# 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 (~1-500 kA) and high voltages (2.5-75 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; two configurations are available: trigatron and field distortion. Trigatron switches are the simplest design to install and offer the lowest cost. For those applications that demand a very compact and low-inductance design, the field-distortion switch is the optimum choice. 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 | Laser Triggered |
|---|---|---|---|---|
| **Form Factor** | compact | moderate height | compact | tall height |
| **External Trigger Complexity** | none required | simple | complex | very complex |
| **Required Trigger Rise Time** | not applicable | slow | fast | very fast |
| **Breakdown Time** | slow | moderate-fast | fast | very fast |
| **Jitter** | large | moderate | low | very low |
| **Life Expectancy** | moderate-high | low-moderate | moderate-high | moderate-high |
| **Trigger System Cost** | none | low | moderate-high | high |
| **Switch Cost** | low | moderate | moderate | 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. A gas supply is required for all switches — we do not manufacture hermetically sealed or vacuum switches. A guide to switch selection is given in Table I.

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**Table II. Switch Selection Guide**

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

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

SG-xxx = high repetition rate
SG-xxx = miniature
Special switches are only available with complete systems.

# 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 model, and all fasteners are stainless steel, nylon, or glass-fiber polyetherimide. 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.

# Triggering Requirements

Triggering requirements for the electrically initiated models demand a fast pulse having a peak voltage $>|V_g|/3$, a rise time ~1–10 kV/ns (field-distortion) or ~0.1 kV/ns (trigatron), and an energy >5 mJ, where $V_g$ is the switch operating voltage, i.e., initial voltage across the gap. Our model PG-103D trigger generator ideally suited for trigatron and smaller field-distortion switches. For the trigatron models, the trigger transformer is connected to the trigger plug and adjacent electrode. 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. The trigger pulse distorts the field distribution in the main gap and the resulting field enhancement leads to avalanche ionization and gas breakdown. A custom trigger generator will be required with our larger field-distortion switches. The peak voltage from the trigger generator must be properly adjusted to optimize either trigger method.

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 $>10^{11}$ W/cm$^2$ and an energy of >1 mJ. A trigger jitter <1 ns is readily attainable. 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 two 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. 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. For electrically triggered switches, $t_{bd}$ ~ 100 ns at the lowest operating voltage and decreases rapidly to <20 ns as $V_g \longrightarrow V_{sb}$, where $V_{sb}$ is the self-breakdown voltage. For laser triggered switches, $t_{bd}$ < 10 ns. Optimum breakdown conditions occur when $V_g = (0.8–0.9)V_{sb}$. Jitter is a measure of the statistical variation in $t_{bd}$ from one shot to the next. Curves of the minimum, recommended, and self-breakdown voltages as a function of pressure are supplied with each switch. A more detailed 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 of a milliohm. 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 independent of the peak current provided that there is sufficient current to sustain conduction (10 A). Switch energy losses for representative discharge circuits are typically a few percent. This value may be substantially greater for highly oscillatory circuits.

# 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 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 milliseconds following each discharge.

# 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. The trigger plug, however, 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. 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 the 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. Standard-duty switches can also be upgraded for heavy-duty operation by replacing the used electrodes with our -75C series electrodes. Please inquire for further information and a quotation. The following unaltered photograph shows a trigatron switch after several continuous-operation periods at a 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 ($H_2$ gas, 50-100 pps, 5-10 kV, 4-8 kA).

## Operating Characteristics and Ratings

Abbreviated specifications for our standard switch models are given in Table III. Specifications are subject to change without notice as we are continually striving for improvement, so please frequently consult our web site (http://www.reb3.com) for the latest information. Individual data sheets may be downloaded by clicking on the model number in the left-hand column. Various application guides 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

| 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-102M | Passive | 20–30 | 50 (40) | 0.2 | <20 | — | 5.00 x 1.60 127 x 40.5 | 1 |
| SG-103M | Laser | 10–30 | 50 (40) | 0.2 | <20 | <5 | 5.00 x 1.60 127 x 40.5 | 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-112M | Passive | 15–28 | 50 (40) | 0.2 | <20 | — | 5.00 x 1.60 127 x 40.5 | 1 |
| SG-113M | Laser | 5–20 | 50 (40) | 0.2 | <20 | <5 | 5.00 x 1.60 127 x 40.5 | 1 |
| SG-121M | Trigatron | 20–65 | 75 (50) | 0.3 | <35 | <200 | 5.00 x 2.10 127 x 53.3 | 1 |
| SG-122M | Passive | 33–60 | 65 (50) | 0.3 | <35 | — | 5.00 x 2.10 127 x 53.3 | 1 |
| SG-123M | Laser | 20–65 | 65 (50) | 0.3 | <35 | <5 | 5.00 x 2.10 127 x 53.3 | 1 |
| SG-124M | Field Distortion | 15–75 | 75 (50) | 0.3 | <35 | <10 | 5.00 x 2.10 127 x 53.3 | 0.5 |

## Standard Switch Specifications (Continued)

| 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-131M | Trigatron | 10–40 | 10<br>100(g) | 0.05<br>0.5(g) | <30 | <100 | 5.00 x 1.80<br>127 x 45.7 | 100<br>0.02(g) |
| SG-141M | Trigatron | 5–20 | 10<br>100(g) | 0.05<br>0.5(g) | <20 | <150 | 5.00 x 1.60<br>127 x 40.6 | 50<br>0.02(g) |
| SG-151M (h) | Trigatron | 10–45 | 400<br>(250) | 8 | <30 | <100 | 10.5 x 2.43<br>267 x 61.7 | 0.02 |
| SG-161M (h) | Trigatron | 35–75 | 400<br>(250) | 10 | <45 | <50 | 10.5 x 3.23<br>267 x 82.0 | 0.02 |
| SG-171BM | Trigatron | 10–35 | 200<br>(150) | 5 | <35 | <100 | 10.5 x 2.43<br>267 x 61.7 | 0.02 |
| SG-172CM | Trigatron | 5–30 | 250<br>(250) | 20 | <50 | <250 | 10.5 x 3.23<br>267 x 82.0 | 0.02 |
| SG-173BM | Trigatron | 12–40 | 250<br>(200) | 5 | <40 | <50 | 11.7 x 2.6<br>296 x 67 | 0.02 |
| SG-174M | Trigatron | 2.5–13 | 200<br>(150) | 5 | <40 | <500 | 10.5 x 2.6<br>267 x 67 | 0.02 |
| SG-181BM | Trigatron | 15–60 | 250<br>(200) | 8 | <50 | <100 | 10.5 x 3.23<br>267 x 82.0 | 0.02 |
| SG-182 (i) | Trigatron | 15–60 | 250(j) | 1(j) | <30 | <25 | 6.26 x 4.92<br>159 x 125 | 0.02 |
| SG-182L(i) | Laser | 15-60 | 250(j) | 1(j) | <30 | <5 | 6.26 x 4.92<br>159 x 125 | 0.02 |
| SG-183 (i) | Field Distortion | 10–36 | 200(j)<br>250(g) | 0.5(j)<br>1(g) | <30 | <2 | 6.26 x 4.92<br>159 x 125 | 1<br>0.05(g) |
| SG-184M | Field Distortion | 20–75 | 250<br>(200) | 10 | <45 | <2 | 10.5 x 3.15<br>267 x 80.1 | 0.02 |
| SG-185 | Field Distortion | 40-200 | 200 | 1 | <100 | <20 | 6.05 x 4.69<br>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 width, beam waist and divergence). All large form-factor trigatron switches are now equipped with our poco-graphite trigger electrodes. The trigger rod is replaceable in the field.

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 30–40 kV require immersion in a dielectric medium such as $SF_6$ 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) Jitter under optimum operating conditions, i.e., when $V_g \approx 0.8V_{sb}$. Jitter is considerably greater when $V_g << V_{sb}$.

e) Body dimensions excluding gas tubulations and trigger electrode. Switches shipped to countries using the Imperial standard are provided with English sized tube 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.

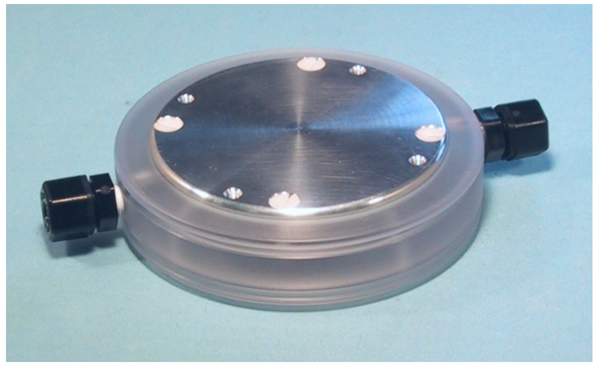
h) Four independent gaps within a common housing; requires four individual capacitors or capacitor banks and a special trigger generator for operation.

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.

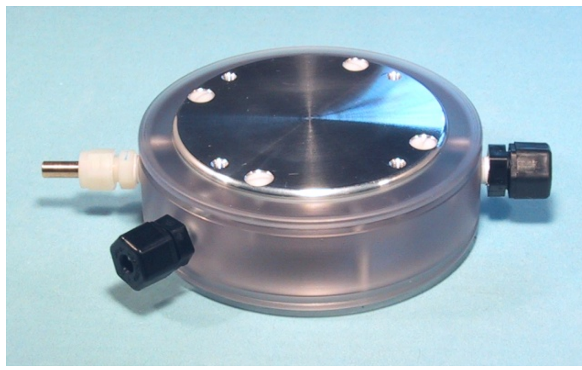
## Representative Standard Switches

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

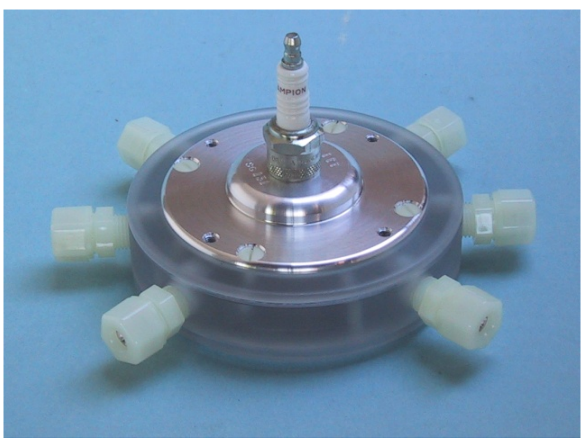


Model SG-102M passive (self-breakdown) switch: 20–30 kV, 50 kA, ≤20 nH

Model SG-103M laser-triggered switch for precise, low-jitter (<5 ns) operation: 10–30 kV, 50 kA, ≤20 nH

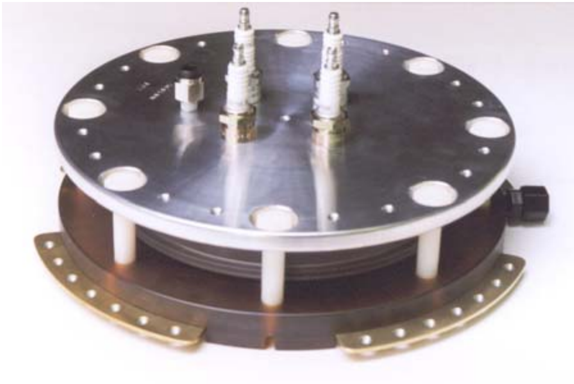


Model SG-124M field-distortion switch: 15–75 kV, 75 kA, <35 nH

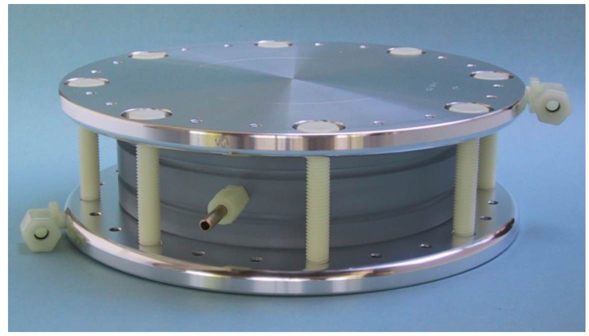


Model SG-131M trigatron switch for high-average power, burst-mode applications: 10–40 kV, 10 kA, 100 pps

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

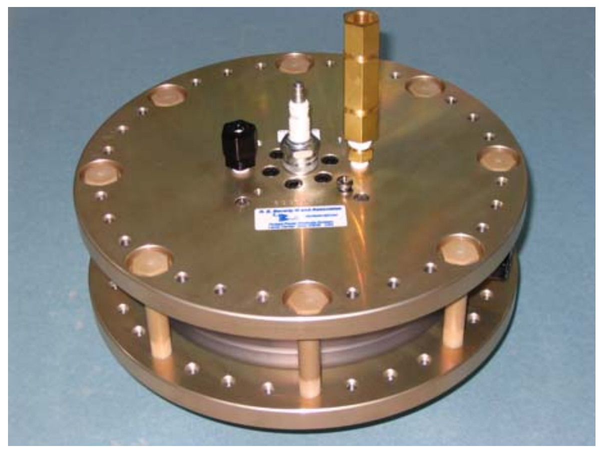


Model SG-151M multichannel trigatron switch for extreme current, large charge-transfer applications: 10–40 kV, 400 kA, 8 C, ≤30 nH

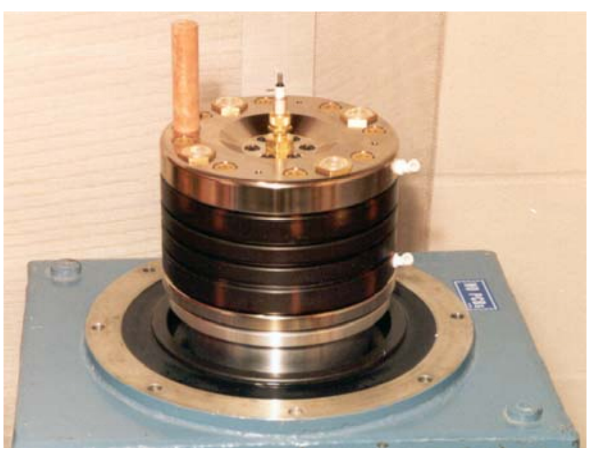


Model SG-184M field-distortion switch for high-current, large charge-transfer applications: 20–75 kV, 250 kA, 10 C, ≤45 nH

Model SG-171M trigatron switch for high-current, large charge-transfer applications: 10–35 kV, 200 kA, 5 C, ≤35 nH



Model SG-172M trigatron switch for very large charge-transfer applications: 5–30 kV, 250 kA, 20 C, ≤50 nH

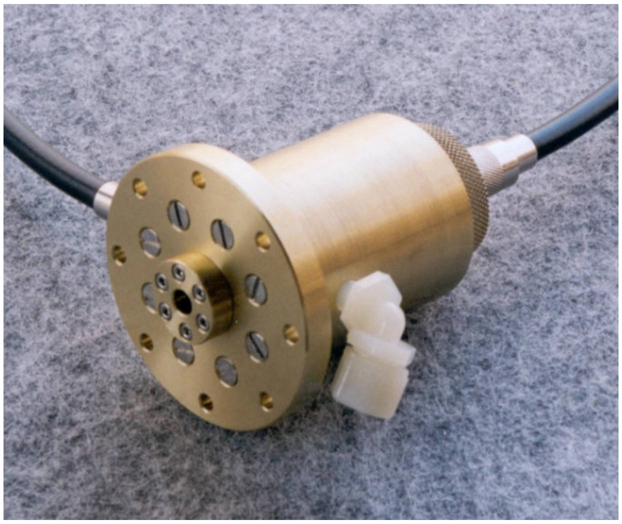


Model SG-182 trigatron switch for direct mounting on Scyllac-style capacitors: 15–60 kV, 250 kA, 1 C, 27 nH (companion shield canister not shown)

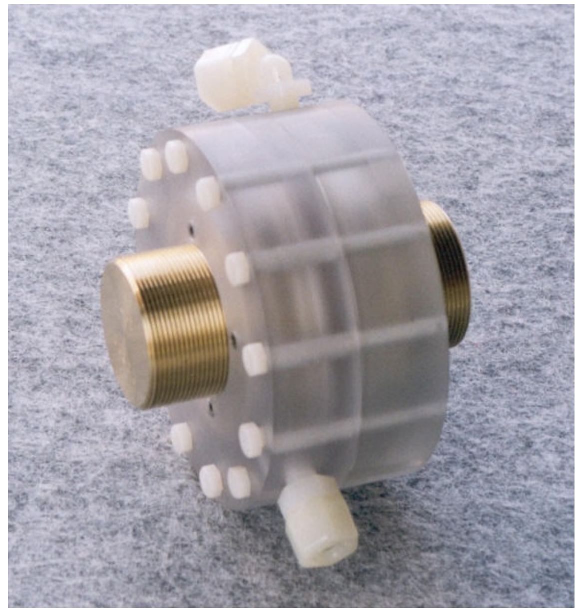
Model SG-183 field-distortion switch for direct mounting on Scyllac-style capacitors: 10–36 kV, 250 kA, 1 C, 26 nH


## 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)

***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.



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