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The 12 kV, 50 kA Pulse Generator for the SPS MKDH Horizontal Beam Dump Kicker System, equipped with Semiconductor Switches

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Abstract

The high current pulses for the MKDH magnets are generated with capacitor discharge type generators which, combined with a resistive free-wheel diode circuit, deliver a critically damped half-sine current with a rise-time of 25 μs. Each generator consists of two 25 kA units, connected in parallel to a magnet via low inductance transmission lines. They are equipped with a stack of four Fast High Current Thyristors.

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1. Introduction

The Beam Dump kicker system for the SPS is composed of a series of vertical deflection magnets (MKDV), a series of horizontal deflection magnets (MKDH) and a set of absorber blocks (TIDV, TIDH). See ref. 1.

The high current pulses for the MKDH magnets are generated with classical capacitor discharge type generators which, combined with a resistive free-wheel diode circuit, deliver a critically damped half-sine current with a rise-time of 25 μs.

Each generator consists of two 25 kA units, connected in parallel to a magnet via low inductance transmission lines. The maximum operating voltage is 12 kV, the minimum pulse repetition rate is 5 s and the dissipated energy per switch is about 150 J per discharge at 12 kV.

Originally the pulse generators were equipped with ignitron switches. Unfortunately ignitron switches suffer sporadically from self-firing. In addition, these mercury filled devices present a serious danger of environmental pollution in case of an accident.

Since the development of new power semiconductor devices now offers a good alternative, replacement of the ignitron switches was decided. A suitable semiconductor switch was developed with the same dimensions as the ignitron and compatible with its trigger unit.

It consists of a stack of four modified Gate Turn Off (GTO) devices, which are optimised for high dI/dt turn-on, called Fast High Current Thyristor (FHCT), together with snubber capacitors, a voltage divider and a specially designed trigger transformer.

2. Basic Circuit Description

As is shown in fig. 1 , Capacitor C_p is charged to the required positive voltage with a regulated dc power converter U_{pc}, via resistor R_l.

The first phase of the magnet pulse starts at the moment switch Sw is closed and a current I_m starts to flow from capacitor C_p into the magnet L_m.
Due to the polarity of the free-wheel diode D_{fr}, during this phase no current can flow into the freewheel circuit D_{fr}, R_{fr}.

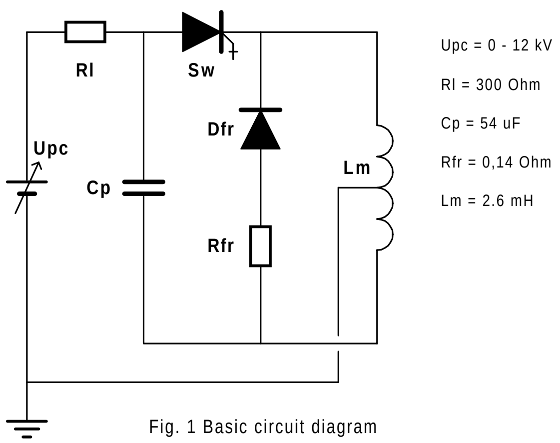

Fig. 1 Basic circuit diagram

The magnet current is a damped sine wave:

$$I_m(t) = \frac{e^{-\delta t}}{\sqrt{1-\xi^2}} \cdot \frac{U_0}{Z_0} \cdot \sin \omega t \text{, with } \delta = \frac{R_m}{2L_m},\ \xi = \frac{R_m}{2Z_0},\ Z_0 = \sqrt{\frac{L_m}{C_p}}$$

$$\omega \approx \omega_0 = \sqrt{\frac{1}{L_m C_p}} \quad \rightarrow \quad \text{The period time } \tau_0 \approx 105\ \mu\text{s.}$$

Operation of MKDH requires deflection of the beam only during the first quarter of the sine wave, thus at $\tau_0/4$ the factor $e^{-\delta t} \approx 0{,}995$ can be neglected.

The output current can therefore be damped after the first maximum when the magnet voltage U_m changes polarity and becomes negative.

The second phase starts at the moment the current from the capacitor into the magnet reaches its maximum and the magnet voltage U_m becomes negative. The free-wheel diode D_{fr} starts to conduct. The magnet current $I_m(t)$ then decays exponentially with a time constant: $t_d = \frac{L_m}{R}$, with $R = R_{fr} + R_m \approx R_{fr}$ (Ref. 5).

3. Generator Development

In order to limit the voltage the insulation of the magnet inductance has to withstand, a design with two symmetrical half-windings and a grounded centre connection has been chosen. See ref. 2. In order to limit transient over-voltages, mainly due to cable reflections, each half-winding is protected with a RC filter (R_m, C_m in fig. 2).

The excitation of such a magnet would normally require a bipolar pulse generator. However, due to economical reasons the pulse generator has been equipped with a grounded, unipolar dc power converter. Therefore, the storage capacitor is floating. See fig. 1.

A complication of such a circuit could be the fact that the charging current of the capacitor flows through one half of the magnet and its grounded centre connection. The parasitic magnet field thus generated could create problems for the particle beam in the SPS. However, the maximum output current of the power converter being only 0.5 A, the parasitic field can be neglected.

Originally the capacitor discharge units were equipped with water-cooled, high-density graphite anode, ignitrons, type National™ NL488A. This type of ignitron has a height of 50 cm, a diameter of 14 cm and a peak anode voltage of 25 kV.

As mentioned above, at the start of the second phase the voltage changes polarity and becomes negative. Because at that moment the ignitron has not yet completely recovered, the reverse magnet decay current flows partially through the switch, causing damage to the anode. Therefore, although the ignitron has a forward current capability considerably higher than required, the installed devices had a rather poor lifetime due to their limited reverse current capability.

As a first improvement around 1986 the generator was split into two separate identical units, allowing the switch in each unit to conduct only half of the reverse current. In addition, such a design presents an important improvement in the operational safety of the MKDH system. In case of failure of a unit the magnet current is reduced by 50% only.

In 1991 a further improvement was possible when high power diodes with the required ratings became available. Each switch was equipped with a series diode, thus blocking the reverse current entirely. The result of this modification was a doubling in lifetime of the ignitrons.

The latest modification in the design was the replacement of the ignitrons by high power semiconductor switches, described in detail in the next chapter. Of course, the absence of self-firing in semiconductor switches is another important improvement in operational safety.
Fig. 2, at the end of this note, shows the simplified circuit diagram of a double-unit generator. Safety devices and measurement facilities are not shown.

4. The semiconductor switch

4.1 The switch

Fast High Current Thyristors have been chosen as switching devices. They are an offspring of Gate Turn Off Thyristor developments. Application research has demonstrated that GTO devices, although originally developed for turn-off operation, are in addition well suited for fast turn-on. The highly interdigitated (resulting in fast current spread) devices, with a gate structure that supports very high switch-off currents, were found to be capable of fast turn-on with medium high gate current. Further optimisation for high di/dt turn-on resulted in the FHCT (See ref. 3, 4).

Because the required dc voltage holding level cannot be obtained with a single device, a stack of four asymmetrical FHCT's was mounted in series, thereby keeping the voltage per device well within the rated values. However, such a stack requires a trigger transformer with four separate outputs.

In order to reduce both stray inductances and radiation of electrical noise the stack is, as much as possible, constructed as a coaxial assembly.

The circuit diagram of the semiconductor switch is given in fig. 3 at the end of this note, showing the FHCT's with their snubber capacitors, a voltage sharing divider and the trigger transformer. A picture of a complete switch, with a second switch in the rear is given in fig. 6, also at the end of this note.

4.2 The trigger transformer

As mentioned in the introduction, the semiconductor switch was designed for operation with the existing ignitron trigger unit. The output pulse of the capacitor discharge unit has an amplitude of 2400 V peak, a rise time of better than 1.5 μs and a pulse width of approximately 50 μs.

In order to obtain a slightly higher di/dt on the secondary side than on the primary side (factor 1.25), the trigger transformer has a ratio of 5:1. The secondary windings of the transformer (400 V peak) are floating and the insulation voltage between primary and secondary windings is 20 kV.

Identical coupling between the primary side of the transformer and each floating secondary winding being required, the primary is divided into four separate windings, connected in parallel, with each primary winding coupled to one of the secondary windings.

A very important factor for the design of the trigger transformer is the conduction process of the FHCT's. The conduction is determined mainly by three parameters.

- The first and most important parameter is the dI/dt of the gate current. During tests, described in refs. 3 and 4, it was found that in this kind of application the dI/dt of the gate current has to be 160 A/µs minimum. This corresponds to a dI/dt at the primary side of the trigger transformer of 130 A/µs.
As mentioned above, the output voltage of the original trigger unit is 2400 V. Thus, for a gate current dI/dt of 130 A/µs minimum, the total inductance has to be smaller than 18.5 µH ($U = L\frac{dI}{dt}$).
The inductance of the 18 m long trigger cable being approximately 5 µH, the stray inductance of the trigger transformer for this parameter has to be smaller than 13.5 µH.

- The second parameter is the amplitude of the gate current. For this parameter the tests described in refs. 3 and 4 have shown that the optimum amplitude is approximately 180 A. This corresponds to a primary current amplitude of 150 A. Therefore, the impedance of the trigger circuit ($Z = \sqrt{R^2 + \frac{L}{C}}$), seen from the primary side of the transformer, shall be smaller than 16 Ω. The trigger unit has a current limiting resistor of 6.75 Ω and the total gate-cathode resistance of the four FHCT's, referred to the primary side, is approximately 0.35 Ω. Thus the total resistance in the trigger discharge circuit is 7.1 Ω.
Operation with the optimised transformer at minimum trigger energy allowed the reduction of the capacitor in the trigger unit from 470 nF to 100 nF while still generating a sufficiently high gate current. Thus, for this parameter the maximum allowable total stray inductance is 20 µH. As mentioned above, the cable inductance being approximately 5 µH, the maximum allowable stray inductance of the transformer for this parameter is 15 µH.

- The third parameter is the gate pulse duration. The conduction time of the switch is about 50 µs, during which the gate current has to remain greater than 50 A. Therefore a free-wheel diode is introduced on the primary side of the transformer. A time constant ($\tau = \frac{L}{R}$) of 25 µs for the free-wheel current proved to be sufficient. The total resistance in the free-wheel circuit being 0.4 Ω, for the third parameter the minimum allowable stray inductance of the transformer is 10 µH.

As a result of the above-explained considerations, the final value specified for the primary stray inductance of the transformer is 10 µH.

The final values for the most important parameters of the transformer are:

- V.t factor	- 30 mVs
- Primary voltage (peak)	- 2000 V
- Primary current (peak)	- 275 A
- Secondary voltage (peak, per winding)	- 400 V
- Secondary current (peak, per winding)	- 300 A
- Primary stray inductance	- ≤ 10 µH
- Primary-Secondary insulation voltage	- ≥ 20 kV

5. Circuit Simulations and measurement results

Circuit simulations for the MKDH generator have been done with PSpice ™. All stray inductances that could be measured or calculated were included in the simulated circuit.

Good agreement is obtained between circuit simulation and measurement results. In addition, both agree satisfactorily well with the circuit calculations.
The measurement results are shown in fig. 4 and 5, at the end of this note. As is mentioned, the measurements were made at 11 kV operation voltage.

6. Operational experience

Two switches operated successfully in the SPS for more than a year without any failure. Thereafter the remaining ignitrons were replaced during the 2000-2001 shutdown.

7. Acknowledgments

We wish to thank Jean-Louis Bretin who designed and tested the triggering for the new semiconductor switches.

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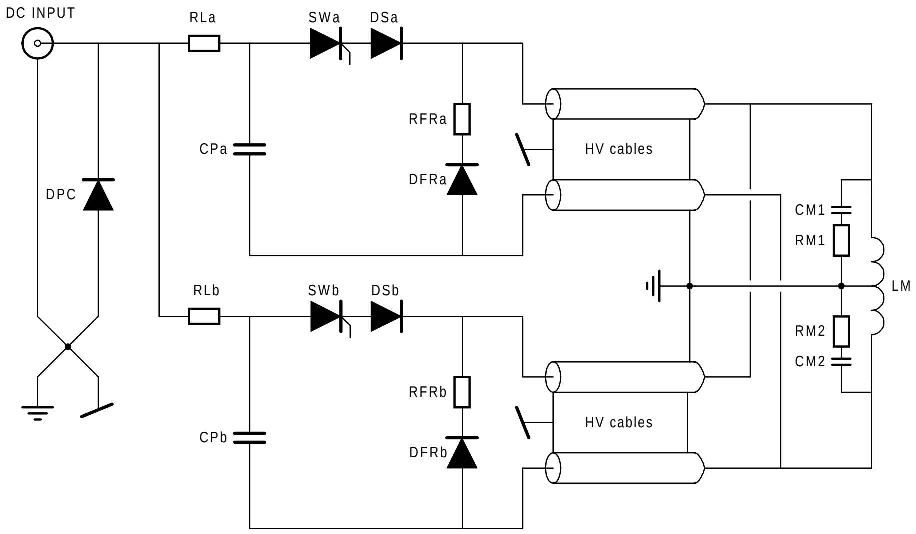
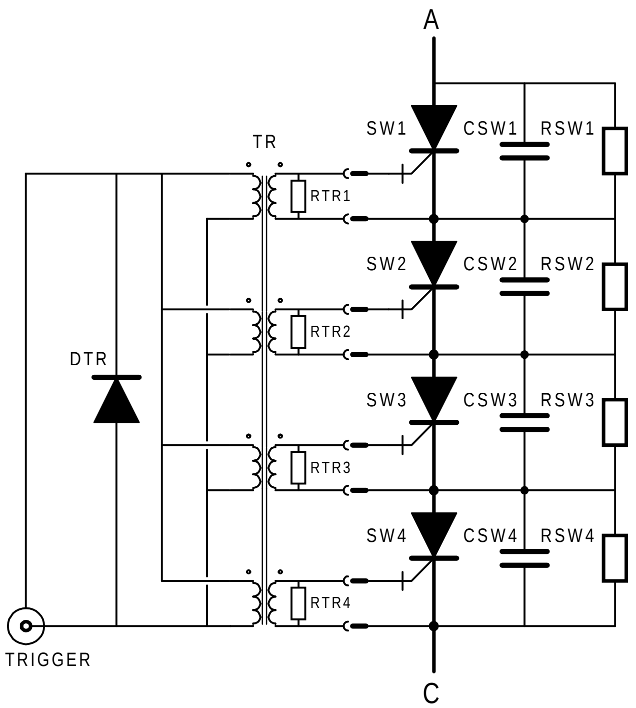


LEGEND:

DPC - UGE 5, 4x series
RL - 330 Ohm
CP - 54 uF / 17 kV
SW - See fig. 3
DS - See fig.3
RFR - 0.14 Ohm
DFR - DS2009SN40 6x series
LM - 2.61 uH
CM - 2 uF / 6 kV
RM - 10 Ohm

<u>Fig. 2 : Circuit Diagram - MKDH Pulse Generator Power Part</u>



LEGEND:

DTR - UGE 0421AY4
TR - SI-13441
RTR - 100 Ohm
SW - DG648BH45-185
CSW - 0,25 uF / 3,5 kV
RSW - 200 kOhm

<u>Fig. 3 : Circuit Diagram - MKDH Semiconductor Switch</u>

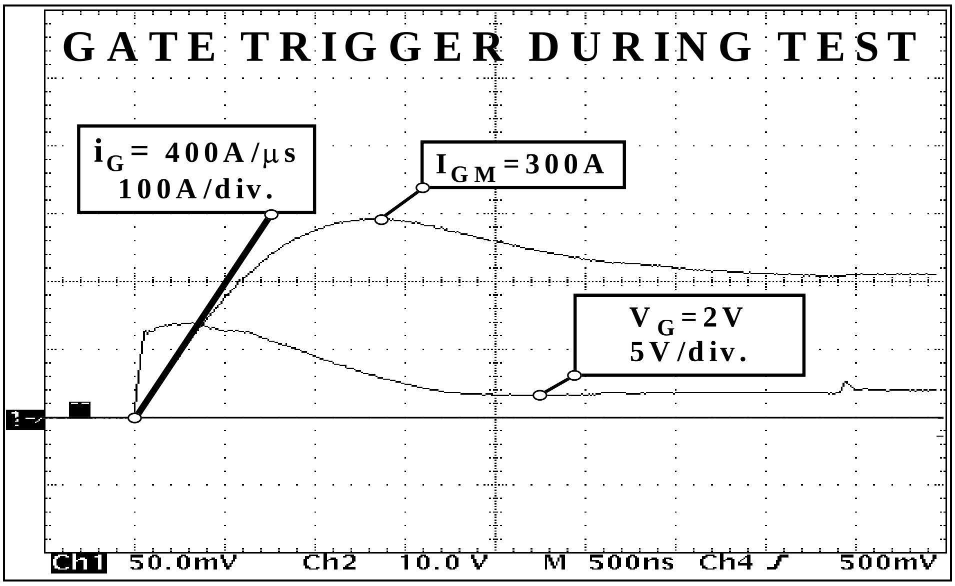


Fig. 4 Measured waveforms – Gate trigger

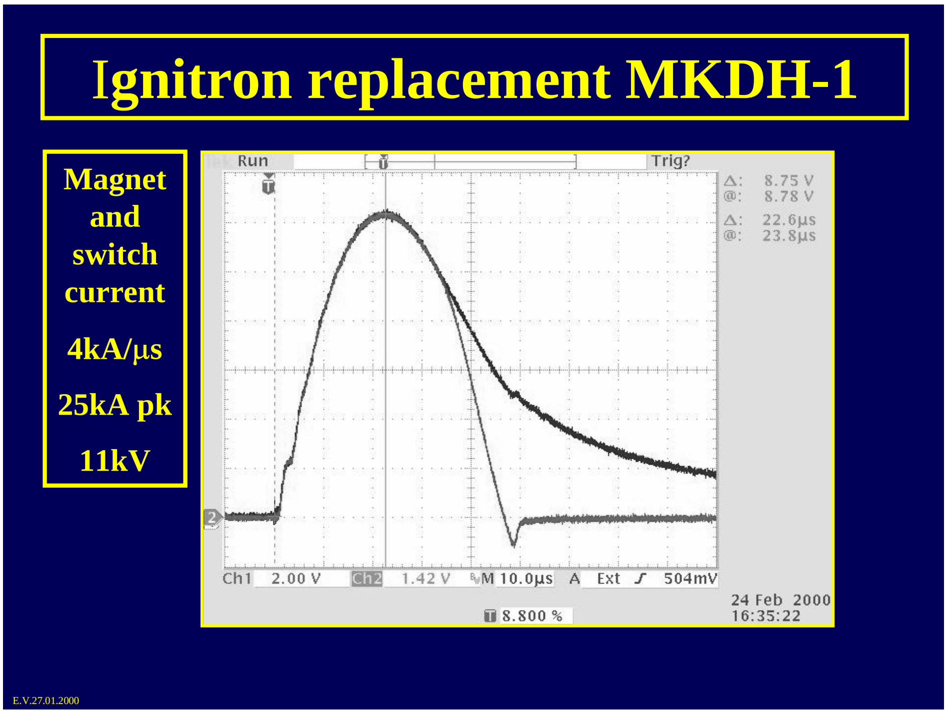


Fig. 5 Measured waveforms – Magnet and Switch Current

Fig. 6 The MKDH Semiconductor Switch