EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
CERN – ACCELERATORS AND TECHNOLOGY SECTOR

CERN-ATS-2012-220

A 12 kV, 1 kHz, Pulse Generator for Breakdown Studies of Samples for CLIC RF Accelerating Structures

R. H. Soares, M.J. Barnes, J. Kovermann, S. Calatroni, W. Wuensch, CERN, Geneva, Switzerland

Abstract

Compact Linear Collider (CLIC) RF structures must be capable of sustaining high surface electric fields, in excess of 200 MV/m, with a breakdown (BD) rate below 3×10^{-7} breakdowns/pulse/m. Achieving such a low rate requires a detailed understanding of all the steps involved in the mechanism of breakdown. One of the fundamental studies is to investigate the statistical characteristics of the BD rate phenomenon at very low values to understand the origin of an observed dependency of the surface electric field raised to the power of 30. To acquire sufficient BD data, in a reasonable period of time, a high repetition rate pulse generator is required for an existing d.c. spark system at CERN. Following BD of the material sample the pulse generator must deliver a current pulse of several 10's of Amperes for ~2 µs. A high repetition rate pulse generator has been designed, built and tested; this utilizes pulse forming line technology and employs MOSFET switches. This paper describes the design of the pulse generator and presents measurement results.

Presented at the 3rd International Particle Accelerator Conference (IPAC 2012),
20-25 May 2012, New Orleans, Louisiana, USA

Geneva, Switzerland,
July, 2012

A 12 KV, 1 KHZ, PULSE GENERATOR FOR BREAKDOWN STUDIES OF SAMPLES FOR CLIC RF ACCELERATING STRUCTURES

R. H. Soares, M.J. Barnes, J. Kovermann, S. Calatroni, W. Wuensch, CERN, Geneva, Switzerland

Abstract

Compact Linear Collider (CLIC) RF structures must be capable of sustaining high surface electric fields, in excess of 200 MV/m, with a breakdown (BD) rate below 3×10^{-7} breakdowns/pulse/m. Achieving such a low rate requires a detailed understanding of all the steps involved in the mechanism of breakdown. One of the fundamental studies is to investigate the statistical characteristics of the BD rate phenomenon at very low values to understand the origin of an observed dependency of the surface electric field raised to the power of 30. To acquire sufficient BD data, in a reasonable period of time, a high repetition rate pulse generator is required for an existing d.c. spark system at CERN. Following BD of the material sample the pulse generator must deliver a current pulse of several 10's of Amperes for ~2 µs. A high repetition rate pulse generator has been designed, built and tested; this utilizes pulse forming line technology and employs MOSFET switches. This paper describes the design of the pulse generator and presents measurement results.

INTRODUCTION

CLIC is a 50 km long accelerator for electron-positron collisions under study at the European Laboratory for Particle Physics (CERN), by an international collaboration. One of the issues concerning CLIC's feasibility is the capability of the Radio Frequency (RF) structures to sustain high surface electric fields: a field superior to 200 MV/m, with a breakdown (BD) rate below 3×10^{-7} breakdowns/pulse/m is required [1]. To investigate BD rate phenomena for different materials, a d.c. spark system, which creates similar surface electric field as in a RF structure, was designed and built at CERN [2]. Historically a relay was used to apply and remove high voltage to the sample in the d.c. spark system: however the switching rate of the relay was limited to a few Hertz repetition rate. To acquire sufficient BD data, in a reasonable period of time, a high repetition rate system was required to replace the relay.

PULSE POWER SYSTEM DESIGN

Requirements

A voltage pulse of up to 12 kV is required to be applied to the sample in the d.c. spark system. From the point of view of the pulse power system required, the electric field on the surface of the material sample under test either will or will not cause BD. Table 1 summarizes the main requirements for the system: if the sample does not BD, the pulse is applied at a repetition rate of 1 kHz. The stored energy should be more than 1 J so that, when the sample does BD, the pulse power system can deliver a "rectangular" current pulse of several 10's of Amps and 2 µs duration. Under BD conditions it is permissible to limit the repletion rate to a maximum of 1 Hz.

Table 1: Pulse Power System Specifications

Sample	Specification		Units
Does not breakdown	Voltage	≤ 12	kV
	Rise time	≤ 100	ns
	Frequency	1,000	Hz
Does breakdown	Current	10's	A
	Repetition rate	≤ 1	Hz
	Pulse shape	Rectangular	
	Pulse duration	~2	µs

General layout

The applied voltage pulse, of up to 12 kV, should have a rise time of less than 100 ns. A BD of the sample under test is a phenomenon with an ignition time typically of tens of nanoseconds [3]. To meet the specifications for a pulse power system capable of running reliably, long-term, at up to 1 kHz with fast voltage and current rise times, MOSFET switch technology was chosen. In addition, to achieve a rectangular current pulse, a Pulse Forming Line (PFL) was selected for the energy storage system.

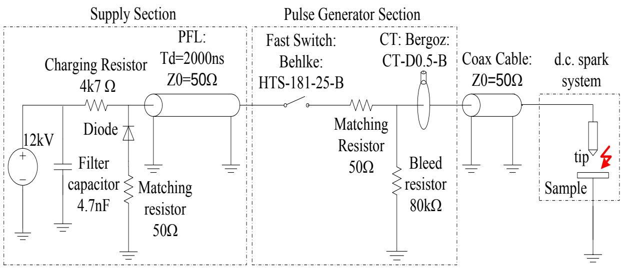

Figure 1: Simplified schematic of pulse power system and d.c. spark system.

A simplified schematic of the high repetition rate pulse power system is shown in Fig. 1. To make use of commercially available components, such as coaxial cables and feedthroughs, a characteristic impedance of 50 Ω was chosen for the system. The system consists of the following main components: a 12.5 kV commercial capacitor charging power supply, a filter capacitor, a charging resistor, a stack of inverse diodes and a matching resistor, a 50 Ω PFL, a fast MOSFET switch, another matching resistor, a bleed resistor, a current transformer and a 3Y430 lemo socket. The d.c. spark system is connected to the pulse power system via a HV coaxial cable and a coaxial feedthrough.

The power supply is positive polarity; hence the drain side of the MOSFET switch is connected to the PFL. Both the PFL and the coaxial cable between the output of the pulse generator and the d.c. spark system are HTC-50-7-2, rated at 18 kV d.c.: this cable has a capacitance of 100 pF/m and a delay of 5 ns/m.

In order that the pulse generator can operate at 1 kHz, with 12 kV across the load, when the sample does not BD, the effective capacitance on the d.c. spark system (load) side of the MOSFET switch must be kept to a reasonable minimum. Hence the system is divided into two parts: a pulse generator section and a supply section (Fig. 1). The pulse generator section is designed to be physically as close as possible to the d.c. spark system – to minimize cable length between the MOSFET switch and the sample under test.

The system has been designed to drive a total effective capacitance of up to 300 pF at 1 kHz: this requires an average power of ~22 W, the majority of which are switching losses in the MOSFET switch.

d.c. spark system

The d.c. spark system has a sample holder and a tip, inside a vacuum chamber (Fig. 1). The sample holder is connected to the metal vacuum chamber while the tip is connected to the pulse generator via a coaxial, 50 Ω, vacuum feedthrough (SHV-20). The same feedthrough also connects the outer of the coaxial cable to the vacuum chamber body. Fig. 2 shows a photograph of the d.c. spark system, pulse generator and controls.

Pulse generator section

A Behlke HTS-180-25-B MOSFET switch [4] has been chosen for the high power switch of the pulse generator. The HTS-180-25-B is a fast switch rated at 18 kV d.c. and 250 A pulse current, for a case temperature of less than 25˚C, pulse width less than 100 µs and a duty cycle less than 1 % [4]. The MOSFET switch is operated at below 70 % of its voltage specification, a reasonable value for reliable long-term operation. The HTS-180-25-B has a specified typical current rise time of 42 ns when operating at 80 % of rated voltage and 100 % of rated pulse current. In addition the HTS-180-25-B is capable of operating at frequencies up to 1.8 kHz. However the power rating of the HTS-180-25-B, for a standard plastic case held at 25˚C, is only 33 W. Since it would be difficult to maintain a case temperature of 25˚C, it was required to improve cooling of the switch without adding fins or a grounded cooling flange: these would increase the parasitic capacitance of the switch. Thus, instead, a ceramic cooling surface option was chosen.

Following a BD of the sample under test, a current of several 10's of Amperes is required for ~2 µs. The HTS-180-25-B datasheet specifies a typical, static, on-resistance of 1.5 Ω and 3.7 Ω at 25 A and 250 A, respectively. In order to ensure a reasonably flat current pulse, and to limit the resulting current in the HTS-180-25-B to well below 250 A, the source side of the MOSFET switch has a 50 Ω matching resistor. A low inductance, 47 Ω, HVR 701 rod tube resistor was readily available and was thus used: this resistor is capable of handling 90 W [5]. The switch current, following BD of the sample, is ~120 A for a PFL pre-charge of 12 kV.

In the event that the sample under tests does not BD, when voltage is applied, it is required that the sample voltage is reduced to below 1 % of the applied pulse voltage, to stop any field emission of the sample, prior to reapplying the next voltage pulse. For example, if the sample does not BD when 12 kV is applied to it, the sample voltage must be reduced to 120 V or less prior to reapplying 12 kV, 1 ms later.

A single HTS-180-25-B MOSFET switch was chosen rather than two MOSFET switches operating in push-pull. A push-pull arrangement would allow a fast fall time, which is not required, but the effective load capacitance would increase due to the drain-source capacitance of the second switch. Instead a bleed resistor (Fig. 1) was chosen to discharge the effective load capacitance.

To achieve the repetition rate of 1 kHz, the bleed resistor must dissipate the majority of the energy stored in the effective load capacitance, in a time less than 1 ms: the time-constant should be less than ~200 µs. A resistance of 80 kΩ was chosen as it gives a time-constant for discharging 300 pF of only ~24 µs. In addition, the specified leakage current of 50 µA for the HTS-180-25-B, at 75˚C case and 80 % of rated voltage, results in a voltage drop of 4 V across 80 kΩ, well within the specification of 1 % of the pulse voltage. Due to their availability, two CGS HVR 50 were used in series (yellow rods in Fig. 2): each CGS 50 is rated at 25 W at 75˚C [6].

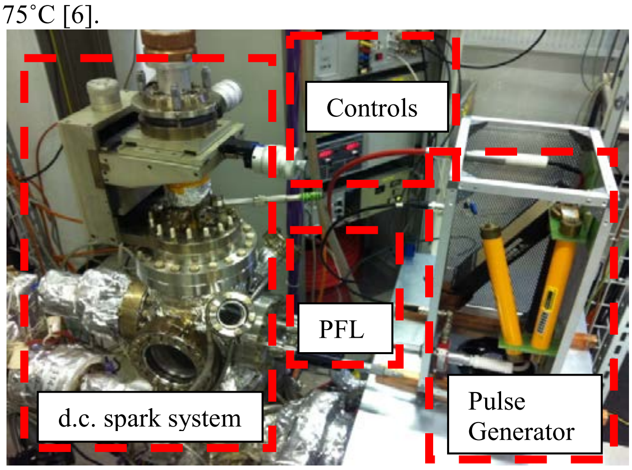

Figure 2: Pulse generator, PFL, d.c. spark system and controls.

Supply section

To achieve a current pulse width of 2 µs in the sample under test, following BD of the sample, a 200 m length of PFL is used: this corresponds to a total capacitance of 20 nF, and a stored energy of 1.44 J at 12 kV. In addition ~0.34 J is stored in the filter capacitor (see below). The PFL is charged from a FuG capacitor charging power supply, rated at 12.5 kV and 10 mA. A filter circuit between the FuG supply and PFL, consisting of a capacitance to ground of 4.7 nF and a series resistance of

4.7 kΩ; this filter significantly reduces the magnitude and rate-of-change of transients imposed on the output of the FuG supply. In addition the supply section contains a series stack of eight DSEE 55-24N1F inverse diodes, in series with 50 Ω: the purpose of this circuit is to, in the event of a BD on the load side of the MOSFET switch, terminate the resulting inverse current pulse.

Assuming BD of the sample at a repetition rate of 1 Hz, the average current drawn is 300 µA. If the sample does not BD, an average current of 1.8 mA is required to charge an effective capacitance of 300 pF to 12 kV at 1 kHz. However, in addition to this, the power supply must provide current to the bleed resistor during the time that the MOSFET is in the on-state: thus for a 3 µs (default) on-time of the MOSFET switch, and 80 kΩ, the additional average current required is ~0.5 mA, giving a total of 2.3 mA drawn from the FuG power supply.

Driver and control circuit for MOSFET switches

The control circuit provides a 3 V trigger pulse to the MOSFET switch: the measured turn-on delay of the HTS-180-25-B is ~300 ns. A current transformer, a CT-D0.5-B, terminated in 50 Ω (giving a sensitivity of 0.25 V/A), mounted around the 3Y430 output socket of the pulse generator, is used to measure the load current. During normal operation, without a BD, the pulse current charges the parasitic capacitance on the output of the pulse generator: during operation at 12 kV a peak current of 30 A is measured with the d.c. spark system connected. In the event of a BD, at 12 kV, a current of ~120 A flows. The control system compares the pulse current with a threshold: if it is greater than 55 A, at 12 kV, a BD is assumed to have occurred and the frequency is limited to 1 Hz. In addition the trigger to the MOSFET switch is increased in duration for 3 µs from the instant of the BD. The later is a precaution to minimize the probability that the HTS-180-25-B will switch-off while a high-current is flowing: otherwise voltage transients could result in damage to one or more MOSFETs in the switch. However, if the control system has already removed the trigger pulse but the HTS-180-25-B has not yet turned-off, and a BD occurs, the HTS-180-25-B will switch-off the load current: hence it is desirable to keep the inductance associated with the BD current path to a reasonable minimum.

MEASUREMENTS

The average current drawn from the FuG supply, without any load connected to the output of the pulse generator, at 12 kV, when corrected for the current in the bleed resistor, gives an effective (linearized) capacitance of 135 pF on the source side of the HTS-180-25-B. During test the pulse generator was operated with a 155 pF dummy load (coaxial cable), connected to the output of the pulse generator, to give a total of 290 pF. A "long term" test of 7 days at 12.5 kV and 1.1 kHz was carried out. Temperatures were measured using a thermal camera: the ambient temperature was 28˚C. The maximum temperatures were: body of the HTS-180-25-B 56˚C; bleed resistor 59˚C; and load side matching resistor 92˚C. Similarly long-term tests were successfully carried out at 12 kV and 1 Hz with a short circuit connected.

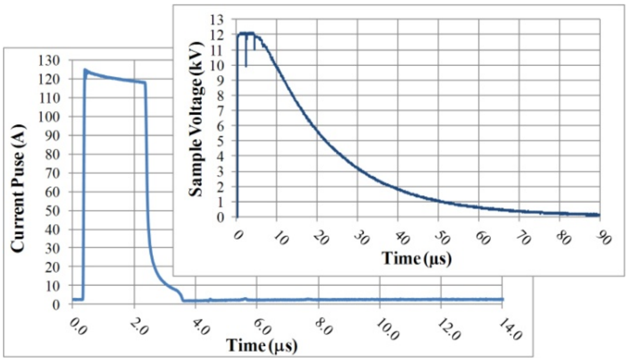

Figure 3: Sample voltage without BD (right) and measured current following BD at 12 kV (left).

Subsequently the system was connected to the d.c. spark system: the total effective load capacitance, calculated from the average current corrected for current through the bleed resistor, is 200 pF. The measured voltage rise time is less than 55 ns (10 % - 90 %) and the sample voltage reduces below 1 % of the applied voltage within 100 µs (Fig. 3, right): both values are well within specifications. Fig. 3 (left) shows an example of a BD during operation at 12 kV: the measured current has a 2 µs "flat top" of ~120A and a rise time of 14 ns (10 % - 90 %). The estimated inductance, based on the 14 ns rise time, is approximately 320 nH.

ACKNOWLEDGEMENTS

The authors would like to thank N. Shipman for his assistance carrying out tests and measurements.

CONCLUSIONS

The high repetition rate system is now working with the d.c. spark system and BD rate data is being collected. Possible future upgrades include an increase of the voltage and frequency.

REFERENCES

[1] CLIC Conceptual Design Report, http://project-clic-cdr.web.cern.ch/project-CLIC-CDR/.

[2] S. Calatroni, "Breakdown Studies for the CLIC Accelerating Structures", Proceedings LINAC2010, Tsukuba, Japan.

[3] N. Shipman, S. Calatroni, R. Jones, W. Wuensch, "Measurement of the Dynamic Response of the CERN DC Spark System and Preliminary Estimates of the Breakdown Turn-on Time", Proceedings of IPAC 2012, New Orleans, USA.

[4] Behlke Electronic GmbH, http://www.behlke.de.

[5] HVR GmbH, http://www.hvrint.com/.

[6] Tyco Electronics GmbH, http://www.te.com/.