Modular Solid-State Switch for the SPS and LHC Beam Dump Systems

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Abstract

A modular coaxial solid-state closing switch has been developed for the physical replacement of a NL488A high-density graphite anode, water-cooled ignition in the horizontal sweeper generator of the beam dump system of the CERN SPS accelerator. The main reasons for the development in this application were environmental, low maintenance and exclusion of erratic firings. Two prototype switches have been made for a hold-off voltage of 12 kV. They consist each of a stack of four asymmetrical Fast High Current Thyristors together with capacitive over-voltage protections and resistive dividers. A specially designed trigger transformer allows the reuse of the original ignitron trigger unit without modification. The switches conduct a 46 μs half sine wave peak current of 25 kA at an initial rate of 2 kA/μs. Their losses are about 80 Joules per discharge at 12 kV. The minimum repetition rate is 5 seconds. The two switches have successfully operated for one year and the series is now under installation.

A similar switch has been designed for the LHC beam extraction system to prevent erratic firings. It consists of 10 series connected asymmetrical FHCT's and its total stray inductance is less than 150 nH. It has a hold-off voltage of 30 kV and switches a peak current of 20 kA in less than 2.7 μs. The 10:1 trigger transformer has a 5 μH stray inductance, which allows, at 2 kV primary trigger voltage, a peak gate current of 250 A with a rate of rise of 400 A/μs. This switch has been tested over several years and has already demonstrated some 300.000 shots without any break-down or erratic firing. The test repetition rate of the switch varies between 8 hours and 20 seconds.

For reliability and standardization reasons, this switch will also be used in the pulse generators for the horizontally and vertically deflecting diluter systems of the LHC beam dumping system. The particularity of the switch for the horizontal system is the fact that its current is an attenuated sinusoidal oscillation of 25 kA amplitude at a frequency of 14 kHz. Tests have shown that, due to the lifetime constant of the charge carriers of about 500 μs, no anti-parallel diodes are required for the reverse current in the FHCT's.

Introduction

Horizontal Sweeper Generator Beam Dump system SPS (MKDH)

The horizontal beam dump system uses 3 fast kicker magnets per beam to deflect horizontally the particles in one revolution of the accelerator on an absorber block, which is located in the SPS tunnel. Each kicker magnet is powered by two pulse generators, which are connected in parallel. They consist of a discharge capacitor, a resistive crowbar circuit and a switch, that produces at 12 kV a magnet current pulse of 25 kA amplitude of 25 μs rise time and 120 μs fall time. The magnet current has to be proportional to the beam energy over a dynamic range of 30, from injection at 15 GeV/c to a top energy of 450 GeV/c. During a SPS machine cycle of 14 seconds the horizontal sweeper generators are constantly under a voltage of 10 kV.

As new power switches, semiconductor solid state technology has been chosen to assure the absence of erratic firing.

Beam Extraction system LHC (MKD)

The beam extraction system uses 14 fast kicker magnets per beam to deflect horizontally the particles in one revolution of the collider in an extraction channel and after being diluted the beam is disposed on external absorbers blocks, which are located at the end of tunnels excavated roughly tangentially to the LHC ring. Each extraction kicker magnet is powered by its own pulse generator, which consists of a discharge capacitor and a semiconductor solid state switch, that produces a magnet current pulse of 20 kA amplitude of

2.7 µs rise time and 90 µs flattop. The magnet current needs to be proportional to the beam momentum over a wide dynamic range, from injection at 450 GeV/c to a top momentum of 7 TeV/c. During a collider run of e.g. 6h the beam extraction generators are continuously under a voltage of 30 kV.

Also here semiconductor solid state technology has been chosen for the power switches to assure a high level of reliability and availability and the absence of erratic firing. A fault tolerant re-trigger system will be installed that triggers all the switches in case of a spontaneous discharge in one of the generators.

Dilution system of extracted LHC beam (MKB)

Each extracted beam is diluted upstream the extraction tunnel by a set of orthogonally deflecting kicker magnets. They consist of four horizontally and six vertically deflecting systems. Each system includes a high voltage generator capable to power the corresponding magnet with an attenuated high current sine wave of over 25 kA amplitude at a frequency of about 14 kHz. The magnet current phase shift between the horizontally and vertically deflecting systems is 90 degrees. Each high voltage generator consists of a discharge capacitor and a semiconductor solid-state switch. After the extracted beam has been deflected by the diluter magnets it produces after 650 m at the end of the extraction tunnel an ♏-form like sweep with a radius of 35 cm on the front surface of the beam dump block. In this application the magnet current is also proportional to the beam momentum like for the MKD magnet.

Switch requirements

MKDH

The basic circuit diagram of the MKDH generator, the 12 kV switches (Swa and SWb) and the circuit diagram of the switch are shown in Fig. 1 and Fig. 2. Fig. 3 shows the installed switch in the MKDH generator and Fig. 4 shows the current waveform at 12 kV. The switch requirements are indicated in Table 1.

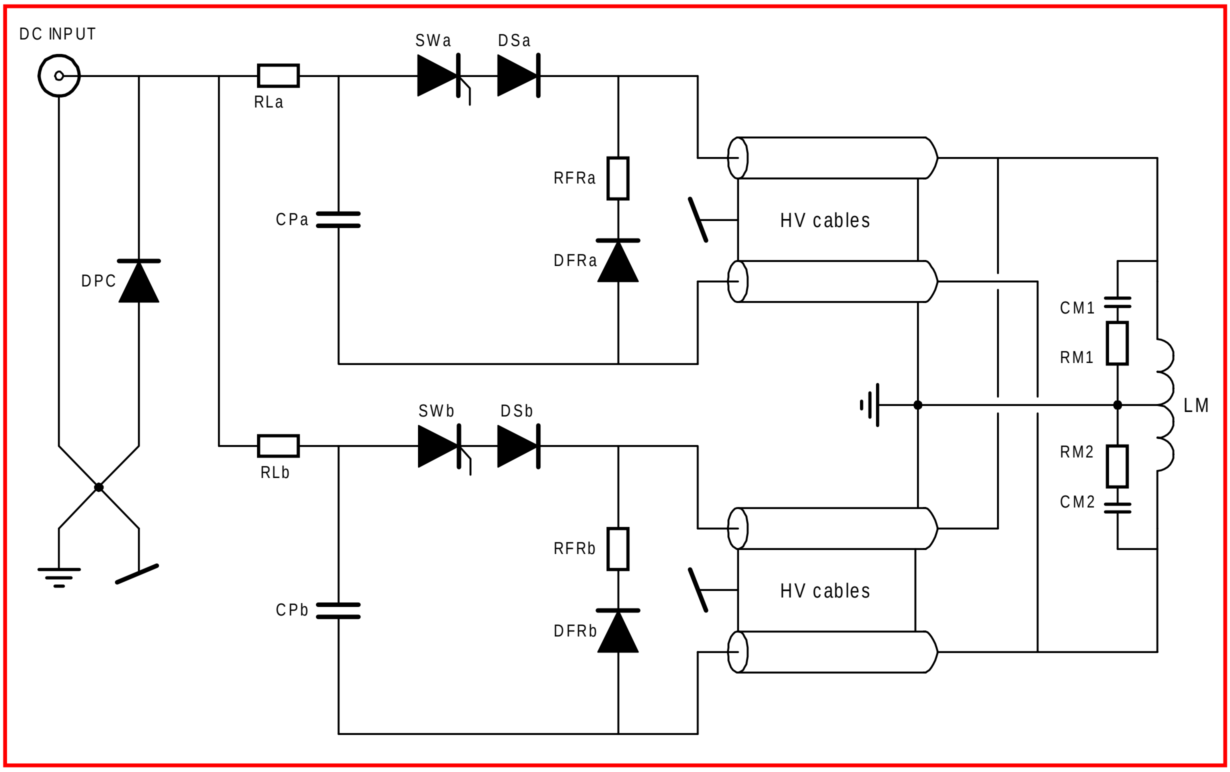

Fig. 1: Basic circuit diagram of MKDH generator

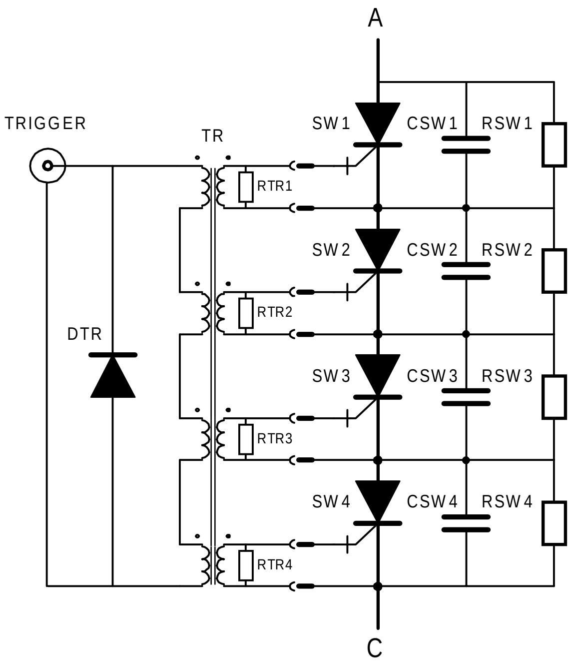

Fig. 2: Circuit diagram of MKDH switch

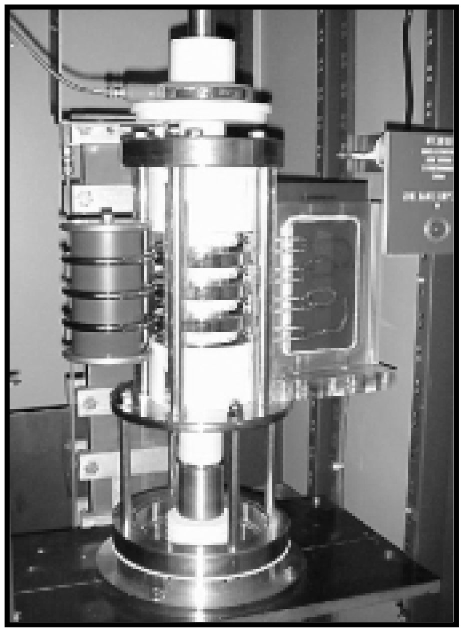

Fig. 3: Installed MKDH switch

D.C. operating voltage range	330-10000	V
Current amplitude	690-21000	A
Current rise/fall time	23/23	µs
Current max rate of rise/fall	2/1.5	kA/µs
Current pulse duration	46	µs
Charge transfer	780	mC
Max. switch conduction losses	82	J
Repetition time min. @ 12 kV	5	s
Repetition time typ. @ 10 kV	14	s
Total lifetime	2000000	pulses
Prefire rate	$< 10^{-4}$	

Table 1: MKDH switch requirements

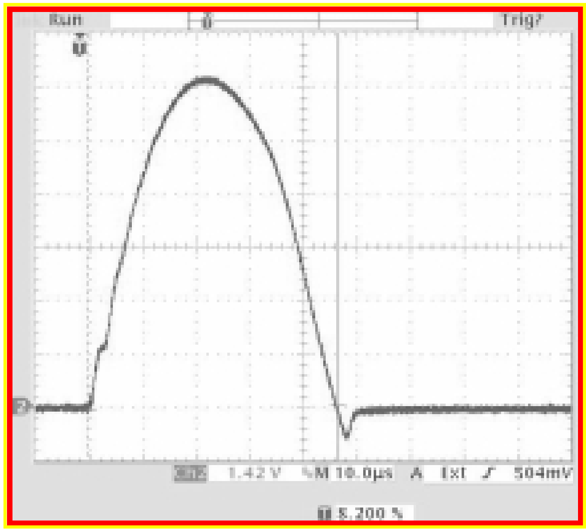

Fig. 4: MKDH switch current at 12 kV
(Hor. scale 10 µs/div., Vert. scale 4 kA/div.)

MKD

The basic circuit diagram of the LHC Beam Extraction generator is shown in Fig. 5. Four 30 kV switches for the LHC beam extraction system have been assembled. The switch is composed of ten asymmetric 4.5 kV thin wafer FHCT's. Anti-parallel diodes are not employed in the switch. In order to safely operate the FHCT's in series with a small spread in turn-on time, gate currents are employed with a high amplitude and high rate of rise. Measurements on the prototype 30 kV switch assembly showed a maximum spread in turn-on time of less than 50 ns. Protection of the FHCT's against over-voltages caused by differences in switching speed and turn-on delay, is realised by capacitors connected in parallel to the FHCT's. The value of these capacitors is kept to a minimum so that they not only protect against over-voltage but also improve the turn-on time by internal discharge over the FHCT's during turning on.

The circuit diagram of the switch is shown in Fig. 6. The measured current of the MKD switch and switch requirements are indicated in Fig. 7 and Table 2.

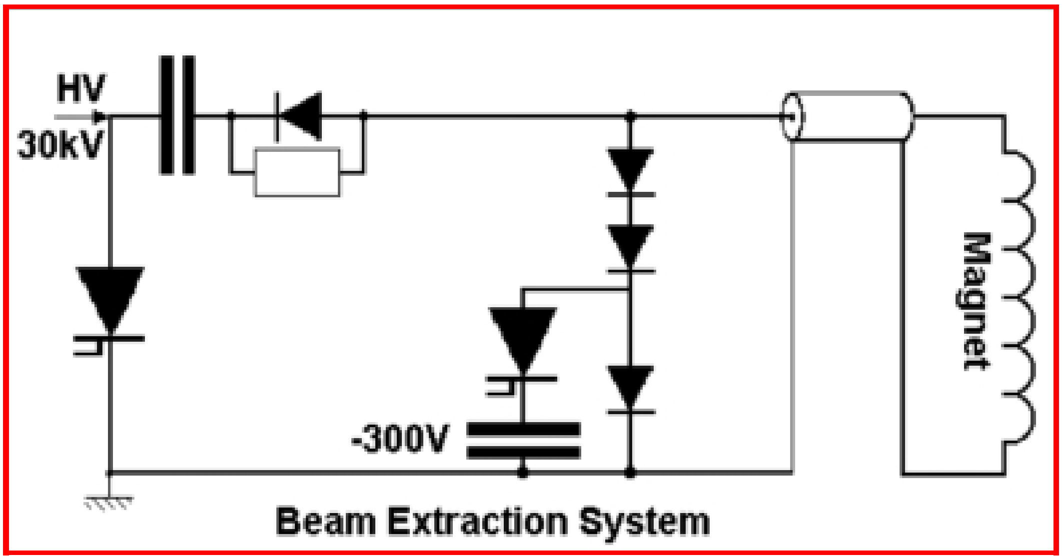

Fig. 5: Basic circuit diagram of MKD generator

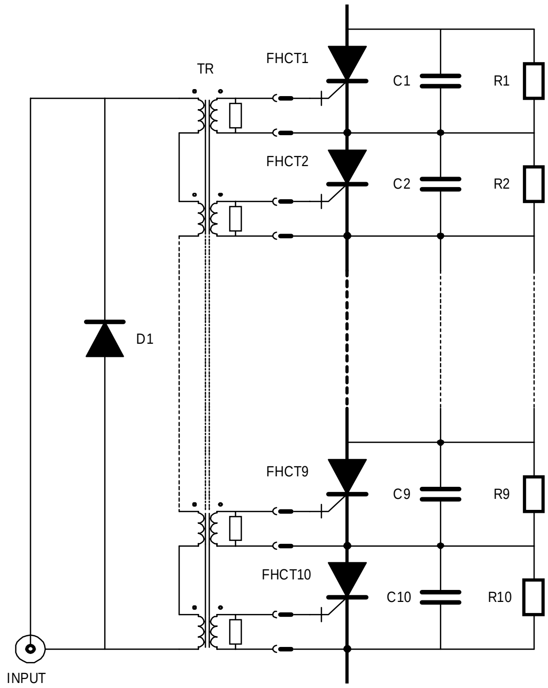

Fig. 6: Circuit diagram of MKD switch

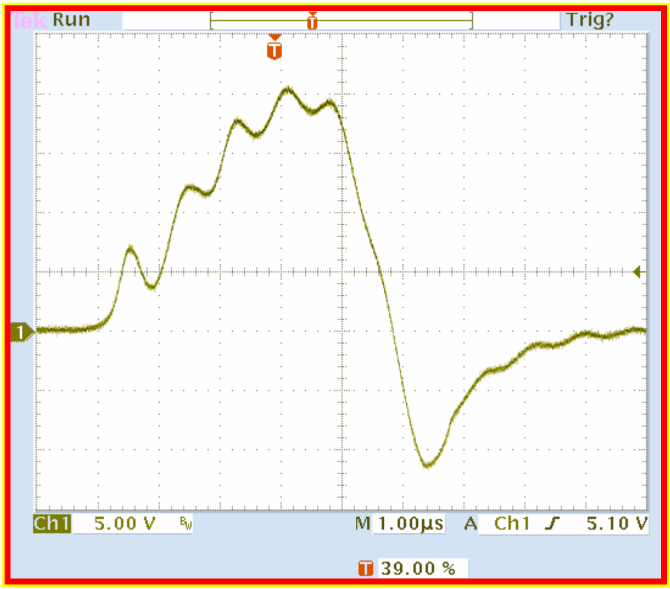

Fig. 7: MKD switch current at 30 kV
(Hor. scale 1 µs/div., Vert. scale 5 kA/div.)

D.C. voltage range	3-30	kV
Max current amplitude pos./neg.	+20/-10	kA
Current rise/fall time	2.75/1.5	µs
Max. current rate of rise/fall	15/20	kA/µs
Current pulse duration pos. + neg.	8	µs
Charge transfer pos./neg.	59/17	mC
Max. switch conduction losses	12	J
Repetition time min. @ 30 kV (test)	20	s
Repetition time typ. @ 30 kV	6	h
Total lifetime	500000	pulses
Prefire rate	$< 10^{-4}$	

Table 2: MKD switch requirements

MKB

The basic circuit diagrams of the LHC Beam Diluter generators are shown in Fig. 8. There are two type of diluter systems: horizontal and vertical. The switch for both systems is similar to the MKD switch. Measurements on a single asymmetric 4.5 kV device showed that in case of the horizontal diluter generator, a damped oscillating switch current of 30 kA, shown in Fig. 9 does not impose anti-parallel diodes for the reliability of the FHCT stack. The switch requirements are indicated in Table 3.

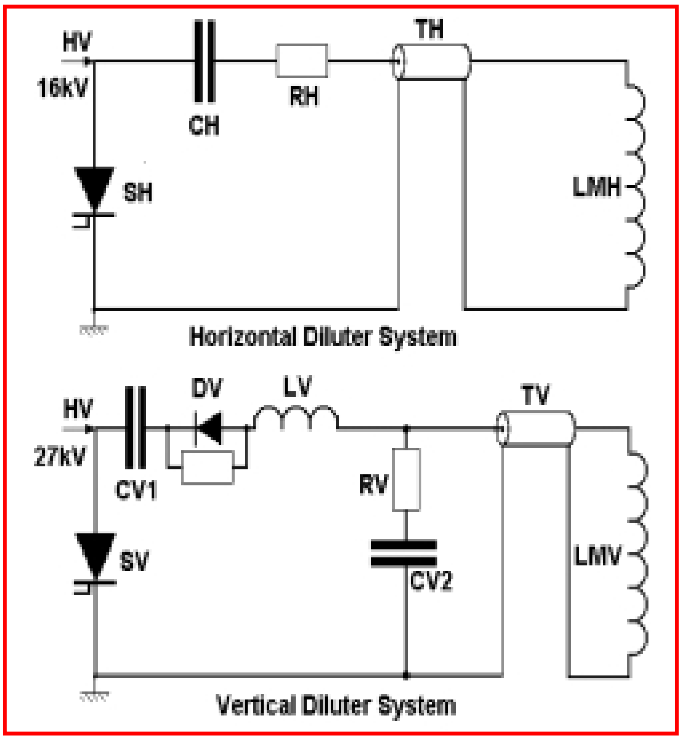

Fig. 8: Basic circuit diagram of MKB generators

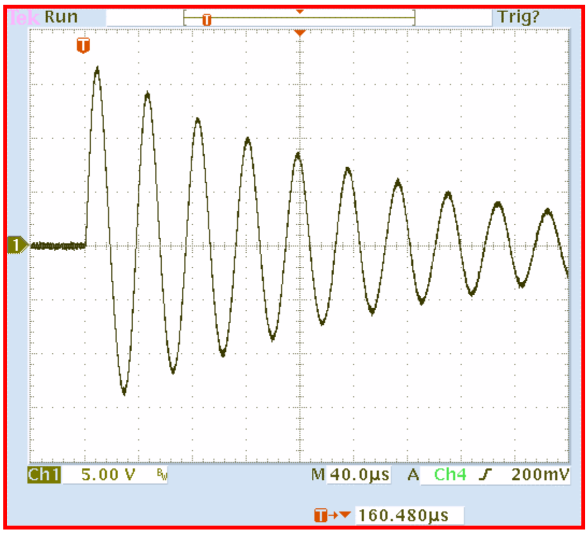

Fig. 9: MKBH test switch current (32 kA)
(Hor. scale 40 µs/div., Vert. scale 10 kA/div.)

D.C. voltage operating range	3-27	kV
Max current amplitude pos./neg.	+25/-22	kA
Current rise/fall time	18/18	µs
Max. current rate of rise/fall	4/4	kA/µs
Current pulse duration	500	µs
Charge transfer pos. + neg.	4.8	C
Max. switch conduction losses	608	J
Repetition time min. @ 30 kV (test)	20	s
Repetition time typ. @ 30 kV	6	h
Total lifetime	500000	pulses
Prefire rate	$< 10^{-4}$	

Table 3: MKB switch requirements

Conclusion

FHCT's with large junction sizes are capable of fast switching high currents. Elements of 4.5 kV can operate as closing switches with a di/dt of 20 kA/µs and peak currents of tens of kiloamps. The life time carrier control and the gate drive power supplies must be optimised for each application. Successful operation of a modular solid state switch has been demonstrated. The switches have been operated at room temperature and at relatively low repetition rates.

Due to the soft turn-on, noise levels are kept to a minimum. For high voltage applications, series connected FHCT's can probably in certain cases replace gas and vacuum switches. Parallel capacitor arrangement can accommodate mismatches in switching speeds of the FHCT's and ensure a satisfactory over-voltage protection during turn-on. The testing of solid state switches in the three applications will start later this year.

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