

Specifications for SG-Series Spark-Gap Switches

Gas-filled spark gaps satisfy a range of plasma-closure switching requirements involving capacitive discharge circuits. Series SG switches manufactured by R. E. Beverly III and Associates are designed for use in low-inductance (e.g., strip-line), fast-pulse systems where large peak currents (10~1000 kA) and high voltages (5~200 kV) are commuted. Although nominally designed for single-pulse operation, repetition rates in excess of 100 Hz are possible for decreased charge-transfer rates. Modular construction allows different configurations to be rapidly assembled from off-the-shelf components. Three basic switch types are available: (i) passive, (ii) electrically triggered, and (iii) laser triggered (see Table I). Passive switches have only two electrodes and operate spontaneously when the applied voltage exceeds the self-breakdown voltage. Electrically triggered switches employ three electrodes and require an external trigger generator to initiate breakdown; three configurations are available: trigatron, field distortion, and railgap. Trigatron switches are the simplest design to install and offer the lowest cost. For those applications that demand a compact design with low jitter, the field-distortion switch is the optimum choice. Railgaps offer the features of a field-distortion switch with the capability for very large charge transfer and exceptionally low inductance. Laser triggered switches consist of two electrodes and a lens that focuses laser radiation onto an on-axis, mid-plane point between these electrodes; the laser-generated spark initiates breakdown. This trigger method offers the fastest turn-on and lowest jitter of all of our switches.

Table I. Preliminary Switch Selection Guide by Triggering Method

	Passive	Trigatron	Field Distortion	Railgap	Laser Triggered
Form Factor	compact	moderate height	compact	wide, planar	taller height
External Trigger Complexity	none required	simple	complex	complex	very complex
Required Trigger Rise Time	not applicable	slow	fast	fast	very fast
Breakdown Time	slow	moderate-fast	fast	fast	very fast
Jitter	large	moderate	low	low	very low
Life Expectancy	moderate-high	low-moderate	moderate-high	moderate-high	moderate-high
Trigger System Cost	none	low	moderate-high	high	high
Switch Cost	low	moderate	moderate	very high	high

For all switch models, the breakdown characteristics are determined by the gas type, internal pressure, and electrode geometry. The operating voltage is therefore adjustable over a wide range by changing the internal pressure. An external, pressurized gas supply is required for all switches — **we do not manufacture hermetically sealed or vacuum switches**. A general guide to switch selection is given in Table II: first select the column appropriate to your maximum charge transfer, then the row that most closely matches your operating voltage. Select switch model(s) for further study based upon their technology and your particular application.

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Table II. Switch Selection Guide

Operating Voltage	Charge Transfer, Q							
	Q ≤ 1 Coulomb				1 < Q ≤ 20 Coulombs			20 < Q ≤ 200
	T	P	FD	L	T	FD	Special	Various
Low Voltage (↓ 5 kV)	SG-104 SG-111 SG-141	SG-112	—	SG-113	SG-174	—	SG-206 (SD) SG-207 (SD)	—
Moderately High Voltage	SG-101 SG-104 SG-131	SG-102 SG-105	SG-124	SG-103	SG-151 SG-171 SG-172 SG-173	SG-183	—	SG-175 (T)
High Voltage (>50 kV)	SG-121	SG-122 SG-202	SG-124	SG-123	SG-161 SG-181 SG-182	SG-184 SG-185	SG-203 (P) SG-204 (T) SG-301 (SD)	RG under development

T = trigatron
P = passive
FD = field-distortion
L = laser
SD = surface discharge
RG = railgap

SG-xxx = high repetition rate
SG-xxx = miniature, adjustable electrode gap
Special switches are only available with complete systems
Direct mounting onto Scyllac-style capacitor bushing
Special design for photo-triggered Marx generator

Construction

Series SG switches are designed for reliability and durability. Sintered tungsten-alloy electrodes ensure long life and low probability for misfire or prefire. The translucent polycarbonate, polyoxymethylene (acetal), or polyetherimide insulator makes firing easily and safely visible without UV hazard. The top and bottom plates are brass or aluminum alloy; the bolt circles are identically dimensioned and located for easy attachment of conductors. Buna-N® (Nitrile elastomer) O-rings seal the top and bottom plates and trigger plug(s). The gas fittings are made of nylon, polypropylene, or PVDF depending upon the switch model, and all attachment hardware is provided with your order. All components, including the trigger plug for the trigatron models, the trigger ring for the field-distortion models, and the lens for the laser triggered models, are readily replaceable and the entire switch can be disassembled for inspection and cleaning using ordinary tools. Electrodes within our larger form-factor switches can be replaced in the field. Most switches can be immersed in dielectric oil.

Triggering Requirements

Triggering requirements for the electrically initiated models demand a fast pulse having a peak voltage $>|V_g|/2$, a rise time $\sim 1\text{--}10$ kV/ns (field-distortion and railgap) or ~ 0.1 kV/ns (trigatron), and an energy >100 mJ (field-distortion and railgap) or >10 mJ (trigatron), where V_g is the switch operating voltage, i.e., initial voltage across the gap. Our [THD-series trigger generators](#) are ideally suited for trigatron switches and employ fiber-optic command for complete isolation from electrical inference. We also offer a range of [OEM trigger modules](#) for integration into pulsed power systems of the user's design. Optimum switch operation occurs with breakdown simultaneously between the trigger electrode and adjacent electrode and also between the trigger plug and opposite electrode.

For the field-distortion models, the trigger ring must be properly biased relative to the main electrodes and decoupled from the incoming trigger pulse using a capacitor or ancillary spark gap. The trigger pulse distorts the field distribution in the main gap and the resulting field enhancement leads to avalanche ionization and gas breakdown. We offer various [custom trigger systems](#) for trigatron and field-distortion switches that are capable of firing multiple switches simultaneously. This technique is also called *multichannel* operation.

The precise triggering demands of large field-distortion and railgap switches led us to develop our TG-series low-jitter, very-high-voltage trigger systems. These systems offer very high open-circuit voltage (>100 kV), exceptionally fast rise time (<3 ns), and precise timing with representative jitter <2.5 ns. The smaller and lower energy [TG-102](#) system is designed for modest-size field-distortion switches. The larger and higher energy [TG-103](#) is capable of driving the largest field-distortion and railgap switches. Both systems utilize robust coaxial cable as the transmission line between trigger generator and switch.

[Laser triggered models](#) rely upon a laser generated plasma channel to initiate breakdown. For short pulse-width excimer or Nd:YAG lasers, for example, this requires a peak intensity at focus $\geq 10^{12}$ W/cm² and an energy of >1 mJ. A switch jitter <1 ns is readily attainable if the laser pulse width is ≤ 5 ns. Light enters the switch through an on-axis aperture. The integral focusing lens is selected based upon the customer's laser (please provide the following laser parameters: wavelength, pulse energy, pulse width, beam waist, mode quality, and divergence). Standard models rely upon free-space beam transport; upon special order, fiber-optic transport is possible. To protect the lens from discharge vapor, the focusing chamber is pressurized and gas flows from this chamber through the hole in the main electrode, into the switch housing, and then exits through tube fittings in the insulator.

Breakdown Characteristics

The breakdown potential is determined by the electrode separation (gap), gas fill, internal gas pressure, and initial polarities of the different electrodes. V_{sb} is the self-breakdown voltage, which is usually expressed as the median statistical value. If V_g is the voltage applied across the switch gap, then the self-break fraction $f = V_g/V_{sb}$ is a parameter that is often used to describe the switch's operating condition. Unlike a mechanical switch such as a reed relay, **a plasma switch is a dynamic element that is not independent of the external circuit elements**. As long as the peak current is less than the manufacturer's rating, a reed relay will behave identically in all situations with respect to the turn-on time, contact resistance, etc. **The same is not true of a plasma switch.**

The breakdown time t_{bd} is defined as the time duration between arrival of the voltage pulse at the trigger electrode (electrically triggered models) or laser pulse (laser triggered models) and main gap conduction. Full conduction is accompanied by voltage collapse across the main electrodes. The breakdown time is sometimes referred to as the *switch runtime*. For electrically triggered switches, typically $t_{bd} \sim 100$ ns at the lowest operating voltage and decreases rapidly to <20 ns as $f \rightarrow 1$. For laser triggered switches, $t_{bd} < 10$ ns. Jitter is a measure of the statistical variation (one sigma, σ) in t_{bd} measured over a statistically significant number of shots N . Optimum breakdown conditions typically occur when $f = 0.8-0.9$. If f is too close to unity, then the probability of a *prefire* increases to a statistically unacceptable level; if f is too low, then the jitter increases dramatically. In the extreme case of $f \rightarrow 0$, then the switch fails to fire, which is called a *misfire*.

Curves of the minimum, recommended, and self-breakdown voltages as a function of internal gas pressure are supplied with each switch. A discussion of breakdown physics and representative discharge circuits are given in our [Application Guide for SG-Series Spark-Gap Switches](#).

Switch Resistance and Loss

As the gas changes state from an insulator to a conducting plasma, the switch resistance decreases rapidly to the order 1–10 m Ω . This assumes there is sufficient electrical energy store and current drive to maintain a conductive plasma column (spark), namely a peak current >10 kA. The minimum voltage drop across the switch is limited by the electrode fall layers (principally the cathode fall layer) and is typically 130-370 V, with the precise value dependent upon the gas fill and charge transfer. For a constant value of charge transfer, the voltage drop is roughly independent of the peak current provided that there is sufficient current to sustain conduction (>10 kA). Switch energy losses for representative discharge circuits are typically a few percent. This value may be substantially greater for highly oscillatory circuits. In the extreme case, this value can approach 50%.

Electrical Recovery

The hold-off potential of a spark-discharge switch is greatly reduced following discharge and a finite duration is required before the gap recovers its quiescent breakdown strength. The gap recovery time or *deionization time* depends upon the peak current, charge transfer, and the gas type, pressure, and flow rate. Minimum recovery times are only obtained when the discharge waveform is critically damped or over-damped; recovery will be prolonged for discharges with significant voltage reversal. Recharging of the energy-storage capacitor should occur slowly, preferably by means of an inductive or resonant L-C charging system. For repetitive operation, best results are obtained using a command charging source that delays recharging for a few to several tens of milliseconds following each discharge (see the Appendix in our [PG-103D Trigger Control Unit](#)).

Life Expectancy

Energy losses in the switch are due to three mechanisms: (i) plasma sheath dissipation including various electrode sputtering phenomena, (ii) heating of the gas column in the spark and associated radiative losses, and (iii) resistive (Joule) heating in the bulk electrode material. There is unfortunately no precise method for predicting life expectancy since operating conditions vary widely. Under maximum rated operating conditions, typical life expectancies are 5,000 to 20,000 shots. Life expectancies up to 1,000,000 shots can be realized under derated operating conditions. Although we provide estimates based upon the total accumulated charge transfer, we recommend that the user perform lifetime tests for critical applications.

Life expectancy is primarily limited by erosion of the main electrodes due to mechanism (i) and is therefore dependent upon total accumulated charge transfer. For the trigatron switch, erosion of the trigger pin can also lead to erratic operation, however, the trigger plug can be easily replaced in the field without disassembly of the entire switch. In most circumstances, the life of the trigger plug will be shorter than the life of the main electrodes. Intense radiation from the spark [mechanism (ii)] causes ablation of insulator material. Sputtering of the electrodes also adds impurities to the internal gas. Subsequent plasma-chemical reactions in the spark discharge produce contaminants that are adsorbed onto internal surfaces thereby reducing the self-breakdown voltage and causing intermittent prefires and misfires. Proper preventative maintenance of the switches can prolong their useful life (see [Application Note AN-101](#)). For repetitively pulsed applications, average heating due to mechanism

(iii) may also be an important factor, especially if the temperature of the bulk electrode material is allowed to increase well above ambient. Series SG switches are cooled primarily by internal gas flow and maximum life expectancy will only be obtained using the recommended gas flow rate.

Our switches can be refurbished at the factory for approximately one-third the cost of a new unit. This procedure involves cleaning the switch and replacing both main electrodes and the trigger electrode. Please inquire for further information and a quotation. The following unaltered photograph shows a trigatron switch after several continuous-operation periods at high repetition rate. Note the dimpling in the opposite electrode (left) and the erosion of the adjacent electrode (right) around the trigger-plug opening. This wear gave erratic operation only at lower voltages.



Model SG-141M trigatron switch after ~1M shots (H₂ gas, 50-100 pps, 5-10 kV, 4-8 kA).

Operating Characteristics and Ratings

Abbreviated specifications for our switch models are given in Table III. Specifications are subject to change without notice as we are continually striving for improvement, so please frequent our web site (<http://www.reb3.com>) for the latest information. Only certain models are stocked, therefore certain models may require a minimum order quantity to justify a production run. Individual data sheets may be downloaded by clicking on the model number in the left-hand column. Various application guides and application notes are also available on-line (see the section entitled **References**). Custom designs are available in excess of 200 kV and 2 MA. Full engineering assistance is available on a contract basis.

Table III. Standard Switch Specifications (small form-factor models)

Model Number ^a	Trigger Method	Operating Voltage Range, ^b kV	Max Peak Current, ^c kA	Max Charge Transfer, Coulomb	Switch Inductance, nH	Trigger Jitter, ns	Dimensions (dia x hgt) ^d inches millimeters	Repetition Rate (max), ^e Hz
SG-101BM	Trigatron	10–40	100 (85)	0.5	<35	<100	5.00 x 2.10 127 x 53.2	1
SG-102BM	Passive	20–40	85	0.4	<35	—	5.00 x 1.74 127 x 44.2	1
SG-103BM	Laser	10–40	100 (85)	0.4	<30	<1–3	5.00 x 1.75 127 x 44.5	1
SG-104B	Trigatron	5–40	65	0.1	≈35	<200	2.90 x 2.36 74 x 60	5
SG-105B	Passive	16–50	65	0.1	≈35	—	2.90 x 2.36 74 x 60	5
SG-111BM	Trigatron	5–25	100 (85)	0.5	<35	<150	5.00 x 2.10 127 x 53.2	1
SG-112BM	Passive	15–28	85	0.4	<35	—	5.00 x 1.74 127 x 44.2	1
SG-113BM	Laser	5–25	100 (85)	0.4	<30	<1–3	5.00 x 1.75 127 x 44.5	1
SG-121BM	Trigatron	20–65	100 (85)	0.5	<35	<200	5.00 x 2.10 127 x 53.3	1
SG-122BM	Passive	33–60	85	0.4	<35	—	5.00 x 1.74 127 x 44.2	1
SG-123BM	Laser	20–65	100 (85)	0.4	<30	<1–3	5.00 x 1.75 127 x 44.2	1
SG-124BM	Field Distortion	10–75	100 (75)	0.3	<35	<10	5.00 x 2.10 127 x 53.3	0.5
SG-131BM	Trigatron	10–40	10 100(g)	0.05 0.5(g)	<30	<100	5.00 x 1.75 127 x 45.5	100 0.02(g)
SG-141M	Trigatron	5–20	10 100(g)	0.05 0.5(g)	<20	<150	5.00 x 1.60 127 x 40.6	50 0.02(g)

Standard Switch Specifications (large form-factor models)

Model Number ^a	Trigger Method	Operating Voltage Range, ^b kV	Max Peak Current, ^c kA	Max Charge Transfer, Coulomb	Switch Inductance, nH	Trigger Jitter, ^d ns	Dimensions (dia x hgt) ^e inches millimeters	Repetition Rate (max), ^f Hz
SG-151M (h)	Trigatron	10–45	400 (250)	8	<25	<100	10.5 x 2.43 267 x 61.7	0.02
SG-161M (h)	Trigatron	35–75	400 (250)	8	<45	<50	10.5 x 3.23 267 x 82.0	0.02
SG-171CM	Trigatron	10–35	225 (180)	5	<35	<100	10.5 x 3.12 267 x 79.2	0.02
SG-172DM	Trigatron	5–30	250 (250)	25	<50	<250	10.5 x 3.92 267 x 99.5	0.02
SG-173BM	Trigatron	10–45	250 (200)	5	<40	<50	11.7 x 2.6 296 x 67	0.02
SG-174M	Trigatron	2.5–13	200 (150)	5	<40	<500	10.5 x 2.6 267 x 67	0.02
SG-175M	Trigatron	8–32	250	120	<100	<600	10.5 x 9.9 267 x 251	0.02
SG-181CM	Trigatron	20–60	225 (180)	8	<50	<100	10.5 x 3.89 267 x 98.8	0.02
SG-182 (i)	Trigatron	15–60	250(j)	1(j)	<30	<25	6.26 x 4.92 159 x 125	0.02
SG-182L(i)	Laser	15–60	250(j)	1(j)	<30	<3	6.26 x 4.92 159 x 125	0.02
SG-183 (i)	Field Distortion	10–36	200(j) 250(g)	0.5(j) 1(g)	<30	<5	6.26 x 4.92 159 x 125	1 0.05(g)
SG-184M	Field Distortion	20–75	250 (200)	10	<45	<5	10.5 x 3.15 267 x 80.1	0.02
SG-185	Field Distortion	40-200	200	1	<100	<20	6.05 x 4.69 154 x 119	0.02

Table Notes:

- a) Suffix M denotes metric fasteners; we no longer manufacture switches with English fasteners (-E suffix). Laser switches are optimized for a particular wavelength (please specify wavelength, pulse energy, pulse width, beam waist and divergence). All large form-factor trigatron switches are now equipped with our trigger electrodes. The trigger rod is replaceable in the field (see [Application Note AN-104](#)).
- b) Operating voltage range is dependent upon gas or gas mixture and internal pressure; please consult the individual data sheet for details and breakdown curves. Switches operating above approximately 35–40 kV typically require immersion in a dielectric medium such as SF₆ or oil.
- c) Maximum peak current for a non-oscillatory discharge (<20% current reversal); values in parentheses () denote recommended maxima for highly-oscillatory discharges (up to 80% current reversal).
- d) Typical worst-case jitter; minimum jitter occurs under optimum operating conditions, i.e., when $V_g \approx 0.8 V_{sb}$, and is considerably greater when $V_g \ll V_{sb}$.
- e) Body dimensions excluding gas fittings and trigger electrode. Switches shipped to countries using the Imperial standard are provided with English fittings, otherwise metric fittings are supplied. Please consult the individual data sheet for specifics. All fasteners and gas fittings are provided.
- f) Maximum repetition rate under maximum rated peak voltage, peak current, and charge transfer; much higher repetition rates are possible by reducing the charge transfer per pulse.
- g) Single-pulse operation.
- h) Four independent gaps within a common housing; requires four individual capacitors or capacitor banks and a special trigger generator for operation.
- i) Mounts directly onto General Atomics capacitors with Scyllac-style bushings (consult factory) and drives four DS-2248 (RG-1714) coaxial cables; requires shield canister for low-inductance operation. Data sheets available only by special request.
- j) When driving four DS-2248 cables in parallel, the maximum peak current and charge transfer are reduced to 160 kA and 0.4 Coulombs, respectively, due to the cable's limitations.
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Representative Standard Switches



Model SG-101BM trigatron (electrically triggered) switch for moderate HV applications: 10–40 kV, 100 kA, <35 nH



Model SG-102BM passive (self-breakdown) switch: 20–40 kV, 85 kA, <35 nH



Model SG-103BM laser-triggered switch for precise, low-jitter (<3 ns) operation: 10–40 kV, 100 kA, <30 nH



Model SG-124BM field-distortion switch: 10–60 kV, 100 kA, <35 nH



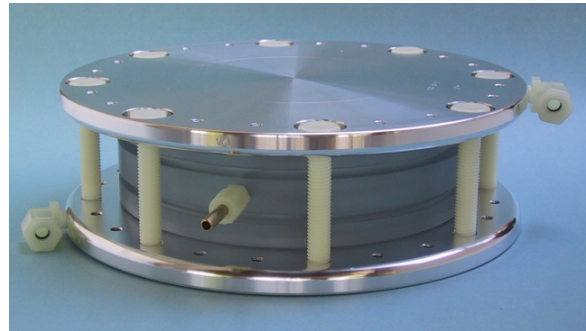
Model SG-131BM trigatron switch for high-average power, burst-mode applications: 10–40 kV, 10 kA, 100 pps



Model SG-104B demountable mini-trigatron switch: 5–40 kV, 65 kA, ≈35 nH



Model SG-151M multichannel trigatron switch for extreme current, large charge-transfer applications: 10–40 kV, 400 kA, 8 C, <30 nH



Model SG-184M field-distortion switch for high-current, large charge-transfer applications: 20–75 kV, 250 kA, 10 C, <45 nH



Model SG-181BM trigatron switch for high-current, large charge-transfer applications: 20–60 kV, 225 kA, 8 C, <50 nH



Model SG-172CM trigatron switch for very large charge-transfer applications: 5–30 kV, 250 kA, 25 C, <50 nH



Model SG-182 trigatron switch for direct mounting on Scyllac-style capacitors: 15–60 kV, 250 kA, 1 C, 27 nH (companion shield canister not shown)



Model SG-183 field-distortion switch for direct mounting on Scyllac-style capacitors: 10–36 kV, 250 kA, 1 C, 26 nH

Representative Custom Switches



Model SG-193 laser switch for coaxial cable PFL



Model SG-202 pulse sharpener switch for MM-101



Model SG-203 photo-triggered switch for MV-1 Marx generator: 25–85 kV, 100 kA, 0.5 C



Model SG-204 trigatron and laser switch for MV-1 Marx generator: 25–85 kV, 100 kA, 0.5 C

References

R. E. Beverly III and R. N. Campbell, "Transverse-flow 50-kV trigatron switch for 100-pps burst-mode operation," *Review of Scientific Instruments* **67**, 1593 (April, 1996)

Jane Lehr and Prahlad Ron, *Foundations of Pulsed Power Technology* (IEEE Press, Wiley, Piscataway, NJ, 2017), see Ch. 4 in particular.

[Application Guide for SG-Series Spark-Gap Switches](#), R. E. Beverly III and Associates.

[Care and Feeding of Spark-Gap Switches](#), Application Note AN-101, R. E. Beverly III and Associates.

[Massively Paralleled Systems](#), Application Note AN-102, R. E. Beverly III and Associates.

[Installation of Switch Couplers](#), Application Note AN-103, R. E. Beverly III and Associates.

[Poco-Graphite Trigger Electrodes](#), Application Note AN-104, R. E. Beverly III and Associates.

[Transmission Lines – A Basic Primer on Strip Lines](#), Application Note AN-105, R. E. Beverly III and Associates.

[Mitigation of Pre-Firing in High-Voltage Switches](#), Application Note AN-106, R. E. Beverly III and Associates.

[Coincidence Detection Systems](#), Application Note AN-107, R. E. Beverly III and Associates.

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