Coaxial Capacitive Dividers for High-Voltage Pulse Measurements in Intense Electron Beam Accelerator With Water Pulse-Forming Line

Jin-Liang Liu, Bing Ye, Tian-Wen Zhan, Jia-Huai Feng, Jian-De Zhang, and Xin-Xin Wang

Abstract—In this paper, a new coaxial capacitive divider is investigated. The electrical characteristics of the capacitive divider are theoretically analyzed, and the parameters of the capacitive divider are calculated and measured. Its rise time is about 8 ns, and the divider ratio is over 2000. The divider is employed to measure the pulsed high voltages of an intense electron beam accelerator with a water pulse-forming line (PFL) in our laboratory. The capacitive divider can directly measure the diode voltage within nanoseconds, and when combined with an integrator, it can measure the PFL charging voltage with a duration of several microseconds. Compared with conventional resistance dividers, the capacitive divider has more advantages, such as compactness, stability, a relatively high divider ratio, a fast response time, and not much of an effect on the accelerator.

Index Terms—Accelerator, capacitive divider, high-voltage pulse, pulse-forming line (PFL), resistance divider.

I. INTRODUCTION

R EPEITION is currently one of the most important development trends for intense electron beam accelerators [1], [2]. The measurement of the diode voltage and the pulse-forming line (PFL) charging voltage is important in the research of such accelerators. Two common instruments for measuring the transient pulse voltages are the resistive divider and capacitive divider. In particular, the capacitive divider has been widely employed in many laboratories. Several successful designs of the capacitive divider have been reported [3]–[5]. However, the voltages of intense electron beam accelerators with a water PFL are difficult to measure using these capacitive dividers, which have been applied in high-power microwaves, free-electron lasers, and environmental protection [6]–[9]. In an accelerator with a water PFL that works at a single rate, the resistance divider is traditionally used [10], [11]; whereas in a repetitive-rate accelerator with an oil PFL, the capacitive divider with thin synthetic plastic films over a flat electrode surface is often employed [12]. However, in a repetitive-rate accelerator with a water PFL, it is difficult to measure the diode voltage and the PFL voltage by a resistance divider or a capacitive divider with a copper membrane. Two problems are common to both types of accelerators. The first one is that the divider ratio of the resistance divider is insensitive to temperature, which will rise when current is passed through the resistance of the divider. This effect on the single-rate accelerator may be small, but it has a notable influence on the repetitive-rate accelerator. Another is that the resistance divider is connected to the resistance load of the accelerator in parallel. If the resistance of the divider is not significantly larger than the load of the accelerator, the energy efficiency of the accelerator will be influenced. The aforementioned problems are avoided when a capacitive divider is employed to measure the voltage of the accelerator with a water PFL. However, for the traditional capacitive divider with thin synthetic plastic films over a flat electrode surface, the film with the electrode is affixed onto the inside shell of the PFL, which makes it easy for water to erode it. It contaminates the deionized water in the accelerator and lowers the breakdown electrical strength of the PFL, forcing an electrical breakdown between the film with the electrode and the pole with a high voltage to occur more often. To accurately measure the voltage of the repetitive-rate accelerator with a water PFL and solve the aforementioned problems, a coaxial capacitive divider that is characterized by its compactness, ease of use, stability, and reliability is presented and constructed in this study. The capacitive divider has been employed to measure the pulsed high voltage of an intense electron beam accelerator with a water PFL in our laboratory. The measured diode voltage is over 500 kV, with a duration of 80 ns. A capacitive divider with an integrator has also been employed to monitor the charging voltage of the PFL, with a duration of several microseconds and a measured voltage over 600 kV.

II. NEW CAPACITIVE DIVIDER

A. Theoretic Analysis

Ideally, a capacitive voltage divider consists of two capacitors that are connected in series, as shown in Fig. 1. $C_1$ is the capacitance of the low-voltage arm, $C_2$ is the capacitance of the...
Fig. 1. Circuit of a simple capacitive divider.


Fig. 2. Schematics of the coaxial capacitive voltage divider.

The high-voltage arm, and R is the impedance of the oscilloscope for measuring voltage. \( U_0 \) is the voltage measured by the oscilloscope. The following equation is derived based on the circuit theory:

\[
\frac{dU_i}{dt} = \frac{C_1 + C_2}{C_2} \frac{dU_0}{dt} + \frac{U_0}{RC_2},
\]

As \( R(C_1 + C_2) \gg \tau \), we may write

\[
U_0 = \frac{C_2}{C_1 + C_2} U_i = \frac{1}{\beta} U_i.
\]

When \( R(C_1 + C_2) \ll \tau \), (1) becomes

\[
U_0 = RC_2 \frac{dU_i}{dt}
\]

where \( \tau \) is the duration of \( U_i \). From the above equations, we see that when \( R(C_1 + C_2) \ll \tau \), an integrator is necessary, and when \( R(C_1 + C_2) \gg \tau \), the capacitive divider can directly monitor the high-voltage pulse.

B. Configuration of the Novel Capacitive Divider

The proposed capacitive voltage divider has a coaxial configuration, as shown in Fig. 2, which consists of connecting the flange, the outer crust, the cover board, the Q9 cable plug, the seal ring, the inner electrode, etc. The high-voltage arm capacitor \( C_2 \) is formed between the high-voltage electrode of the accelerator and the inner conductor of the capacitive divider and the inner conductor and the outer crust with a coaxial structure form the low-voltage arm capacitor \( C_1 \). In an intense electron beam accelerator with a water PFL, both capacitors \( C_1 \) and \( C_2 \) are filled with high-resistivity water (more than 10 M\( \Omega \)·cm), which acts as an insulating dielectric. Two seal rubber rings are used to prevent the water in the divider from leaking. The divider is connected to a high-impedance wideband oscilloscope. The cable connects the divider to the oscilloscope through \( Q_9 \) cable plugs. To measure the high-voltage pulse with a duration time of several microseconds, an integrator is necessary in the output port of the divider.

C. Capacitance and Divider Ratio of the Capacitive Divider

1) Capacitance of the Capacitive Dividers: The low-voltage arm capacitor \( C_1 \) is not long enough, and therefore, the edge effect cannot be ignored, and accurately calculating such a capacitor using the formula for the coaxial capacitor becomes difficult. The capacitance is directly measured by an HP precise RLC meter, and the result is 18.2 nF.

For calculation of the capacitance of the high-voltage arm capacitor \( C_2 \), we suppose that the electric field between the inner and outer (middle) conductors of the PFL is uniform, and the edge effect is ignored. \( R_{\text{out}} \), \( R_{\text{mid}} \), and \( R_{\text{in}} \) are the radius of the outer, middle, and inner conductors of the PFL of the accelerator, respectively, and \( r \) is the radius of the inner electrode of the capacitive divider. The capacitance of the high-voltage arm capacitor between the inner and outer conductors is

\[
C_{\text{2in}} = \frac{2\pi \varepsilon}{\ln(R_{\text{out}}/R_{\text{in}})} \times \frac{\pi r^2}{2\pi R_{\text{out}}}
\]

and the capacitance of the high-voltage arm capacitor between the middle and outer conductors is given by

\[
C_{\text{2mid}} = \frac{2\pi \varepsilon}{\ln(R_{\text{out}}/R_{\text{mid}})} \times \frac{\pi r^2}{2\pi R_{\text{out}}}
\]

As for the designed capacitive dividers, \( R_{\text{out}} \), \( R_{\text{mid}} \), \( R_{\text{in}} \), and \( r \) are 280, 185, 82, and 36.5 mm, respectively. With the formulas above, the following calculated results are obtained:

\( C_{\text{2in}} = 8.72 \) pF, and \( C_{\text{2mid}} = 25.84 \) pF.

2) Theoretical Calculation of the Divider Ratios of the Capacitive Dividers:

The capacitive divider for diode voltage measurement: When the main switch of the accelerator is closed, the voltage of the inner conductor (the voltage of the field emission vacuum diode) can be measured by the capacitive divider, which is fixed between the inner and outer conductors of the PFL. The pulselength of the diode voltage is about 100 ns. When the impedance of the oscilloscope is 1 M\( \Omega \), \( R(C_1 + C_{\text{2in}}) \), i.e., the characteristic time of the capacitive divider, is about 0.02 s; therefore, the condition \( R(C_1 + C_{\text{2in}}) \gg \tau \) is satisfied. For this case, the integrator is not needed. From (2) and the geometric dimensions of the PFL and the capacitive divider, the divider ratio is about 2088.
The capacitive divider for PFL charging voltage measurement: When the capacitive divider is employed to measure the charging voltage of the water PFL, which is also the breakdown voltage of the main switch, whose pulsewidth is around several microseconds, the condition $R(C_{1} + C_{2\text{mid}}) \ll \tau$ is satisfied; therefore, an integrator is required. The circuit for this capacitive divider is shown in Fig. 3. In the designed integrator, we select $R_{1} = 3 \, \Omega$ and $C_{3} = 50 \, \text{nF}$, and the impedance $R_{2}$ of the oscilloscope is 1 M$\Omega$.

From Fig. 3, the circuit equation can be expressed as

$$
(C_{1} + C_{2\text{mid}})C_{3}R_{1}\frac{dU_{0}}{dt} + \left[(C_{1} + C_{2\text{mid}})(1 + \frac{R_{1}}{R_{2}}) + C_{3}\right] \frac{dU_{0}}{dt} + \frac{U_{0}}{R_{2}} = C_{2\text{mid}} \frac{dU_{i}}{dt}.
$$

(6)

Because the input voltage waveform is a square or triangular pulse, according to the circuit theory, the higher order derivative can be ignored, and (6) can be written as

$$
\left[(C_{1} + C_{2\text{mid}})(1 + \frac{R_{1}}{R_{2}}) + C_{3}\right] \frac{dU_{0}}{dt} + \frac{U_{0}}{R_{2}} = C_{2\text{mid}} \frac{dU_{i}}{dt}.
$$

(7)

The pulsewidth is about $10^{-6}$ s, and the magnitude of the expression $R_{2}[(C_{1} + C_{2\text{mid}})(1 + (R_{1}/R_{2})) + C_{3}]$ is about $10^{-2}$ s; therefore, $\tau \ll R_{2}[(C_{1} + C_{2\text{mid}})(1 + (R_{1}/R_{2})) + C_{3}]$ is satisfied. The ratio of the capacitive divider is

$$
\beta = \frac{U_{i}}{U_{0}} \approx \frac{(C_{1} + C_{2\text{mid}})(1 + \frac{R_{1}}{R_{2}}) + C_{3}}{C_{2\text{mid}}} = 2640.
$$

D. Electric Field Simulation of the Divider in the Accelerator

In the theoretical calculations for obtaining the capacitance $C_{2}$ above, we suppose that the electric field is uniform. To verify the reasonability of such an assumption, electric field analysis about the dividers, which are assembled on the accelerator, was carried out by employing ANSYS software, which is based on the finite-element method. Because the propagating velocity of the electromagnetic field is the light velocity and the time scale for the charging voltage of the PFL is microseconds, the distributions of the electric field in the PFL can be regarded as a stationary field. Moreover, the structure of the PFL is coaxial, and therefore, a 2-D axial-symmetric model can be used in simulations, which is also helpful in reducing the calculation scale.

In the simulation, the negative voltage is charged to the middle conductor, and the inner and outer conductors are put to Earth. Fig. 4(a) and (b) shows the electric field contour distributions of the PFL with capacitive dividers and water resistance dividers, respectively. Fig. 4 indicates that the distribution of the electric field in the PFL is uniform in the case of the fixed capacitive divider, and the capacitance divider has little effect on the electric field distribution. Compared with a resistance divider, this is an advantage of a capacitive divider with a coaxial structure.
an attenuator, and its rise time

to the oscillograph, and its rise time

two signals: One was connected to the oscillograph through

calibrating device. Then, the rectangular signal was divided into

about 100 ns generated by the signal generator was fed to the

cable and the output impedance of the signal generator.

is a coaxial transmission line, and its impedance matches that

on the accelerator, it is difficult to test its response time. A cal-

ibrating device and a standard impulse generator were used to

test the performance of the new divider. The calibrating device

were done on an intense electron beam accelerator with a

water PFL [15]. The ratios of the two capacitive dividers were

monitored by two different standard resistance dividers, which

used to be applied on the accelerator.

F. Measurement of the Divider Ratios of the Dividers

Because the high-voltage arm capacitance depends on the position and the geometry of the PFL of the accelerator, it is

no use to test the divider ratio of the capacitive dividers on

the calibrating device. Experiments on testing the ratios of

the dividers were done on an intense electron beam accelerator with a

water PFL [15]. The ratios of the two capacitive dividers were

monitored by two different standard resistance dividers, which

used to be applied on the accelerator.

1) Divider Ratio of the Capacitive Divider for Diode Voltage

Measurement: Under the same operating condition under

which the energy-storage capacitor was initially charged at

40 kV, the diode voltages were measured by the capacitive

divider and the standard resistance divider, respectively.

The voltage and the pulsewidth measured by the resistance divider

are 2.7 V and 89.6 ns, respectively, which are correspondingly

1.2 V and 82.4 ns, as measured by the capacitive divider.

The divider ratio of the resistance divider is 997. The same attenu-

ator with a ratio of 203 was used for the two dividers. Therefore,

the divider ratio of the capacitive divider can be inferred as

follows: \( \beta = 2.7 \times 997/1.2 = 2243 \). The divider ratio is 2088

from the theoretical calculation above. Based on the results of

the theoretical calculation and the experimental test, the error

of the divider ratio of the capacitive dividers is about 10%.

2) Divider Ratio of the Capacitive Divider for PFL Voltage

Measurement: Under the same running condition of the accel-

erator, the PFL voltages measured by the capacitive divider

and the resistance divider were compared. The voltage and

the pulsewidth measured by the resistance divider are 2.7 V

and 3.3 \( \mu \)s, respectively, which are correspondingly 1.1 V

and 3.4 \( \mu \)s, as measured by the capacitive divider.

The divider ratio of the resistance divider is 547. The ratio of the attenu-

ator is 97.2 for the capacitive divider and 203 for the resistance divider.

The divider ratio of the capacitive divider can be inferred as

follows: \( \beta = 2.7 \times 547/1.1 \times 97.2 = 2804 \). The divider

ratio is 2640 from the theoretical calculation above. Based on the

results of the theoretical calculation and the experimental test, the error

of the divider ratio of the capacitive dividers is less than 10% for the microsecond impulse.

E. Performance of the Divider Under Impulse Measurements

Generally speaking, when the capacitive divider is assembled

on the accelerator, it is difficult to test its response time. A cal-

ibrating device and a standard impulse generator were used to

test the performance of the new divider. The calibrating device

is a coaxial transmission line, and its impedance matches that

of the cable and the output impedance of the signal generator.

Fig. 5 illustrates the scheme of the calibration setup [13], [14].

Since the divider monitored an impulse of several nanosec-

onds, a rectangular signal of 200 V with a pulsewidth of

about 100 ns generated by the signal generator was fed to the

calibrating device. Then, the rectangular signal was divided into

two signals: One was connected to the oscillograph through

an attenuator, and its rise time \( t_{11} \) was measured; the other

signal was output from the capacitive divider and connected

to the oscillograph, and its rise time \( t_{22} \) was measured. The

voltage waveforms measured by the capacitive divider is shown

in Fig. 6(a) (trace 2). For comparison, the waveform measured

with a standard impulse divider is also shown (trace 1). From

Fig. 6 and the practice formula in [13],

\( t_{\text{res}} = (t_{\text{res1}}^2 - t_{\text{res2}}^2)^{1/2} \);

the rise time of the capacitive divider to measure the impulse

with a width of several hundred nanoseconds can be obtained

as 8 ns. For the divider with an integrator for measuring a

microsecond impulse, a rectangular signal of 100 V with a

width of 3 \( \mu \)s was fed to the calibrating device. The voltage

waveforms measured by the capacitive divider is shown in

Fig. 6(b) (trace 2). For comparison, the waveform measured

with a standard impulse divider is also shown (trace 1). As

seen in Fig. 6(b), the response time of the new divider with an

integrator is very good for measuring a microsecond impulse.

III. APPLICATION ON PULSED VOLTAGE MEASUREMENT

IN THE ACCELERATOR

The construction of the accelerator is illustrated in Fig. 7. It

consists of a primary storage energy system of the capacitor

bank, a high power air core transformer, a water PFL, and

the field-emission diode. Water with a resistivity greater than

10 M\( \Omega \)·cm is used as the dielectric of the PFL. A capacitor

of about 10 kJ and 40 kV provides primary pulse energy for

the system of accelerators. A spark-gap switch with a trigger
electrode is installed between the capacitor bank and the primary coil of the transformer. The capacitor bank discharges provide a current of about 100 kA for the primary coil of the pulse transformer. The PFL, which is a 10-Ω water line, as shown in Fig. 7, is not only a storage capacitor but is also a PFL with a pulse duration of about 80 ns. It contains an inner conductor, a middle conductor, an outer conductor, and a spark-gap switch (main switch). The vacuum diode is a field-emission diode, which includes a cathode and an anode. The cathode is a stainless-steel rod with a diameter of 20 mm, and the anode is a stainless-steel disk with a diameter of 75 mm. When the capacitor bank is charged to the required voltage, the spark-gap switch is closed by supplying a trigger pulse, and the PFL is charged by the pulse voltage deposited in the capacitors through the pulse transformer to heighten the voltage. The main switch will close when the self breakdown voltage is reached, and then, the PFL will discharge to the field emission diode. Thus, high-power electron beams can be obtained from the diode.

An inducing ring is fixed on the bottom board of the diode to measure the diode current. Two capacitive dividers are assembled on the outer conductor of the PFL of the accelerator to test the voltage of the diode and the charged voltage of the PFL, respectively. To compare the measured results, two conventional resistance dividers with a CuSO$_4$ solution were also fixed on the outer conductor of the PFL to test such voltages under the same operating condition of the accelerator.

The waveforms of the diode and PFL voltages measured by the new capacitive divider are illustrated in Fig. 8, and those measured by the resistance divider are shown in Fig. 9. From Figs. 8 and 9, the peak diode and peak PFL charging voltages are $-500$ and $-570$ kV, respectively, as measured by the conventional resistance divider, and they are $-530$ and $-560$ kV, respectively, by the new capacitive divider. We can also see that the new capacitive divider is better than the conventional resistance divider for the pulse voltage of such an accelerator.

### IV. Conclusion

In summary, the proposed capacitive divider has practical applications for measuring the pulsed voltage of an accelerator with a water PFL because of its compact structure, relatively high divider ratio, fast response time, stable divider ratio, and not much of an effect on the characteristic of the accelerator. How to accurately test the divider ratio of such a capacitive divider and monitor a high-voltage pulse with a repetitive rate by the capacitive divider needs more study in the future.
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