Miniature solid-state switched spiral generator for the cost effective, programmable triggering of large scale pulsed power accelerators

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This paper presents the design and testing of several different configurations of spiral generator, designed to trigger high current switches in the next generation of pulsed power devices. In particular, it details the development of spiral generators that utilize new ultrafast thyristor technology as an input switch, along with a polarity dependent output gap to improve the efficiency of the spiral generator design. The generator produced 50 kV from a 3.6 kV charging voltage, with a rise time of only 50 ns and a jitter of 1.3 ns—directly comparable, if not better than, a generator employing a triggered spark gap as the input switch. The output gap was constructed in house from commonly available components and a 3D printed case, and showed remarkable repeatability and stability—simple alterations to the output gap could further reduce the rise time. The entire spiral generator, along with control and charging electronics, fitted into a case only $210 \times 145 \times 33$ mm.

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I. INTRODUCTION

The most common way to trigger the high current, high voltage spark gaps utilized in mega-ampere pulsed power facilities is through distortion of the electric field at the gap's electrodes. To keep jitter to a minimum, this typically requires a "trigger" voltage pulse tens–hundreds of kV in magnitude with a fast rise time, a few ns to tens of ns applied to/near the electrodes. Producing such pulses, however, can be complicated and costly. Often trigger generators consist of miniature Marx banks, with a small spark gap as a first stage, itself initiated by a kV silicon controlled rectifier (SCR) or MOSFET coupled to an air cored transformer to increase its output. Whilst with the correct design one such trigger generator can feed multiple high current spark gaps simultaneously, any desire for shaping the output of the facility through staggered firing of these high current spark gaps requires multiple independent trigger generators. A relatively simple to build, cost effective, yet reliable trigger generator would rapidly find multiple uses.

Spiral generators—also known as vector field invertors—are a good candidate for such trigger generators. First described by Fitch and Howell in 1964, they utilize a spirally wound stripline charged to a few kV, to produce an output ~50 kV or more [1]. A simple self-breakdown output gap can be added to sharpen the voltage pulse produced. From the 1970s to early 2000s several trigger generators of this type were commercially available—for example the PT55 produced by Pacific Atlantic Electronics [2]. However, producing an efficient, high voltage spiral generator is not straightforward. In particular, the "input switch" that initiates the spiral has to be capable of switching currents of hundreds of amps to kiloamps on a timescale <10 ns. This precludes the use of many semiconductor switches/arrays of semiconductor switches—in the PT55 a Krytron switch, now no longer manufactured, was used. A secondary issue is the relatively low capacitance of the stripline and the size of the winding. The PT55, for instance, measured $172 \times 172 \times 225$ mm without its power supply and control electronics (a 2u 19" rack unit), but had only tens of pF output capacitance and so could usually be used to trigger just one high current spark gap. We should note here that the size of the PT55 was partly due to a lack of encapsulation (potting) of its spiral winding. The copper tape used to construct this was simply adhered to Mylar insulation layers and wound in air—the Mylar insulation then had to be relatively wide (~15 cm) to prevent any surface breakdown effects in the spiral during discharge. The low capacitance and relatively large size, together with the cost of the Krytron and control electronics, limited use of the PT55.

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In this paper we describe the development of a new spiral generator with the same low jitter, high voltage output as a PT55, yet made with readily available parts and taking advantage of modern construction techniques. It is relatively cheap to produce, with < $700 component cost; extremely compact at only $210 \times 145 \times 33$ mm including all electronics; requires only 24 V to operate; and is initiated by either an electrical transistor-transistor logic (TTL) or fiber optic pulse. The rest of this paper is laid out as follows. The design of the spiral generator is detailed in Sec. II, including how the stripline was made, the different types of input switch used in experiments to initiate the spiral (a miniature triggered spark gap and high speed thyristors), and how a polarity dependent output gap was developed to increase the efficiency of the generator and sharpen its output pulse. Section III describes the apparatus and testing methods used to measure, compare and contrast the performance of different generators. Section IV details the results, including measurements of magnitude, rise time and jitter for the different spiral configurations and initial comparison of results to simulation. Section V summarizes our work, and discusses future development directions. Finally, the Appendix gives more details on the use and reliability of the polarity dependent output gap.

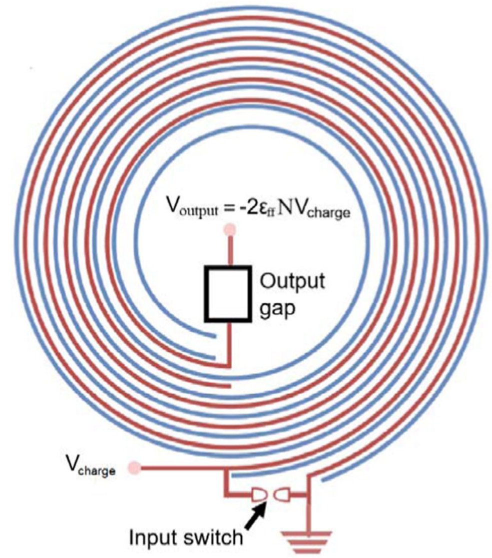

FIG. 1. General schematic of a spiral generator, with input switch and pulse sharpening output gap. Red represents conductor (usually copper tape), blue insulation (usually Mylar). Generally, 10 or more turns are used. V_{charge} is the charging voltage of the stripline, N is the number of turns of the spiral, $\varepsilon_{\mathrm{ff}}$ is a measure of the efficiency of multiplication, and V_{output} the output voltage.

II. DESIGN OF THE SPIRAL GENERATOR

A schematic of a complete spiral generator is shown in Fig. 1. The stripline is initially charged to several kV. An input switch—either a small triggered spark gap or an array of thyristors—initiates the propagation of a wave along the strip line, multiplying the voltage across the spiral. At the output of the spiral, a self-breakdown output spark gap sharpens the voltage pulse seen by the load.

The generator is housed in a 3D printed acrylonitrile butadiene styrene (ABS) plastic case, using an advanced printing method that enables dc standoff voltages of >70 kV with only a few mm wall thickness. The size of the casing, $210 \times 145 \times 33$ mm, was determined by external factors—it was designed to integrate directly onto a high current Kovalchuk ball switch, becoming part of a new type of pulsed power building block or "brick" for future pulsed power facilities (Fig. 2) [3]. The same external factors determined that all charging and control electronics would be also housed within the case.

A. Spirally stripline winding

The open circuit output of a spiral generator is given by $V_{\mathrm{output}} = -2\varepsilon_{\mathrm{ff}} N V_{\mathrm{charge}}$, where $\varepsilon_{\mathrm{ff}}$ is a measure of the efficiency of multiplication, N is the number of turns in the spiral and V_{charge} is the charging voltage of the stripline [1]. Compact power supplies are readily available with voltages up to ~5 kV for only $200–$300 setting a limit for V_{charge}. The casing of the generator set the maximum outer diameter of the spiral winding to ~139 mm. We note that whilst much smaller coils could be utilized, a key parameter affecting efficiency is the rate at which the input switch can turn on compared to the transit time for the voltage wave around one turn of the spiral—if the switch is much slower than this, the efficiency is very low. Typically, the largest possible spiral should be employed, providing the rate of rise of the output pulse from the spiral does not then become so small that it introduces a significant jitter in whatever the spiral is driving. Tests with small charging voltages and hand wound spirals suggested that $\varepsilon_{\mathrm{ff}}$ would be ~0.3 for a 20 turn coil with ~100 mm inner diameter—so to allow for any small variances away from this we chose to use a 24 turn spiral generator to ensure voltages of ~50 kV would still be produced even if $\varepsilon_{\mathrm{ff}}$ fell to 0.2. The rise time of the pulse from the spiral generator is estimated as ~2 times the transit time of a pulse traveling through the spiral $= 2N\pi D/(c/\varepsilon_r^{1/2})$, where D is the average diameter of one turn and ε_r the relative permittivity of the Mylar, taken to be 3 ($c/\varepsilon_r^{1/2}$ is the electromagnetic wave speed). This suggests voltage will take ~105 ns to reach a peak. From experience a voltage pulse rising to ~50 kV over ~100 ns could readily be shortened through use on a simple, self-breaking output gap.

The final version of the spiral winding employed for our tests (Fig. 3) used 12.5 mm wide copper tape, 30 μm thick, laminated onto 25 mm wide Mylar strip, 250 μm thick. A 3D printed former of 100 mm diameter was used to support the windings, which were performed under constant tension. After the windings were secured, they were

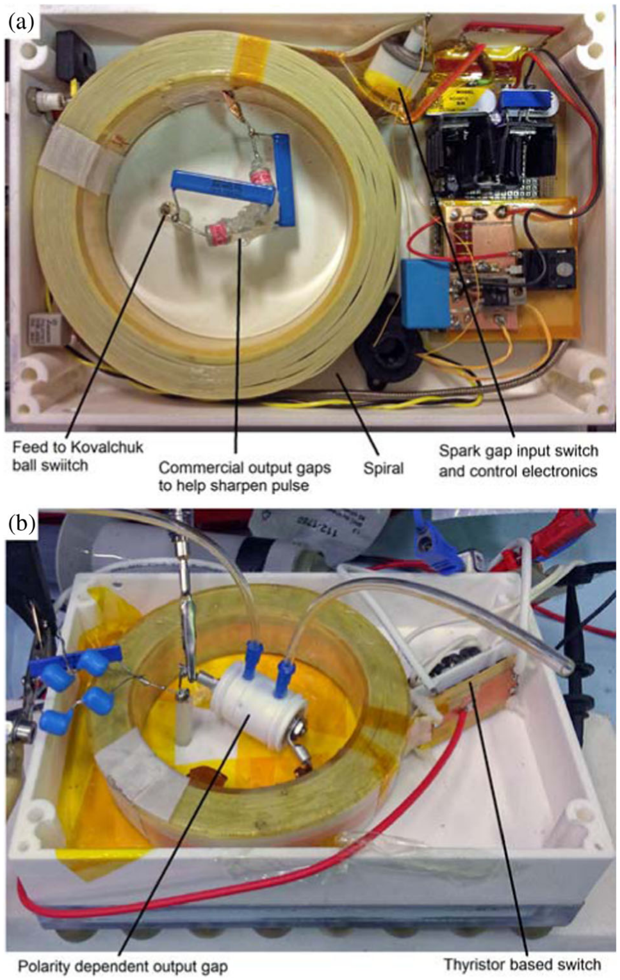

FIG. 2. (a) Complete spiral generator utilizing spark gap input switch and commercial self-breakdown spark gaps on the output (in the center of the spiral winding). (b) Spiral generator utilizing thyristor based input switch and custom polarity dependent output gap. Note in (b) the generator is pictured with test leads and a gas supply to the output gap—these are removed prior to usual use. Also visible in (b) is the Kovalchuk ball gap underneath the spiral that it is designed to trigger.

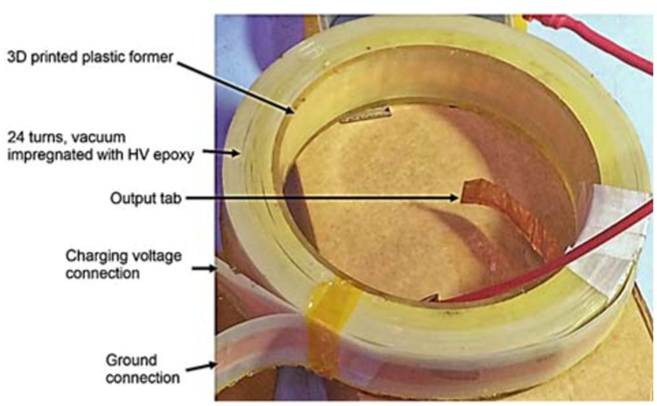

FIG. 3. Picture of finished spiral stripline after impregnation with high voltage insulating epoxy.

impregnated with high voltage epoxy using a vacuum oven and then dried. The outer diameter of a finished spiral was ∼137 mm and the dc breakdown voltage across the layers of the stripline in the spiral better than 10 kV. The output capacitance of the spiral is calculated to be ∼11 pF and the inductance ∼83 μH which would give an output impedance of ∼2700 Ω.

B. Input switches

1. Miniature triggered spark gap

Our first investigations of the spiral generator utilized a small RU87-7 triggered spark gap, manufactured by Pulsetech, as an input switch [4]. In order to maintain a fast rate of switching, the inductance of the connections between the spark gap and spiral were minimized, with it mounted on the onside turn of the spiral and the stripline closely coupled to its body. The gap was triggered via a −5 kV fast rising pulse, ∼1 μs in duration supplied via discharging a 200 V capacitor through a 1∶20 turn ratio, air cored transformer. A schematic of the trigger circuit is shown in Fig. 4. The stripline was charged +5 kV for these experiments, as the output required from the generator was −50 kV to ensure maximum field distortion of the Kovalchuck ball switch.

2. Solid state (thyristor) switch

Whilst the triggered spark gap was able to initiate the spiral generator and produce output pulses with good characteristics (see Sec. IV), it also had several limitations. The circuitry required to trigger the spark gap was itself quite complex, requiring circuits at 5, 24 and 200 V in addition to the charging voltage and a carefully constructed air cored transformer. Further, to prevent a high degree of jitter the spark gap had to be used at or near its design voltage—at much lower voltages ionization processes

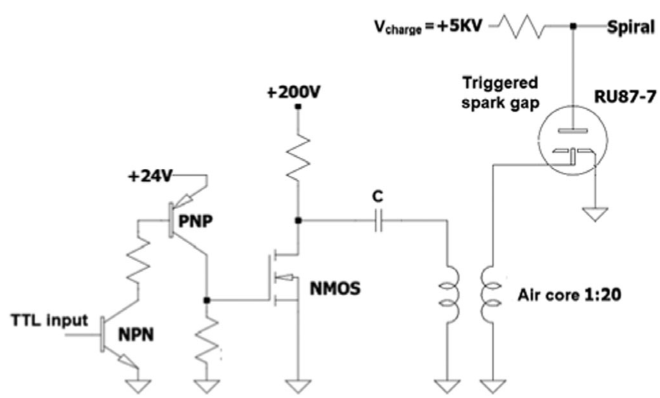

FIG. 4. Schematic of the circuit used to trigger the RU87–7 miniature spark gap, when it was used as an input switch to the spiral winding. The TTL input signal triggers the MOSFET via an NPN and PNP transistor. This in turn discharges a 200 V capacitor to ground via a 1∶20 air core transformer, the output of which triggers the miniature spark gap.

within the gap would be inefficient and spark gap would not switch properly. A solid state switch, if it were possible, could be significantly easier to trigger and operate over a much larger range of voltages.

Early tests demonstrated that most MOSFETs and SCRs, even those designed for fast switching, could not be used due to having too low a slew rate to initiate the spiral properly, or due to having too low a standoff voltage that their use became impractical even in an array. However, the ultrafast SP205-01 thyristors, also known as “Solidtrons,” recently developed by Silicon Power Corporation could operate with high enough speed, being rated at up to 65 A/ns with a peak anode current of 2.7 kA [5]. Further whilst each single thyristor has a holdoff voltage of 1.5 kV, they were made to be stacked in an array enabling higher voltage use.

Two different input switch circuits based on the SP205-01 thyristors were subsequently designed and employed for the project: the first, a simple test unit, had six thyristors in series; the second, a more optimized version has only four. Both circuits utilized surface mount components, and the four thyristor version was designed from the outset to have much lower inductance being more compact and utilizing a double sided circuit board with a closely coupled return conductor on one side.

Both switch circuits had a similar component structure, as shown in Fig. 5(a). Each thyristor S is connected in parallel with a resistor R_d of 100 MΩ (2512 package) to equalize the voltage distribution. Diodes D in reverse protect the thyristors from reversal—the diodes are SiC Schottky types (PG-TO252-2 package) with holdoff voltage and pulse peak currents 1.2 kV and 472 A respectively. The charging resistor R_C is 1 MΩ (2512 package), whilst the dc power supply, based around an XP Power Q50 dc-dc converter providing voltages up to 6 kV, was mounted separately.

All the thyristors in the circuits had to switch on simultaneously. To accomplish this the input TTL signal/optical fiber signal (converted to TTL) was fed through a gate driver to the circuit shown in Fig. 5(b). Here a ∼24 V supply, U, charged a small 1 nF capacitor, C_t, through a 1 MΩ charging resistor. Switching of a fast 100 V, 100 A N-channel MOSFET, S_t, then generated a pulse that traveled through a series of ZnNi ferrite cores (16 mm outer diameter, 9.6 mm inner diameter, 4.75 mm length) via 22 AWG, 15 kV silicone insulated wire. The secondary

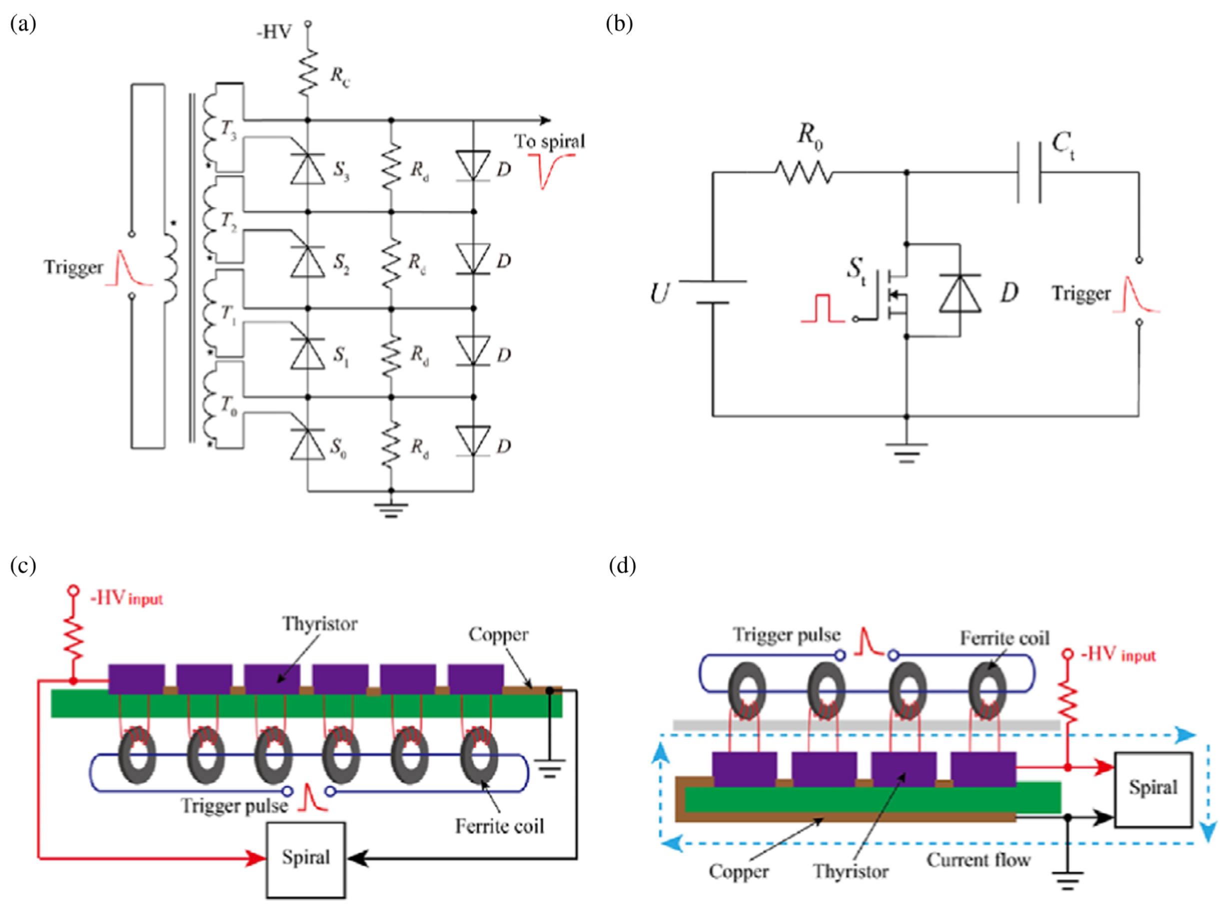

FIG. 5. (a) Schematic of thyristor circuit used for the input switch. (b) Trigger circuit that supplies the thyristor circuit in 5(a). (c) Circuit with six thyristors in series, used in early experiments. (d) The more optimized circuit with four thyristors.

winding of each core fed the gate of a single SP205-01 thyristor with a 3 Ω resistor (1206 package) in series and a diode (SOD123 case) in parallel for protection (not shown in Fig. 5). We note that the MOSFET, ferrite cores and silicone wiring were far from optimized for this application—they were used due to availability at the time and could readily be replaced with smaller versions.

C. Pulse sharpening output gap

Our early experiments, using a spiral generator with the miniature triggered spark gap as an input switch, hoped to employ small, commercial self-breakdown gaps to sharpen the pulse seen by the load. Such gaps are readily available at voltages up to 5 kV to protect circuitry from over voltages—for instance the Epcos SSG5X gap series [6]. Tests were performed with one and two gaps in series, and whilst the results were promising it became apparent that fielding enough of these gaps to properly sharpen the pulse would take up too much space. At the same time, it was noted that the output from the spiral generator (see Sec. IV) consisted of an oscillating sinusoid, with a second peak significantly larger in magnitude than the first. In order to maximize the efficiency of the spiral generator, instead of utilizing the first pulse to trigger a load, it would be highly desirable to use this second pulse. To achieve this, we developed our own output spark gap that was sensitive to the polarity of the applied voltage.

Previous research has demonstrated that the breakdown of a gas between point and plane electrodes is highly dependent on the polarity of the applied voltage [7]. If the point electrode is charged negatively, volumetric space charge can surround the sharp point, screening it; whilst in the opposite polarity this effect does not occur. Hence a negatively charged point electrode has a higher breakdown voltage than one positively charged. Our output gap design, shown in Fig. 6 utilizes the same principles. The electrodes are made from commonly available A2 stainless steel bolts.

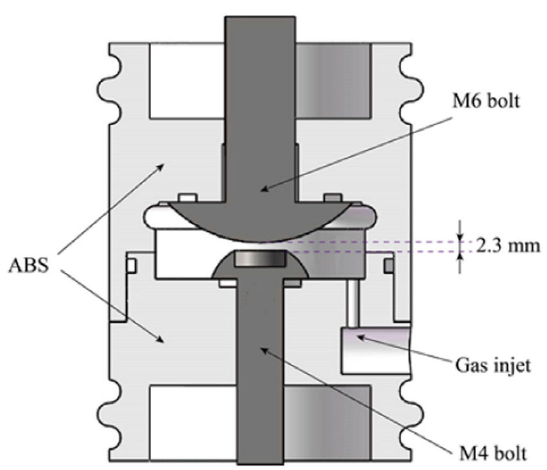

FIG. 6. Design of the polarity dependent output gap developed in the project.

The spiral winding is connected to an M6 Mushroom headed bolt, which has a large, relatively flat surface. The load is connected to an M4 cap head bolt, which provides a smaller surface with sharp edged grooves. If the spiral is negatively charged, the first pulse at the output gap is positive—this is equivalent to the situation where the M4 bolt is negative, and the M6 bolt is grounded. In such conditions, the gap does not break down. However, when the negative pulse arrives it is equivalent to the M4 bolt being positively charged and the M6 bolt at ground—and the gap can break down. To reduce the effects of any capacitive coupling of the positive pulse through the switch, the output gap was fielded with a small capacitor connected in parallel to any load (C_P in Fig. 7, below). A 200 MΩ grounding resistor (R_G in Fig. 7) was also added to prevent the load from floating.

The casing of the output gap is again made of 3D printed ABS plastic utilizing a technique that allows for high standoff voltages. The spark gap was filled with atmospheric pressure dry air, and the distance between the electrodes, found through multiple generations of design and testing, was set at ∼2.3 mm. This relatively short distance helps ensure that on breakdown the arc between the electrodes rapidly became well conducting, helping ensure a fast rising edge to the voltage pulse at the load.

III. SETUP FOR TESTING

Figure 7 shows an example of the setup used for testing the generator. The different spiral generators were capacitively coupled to the trigger electrodes of a high current 100 kV Kovalchuk ball switch—the same load the spiral generators were intended to drive as part of the new pulsed

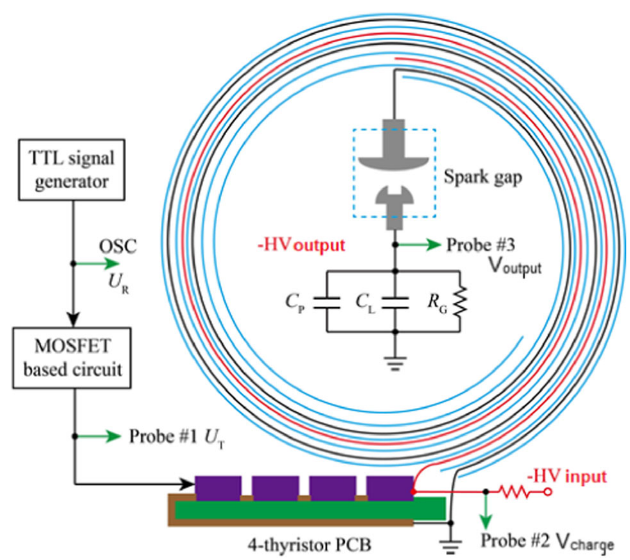

FIG. 7. A typical test configuration, in this case using optimized the four thyristor input switch and output gap. C_L represents the capacitance of the load (the triggering electrodes of a Kovalchuck ball switch).

power brick. Electrically the ball switch can be represented as a small capacitor C_L of value ∼10 pF. A TTL signal provided by a Quantum pulse generator was used to trigger the input switch of the spiral generator along with a Tektronix TDS5054B oscilloscope of bandwidth 500 MHz, sampling rate of 5 GS/s. A Tektronix 0500B probe, rated voltage of 300 V with a bandwidth of 500 MHz, measured the output pulse from the MOSFET driving the air cored transformer for experiments utilizing a miniature triggered spark gap; or the MOSFET driving the ZnNi ferrite cores for the experiments with the SP205-01 thyristors—U_T in Fig. 7. A Tektronix P6015a probe, rated at 40 kV with a bandwidth of 75 MHz, measured the voltage V_{charge} of spiral generator at the input switch, a second probe, of the same type measured the output of the spiral generator. If the output gap was installed this measurement was made after the gap. Note that although the output voltage from the spiral generator was above the rated value of the P6015a probe, the measurement was still possible due to the very short timescale of the output.

IV. RESULTS AND DISCUSSION

A. Output waveforms of three generators

Figure 8 shows the typical output waveforms of the different spiral generator configurations—the configuration using the miniature triggered spark gap as an input switch, with an output gap made from two 5 kV commercial self-breakdown gaps; the configuration using the six thyristors input switch both with and without the polarity dependent output gap; and the configuration with the more optimized four thyristors again with and without the polarity dependent output gap.

With the triggered spark gap configuration, a charging voltage of +5.4 kV had to be utilized to obtain a −50 kV output pulse—a voltage multiplication of 9.3x (an efficiency $\varepsilon_{\mathrm{ff}}$ of only 0.19). The inclusion of the two commercial self-breakdown gaps could be seen to sharpen part of the leading edge of the voltage pulse but did not have a large effect due to their breakdown voltage being too low. These experiments, however, showed the existence of a significantly higher magnitude secondary pulse, +72 kV in this case, a multiplication factor of 13.3× ($\varepsilon_{\mathrm{ff}} \sim 0.28$).

The secondary voltage pulse higher than the first pulse is thought to be a common feature of many spiral generators and is caused by resonance effects between different parts of the wound stripline. Theory suggests that the secondary pulse strongly depends on the characteristics of the input switch and whether the generator is driving a capacitive or resistive load, however it has been rarely studied in detail (or utilized) [8,9]. Indeed, most experiments where it has been observed have also included magnetic cores in the spiral generator, generally improving efficiency at the expense of rise time. If this secondary pulse could be used for our experiments it would enable lower charging voltages for the spiral to be utilized, placing less stress on the input switch and spiral winding. This led to the development of the polarity sensitive output gap described in Sec. II C, which coincided with our experiments in thyristor switching.

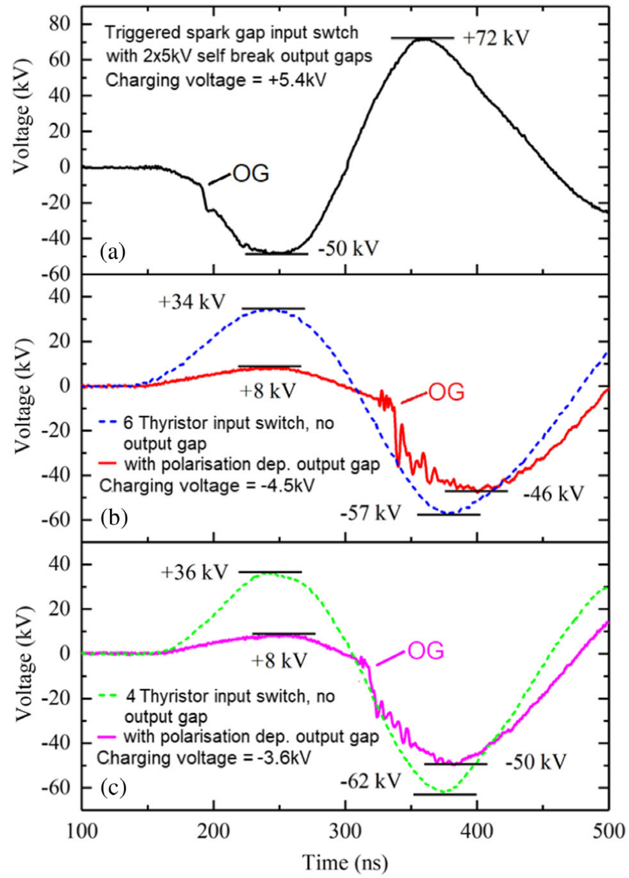

FIG. 8. Output pulses of three versions of the spiral generators. (a) Using the miniature triggered spark gap input switch and +5.4 kV charging voltage. (b) Using the initial six thyristor input switch and −4.5 kV charging voltage. (c) Using the four thyristor input switch and −3.6 kV charging voltage. For experiments with an output gap, "OG" marks its breakdown. Note the start time of 100 ns simply reflects when the scope was externally triggered, not the thyristors.

Experiments with the six thyristor input switch and a charging voltage of −4.5 kV produced an initial pulse of +34 kV and a secondary pulse −57 kV without the output gap. The voltage multiplication factor of the secondary pulse, 12.7x, was comparable to the spark gap, without significant optimization. The addition of the polarity dependent output gap, along with a parallel capacitance of 10 pF (see the Appendix) reduced the initial pulse to only ∼ +8 kV but only decreased the magnitude of secondary pulse to 46 kV, still a multiplication factor of 10.2x. The more optimized four thyristor input switch only required a charging voltage of −3.6 kV to produce similar results, due to the lower overall inductance of the circuit. The initial output pulse of +36 kV was again reduced to only $\sim +8$ kV by the output gap. The secondary pulse was initially -62 kV, representing a very large multiplication factor of 17.2x. This reduced to a -50 kV with the output gap in place, a multiplication of 13.9x (higher than experiments with the triggered spark gap).

The effect of the output gap(s) could be seen in all three spiral generator configurations, sharpening the edge of the output pulse as the gap broke down. As expected, the sharpening effect was most obvious in experiments with the thyristor input switches, where the output gap was developed specially for the generator. In experiments with the four thyristor input switch, the voltage waveform of the secondary pulse gradually dropped to -4 kV, then changed from -4 to -27 kV in only 10 ns as the gap broke down. The voltage continued to decrease to the negative peak, and the total rise time was ~49 ns. This is a little shorter than the rise time of experiments with the triggered spark gap input switch, ~52 ns, and significantly shorter than experiments with the initial six thyristor input switch, which had a rise time of 57 ns.

B. Amplitude, jitter and rise time of the three generators

Figure 9 shows the amplitude, rise time and jitter of the output from the different spiral generator configurations described in this paper. For reliable triggering of a high current spark gap, the amplitude of the output should be as large as possible, whilst the rise time as short as possible. A low jitter, meanwhile, ensures that if separate spiral generators are used to each trigger a high current spark gap, this will be done as simultaneously as possible—vital for the spiral generator's use in a brick as part of a larger pulsed power project. For experiments using a miniature triggered spark gap as the input switch, the measurements refer to the initial pulse observed from the spiral generator; for experiments utilizing thyristor switching, the secondary pulse with and without the polarity dependent output gap. As a comparison the PT55 generator had an output of 50 kV, with a jitter of ~2 ns and a rise time of ~4 ns (though this only referred to the fast changing part of the output pulse).

As can be seen from Fig. 9(a), results could only be obtained from the spiral generator with the miniature triggered spark gap input switch at relatively high charging voltages, 4.3–5.4 kV. This is expected as below 4 kV the spark gap was too far away from its operational design for a discharge between its electrodes to be properly established. Also expected was the increase in output voltage, from 40 to 50 kV with charging voltage. The rise time of the output pulse was only ~45 ns and remained constant over the small range of charging voltages; jitter however was significantly improved, falling from 16 to 5.6 ns at 5.4 kV charging voltage. This highlights the improved performance of the spark gap at higher voltages and discharge currents.

The amplitude of output pulse from the versions of the spiral generator utilizing four and six thyristor input

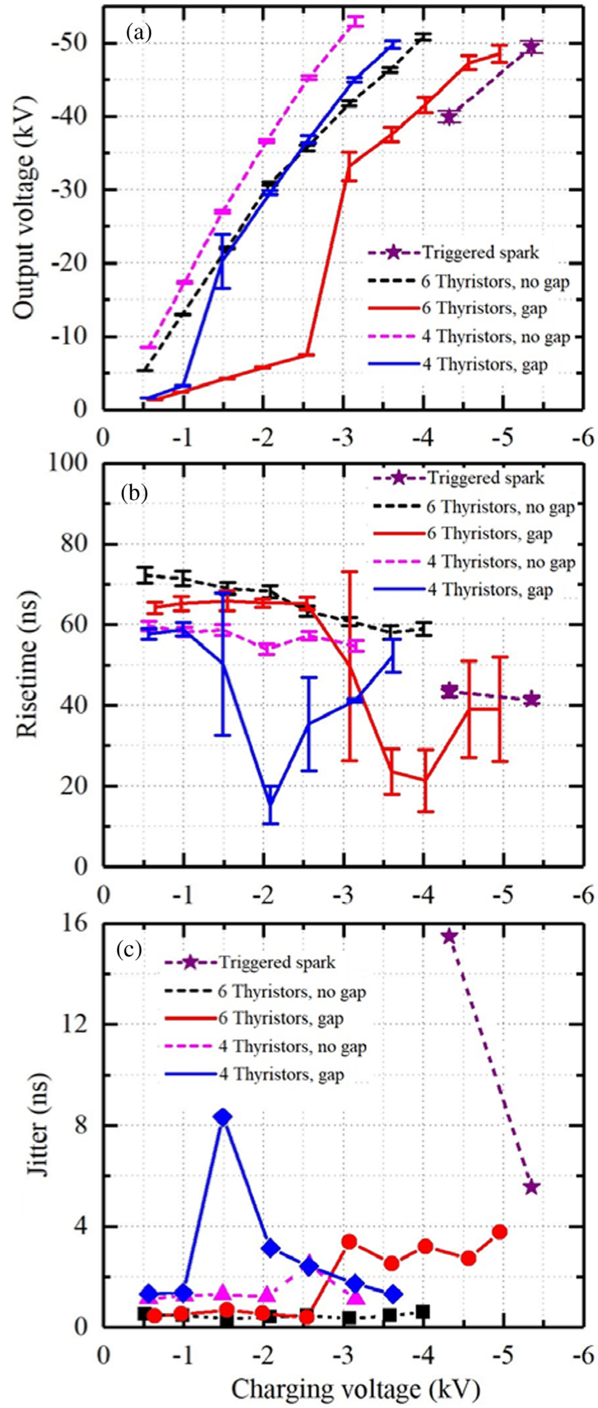

FIG. 9. Relationship between the pulse parameters and the charging voltage for the different configurations of spiral generator. (a) Amplitude; (b) rise time; and (c) jitter.

switches but no output gap scales linearly with the charging voltage over a much larger range—demonstrating the versatility of this switching method. The rise time of the output from the six thyristor version fell slightly from 70 to 60 ns as the charging voltage was increased to 4 kV, perhaps suggesting that the resistance of the thyristors as they switched on was lower when a higher gate voltage (charging voltage per thyristor) was applied and a larger current flowed through the thyristors. The rise time of the four thyristor version was always lower than the six thyristor version, even with the same gate voltage applied to each thyristor—this is due to the lower overall inductance design of this input switch. Again, the rise time with the four thyristor version drops with charging voltage, though at a lower rate than for the six thyristor version, dropping from 60 to 55 ns at a charging voltage of 3 kV. The jitter for both thyristor configurations was very low, <1 ns for the six thyristor version and ~1 ns for the four thyristor version; any differences here could be largely due to measuring technique and small differences in probe positioning.

For versions of the spiral generator where the polarity dependent output gap was used in conjunction with thyristor input switching, the dependence of amplitude, rise time and jitter on charging voltage are complicated by the characteristics of the output gap. At low charging voltages, <3 kV for the six thyristor switch and <1.5 kV with the four thyristor switch, the output gap did not break, and instead the signals observed after the gap were due to capacitive coupling effects. Above these values, the output scaled with input voltage at a similar rate to experiments without the gap, although the output was always lower for the same input voltage, as potential was lost across the gap—for instance to get an output voltage of ~50 kV with a four thyristor switch ~3 kV charging voltage is predicted to be required if no output gap is used, 3.6 kV with. With the output gap operating, plots of the measured rise time vs charging voltage appear to pass through a minimum before rising again. This though is due to the two different parts of the output pulse—the initial part of pulse is dominated by the rapid change in voltage as the output gap breaks down [as seen, for instance in Fig. 8(c)]; following this there is a slow rise to peak. In its present configuration the output gap typically operates at $\sim$25–30 kV, setting the voltage that the rapidly rising part of output pulse reaches. If the charging voltage produces an output close to this, the measured rise time is then dominated by the rapid part of the pulse and so is very fast—for instance with a four thyristor input switch, the rise time at 2 kV charging voltage was only ~16 ns. As the charging voltage then increases, the slow rise in voltage after this rapid change becomes more important—again using the four thyristor input switch as an example, the overall rise time increases from 16 to 51 ns as charging is increased to 3.6 kV. Jitter for both configurations typically remains <3 ns, and in fact drops to ~1 ns for the four thyristor switch at 3.6 kV charging voltage. Note that at 1.5 kV the jitter for this switch appears abnormally high, which was likely due to the output gaps being at too low a voltage for stable operation.

For a ~50 kV output pulse, the specifications of all three configurations of spiral generator reported in this paper are shown in Table I. The polarity dependent output gap was utilized for versions with the six and four thyristor input switch. All configurations should sufficiently meet the triggering requirements for a high current spark gap, particularly the Kovalchuk ball switch which the generators were designed to couple to. Given the relative simplicity, efficiency and versatility of the four thyristor switch version, however, this is the design that will be employed in future experiments.

TABLE I. Parameter comparisons of three generators.

Parameters	Triggered spark gap	Six thyristor switch	*Four thyristor switch*
Amplitude, kV	−50	−46	**−50**
Rise time, ns	52	57	**49**
Jitter, ns	5.6	3.1	**1.3**
Charging voltage, kV	5.4	4.5	**3.6**
Voltage ratio	9.3	11.1	**13.9**

C. Comparison of the output waveforms to simulation

Due to the effects of resonance between different parts of the spiral generator, and the strong dependence of this resonance on the characteristics of the input switch and load, estimates of the output of the generator become difficult. The rise time we measured from the generator, 50–60 ns, is significantly shorter than the simple theoretical value of 105 ns calculated in Sec. II because of the sharpening effect of the output gap. Similarly, there is no simple expression for the efficiency coefficient $\varepsilon_{\mathrm{ff}}$, or the relative magnitudes of the different output voltage pulses.

In order to provide a stronger basis for our research, we have developed a model of the spiral generator similar to that of Pal'chikov *et al.*, who treated the generator as double transmission lines, utilizing telegraph equations to solve the propagation of the E-M waves through the different parts of the stripline [9]. The model, coded using the differential equation solvers in the commercial finite element code COMSOL, includes realistic coupling between the turns of the spiral, and enables the effects of the different input switches and the resistance and capacitance of the load to be explored [10].

Figure 10 shows simulations of the spiral generator compared to the experiments with four and six thyristor input switches described in Sec. IV A. The simulations used the same charging voltages of −4.5 kV for the six thyristor switch and −3.6 kV for the four thyristor switch as their initial conditions. A purely capacitive load of 15 pF capacitor was used (including the parallel capacitance, the capacitance of the probe and the load capacitance). Very good agreement in both the magnitude and shape of the output voltage pulse over the first and second peaks was obtained with an inductance of 50 nH for the six thyristor

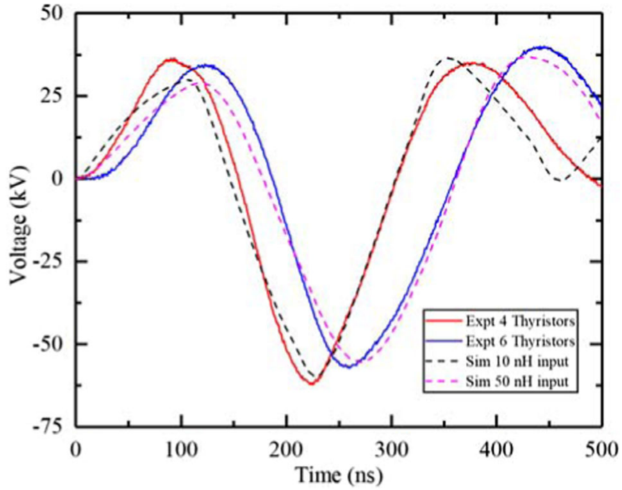

FIG. 10. Comparison between experiment and simulation for spiral generators using six thyristor and four thyristor (optimized) input switches. With the six thyristor switch the charging voltage was −4.5 kV, with the four thyristor switch −3.6 kV. A 15 pF capacitive load was employed for the simulations.

input switch, and 10 nH for the four thyristor switch, which agrees well with estimates based on their configuration and positioning relative to the spiral.

A separate publication giving full details of the model and in depth comparison to several different spiral designs and loads is presently being prepared.

V. SUMMARY

We have demonstrated three different versions of a spiral generator designed to trigger high current spark gaps. The most traditional design used a miniature triggered spark gap as the input switch to the spiral, however designs based on solid state, ultrahigh speed thyristor switching were subsequently developed that could produce the same output voltage of 50 kV, for lower charging voltage (3.6 kV), had comparable rise times of ~50 ns, and an even smaller jitter, 1.3 vs 5.6 ns. Key to this development was the detailed measurement of the output of the spiral generators into the load they were to designed to trigger (a Kovalchuk ball switch)—and the measurements that the output wave from the generator had a sinusoidal structure, with an initially relatively low magnitude first peak, followed by a much larger peak at the opposite polarity. This prompted the development of a polarity dependent output gap to reduce/negate the initial pulse, and breakdown on the pulse that followed it.

Initial modeling of the propagation of EM waves through the spiral was able to accurately simulate the output pulse, including the secondary peak. All of the spirals reported in this paper were extremely compact, fitted into a casing $210 \times 145 \times 33$ mm, including all control and charging electronics. The polarity dependent output gap created for the project was simple to build using commonly available parts and a 3D printed body, and manufacturing multiple output gaps demonstrated their high repeatability.

In future experiments, the gas mix in-between the electrodes of the output gap will be adjusted to enable breakdowns at higher voltages than 30 kV, producing much sharper rise times over the entire 50 kV pulse (we are unable to perform these experiments at present due to Covid-19 temporarily closing our experimental facilities). We will also explore the use of Silicon Avalanche Shaper to replace the output gap. We will then study the characteristics of a complete pulsed power brick with low inductance capacitors discharged via the Kovachuck ball switch triggered by the spiral generator.

ACKNOWLEDGMENTS

This research has been carried out as part of the “Brick 2” project at Imperial College that aims to make the next generation of pulsed power brick incorporating on board high voltage charging, triggering and safety systems; creating a user friendly building block for new pulsed power generators. The brick will be simple to build and easy to adapt for different capabilities. Parts of the research detailed in this paper were funded by First Light Fusion Ltd and the U.S. Department of Energy under Cooperative Agreements No. DE-NA0003764 and No. DE-SC0018088. We would like to express our thanks to Yakov Krasik of Technion, Bucur Novac and Peter Senior of Loughborough University and John Waldron of Silicon Power Corporation.

APPENDIX: THE OUTPUT GAP AND ITS USE

1. Choice of parallel capacitor

As described briefly in Secs. II and IV, until the output gap breaks down and starts conducting, capacitive coupling between its electrodes will still transmit voltage pulses across the gap. This means that the load would still see the initial output voltage pulse from the spiral generator, which is of the opposite polarity yet still ½ the magnitude of the second pulse that we wish to utilize. As the intended purpose of the spiral generator is to trigger high current spark gaps through field distortion at their electrodes, such an output from the spiral generator could cause multiple issues.

To help limit the effect of coupling within the output gap, a small capacitor can be placed in parallel with the Kovalchuk ball switch load (itself effectively a capacitor of 5–10 pF). To explore the effect of this parallel capacitor, tests were performed with a spiral generator utilizing the six thyristor input switch—Fig. 11 shows the results. Even 10 pF of parallel capacitance reduced the magnitude of the initial pulse output from the spiral generator from 14 to 7 kV, and increasing it to 50 pF reduced it to only 4 kV.

As expected increasing the parallel capacitance also decreased the magnitude of the second voltage peak as the spiral had to discharge into effectively a larger

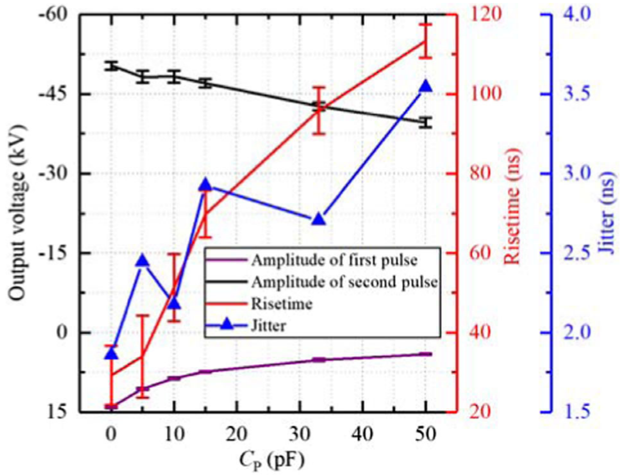

FIG. 11. Effect of different value capacitors placed in parallel with the load on the output characteristics of a spiral generator utilizing a six thyristor input switch. The charge voltage in all experiments was ~5 kV.

impedance load. With a 50 pF capacitor in parallel, the second peak decreased from −50 to −40 kV and the rise time of the pulse increased to ~100 ns. Extrapolating the values in Fig. 11, we might expect the second peak to be halved to ~25 kV with a 100 pF parallel capacitance at which point the rise time would be ~150 ns. Halving of the output voltage represents the point when the load (now ~110 pF in total) is matched to the spiral generator; hence a measure of the output impedance is $Z_{\mathrm{output}} = 1/(2\pi f C_{\mathrm{matched}}) = 870\ \Omega$ where f is the frequency of the output waveform. It should be noted that measurements and calculations described here include the output sharpening switch, rather than the spiral alone.

As well as reducing the magnitude of the second peak and increasing the rise time of the generator, a higher parallel capacitance also resulted in a slightly increased jitter. Considering all these parameters, we decided to use a parallel capacitance of 10 pF as a compromise.

2. Repeatability and reliability of the output gap

As demonstrated in Sec. IV the jitter of the pulse from a spiral generator utilizing thyristor input switching and no output gap is very low, ~1 ns or less. When the polarity dependent output gap is used, it is the jitter and reliability of this gap that dominates these characteristics of the generator. Given that a large pulsed power device could rely on tens or even hundreds of such spiral generators, these characteristics must be explored for multiple output gaps, nominally all manufactured the same way.

Figure 12 shows output voltage, rise time, and jitter measured at the load for four different output gaps all using the spiral generator with a six thyristor input switch. Each output gap was the subject of >100 experiments, and the misfire rate was found to be <2%. It can be seen that the jitter of all four output gaps was nominally the same, ~4 ns. The output voltage and rise time were all also in agreement. This suggests that the design should meet the requirements of synchronous triggering for most applications.

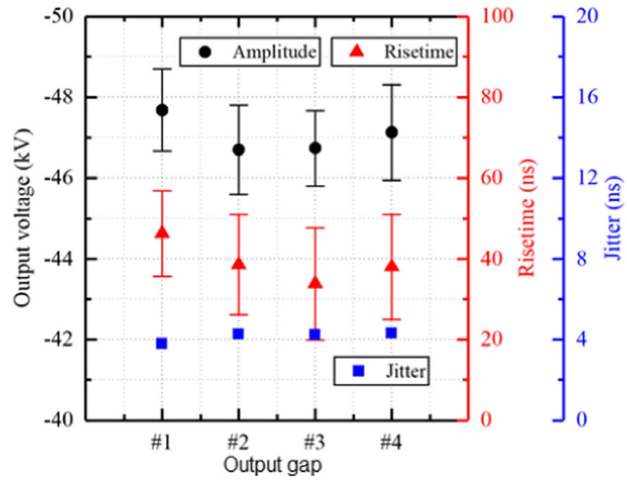

FIG. 12. The output voltage, rise time, and jitter measured at the load for four different output gaps all using the spiral generator with a six thyristor input switch.

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