and 100 m, respectively. The practical heat deposition process is prolonged for an extremely long duration, whereas the simulation process lasts only 340 ns owing to limited time and computing resources. Figures 17 and 18 show that heat deposition on the collimator block was less than 2% of the total power on the collimator and 316L chamber when the bunch rms length = 150 mm.

Furthermore, in the simulation, we assumed that the bunch charge, bunch rms length, and wakefield tracking length were 1 nC, 1000 mm, and 100 m, respectively. Figure 19 [Figure 19: see original paper] shows the total power loss in the collimator and 316L chamber when the bunch rms length = 1000 mm. The power loss is reduced by a factor of 100 when the bunch length increases from 150 mm to 1000 mm, as shown in Figs. 17 and 19. They indicated that the heat deposition is inversely proportional to the bunch length, as described in [41] and [42].

Finally, because the bunch length (root-mean-square) of BRing is larger than 10 m and the maximum beam intensity of BRing will be 1×10^{11} ($^{238}\mathrm{U}^{35+}$), in the simulation, the bunch charge, bunch rms length, and wakefield tracking length were set to 560 nC, 10,000 mm, and 100 m, respectively. Figure 20 [Figure 20: see original paper] shows the total power loss in the collimator and 316L chamber when the bunch rms length = 10,000 mm and the bunch charge = 560 nC. Figure 20 shows the heat deposition on the BRing collimator and can be considered as a reference for establishing a cooling system.

VI. Conclusion

In the framework of this study, we carefully quantified the beam-coupling impedance of the movable collimator with CST, including both Particle Studio and Microwave Studio simulations. We systematically measured the longitudinal and transverse beam-coupling impedances of the movable collimator using single- and two-wire bench transmission measurement methods. Longitudinal and transverse beam-coupling impedance simulations and bench measurements of the movable collimator using the coaxial wire transmission method were in good agreement. A campaign for different distances D from beam center to collimator block measurements on the movable collimator was launched. The measurement results illustrate that the transverse dipolar impedance is inversely proportional to distance D, which is similar to the longitudinal behavior. The results show that both the longitudinal and transverse impedances of the movable collimator are narrow-band coupling impedances. The real and imaginary parts of the longitudinal impedance were very small below 300 MHz. However, the transverse measured result has four narrow-band horizontal dipolar impedances, including the real and imaginary parts below 300 MHz at approximately 69 MHz, 99 MHz, 124 MHz, and 169 MHz. Nevertheless, the beam-coupling impedances of the movable collimator were not expected to significantly affect the beam stability of HIAF.

Finally, the single- and two-wire bench transmission measurements and simulation methods for the movable collimator investigated comprehensively in this study have accumulated experience and engineering foundations for beam-coupling impedance measurements of the key components of the next generation of high-intensity ion accelerators.

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Author Contributions

All authors contributed to the study conception and design. Material preparation, data collection, and analysis were performed by Guang-yu Zhu, Jia-jian Ding, Jian-chuan Zhang, Jun-xia Wu, Wei-ping Chai, Guo-dong Shen, Zi-Shuai Qiu, Yong-liang Yang, Jun Meng, and Jian-cheng Yang. The first draft of the manuscript was written by Guang-yu Zhu and all authors commented on previous versions of the manuscript. All the authors have read and approved the final version of the manuscript.

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Note: Figure translations are in progress. See original paper for figures.