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Review article

Compact intense electron-beam accelerators based on high energy density liquid pulse forming lines

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Abstract

This paper provides a review of the compact intense electron-beam accelerators (IEBAs) based on liquid pulse forming lines (PFLs) that have been developed at the National University of Defense Technology (NUDT) in China. The history and roadmap of the compact IEBAs used to drive high-power microwave (HPM) devices at NUDT are reviewed. The properties of both de-ionized water and glycerin as energy storage media are presented. Research into the breakdown properties of liquid dielectrics and the desire to maximize energy storage have resulted in the invention of several coaxial PFLs with different electromagnetic structures, which are detailed in this paper. These high energy density liquid PFLs have been used to increase the performance of IEBA subsystems, based on which the SPARK (Single Pulse Accelerator with spark gaps) and HEART (High Energy-density Accelerator with Repetitive Transformer) series of IEBAs were constructed. This paper also discusses how these compact IEBAs have been used to drive typical HPM devices and concludes by summarizing the associated achievements and the conclusions that can be drawn from the results.

PACS codes: 52.80.Wq; 52.59.Mv; 77.22.Jp; 84.70.+p; 88.60.-m

Keywords: High-power microwave (HPM); Intense electron-beam accelerator (IEBA); Pulsed power technology (PPT); Pulse forming line (PFL); Fluid of high energy density; De-ionized water; Glycerin

1. Introduction

The intense electron-beam accelerators (IEBAs) used to drive narrow high-power microwave (HPM) devices typically require an electrical output power from several gigawatts to dozens of gigawatts, pulse durations from dozens of nanoseconds to several hundred nanoseconds, and impedances from 10 to 200 Ω [1]. To satisfy these requirements, several capacitive-energy-storage-type IEBAs have been developed, including the SINUS series of IEBAs by the Institute of High Current Electronics (IHCE) in Russia, the TPG series by the Northwest Institute of Nuclear Technology (NINT) in China, and CHP01 by the China Academy of Engineering Physics (CAEP) in China [2–4], all of which are based on a Tesla transformer and pulse forming lines (PFLs) containing transformer oil with a low dielectric constant of 2.2–2.3 as the energy storage medium. The breakdown strength of this oil is comparable to that of de-ionized water and its energy density is low.

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To overcome the big volume limitations due to the low energy density, the compact IEBAs developed at the National University of Defense Technology (NUDT) are based on low energy density liquid PFLs. In these compact IEBAs, a high dielectric constant liquid in the form of de-ionized water is used as the energy storage medium and a spiral design is adopted to overcome the low impedance limitations. As the specific resistivity of de-ionized water decreases with time, a daily purifying treatment is normally required; however, this frequent purification is not required in the NUDT designs because glycerin is used in place of the de-ionized water. For this reason, researchers at NUDT have studied the properties of both de-ionized water and glycerin.

The achievements in high energy density liquid PFLs and other subsystems have resulted in the development of the compact SPARK(Single Pulse Accelerator with spark gaps) and HEART (High Energy-density Accelerator with Repetitive Transformer) series of IEBAs, which are well suited to drive HPM devices.

2. Overview

Research into pulsed power technology at NUDT began with the development of IEBA 81-7M-01 (SPARK-01) in 1979, which is shown in Fig. 1. At the time, it was the largest IEBA constructed at a Chinese university and it is still operational today with beam parameters of 1 MV, 120 kA, 80 ns in single shot regime [5−7]. Even though this IEBA was state of the art at the time it was constructed, compared to current systems, it is extremely large and heavy and is no longer in optimal working order. This system contains a Blumlein type PFL filled with de-ionized water that is charged by a traditional Marx generator. The electric pulse is formed by the closing of a switch between the end of the inner cylinder and the middle cylinder. Because its aspect ratio is not big, the output waveform is not perfect as its leading edge is slow and there is no flattop. Despite these limitations, the development of the 81-7M-01 accelerator deepened the knowledge of IEBA and pulse power technologies at NUDT.

In the following years, various studies were conducted to improve the performance of this IEBA, to reduce its size and advance the associated technologies. Beginning in the 1990s, pioneering experiments were conducted that employed this machine to drive HPM devices, such as virtual cathode oscillators (VCOs) [8,9] and magnetic insulator line oscillators (MILOs) [10,11]. It was found that when driving HPM devices, it is important that the volume and weight of an IEBA be sufficiently small; it has also become clear that the 81-7M-01 (SPARK-01) is physically quite large.

Fig. 1. Photograph of the IEBA 81-7M-01.

The volume of an IEBA can be reduced by replacing the traditional Marx generator with a pulse transformer, optimizing the volume of water in the PFLs, and reducing the radial dimensions. These alternatives resulted in the SPARK-03 accelerator, which is shown in Fig. 2 [12]. As the requirements of HPM systems have increased, this has highlighted the key need to reduce the radial dimensions of the PFLs in IEBAs. This was accomplished by improving the voltage endurability of PFLs by strengthening many weak links. In addition, the energy storage capacity of de-ionized water in the Blumlein type PFLs was maximized. The result was the SPARK-04 IEBA [13,14], which has a volume much smaller than that of the 81-7M-01 (SPARK-01) accelerator. Fig. 3 shows a photo of the SPARK-04 IEBA. In this design, the PFL diameter is about 40 cm, the length is about100 cm, and the output pulse power is about 25 GW with a pulse duration of about 50 ns.

Subsequent research focused on reducing the accelerator volume and further increasing the output power to satisfy higher requirements. Researchers found that the breakdown

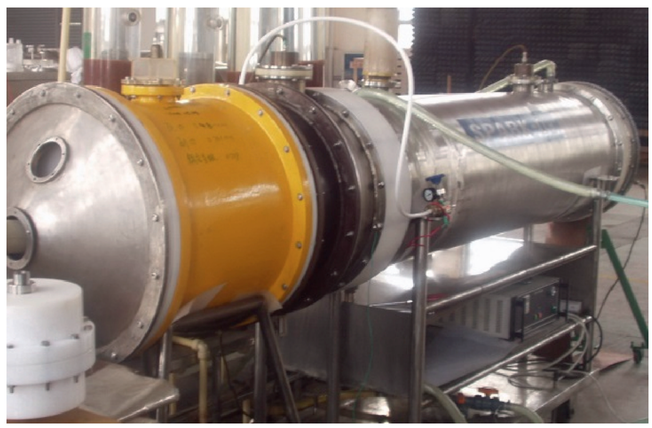


Fig. 2. Photograph of the Spark-03 accelerator.


Fig. 3. Photograph of the Spark-04 accelerator.

stress of de-ionized water is strongly dependent on the polarity of the applied voltage. For example, the breakdown stress for negative polarity liquid is twice of that of positive polarity liquid [15,16]. Because the middle cylinder of a typical Blumlein with three cylinders has two polarities of electric field, the threshold value of the breakdown field strength is characterized by the positive polarity breakdown stress. The de-ionized water in traditional Blumlein type PFLs does not exhibit high energy storage density. In fact, it was found that a single water PFL has more energy storage capacity than that of a water filled Blumlein line. The inner cylinder of a single negatively charged PFL with a higher electric field has a higher breakdown threshold, while the outer cylinder of a single PFL with a smaller electric field has a smaller breakdown threshold. In this way, the volume can be reduced and the output power be raised. The storage energy of a single water PFL is double that of a typical Blumlein water line. The compact IEBA SPARK-06 was constructed using a single water PFL (Fig. 4) [17] and had an output power of 30 GW, a pulse duration of 80 ns, and a diameter of less than 330 mm. SPARK-06 also adopted spiral PFL technology for better regulation of the pulse duration and impedance. The pulse duration of a PFL without spiral technology is

$$\tau = 2\frac{1}{c}\sqrt{\varepsilon_r}, \tag{1}$$

where τ is the pulse duration, l is the length, c is the speed of light in vacuum, and ε_r is the relative dielectric constant of the liquid in the PFL. The pulse duration of a spiral PFL is

$$\tau = 2k\frac{1}{c}\sqrt{\varepsilon_r}, \tag{2}$$

where k is the slow-wave coefficient. A spiral PFL not only widens the pulse duration, but also raises the impedance. The relationship between the impedance with and without spiral technology is

$$Z_1 = kZ_0, \tag{3}$$

where Z_1 is the impedance of a spiral PFL and Z_0 is the impedance of a PFL without a spiral. The addition of spiral technology enables the radial and axial dimensions of a PFL to be balanced to suit the actual requirements. Hence, this indicates it is possible to design a compact IEBA using a liquid with a high dielectric constant.

The IEBAs introduced above all support single-shot mode. However, there is significant interest in burst-operation with several shots in one run and repetitive-operation over a long period of time. Accordingly, two IEBAs were developed that support burst-operation and repetitive-operation, respectively. The machine HEART-50H with a lower impedance and higher output power was developed to drive the MILO HPM device in burst-operation mode. At the same time, another machine was developed with a higher impedance to drive a slow wave oscillator guided by a magnetic field. This HEART-10L supported a repetitive-operation mode with dozens of hertz, and a single run operating time of more than 10 s.

The HEART-50H accelerator (see Fig. 5) was developed based on the principle that a machine with a lower impedance usually has a higher output power. The design goal was an output power of 50 GW at 10Ω load, a pulse duration of 80 ns, and 5 pulses in every run with a repetition rate of 5 Hz. The actual output power was higher than 30 GW in burst-operation mode in which the primary capacitors were supplied by a constant current from a high-voltage power supply. The single PFL in the accelerator was filled with de-ionized water mixed with alcohol, and the dielectric constant of the medium could be adjusted based on the proportion of water and alcohol. The breakdown threshold of the medium was reduced for burst-operation mode and the radial dimensions of the PFL were improved. To increase the energy transformation efficiency of the system, a pulse transformer with a high coupling coefficient and inner and outer magnetic cores was developed. The final design of the HEART-50H IEBA was optimized to drive a low impedance HPM device like MILO, and indeed this accelerator played a very important role in the development of MILO [18].

The repetitive-operation IEBA HEART-10L (see Fig. 6) had an output power of about 10 GW at 50 Ω load, a pulse duration longer than 150 ns, a repetition rate of 30 Hz, and supported several hundred pulses in one run [19,20]. It was developed to drive a slow-wave oscillator and achieve an HPM

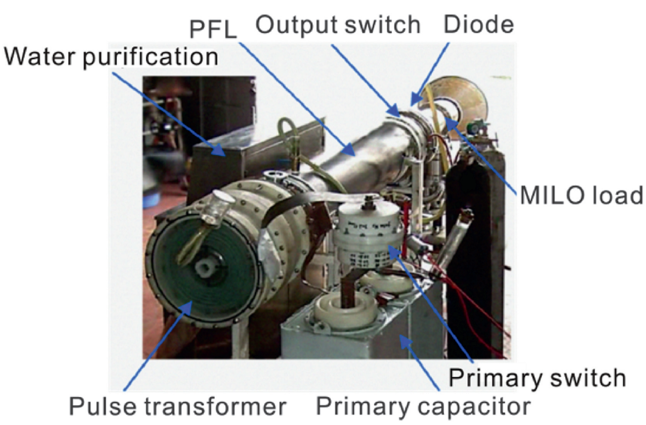


Fig. 4. Photograph of the Spark-06 accelerator.

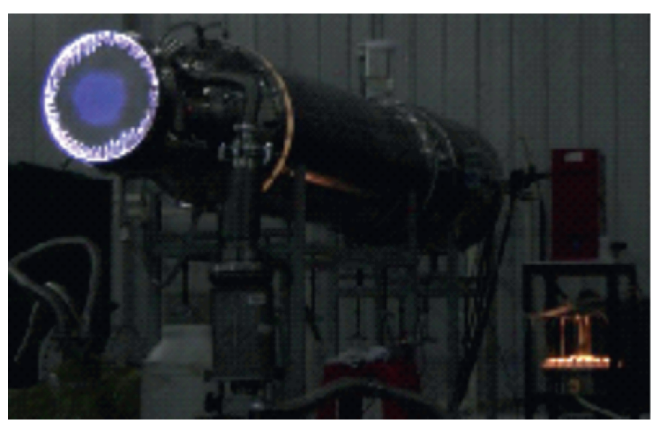


Fig. 5. Photograph of the HEART-50H accelerator.

Fig. 6. Photograph of the HEART-10L accelerator.

output longer than 100 ns. The key feature in this design was the use of a water PFL to construct a repetitive IEBA that supported many pulses in a single run; however, it also required solutions to several problems. First, the triggering of the gas gap switch in the primary circuits of the pulse transformer is complex and the lifetime of gas switch is limited, hence, gas switches were replaced by solid-state switches such as thyristors, which are simple in triggering and can automatically shut off when the current passes through zero [15]. This is necessary to enable repetitive-operation with many pulses in a single run. Repetitive-operation mode also requiresthe stored energy of a capacitance bank. Second, as the operating voltage of the thyristors is only several kilovolts, the transformation ratio increased and the related charging time of the PFL became longer and varied from several microseconds to more than 30 μs. Third, the intrinsic time constant was only dozens of microseconds as it was limited by the specific resistivity of de-ionized water. To address this, de-ionized water mixed with ethylene glycol was used to raise the specific resistivity of the medium by more than three times compared with that of purified water. Moreover, as the mixture had the properties of anti-freeze, it was functional below 0 °C [21]. Finally, the breakdown threshold of the medium decreased when the charging time of the PFL was prolonged. As the properties of an actual high field strength corresponding to a higher negative breakdown threshold of water could be applied to reduce the radial dimensions of the PFL, a single PFL with a negatively charged inner cylinder was adopted. However, if only a single PFL was applied, the output voltage on the matched load was only half of the charging voltage. In order to simplify the transformer insulation, a new type of double PFLwas invented that consists of two separate single PFLs with the same dimensions. The energy density of the invented double PFL was almost the same as that of a single PFL with water [22]. This new double PFL adopted a spiral structure to provide a higher impedance and a longer pulse duration. Thus, the resulting IEBA was well suited to drive an HPM device with high impedance and a long-lasting run time.

As the requirements for IEBAs continued to increase, the limitations of the HEART-10L design became more apparent. The first limitation was that the self-breakdown switch at the end of the PFL had jitter in the microsecond range and therefore could not be precisely controlled. Second, even though the volume of this accelerator was already relatively small, there was still room for improvement in this regard. The two single PFLs in this design performed the same function while charging, but fulfilled the different functions after the pulse was formed. After that point, the function of one PFL was the same as that of the inner line of a traditional Blumlein line, which has a high voltage in the outer cylinder and an amplitude the same as that of the output pulse. The consequence is that it was necessary to include an additional cylinder with a larger diameter to insulate the high voltage in the outer cylinder of a single PFL, which increased the volume of the system accordingly. Third, the specific resistivity of the liquid mixture decreased over time and daily purification was required. It therefore became important to identify an alternative liquid medium that had a high energy density and could enable maintenance-free operation. Subsequent testing demonstrated that the specific resistivity of glycerin was one to two orders of magnitude larger than that of the mixture of water, and it did not decrease over time. In addition, it was possible to renew the specific resistivity after an unexpected breakdown of the medium. No significant polarity dependency was observed for the breakdown strength of glycerin; thus, the separated double PFLs could be positive charged.

In the new HEART-10LT design, the position of the switch was moved from the end of the PFL where it had been immersed in oil to the end of the PFL that was grounded. The benefit of moving the switch is that the triggering generator no longer had to withstand a high voltage. Conversely, if the position of switch had not been changed, it would have been difficult for the triggering generator to insulate the high voltage in the outer cylinder of the PFL, especially in repetitive-operation mode. This change in the position of the switch provided a solid foundation on which to conduct precise triggering studies. The HEART-10LT was designed to support a triggering jitter of 10 ns. The differences between the HEART-10L and the HEART-10LT accelerators are depicted in Fig. 7. In this figure, Fig. 7(a) shows the structure with the self-breakdown switch and Fig. 7(b) shows the structure with the triggered switch [23].

Once the problem of precise triggering was solved, the next task was to optimize the volume of the accelerator. Much of the volume of an IEBA consists of the separated double PFLs. In addition, the second cylinder and the insulation oil in the cylinder both increase the size of the IEBA. Furthermore, the glycerin chosen as the medium of the PFL is a non-polarized liquid with respect to the breakdown stress, which means that the storage energy of the Blumlein PFLs in a particular volume is higher than that of a single PFL with the same dimensions. Thus, the subsequent HEART-10CLT design employed typical Blumlein PFLs to further reduce the volume. Finally, spiral technology was adopted to address the fact that typical Blumlein PFLs filled with glycerin usually have a low impedance. The next challenge was to determine how to realize a high impedance and long pulse duration using a spiral Blumlein line with three cylinders. When analyzed, it was found that the spiral structure grooved in the middle cylinder distorted the output pulse shape by prolonging the rise time

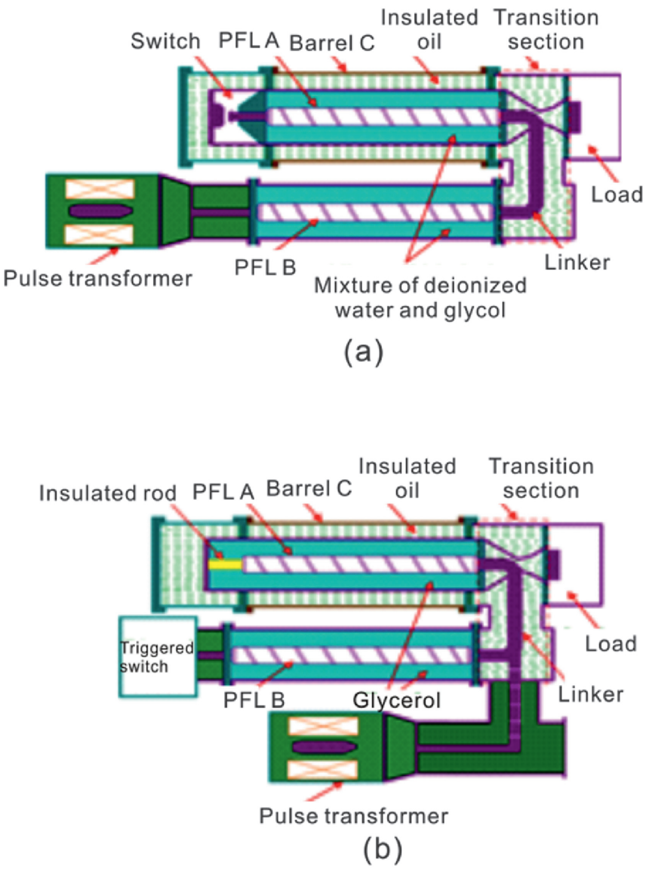


Fig. 7. Changes in the switch position from HEART-10L to HEART-10LT. (a) Separated double line with a self-breakdown switch; (b) Separated double line with a triggered switch.

and eliminating the flattop. Upon further investigation, it was found that the groove in the middle cylinder formed a parasitic line between the inner and outer cylinders. This was resolved by simultaneously grooving both the inner and middle cylinders. Then, if appropriate parameter values were selected, it was possible to obtain an ideal output waveform. The architecture of the HEART-10CLT, which includes Blumlein PFLs filled with glycerin, is shown in Fig. 8. Although glycerin has many advantages, it also has a number of disadvantages, one of which is that its viscosity complicates the PFL filling process.

The next challenges in IEBA development were in determining how to improve the field strength in repetitive-operation mode and how to further reduce the size of compact IEBAs. These will be discussed in the next sections.

3. Studies on de-ionized water

The processes and phenomena associated with pulse breakdown of the medium are extremely complicated and involve many factors. In addition, the breakdown field strength is dependent on the particular application conditions and environment. It is extremely important to understand these aspects when designing PFLs. The breakdown field strength can be determined for a given PFL by testing using a scale model of an actual PFL, and the results can then be used when designing the PFLs of a full-sized IEBA. The development of the IEBAs in the lab at NUDT was conducted in two stages. The first stage involved the design of IEBA PFLs that could be charged in a period of several microseconds in single-shot mode. It was therefore necessary to investigate the breakdown field strength of de-ionized water over the course of several microseconds. The second stage involved a review of the water mixture used in the construction of an IEBA suitable for repetitive operation. The design objectives were to support a repetition rate of dozens of hertz over the course of runs lasting more than 10 s per run. Semiconductor switch thyristors were adopted as the switches in the primary circuits of the pulsed transformer. However, as the operating voltage of the thyristors is only several kilovolts, the output voltage is close to 1000 kV, the transformation ratio is several hundred times, the charging period is elongated, and the charging period varies from several microseconds to more than 30 μs, it was necessary to study the pulse breakdown field strength of the mixed water over the charging period to obtain firsthand knowledge of the process. The experimental setup is shown in Fig. 9.

3.1. Investigating the effects of several microseconds of high voltage on de-ionized water

An effective way to reduce the size of a pulsed power system is to improve the electrical breakdown strength of the de-ionized water, which can be accomplished using

Fig. 8. Photograph of the HEART-10CLT accelerator.

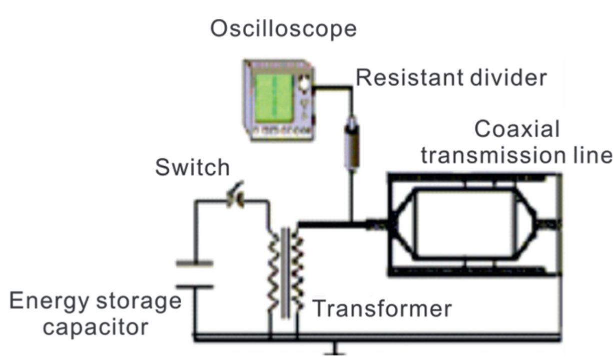


Fig. 9. Schematic showing the experimental setup used in the breakdown test.

pressurization, surface polishing, and ethylene glycol additives. The findings in this regard are detailed in this section.

The coaxial test cell shown in Fig. 9 was used to evaluate various electrode surface polishing levels and different concentrations of ethylene glycol additive, and the results are shown in Fig. 10 where E_t represents the normalized breakdown strength in the experiment, p is hydrostatic pressure in 101325 Pa. For different surface polishing levels and different additive concentrations, the electrical breakdown strength is in proportion to the hydrostatic pressure to the one eighth power while the slope of the detail $E-p$ line unchanged. As the surface roughness R_a decreased or the concentration of added ethylene glycol increased, the slope of this line was observed to increase. It was also found that an improved surface polishing and higher concentration of ethylene glycol substantially increased the electrical breakdown strength of the pressurized de-ionized water. As per the empirical equation $E_{bd} = MA^{-1/10}t_e^{-1/N}$, the normalized breakdown strength can be expressed as $E_t = MA^{-1/10}p^{1/8}$ and the slope of the $E-p$ line was found to be $MA^{-1/10}$. In fact, the breakdown coefficient M was seen to increase with improved surface polishing and additional ethylene glycol. The detailed results areasfollows [24−27].

First, the electrical breakdown strength for pressurized de-ionized water was investigated. The corresponding analytical and experimental results qualitatively confirmed that as per the Mirza theory, the increase in the water breakdown stress was proportional to the hydrostatic pressure to the one eighth power. The magnitude was seen to increase by 31.5% when the hydrostatic pressure increased from 101325 to 1114575 Pa. The increase in the electrical breakdown strength for pressurized water can be understood via the bubble breakdown model postulated by Jones and Kunhardt and the results obtained here are consistent with other published results describing the effects of pressurization for de-ionized water.

Second, the effects of the degree of surface polishing and the concentration of ethylene glycol additive on the properties of pressurized de-ionized water were studied by way of breakdown experiments. The results of which suggest that Mirza's equation is valid, it is independent of the surface roughness and ethylene glycol concentration, and accounts for the improvements in the electrical breakdown strength for surface polishing, ethylene glycol additive, and pressurization, among which the pressurization was found to have the largest effect. Moreover, the increase in the electrical breakdown strength of de-ionized water caused by improved surface polishing was found to be adequately explained via the bubble breakdown model. In conclusion, the highest breakdown stress of 235.5 kV/cm was observed in an ethylene glycol/water mixture that had an ethylene glycol concentration of 80% at a hydrostatic pressure of 1215900 Pa. This breakdown stress was about two times of that in pure water at constant pressure, 101325 Pa.

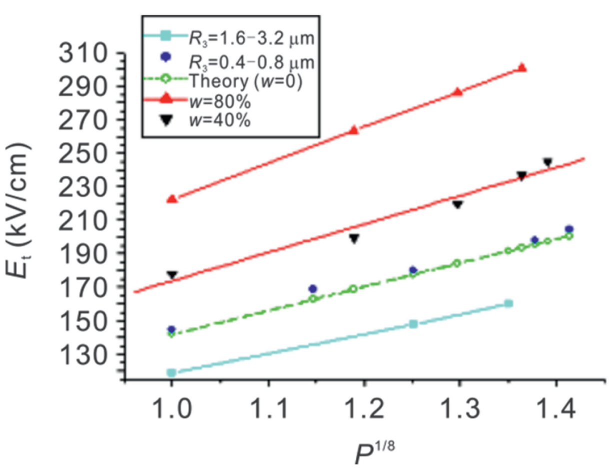


Fig. 10. Breakdown strength versus the pressure at different surface polishing levels and different additive concentrations.

3.2. Investigating the effects of several dozens of microseconds of high voltage on de-ionized water

The primary power supply of the IEBA is a key issue for repetitive operation. The triggering conditions of the thyristors are simple and the thyristors turn off when the current passes through zero. Then, a portion of the energy is stored in the primary capacitors when the voltage is reversed. This stored energy can be reused to charge the capacitors repetitively via a capacitance bank containing stored energy. The charging period is quite long as the transformation ratio of the charging circuit is large. The charging period of PFLs is typically more than 30 μs; however, pure water is unable to withstand high voltages lasting tens of microseconds in repetitive operation. This is because the intrinsic time constant of pure de-ionized water is less than 100 μs and the loss produced by the leakage resistance cannot be ignored, both of which affect the efficiency of the system.

The method is de-ionized water mixed with ethylene glycol. When a purified treatment is implemented, the specific resistivity of the mixture can be improved to three times that of pure de-ionized water. Another challenge is that there are few references that describe the breakdown field strength of de-ionized water when mixed with glycol. Thus, experiments must be conducted to obtain firsthand information. The setup was similar to that shown in Fig. 9, except that the switches were replaced by thyristors.

A test cell composed of two coaxial electrodes was constructed to study the breakdown field strength and the specific resistivity of the mixture, and the circuit parameters were selected such that the charging time was more than 30 μs and the effective time lasted longer than 10 μs, where the effective time was the time for the voltage rising from 0.63 V_{close} to V_{close}, $V_{close}$was the PFL voltage when the main switch was closed. The following results were obtained. The time-dependence was found to be about $t^{-1/6}$ and the area-dependence was the same as that of Martin's equation, whose area-dependence was $A^{-1/10}$, where A is the effective area. The time-dependence of the breakdown field strength of the water became weaker when the effective time was more than 10 μs. While there was some random variation, the breakdown field strength was always higher than 80 kV/cm. It was possible to improve the intrinsic constant time several times when de-ionized water mixed with ethylene glycol and the mixture was purified. These results and conclusions are very relevant in applications involving PFLs filled with the water in a repetitive accelerator. The study of the water when subjected to a high voltage that lasted longer than 10 μs demonstrates that a water mixture can possess a high breakdown field strength, which is counter to the prevailing theory that water can only be used when the high voltage lasts only about a microsecond. Because water was shown to be capable of storing higher energy storage when the effective time was longer than 10 μs, this information was used in the design of a compact repetitive accelerator [28].

3.3. Development of novel double PFLs with de-ionized water

The design of a novel double PFL filled with de-ionized water, which was constructed by combining two separated single PFLs, is illustrated in Fig. 11. The structure and size of both PFLs were the same, but there were differences in how they were joined at the end. To distinguish the two PFLs, one is referred to as PFL A while the other is PFL B [22].

Both PFLs consist of inner and outer conductor cylinders. A spiral groove with an inclined angle θ with respect to the axis was formed on the cylinder by a lathe.

PFL A is surrounded by the oil that fills the insulated cylinder container. One port of PFL A is connected to the main switch, the outer cylinder is connected to one electrode, and the inner cylinder is connected to the other electrode. The other port of PFL A is connected to Transition Section A where the outer cylinder of PFL A gradually transits to the inner conductor of the output transmission line. The structure of this transition is a tapered cone with two holes that are symmetrical around the axis and an aperture large enough to insulate the charging voltage of the PFL between the linker and tapered cone. A cylinder conductor linkage is connected to the end of the inner cylinder of PFL A and extends through the center of the tapered cone, before bending to pass through one of the holes in the tapered cone to reach the end of the inner cylinder of PFLB. One port of PFL B is connected to the transformer while the other port is connected to transition section B. The end of the inner cylinder of PFL B is similarly linked to the inner cylinder of PFL A. The outer cylinder of

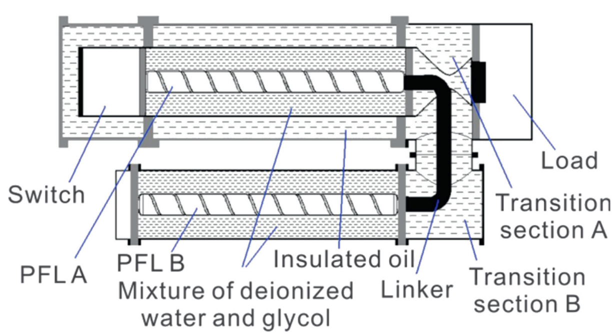


Fig. 11. Design of a novel double PFL.

PFL B is connected to the outer cylinder of transition section B as the ground of the generator. The grounded inductor is wound around the spiral groove on the surface of the insulation plate from the inner cylinder to the outer cylinder of the transmission line.

This design has several advantages.

(1) The adoption of the spiral line elongates the output pulse from τ_0 to τ and satisfies $\tau = k\tau_0$, where k is the slow-wave coefficient of the spiral line. It is possible to estimate k based on the dimensions of the PFL, and it is particularly dependent on the angle θ of the spiral groove with respect to the axis.
(2) When the insulating properties of water are taken into account, the negative electrode has a breakdown field strength about two times that of the positive electrode. In the novel PFL, the inner coaxial electrode is negatively charged, which corresponds to a higher field stress, and the outer coaxial electrode is positively charged, which is corresponding to a lower field stress. The disadvantage of a typical Blumlein line with two different medium electrode polarities is that it is difficult to optimize.
(3) The impedance of the novel PFL is higher than that of a traditional design. The impedance of a single-PFL is about 5−7 Ω when it does not include a spiral groove. In contrast, when the polarity properties of water are taken into account, the impedance of a single PFL with a spiral groove is Z and $Z = kZ_0$, where Z_0 is the impedance of a single PFL without a spiral groove and k is the slow-wave coefficient. The value of k is about three; thus, the impedance of a single spiral PFL is about 15−20 Ω and the impedance of a double spiral PFL is about 30−40 Ω, which is comparable with that of the SINUS series. The advantage of this higher impedance is that it is easier to match loads with medium and high impedance.
(4) When an accelerator fabricated with a double PFL is compared to an accelerator fabricated with a single PFL, such as a SINUS series accelerator, the charging voltage of a double PFL is one half that of a single PFL, which reduces required transformer charging voltage and increases the reliability of the system.

The maximum voltage that can be sustained by the two electrodes in a PFL is larger than 1 MV when the diameter of the outer coaxial electrode is 360 mm. The leakage resistance is improved as the double PFL is composed of two separated single PFLs and the liquid consists of ethylene glycol mixed with de-ionized water.

4. Development of IEBA with glycerin

4.1. Studies of the pulse breakdown characteristics of glycerin

In the experiments used to evaluate the breakdown of the medium, it was found that glycerin exhibited a high breakdown stress and was not dependent on the field polarity.

Because of this high breakdown stress and high dielectric constant, this medium has a high energy storage density. In addition, it also has a higher specific resistivity than de-ionized water by one or two orders of magnitude, which does not vary with the time. Thus, it is suitable for use when fabricating liquid PFLs as it allows the PFLs to be compact and packaged much like a solid part. To better elucidate the characteristics of glycerin, the specific resistivity of glycerin, and its breakdown stress under various conditions, several experiments were conducted. The results are as follows.

First, it was found that different brands of glycerin have different specific resistivity which does not vary with time when in a confined space and at constant temperature. If the temperature is increased, the specific resistivity decreases, and vice versa. Moreover, the specific resistivity recovers when the temperature returns to its original value. The value of the specific resistivity of a purified glycerin is about one or two orders of magnitude higher than that of de-ionized water at 20 °C; however, when heated to more than 60 °C, the specific resistivity drops significantly.

Second, an experimental setup was constructed with which to investigate the breakdown stress for different pressures, temperatures, and electrode roughness when the guiding magnetic field was less than 1T. It was found that the breakdown stress for a charging period of 20−30 μs was greater than 200 kV/cm, and the breakdown stress for a negative polarity was almost the same as that of positive polarity. In terms of the factors mentioned above, the pressure, temperature, and roughness of the surface of the electrode significantly affected the breakdown stress of the glycerin. At the same time, the breakdown stress of the glycerin was not affected by the presence of the guiding magnetic field [29,30].

Third, glycerin is a very viscous liquid. When a PFL is filled with glycerin, it is easy for gas to be mixed into the liquid to form bubbles. As time passes, these bubbles are likely to be deposited on the surface of the electrode, and tiny bubbles then combine to form larger bubbles, which then contribute to the breakdown of the glycerin. Thus, it was necessary to determine how to fill glycerin into the PFLs with least bubbles to be deposited on the surfaces of the electrode. The solution was to fill the PFL with glycerin under vacuum conditions while applying vibration and heating the glycerin. This new understanding of the properties of glycerin allows it to be the medium in the PFLs of the HEART-10LT and HEART-10CLT designs.

4.2. Development of compact IEBA based on three coaxial spiral Blumlein line

As was mentioned above, the breakdown stress of glycerin is independent of the polarity of the electric field. When investigated further, it was found that the amount of energy that could be stored in a glycerin Blumlein line with three coaxial cylinders was greater than that of other electromagnetic structures. As it has been shown that the impedance and pulse duration can be easily adjusted with a spiral line, it became necessary to investigate the characteristics of a typical Blumlein line combined with spiral line structure. An understanding of a spiral Blumlein line was arrived at in a round about way. At first, a helix groove was only applied to the middle cylinder because it was thought that the characteristics of the inner and outer lines were determined by the helix on the middle cylinder; however, subsequent experimental results observed a distorted waveform with a long rise time and no flattop. After the electromagnetic structure was analyzed, it was determined that a parasitic line formed between the inner and outer cylinders when the middle cylinder had a helix shaped groove. The observed parasitic line had a short pulse duration and a low impedance, but did not pass through the spiral line. When the switch was closed to form the pulse, the pulse arrived at the load via two paths, namely, the spiral line and the parasitic line, and the pulse that arrived through the parasitic line was faster than that through the normal path. The result was that the pulse that arrived at the load was the superposition of the two parts. Thus, the presence of the parasitic line caused the output waveform to become distorted. To obtain an ideal waveform, it is essential that the pulse duration of the spiral and parasitic lines were virtually identical, which would allow the pulses to be overlaid and ensure the output pulse had the required rise time and flattop. The method used to match the optical distance of the spiral line to that of the parasitic line was to groove a helix structure on both the inner and middle cylinders. The slow-wave coefficient of the parasitic line was the same as that of the main PFLs. It was also observed that the complicated structure of the PFLs affected the quality of the output waveform. To overcome this, a field-road collaborative simulation was conducted to accurately design a spiral Blumlein line in which both the inner and middle cylinders were grooved with a helix structure. This simulation was accomplished by modeling and packaging the spiral Blumlein line as a PSpice circuit element with input and output links. This model was then used in a simulation in CST Microwave Studio to investigate the characteristics and evolution of the electromagnetic field. The simulation allowed the parameters of the inner cylinder helix structure to be optimized so that an acceptable output waveform could be obtained. The simulation environment is shown in Fig. 12, including the circuit (Fig. 12(a)) and the structure of the optimized spiral Blumlein line (Fig. 12(b)). Waveforms of aspiral Blumlein with and without spirals on the inner cylinder are shown in Fig. 12(c). The results of the simulation confirmed that the use of a spiral Blumlein line with helix spirals on both the inner and middle cylinders provides an ideal pulse output [31].

5. Achievements regarding the IEBA subsystems

The development of pulse power technology at NUDT has focused on developing a compact IEBA that incorporates PFLs with a high energy density liquid. Such a liquid must be capable of dissipating heat and provide good insulation recovery. In addition, it must be easy to fill into a PFL. It is important that the output waveform produced by IEBAs with liquid filled PFLs is capable of driving an HPM device, which

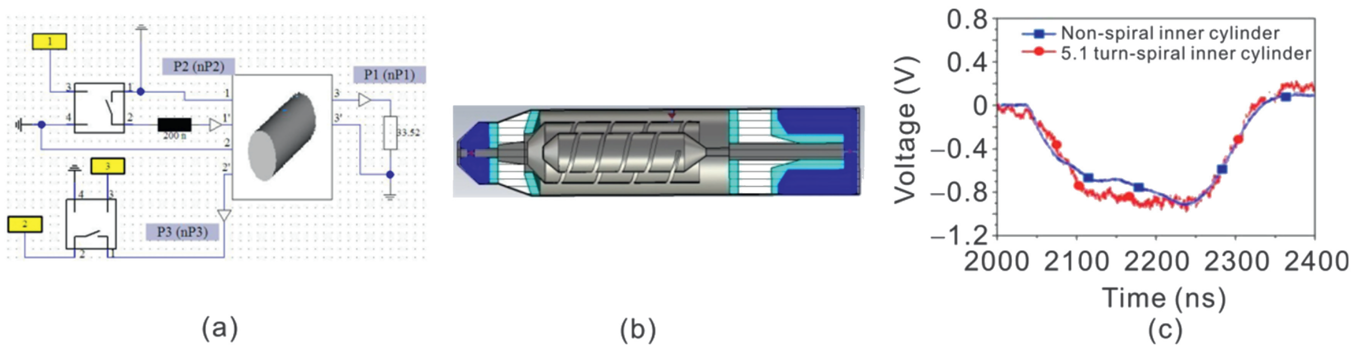


Fig. 12. Field-road collaborative simulation of a spiral Blumlein line. (a) Circuits used in the field-road collaborative simulation; (b) Spiral Blumlein line with an optimized structure; (c) Comparison of the waveforms obtained from a non-helix cylinder and an optimized helix inner cylinder.

requires the rising and falling edges of the pulse to be sufficiently short and the pulse to have a flattop. It is desirable that most of the stored energy be expended in the pulse as any remaining energy will cause damage to the cathode and diode. The results of the studies on PFLs filled with a high energy density fluid were used in the design of the single-operation IEBA series referred to as Spark and the repetitive-operation IEBA series referred to as HEART. The research has contributed to a number of advances in the field of pulse power technology, which are detailed as follows.

5.1. Primary power supply

Significant advancements were made in the area of the primary power supply. The pulsed charging of a PFL filled with liquid provides a high voltage and the primary capacitors play a key role in the energy transfer in the system. Note that the power supply to the primary capacitors is very important, especially for repetitive operation. Metalized film capacitors and thyristors are used extensively in the repetitive IEBA in a parallel configuration, which is depicted in Fig. 13(a). In order

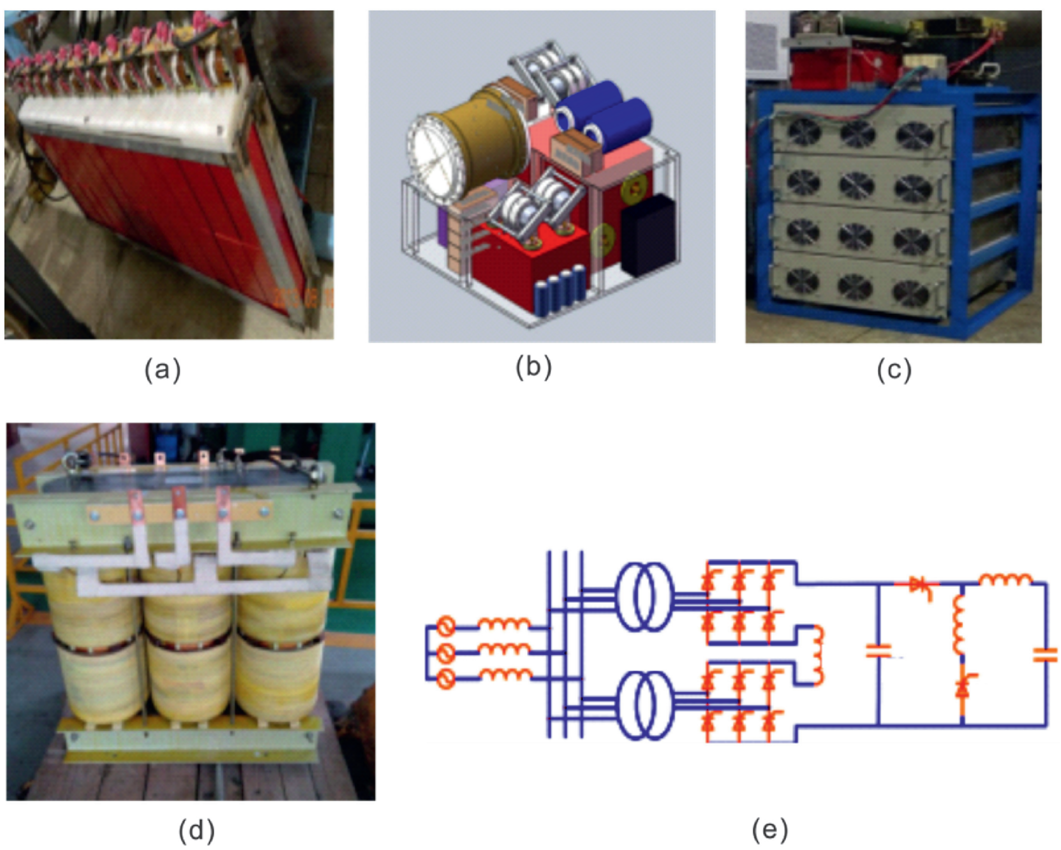


Fig. 13. Details of the primary power supply. (a) Photograph of metallized film capacitors with thyristors in parallel; (b) A power supply for burst-operation; (c) Super-capacitor bank and its power supply for repetitive-operation; (d) Three phase with twelve traction transformer and rectifier; (e) Schematic diagram of three phase with twelve traction transformer and rectifier.

to reduce the instantaneous power of the IEBA in burst-operation involving several pulses in a single run or repetitive-operation over a long time in a single run, two types of primary power supply were developed. The primary power supply shown in Fig. 13(b) was designed to support the application of several repeated pulses in a single run with the energy stored in metalized film capacitors with a high energy storage density [32], while the primary power supply shown in Fig. 13(c) was designed to support repetitive operation over a long time period in a single run with the energy stored in super capacitors with a higher energy storage density. Several studies were conducted to facilitate repetitive operation with the energy supplied by capacitors [33,34], and the findings were used in the designs of the HEART-10L, HEART-10LT, and HART-10CLT accelerators. To increase the operating time, a simple three phase power supply was constructed using a twelve traction transformer and rectifier. This supply is shown in Fig. 13(d) and (e). The repetitive operation of an IEBA can be supported directly by a suitable energy source or by using the energy stored in a bank of super-capacitors.

5.2. Pulse transformer

To overcome the limited specific resistivity of the liquid in a PFL, a high voltage is required between the electrodes, which necessitate the use of a pulse transformer and related elements. As it is essential that the properties of the transformer are well suited for the specific IEBA design, many types of compact pulse transformer have been developed. Pulse transformers with an air core were used in the Spark series of accelerators, as shown in Fig. 14(a), and pulse transformers with a magnetic core were used in the HEART series accelerators, as shown in Fig. 14(b). Pulse transformers provide an output voltage ranging from hundreds of kV to 1000 kV and have a coupling coefficient ranging from 0.7 to 1. As transformers capable of supporting high voltage operation in single shot applications are different than those capable of supporting repetitive operation over a long time in each run, the transformation ratio should be optimized for the specific requirements [35,36].

5.3. New types of PFLs

Many types of PFLs have been analyzed and applied. The analyses are focused on the application of high energy density fluid in PFLs, the characteristics of the medium, the filling process, and the electromagnetic structure of the PFLs required to achieve a maximum energy storage density. Several forms of PFL have been developed, including single PFLs, Blumlein PFLs, or double PFLs formed from two separate single PFLs, which can be selected based on the required characteristics of the medium and the actual design requirements. The application of a spiral line in PFLs filled with a high energy storage density medium was an important achievement. A photograph of one cylinder of a spiral line is shown in Fig. 15. The use of spiral technology allows the impedance and pulse duration to be adapted to match the actual requirements. It also allows the axial dimensions of the PFL to be shortened by increasing the slow-wave coefficient. At the same time, the radial dimension may be increased to reduce the actual field strength [22,31,37,38].

5.4. Precise control

A great deal of progress has been made on the technology used to control the IEBA. The developed systems have advanced from broad to precise patterns, from manual to intelligent operating schemes, from tolerating some randomness and unpredictability to running reliably. This progress is due to the following three factors. 1) Solid switches, such as thyristors, are now applied extensively. Their low triggering voltage requirements make it easy to implement large scale semiconductor switches with precise control. 2) The challenges of implementing gas spark gap switches with low jitter electrical pulse triggers in high pulse voltage environments have been overcome, and it is now possible to produce output waveforms with a jitter less than 10 ns, which allows multi-accelerators to be synchronized. A photo of a triggering switch is shown in Fig. 16(a) and a sketch of an electrical triggering generator is shown in Fig. 16(b). Here, the output

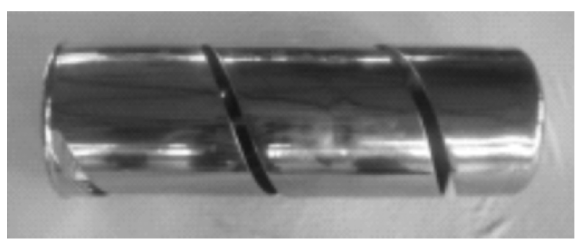


Fig. 15. One cylinder of a spiral PFL.

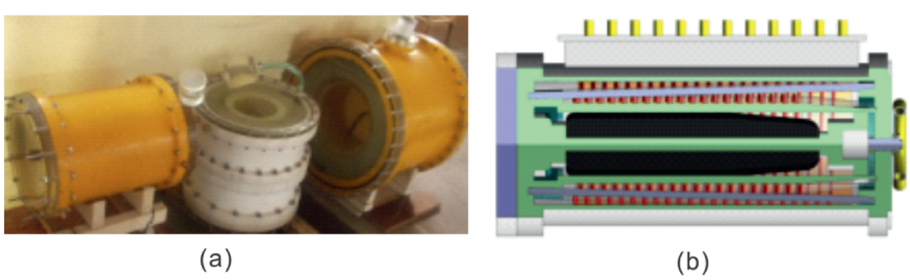
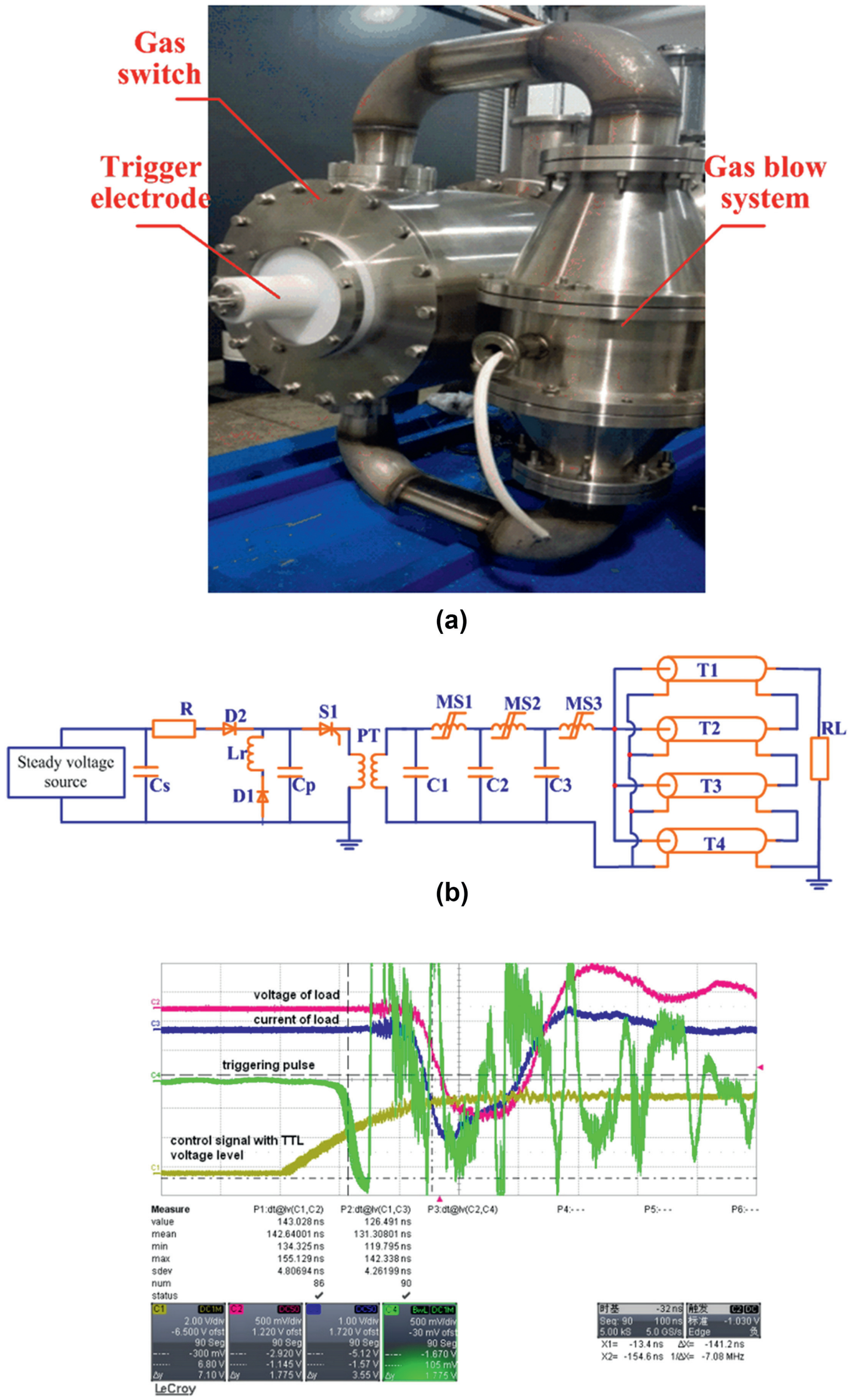


Fig. 14. Development of a pulse transformer. (a) Air-core compact pulse transformers; (b) Pulse transformer with a magnetic core and a large transformation ratio.



(c)

Fig. 16. Precisely triggered switch with low jitter. (a) Photograph of a triggering gas switch; (b) Sketch of a low jitter triggering generator; (c) High power pulse output controlled by a TTL voltage signal with low jitter.

high power pulse can be controlled by a TTL voltage signal with a jitter less than 10 ns [39–41], as shown in Fig. 16(c). 3) Finally, the control technology has been greatly improved by the addition of intelligence, greater integration, and improved code and electromagnetic compatibility. In addition, optical fiber was used to further reduce the size of the hardware and to improve signal transmission between the accelerator and the control system [42,43].

5.5. Pulse output

The systems used to generate the pulse output have also been significantly improved, including the high voltage insulation and ceramic packaging of diodes. There were two achievements in this regard. The first is with regard to the ceramic packaged diodes used in the low impedance IEBA. Generally, ceramic diodes consist of a hard tube and a compact HPM device, such as a MILO device. The difficulty lies in resolving the conflict between the limitations of the radial dimensions and the need to withstanding a high electrical field strength. In addition, it is important to shield the high dielectric constant fluid on one side of the ceramic from the electrode on the vacuum side. A photograph of a ceramic diode is shown Fig. 17(a), and the electrical field analysis and design of a ceramic diode are shown in Fig. 17(b) [44]. A long pulse and high impedance compact diode that supports a guided magnetic field was developed. This required two main problems to be overcome. The first is how to prevent the back flow of the electron beam from the cathode emissions, and the other is to overcome the pulse shortening effect. An example of a diode with long-pulse guided by a magnetic line is shown in Fig. 17(c) [45].

6. Applications of IEBAs to drive HPM devices

6.1. Development of the MILO

Electrons are emitted from the side and end faces of the cathode in the MILO. The electrons emitted from the end face are used to produce a strong azimuthal magnetic field to insulate the electrons emitted from the side face of cathode. Thus, the impedance of the MILO is typically low and the device is very compact. The advantage of an HPM output with a low impedance is that it can be driven by an accelerator based on a PFL filled with a high dielectric constant fluid. The development of the HPM device with a low impedance was supported by the development of an IEBA comprised of PFLs filled with de-ionized water. The key technologies and knowledge of IEBAs obtained from SPARK-04 to SPARK-06 and HEART-50L have improved significantly. The engineering level and operating lifetime of these devices have also been improved, and they now support single-operation mode to burst-operation mode to repetitive-operation mode with many pulses. In the HPM devices with a low impedance, the MILO has a higher efficiency and higher power output. Even though part of the electron beam was used for magnetic insulation, improvement was made in MILO to improve the conversion efficiency to nearly 20%. Fig. 18 shows a five pulse, 5 Hz shot series of MILO driven by a HEART-50H. The next step is to improve the number of repeated pulses in a single run, which is the goal of the compact IEBA [46−50].

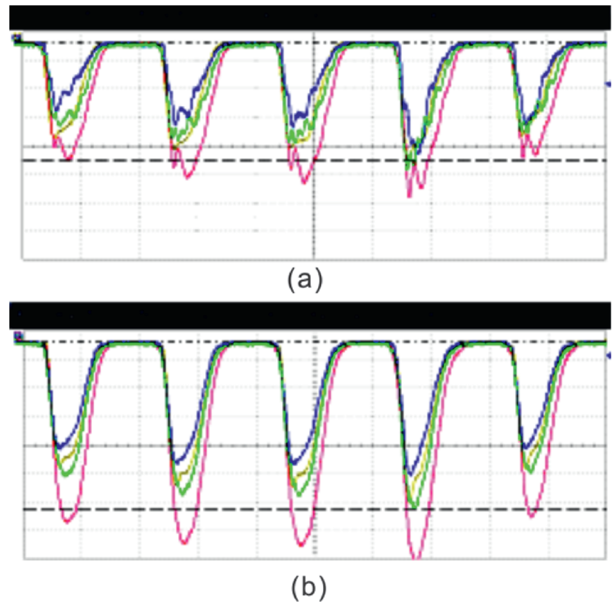


Fig. 18. Five pulse, 5 Hz shot series driven by the HEART-50H. (a) 0°−18° microwave power; (b) 24°−42° microwave power.

6.2. Development of a slow-wave oscillator

Slow-wave oscillators with a high impedance usually have a higher conversion efficiency and are suitable for repetitive-operation over a long time period. To support repetitive operation of slow-wave oscillators under a long-pulse duration, a long-pulse repetitive accelerator is needed. The development of HEART-10L, which included separated double lines filled with a mixture of de-ionized water advanced ongoing studies into the production of long-pulse HPMs. O-type slow-wave devices using the Cerenkov mechanism with a high impedance are promising HPM sources to achieve a long-pulse output. Recent experimental results show that S−, C−, and X-band O-type HPM devices can generate HPMs with GW-level output power and a pulse duration of about 100 ns.

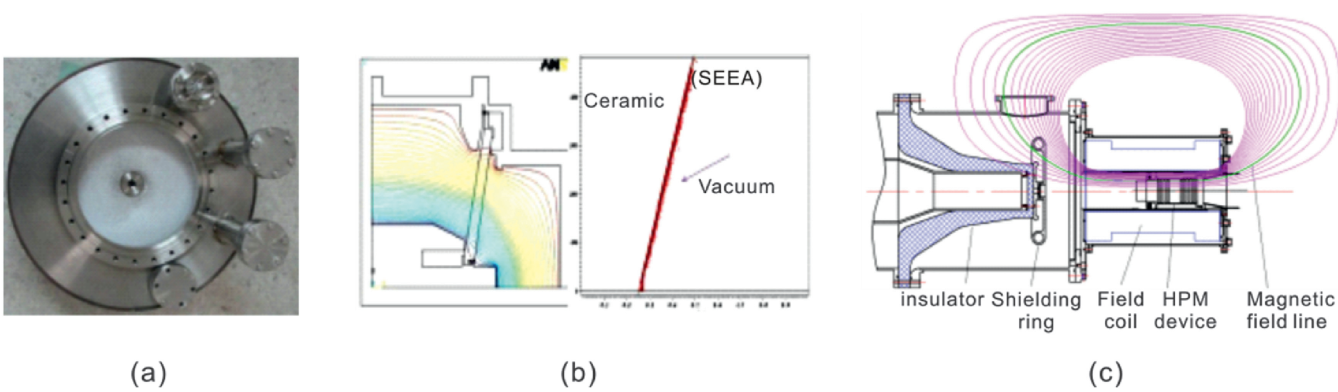


Fig. 17. HPM diode design. (a) Photograph of a ceramic diode; (b) Electrical field analysis of a ceramic diode; (c) A diode design involving a guided magnetic line with a long-pulse and high impedance.

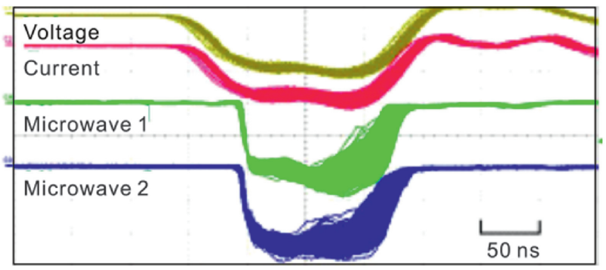


Fig. 19. Experimental results of an X-band microwave with 2 GW output and a 30 Hz repetition rate lasting 10 s.

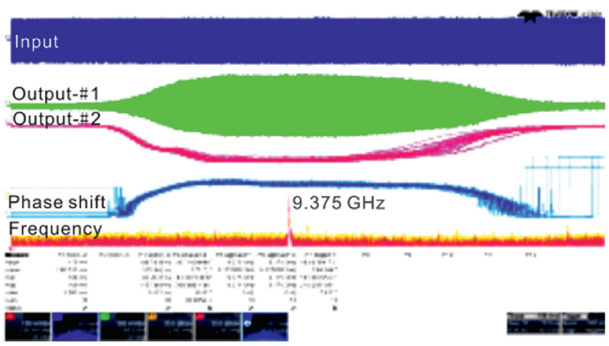


Fig. 20. Superposition of a microwave pulse, phase, and frequency of a TKA with 20 pulses.

The experimental results of X-band microwave production with a 2 GW output and a 30 Hz repetition over a period of 10 s are shown in Fig. 19. The next step in this development is to create an accelerator capable of driving HPM devices with more pulses in a single run [51−54].

6.3. Development of X-band HPM amplifier

The radio-frequency breakdown due to ultrahigh electric field strength essentially limits power handling capability of an individual HPM source, and it is more challenging for high frequency bands. Coherent power combining therefore provides an alternative approach to achieve higher power capability, which consequently provides opportunities to explore microwave related physics at extremes. A long-pulse microwave generated by an individual HPM amplifier is required to enhance the efficiency of coherent power combining. The output characteristics of an amplifier can be controlled quite well with the provision of a low power master seed source, so that the moment of feed-in of the seed signal will be in synchronization with the electrons beam and the guiding magnetic field. The moment the accelerator generates an output electrical pulse should be accurate within tens of microseconds. To investigate the precise control of the output electrical pulse of a triaxial klystron amplifier (TKA), the key issue of triggering the high voltage switch in the PFL must be addressed. The triggered high voltage switches with the jitter less than 10 ns have been developed, and they are used in HEART-5LT and HEART-10LT, which are based on the separated double PFLs filling with glycerin. The experimental results of an X-band TKA show that HPMs more than 1 GW with pulse duration more than 100 ns were got, the shot-to-shot fluctuation standard deviation of phase shifts between input and output microwaves is less than 10°. Fig.20 shows the 20-pulse superposition of microwave pulse, phase, and frequency of the TKA. As there are strict requirements on phase and frequency control, the flattop duration of an electrical pulse is very important. The electrical pulse formed by the PFL usually has good flattop duration, thus the IEBA based on a PFL with precise control and filled with maintenance-free liquid glycerin has a bright prospect [55−57].

7. Discussion and conclusion

Coaxial PFLs filled with liquid are suitable for application because they do not require edge field enhancement and are easy to fabricate. The challenge lies in how to improve the amount of energy stored in a coaxial line. The energy storage capacity depends on the maximum field and its breakdown threshold in the PFL. The inner electrode typically has the highest field energy in PFLs and the space of the inner cylinder cannot be used to store energy. Thus, it is necessary to balance the tradeoff between the uniformity of the field distribution in the PFLand the space of the inner electrode. If the medium is a type of polar liquid, it is best to use a single coaxial PFL to avoid having two types of polarity field strength in one electrode. However, if the medium is a type of non-polarity liquid, the insertion of a middle cylinder between the inner and outer cylinders with the same electrical potential on the charging process can reduce the field strength of the inner electrode to increase the energy storage. When the history of high energy storage density liquids at NUDT is reviewed, it can be seen that it is possible to achieve the full potential of the liquid for various breakdown characteristics. This allows a suitable electromagnetic structure to be adopted to obtain the maximum energy storage capacity of a coaxial line. Because of the strong polarity of de-ionized water, a single coaxial PFL was used to replace a typical Blumlein with three coaxial cylinders during the upgrade of Spark-04 to Spark-06. Another innovation was that HEART-10L was designed to leverage the properties of de-ionized water with a high energy storage density and a strong polarity dependence of the breakdown strength. During the process of searching for a maintenance-free medium with a high energy storage density, it was found that glycerin not only has a high energy storage density but also has non-polarity dependent breakdown strength. Thus, a typical Blumlein structure with three coaxial cylinders was capable of storing more energy than a single PFL in a limited space, which led to the development of the HEART-10CLT accelerator. Although the microscopic energy storage density did not change, the energy stored in a fixed space was different due to the electromagnetic structure of the PFL and the properties of the medium.

It was important to improve the pulse breakdown stress of a liquid medium with a high specific resistivity. One way to improve the energy storage density of a high dielectric constant liquid is raising the breakdown stress. This provides a foundation on which to construct a compact IEBA. There are many factors related to the breakdown stress, especially when the objective is repetitive operation, the most important of which is the accumulation of micro-bubbles on the surface of electrode. Bubbles in the PFL result in a higher field strength because their dielectric constant is one, which is much lower than that of a liquid with high dielectric constant in a PFL. In addition, the bubbles may be ionized under a repetitive high voltage pulse, which may cause the temperature around the bubbles to increase along with the volume of the bubbles. Consequently, an irreversible breakdown will occur. As the existence of bubbles on the interface of the electrodes is inevitable, it is important to determine the size of bubbles that can be tolerated in repetitive operation. For this reason, it is necessary to investigate the dynamics of bubbles in the interface of the electrodes and minimize the impact of bubbles.

A systematic approach is essential when designing a compact IEBA based on PFLs filled with a fluid with a high energy storage density. Because of the limited specific resistivity of such fluids, the PFLs are usually charged via a pulsed charge. For this reason, a pulse transformer and associated circuitry is required in a compact design. A compact IEBA based on fluid PFLs must necessarily be accompanied a pulse transformer and its primary circuits as together they represent a complete system. Among the PFLs, pulsed transformer, and related circuitry, the PFLs are the most important as the output parameters, such as the impedance, electrical power, and pulse quality, are dictated by the PFLs. The two stages in the operation of PFLs include charging and discharging processes. The process of forming the electrical pulse is related to the discharging of the PFLs and the properties of the pulse are determined by the electromagnetic structure of the PFLs and the properties of switch linked to the end of the PFL. The charging capacity of the PFLs is dependent on their equivalent capacitance and the parameters related to the pulse transformer and the components used in the primary transformer circuits. There are many factors to consider, such as the application of thyristors, which support a charging period longer than 10 μs, a transformation ratio in the hundreds, and the use of a capacitive bank to supply energy in repetitive operation. It is important to carefully consider the choice of PFL parameters, the transformer parameters, and the parameters used in the design of the primary circuits of transformer when specifying the design of an IEBA. A good approach is to use the best possible components when constructing the IEBA, to ensure every component in the system is assigned an appropriate load, and to ensure there are no particularly weak links in the system. The design of a compact IEBA will vary depending on the particular application: some applications require a long operating time in each run, while other applications require many repetitions at a very high output electrical power, and so on.

Conflict of interest

We declare that in this paper there is no conflict of interest with any other person and organization.

Acknowledgements

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