CM-P00061153

NIZATION FOR NUCLEAR RESEARCH

CERN - SL DIVISION

CERN-SL 93-34 BT

WS 335

9

CERN SL/93-34 (BT)

CERN AT/93-25 (DI)

LHC Note 236

HIGH-POWER GAS SWITCHES TRIGGERED BY FERROELECTRICALLY GENERATED ELECTRON BEAMS

P. Faure, H. Riege, K. Schmidt & G.H. Schröder
P. Benin & L. Courtois (1), J. Handerek (2)

Abstract

The triggering of low-pressure, hollow-cathode gas switches with electron beams generated by polarization switching of ferroelectric material was first demonstrated at CERN in 1989. This method is applied for the development of high-power switches which might be used for the pulse generators of the beam-dumping system of the CERN Large Hadron Collider (LHC). The sealed-off multi-gap switches have to commute 30 kA with very high reliability at any time during the accelerator operation in a range from 1.5 to 35 kV. The LHC application requires less than 10^4 pulses per year, but the spurious breakdown rates must be extremely low. The ferroelectric trigger emits a pulsed electron beam of 20 A current amplitude (60 A/cm^2) and 200 ns length by polarization switching with HV pulses of 1-2 kV amplitude. Experimental results of measurements on trigger efficiency, on erratic breakdown rates, on electrode erosion and metal-vapour deposition, on main insulator deterioration, and on the influence of electrode geometry on current quenching have been obtained with several prototype switches. Improvements of the switches for the LHC beam dump and for other future applications are suggested.

*Invited Talk at the 9th IEEE International Pulsed Power Conference,
Albuquerque NM, USA, June 21-23, 1993*

- 1) Thomson/CSF, Bagneux, France
- 2) Institute of Physics, University of Silesia, Katowice, Poland

Geneva, Switzerland
17 August, 1993

HIGH-POWER GAS SWITCHES TRIGGERED BY FERROELECTRICALLY GENERATED ELECTRON BEAMS

P. Faure, H. Riege, K. Schmidt and G.H. Schröder
CERN AT & SL Divisions, CH-1211 Geneva 23, Switzerland

J. Handerek
Inst. of Phys., University of Silesia, P-40007 Katowice, Poland

P. Benin and L. Courtois
Thomson/CSF, F-92223 Bagneux CEDEX, France

Abstract

The triggering of low-pressure, hollow-cathode gas switches with electron beams generated by polarization switching of ferroelectric material was first demonstrated at CERN in 1989. This method is applied for the development of high-power switches which might be used for the pulse generators of the beam-dumping system of the CERN Large Hadron Collider (LHC). The sealed-off multi-gap switches have to commute 30 kA with very high reliability at any time during the accelerator operation in a range from 1.5 to 35 kV. The LHC application requires less than 10^4 pulses per year, but the spurious breakdown rates must be extremely low. The ferroelectric trigger emits a pulsed electron beam of 20 A current amplitude (60 A/cm^2) and 200 ns length by polarization switching with HV pulses of 1–2 kV amplitude. Experimental results of measurements on trigger efficiency, on erratic breakdown rates, on electrode erosion and metal-vapour deposition, on main insulator deterioration, and on the influence of electrode geometry on current quenching have been obtained with several prototype switches. Improvements of the switches for the LHC beam dump and for other future applications are suggested.

1. INTRODUCTION

The pseudospark – an electrical breakdown phenomenon in low-pressure gas on the left-hand branch of the Paschen curve – was discovered in 1977 by Christiansen and Schultheiss [1]. The first prototype switch based on the pseudospark discharge was built and successfully operated at CERN in 1981 [2,3]. The pseudospark switch was triggered with the tiny spark of a low-power surface discharge across an insulating surface. In 1987 strong electron emission from ferroelectrics without extraction potential was discovered when switching an appreciable amount of the spontaneous polarization P_s by means of high-voltage pulses of several kV amplitude and submicrosecond pulse widths [4, 5]. The first application of this field-excited electron emission (FEEE) from ferroelectrics was the generation of strong pulsed electron beams for triggering pseudospark discharges with nanosecond precision [6]. In 1989 development of high-power pseudospark switches (PSS) started at CERN with the purpose of commuting the future pulse generators of the CERN LHC beam-dumping system with high reliability. Pseudospark-like structure and ferroelectric-trigger electron-beam generation

have both been implemented into the design of the prototype switches [7–9]. The results obtained in the development period of this specific application and which are reported in this paper may have consequences also for other switching applications.

2. GOALS AND SPECIFICATIONS

The LHC is a 7 TeV superconducting hadron collider with two beams circulating in opposite directions, each having a stored energy of up to 550 MJ. In order to dispose of the high amount of stored energy in case of a failure or after several hours of normal LHC operation, the beam-dumping system [10,11] must, at any time and at beam energies ranging from 450 GeV to 7 TeV, very reliably extract both beams from the collider orbits and direct them in a controlled way onto beam absorber blocks. Between controlled abort operations the beam-dumping system must stay absolutely reliably in the ready-to-abort state without any erratic switching, otherwise it would cause severe damage to the accelerator components. The major part of the safety and reliability functions of the beam-dumping system has to be carried by the 50 high-power switches [8] of the pulse generators which feed the extraction kicker magnets. Each switch has to hold a voltage of 35 kV and commute currents of 30 kA with a half sinewave pulse of 6 μs base-line width. Very low erratic breakdown rates of the order of one per 20 years have to be guaranteed. The pseudospark structure of the switch favours low erratic breakdown rates since neither hot cathodes nor continuous auxiliary discharges are used in the main discharge volume, as is done in thyatron-type switches. The switching has to be triggered with a jitter of less than 30 ns in an operating range of anode voltage from 1.5 to 35 kV. Also the ferroelectric (FE) trigger cathode, though cold, operates efficiently without the need for heating or for auxiliary discharges. The FE emitter disk is subject to a small extraction potential of 300 V and placed inside the hollow cathode. When it is excited by a low-power HV pulse, it ejects an intense electron beam into the axial or annular holes of the main electrodes. The LHC beam-dumping pulse generator has a capacitor discharge circuit with a free-wheel loop [11]. During normal operation the LHC beam is dumped approximately two or three times per day. The required lifetime is more than 10 years corresponding to about 10^5 pulses per switch.

3. RESULTS AND PROGRESS

As proposed in Ref. [8] a two-gap PSS prototype version was designed, built and tested at 35 kV anode voltage and 48 kA discharge current (Fig. 1). Each gap has its own FE trigger system, but both gaps share a common gas volume. The two-gap PSS can also work with one single FE trigger

Figure 1. Basic design of a two-gap PSS with two FE triggers.

system, but with a less precise synchronization between the breakdowns of both gaps and a reduced trigger efficiency which results in a smaller working range of the switch. Figure 2 shows the not perfectly synchronized waveforms of anode voltage (top) and voltage on the intermediate electrode (bottom). For a short time the intermediate voltage almost reaches the anode potential when the lower gap fires too early. This can be avoided by well synchronizing the electron-beam emission from both FE cathodes as shown in Fig. 3. Though the two FE emitters were made of different material and differed in emission strength, the breakdown of both gaps could be initiated at the desired moment with a jitter of about 10 ns. The FE emission-current density excited by switching a typical trigger disk of 16 mm diameter, 0.3 mm thickness with an annular grid of 40 mm² bare FE surface is of the order of 20–70 A/cm². The presence of a low-pressure gas (50 Pa) atmosphere and of an auxiliary bias potential between the FE

cathode and the bias electrode causes amplification of the total emission current beyond an amplitude of 100 A. With such powerful electron beams, nanosecond switching precision and a dynamic range of switchable anode voltage from 200 V to 40 kV were obtained. The FE material of the trigger cathodes was zirconium-rich PLZT (lead-lanthanum-zirconium-titanate) ceramics. Amongst the heavily charged components of the PSS the FE trigger cathodes appeared to be the most reliable ones. During several life tests not a single missing trigger pulse was observed.

Figure 2. Voltage wave forms of the anode and of the intermediate electrode with the not exactly synchronized triggers of a two-gap PSS.

Figure 3. Synchronized electron-beam current wave forms of two differing FE cathodes in a two-gap PSS.

Progress was achieved also by changing from the classical pseudospark design, characterized by axial electrode holes of 4 mm diameter, to electrodes with annular holes of 2.5 mm width (Fig. 4). While maintaining a high anode voltage holdoff capability, the annular holes lead to a reduction of

current density by one order of magnitude for the same current. Though the voltage during the discharge phase and the internal ohmic resistance of the PSS are higher than with axial electrode holes, a net decrease of electrode erosion was observed. Furthermore, quenching was shifted to a voltage level around 800 V, hence out of the operating range of the switch [8]. A long-term test of a one-gap PSS with pure tungsten ring electrodes and central pieces of tungsten with 5% rhenium (Fig. 4) was carried out over 511 hours with 22 000 pulses of 1.4 kJ pulse energy. Afterwards the PSS was still working well. About 100 erratic breakdowns were observed during this test, but there was not a single missing triggered discharge.

Figure 4. Section of PSS hollow electrodes with annular holes.

Switching of pulse energies in the kJ range at impedance levels below $100\text{ m}\Omega$ and current densities above 10^4 A/cm^2 inevitably causes degradation of electrodes and insulators after a finite number of shots. In order to limit the damage the most robust electrode material has to be used. Central electrode parts made of stainless steel or graphite, or pure or thoriated tungsten were inserted in different PSS prototypes and tested for several ten thousand shots at nominal voltage and current. Up to now minimum erosion was obtained with tungsten-rhenium alloys. As the metal plasma formation is part of the discharge in the high-density regime, care must be taken even with the best electrode material to force the metal vapour to precipitate at places where it only negligibly deteriorates the PSS performance. The vapour deposition is strongly influenced by the temperature distribution inside the PSS after a switching action. Precipitation has to be limited on the electrode parts of the central main gap region as well as on the main insulator walls. The insulators are protected with large chicanes which favour the plasma dilution and which should preferably be water-cooled to act as traps for the metal vapour.

All previous PSS prototype switches have been tested in an open gas circuit with continuous pumping and injection of fresh filling gas. For the final pulse generators of the LHC beam-abort system this technique is not acceptable. CERN

and Thomson/CSF designed together a new prototype (Fig. 5) which was built by Thomson and tested at CERN. In this PSS the flanges are brazed to the main ceramic insulator and a gas reservoir filled with deuterium is incorporated into the discharge volume. The first short tests at nominal voltage and current have been successfully carried out, long-term tests are planned for the near future.

Figure 5. View of a sealed-off CERN-Thomson/CSF prototype switch.

4. MAIN R&D PROBLEMS

Though the development of the PSS for the LHC beam-abort system has made good progress, the very stringent safety requirements imposed by the design of the LHC beam-dumping system have not yet been fully satisfied. Further reduction of the erratic rate is of major importance. We have indications that the contamination of the main insulator with metal vapour is not a major problem within the required lifetime of 10^5 pulses of the PSS. The erratic breakdown rates have been measured in an accelerated test procedure simulating the real LHC beam-abort operating conditions: during daytime the PSS was switched every 20 to 30 seconds, whereas during nights and weekends the PSS was subjected to the nominal d.c. voltage without any switching. From the start of the tests the prefiring rate was decreased by pulse discharge conditioning of the PSS. Later on, erratic breakdowns mainly occurred immediately after some change in the test procedure, e.g. after starting the switching phase or after a major pressure change inside the PSS. During long periods under d.c. voltage the erratics rate virtually decreased to zero. This points to irregularities of charging and relaxation processes on insulators and electrodes as reasons for the remaining erratic breakdown rate. It is foreseen to decrease the electric field strength in the PSS by increasing the number of principal

discharge gaps up to three. This should considerably decrease the erratic breakdown rate. It is of prime importance to keep absolute cleanliness during mounting of the PSS and to bake it out before starting operation. The electrode material has to be homogeneous and free from oxidic or other dielectric inclusions. It is imperative to degas the electrodes at temperatures above 1000°C. The geometrical layout of the central electrode parts influences the metal-vapour deposition inside the electrode holes and inside the hollow cathode. The long-term behaviour of the gas composition in the PSS and of the reservoir and their influence on erratic breakdown will be investigated in a long-term test.

The LHC application is characterized by a very low average switched power. Since Thomson/CSF intend to use a similar PSS for high-repetition-rate application, the average power dissipation in the PSS circuit becomes an important issue. Electrode cooling, which in the LHC beam-dump application enhances metal-vapour condensation, is foreseen to reduce the average operating temperature in the high-repetition-rate case. The ferroelectric trigger cathode should not be a limitation, since it has been operated in burst mode with a high-current excitation pulse generator at repetition rates up to 2 MHz [5].

5. CONCLUSIONS AND OUTLOOK

The implementation of a two-gap version and the mastering of the related synchronization problems was a major progress in the PSS development for the LHC beam-dumping generator. Electrodes with annular holes eliminated quenching problems and reduced erosion rates.

Use of tungsten rhenium alloys further reduced erosion and erratic breakdown rates. The first tests of a sealed-off version with a gas reservoir have been successfully completed. The results of the R&D carried out up to now are encouraging and the objectives for the LHC beam dump and the high-repetition-rate applications will probably be met in the near future. Other applications of PSS, even if quite different from the specialized case of the LHC beam-dumping pulse generator, should benefit from the development reported in this paper. The reliable, easy and efficient electron-beam generation with FE cathodes may be used for triggering new plasma or low-pressure gas, high-power pulsed PSS or other devices. The combination of pseudospark technology with ferroelectric electron emission seems to be a significant step forward in pulsed-power application.

ACKNOWLEDGEMENTS

We would like to thank our colleagues J.L. Bretin, R. Chappuis, L. Ducimetière, J. Janton, J.P. Pianfetti and G. Vossenberg for their help at various stages in the development programmes.

REFERENCES

- [1] J. Christiansen and C. Schultheiss, "Production of High-Current Particle Beams by Low-Pressure Spark Discharges", *Z. Phys.*, vol. A 290, p. 35, 1979.
- [2] D. Bloess, I. Kamber, H. Riege, G. Bittner, V. Brückner, J. Christiansen, K. Frank, W. Hartmann, N. Lieser, C. Schultheiss, R. Seeböck and W. Steudtner, "The Triggered Pseudospark Chamber as a Fast Switch and as a High-Intensity Beam Source", *Nucl. Instrum. Methods*, vol. 205, p. 173, 1983.
- [3] P. Billault, H. Riege, E. Boggasch, K. Frank and R. Seeböck, *Pseudospark Switches*. Geneva: CERN, Report CERN 87-13, 1987.
- [4] H. Gundel, H. Riege, E.J.N. Wilson and J. Handerek, "Copious Electron Emission from PLZT Ceramics with a High Zirconium Concentration", *Ferroelectrics*, vol. 100, p. 1, 1989.
- [5] H. Gundel, J. Handerek and H. Riege, "Time-Dependent Electron Emission from Ferroelectrics by External Pulsed Electric Fields", *J. Appl. Phys.*, vol. 69, p. 975, 1991.
- [6] H. Gundel, H. Riege, J. Handerek and K. Zioutas, "Low-Pressure Hollow Cathode Switch Triggered by a Pulsed Electron Beam Emitted from Ferroelectrics", *Appl. Phys. Lett.*, vol. 54, p. 2071, 1989.
- [7] H. Riege, "New Ways of Electron Emission for Power Switching and Electron Beam Generation", in *Physics and Applications of Pseudosparks*, eds. M.A. Gundersen and G. Schäfer. Plenum Press, 1990, p. 349.
- [8] L. Courtois, P. Faure, J. Handerek, H. Riege and G. Schröder, "Development of High Power Switches for the LHC Beam Dumping Pulser", in *Proc. Third European Particle Accelerator Conf.*, Berlin, 1992. Ed. Frontières, 1992, p. 1597.
- [9] D. Boimond, F. Dothan, K. Geissler, J. Handerek, J. Kuipers, A. Meineke, H. Riege and G. Schröder, "High-Current Electron and Ion Sources Based on Ferroelectrics Switching", *Int. J. Mod. Phys. A*, Proc. Suppl., vol. 2a, p. 185, 1993.
- [10] A. Ferrari, G.R. Stevenson and E. Weisse, "Design of the LHC Beam Dump", in *Proc. Third European Particle Accelerator Conf.*, Berlin, 1992. Ed. Frontières, 1992, p. 1545.
- [11] G.H. Schröder and E.B. Vossenberg, "A Prototype High-Power Pulse Generator for the Beam Abort System of CERN's Proposed 16 TeV Collider LHC", in *Proc. 19th Pulse Power Modulator Symposium*, San Diego, 1990, p. 104.