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High Field Studies for CLIC Accelerating Structures Development

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Abstract
Compact Linear Collider RF structures need to be able to achieve the very high average accelerating gradient of 100 MV/m. One of the main challenges in reaching such high accelerating gradients is to avoid vacuum electrical breakdown within CLIC accelerating structures. Accelerating structure tests are carried out in the klystron-based test stands known as the XBoxes. In order to investigate vacuum breakdown phenomena and its statistical characteristics in a simpler system and get results in a faster way, pulsed dc systems have been developed at CERN. To acquire sufficient breakdown data in a reasonable period of time, high repetition rate pulse generators are used in the systems for breakdown studies, so-called pulsed dc system. This paper describes the pulsed dc systems and the two high repetition rate circuits, which produce high-voltage pulses for it, available at CERN.

Keywords
CLIC; vacuum breakdown; pulsed dc system; breakdown rate.

1 Introduction

The Compact Linear Collider (CLIC) is one of the candidates for the next generation high-energy linear colliders. In order to reach up to the target 3 TeV and maintain an acceptable length, the accelerating gradient must be around 100 MV/m. This results in surface electric fields of more than 200 MV/m on the copper surface of accelerating structures. With such fields, vacuum breakdowns sometimes occur and these breakdowns disrupt the accelerated beam. Breakdowns are one of the main performance limitations for CLIC and other high-gradient linacs. Whenever a breakdown happens, it results in partial or full loss of luminosity for that pulse. The breakdowns have a certain probability of occurring and obtaining a low breakdown rate ($3 \cdot 10^{-7}$ breakdowns per pulse per meter) in CLIC accelerating structures is a critical requirement for a successful operation.

A vacuum breakdown is a sudden exchange of charge occurring between two electrodes with a high potential difference in vacuum conditions and results in large currents [1]. Vacuum breakdown is one of the main limitations to achieve the required accelerating gradient in CLIC. This effect can produce strong back reflection of the incident RF, reduction of the luminosity of the accelerator complex, surface damages and other undesirable effects [2].

For understanding breakdown phenomena in vacuum and for finding the best materials, treatment methods and study the conditioning process for accelerating structures of future colliders several pulsed dc systems have been developed at CERN. The first system, its opportunities and results are described in several publications [1–4]. The initial electrical circuit for the pulsed dc systems was based on a mechanical relay and gave possibilities to apply voltage at a maximum repetition rate of 0.5 Hz [3]. Breakdown field strengths, evolution of field enhancement factor for different materials and other measurements were done [5, 6].

2 Pulsed dc systems

For studying values related to breakdown (breakdown rate, dark current, delay to breakdown and etc.), for finding better parameters of conditioning process with similar surface electric field as in RF structures

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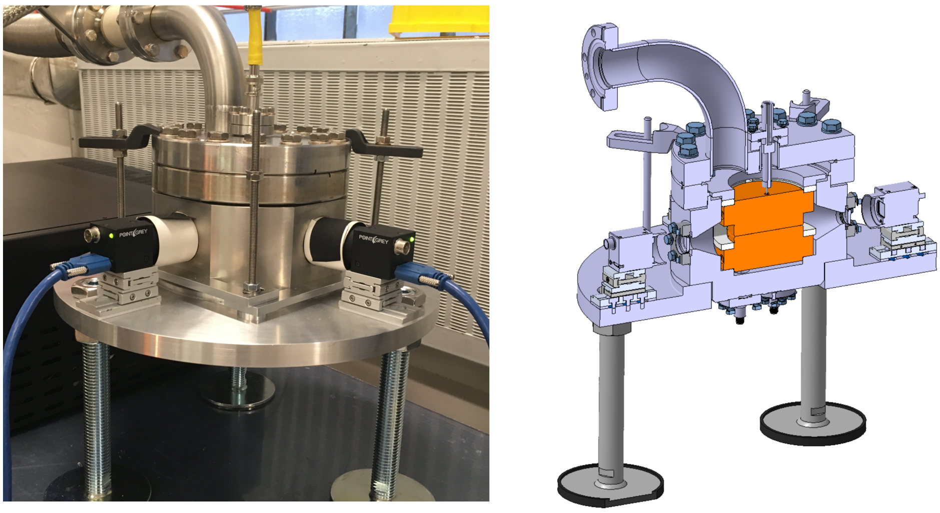
a pulsed dc system capable for much higher repetition rates was designed and built. This system helps to get results much faster than in RF measurements. For example, the same amount of data taken in RF measurements with 50 Hz in 1 months could be taken with a pulsed dc system at 1 kHz during about 2 days.

The pulsed dc system is used for studying breakdown phenomenon between two electrodes. It includes as main parts: a vacuum chamber with electrodes inside, an electrical circuit or generator, and a DAQ system.

2.1 Vacuum chamber for pulsed dc system

Currently the Large Electrodes System (LES) is used as a vacuum chamber for pulsed dc system (Fig. 1). It is a compact vacuum system which contains two plane electrodes. High voltage with a positive polarity is applied to one of them (an anode), while the second electrode is grounded (a cathode). They are held apart by a ceramic ring mounted away from the high-field area, which results in a gap between the electrodes, typically in the range of 60 μm for the experiments described in this report. As both electrodes are planar and the gap distance is small compared to the diameter of their working surfaces, 60 mm, they can be treated like a parallel plate capacitor. The electric field could be estimated as $E = V/d$, where V is applied voltage and d is gap distance.



(a) (b)

Fig. 1: Large Electrodes System: (a) photo, (b) 3D model

The vacuum level required for the tests is $10^{-8} - 10^{-10}$ mbar and is achieved by using two pumps: a roughening pump for initial pumping from atmospheric pressure to the mbar range, and turbo pump to reach a lower pressure.

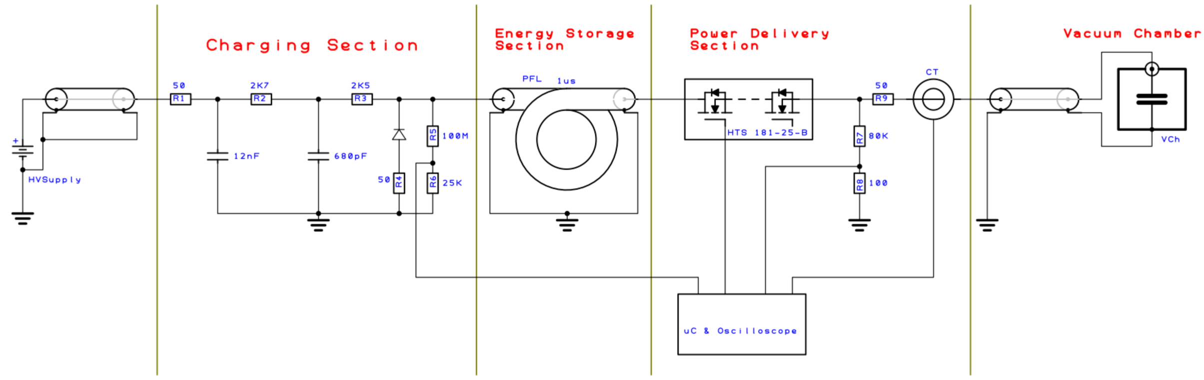
2.2 High repetition rate generators for pulsed dc system

In order to obtain data on the breakdown phenomenon in d.c. with a rate of about $1 \cdot 10^{-7}$ breakdown per pulse and in a reasonable period of time a high-voltage generator with high repetition rate is required.

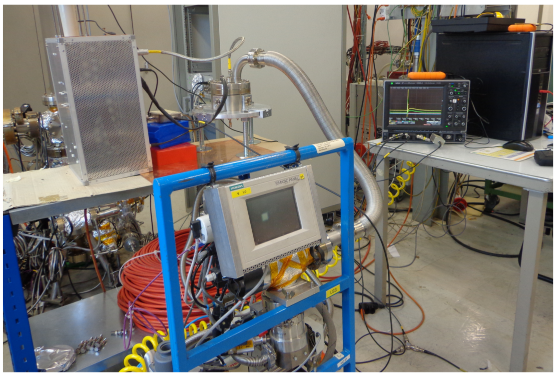
A first high-voltage pulse generator, so-called High Repetition Rate circuit (HRR circuit), for pulsed dc system was designed and built by R.H. Soares and M.J. Barnes [7]. The following performances were achieved: the circuit provides the possibility to apply pulses with voltage up to 12 kV with repetition rate up to 1 kHz across the samples in the pulsed dc system. Following the system specific features, the circuit has two modes:

– *Running mode* - without breakdown - during applying high voltage pulse, if breakdown doesn't happen, the voltage should not drop more than 1% of its maximum value.
– *Breakdown mode* - during applying high voltage pulse the increasing of current should be detected and pulsing should be stopped for several seconds. When breakdown occurs, the circuit should deliver a rectangular current pulse of several 10's of Amps and 2 μs duration.

HRR circuit was build based on MOSFET switch technology and a BEHLKE HTS 181-25-B is used as a switch. The electrical circuit and a photo are shown in Fig. 2.



(a)

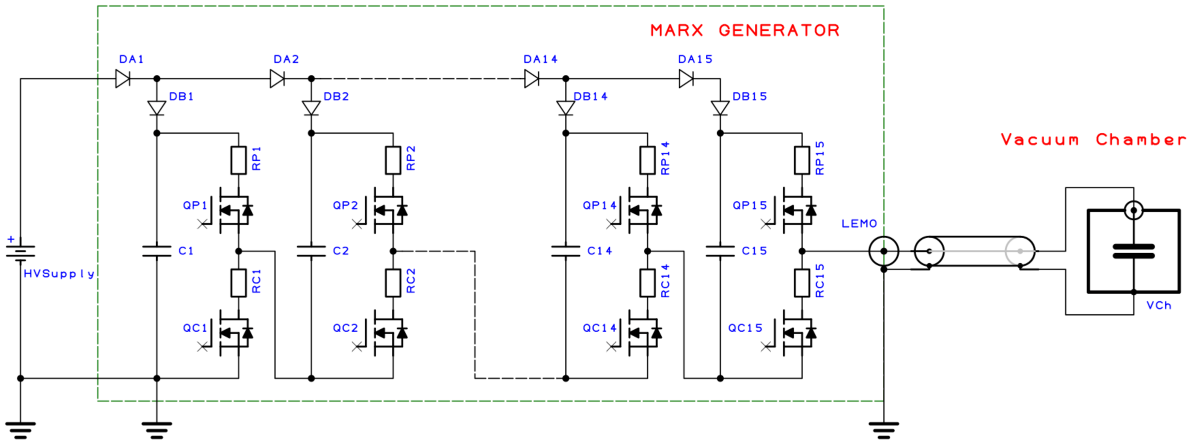


(b)

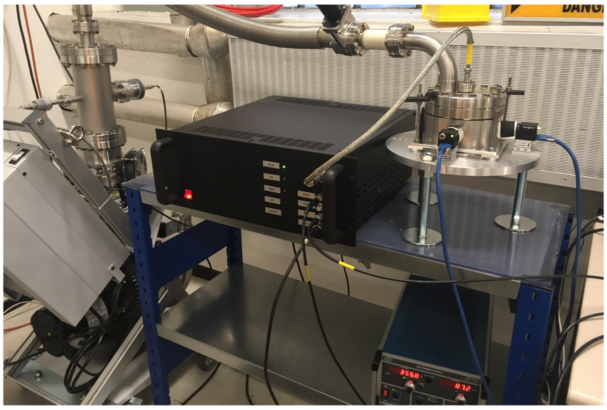
Fig. 2: HRR circuit: (a) schematic of electrical circuit; (b) photo together with Large Electrodes System

After few years of testing pulsed dc systems with the HRR circuit, a new generator started to be exploited. As in RF tests the pulse is roughly rectangular and has 200 ns length, the new generator had this additional requirement: a rectangular pulse shape and pulse length closer to range used in RF. This should make d.c. results more comparable with RF.

The new generator was produced by the Portuguese company "Energy Pulse Systems" [8]. A EPULSUS-FPM1-10 incorporates a positive-voltage Marx generator, with 15 stages, based on state of the art SiC MOSFET technology. The EPULSUS-FPM1-10 (hereinafter simply called as Marx generator) was designed especially for pulsed dc system.
The Marx generator circuit generates a high-voltage pulse from a low-voltage d.c. supply [9]. This is achieved by charging the 15 capacitors of the device which are connected in parallel, then discharging them in series using very fast switching devices. The simplified diagram of the generator is shown in Fig. 3.



(a)



(b)

Fig. 3: The Marx generator for pulsed dc system: (a) the simplified positive solid-state Marx generator circuit, (b) a photo with Large Electrodes System.

The Marx generator can deliver up to 10 kV and 50 A square wave repetitive pulses with adjustable length. Small rise and fall times are provides square-shaped high-voltage pulses. The maximum frequency 6 kHz limited by the internal power dissipation. The d.c power supply in this circuit is external medium voltage power supply reaching up to 1250 V and 250 mA.

The typical waveforms taken with Large Electrodes System for both circuits are shown in Fig. 4. When the capacitor charges a current pulse is produced. If no breakdown occurs, in the HRR circuit the current is discharged slowly through the R7 and R8 resistors (Fig. 2 (a)), while for the Marx generator the discharge is shown by a negative current signal at the end of the pulse (Fig. 4 (d)). If a breakdown occurs, the current increases rapidly to several 10's of Amps (Figs. 4 (c) and (d)). This current increase is used for breakdown detection in both circuits. The current starts getting higher than usual charging current and breakdown is detected. The voltage drops almost to zero during breakdown. Both circuits (HRR circuit and Marx generator) have implemented, in different ways, a so-called "delay after breakdown", i.e. a period during which the current between the electrodes is sustained after a breakdown. The 2 μs delay after breakdown for both circuits is shown in Figs. 4 (c) and (d).

According to Fig. 4, if a 5 μs signal is sent to the controller, the HRR circuit will produce a pulse with effective pulse length 21.3 μs$\pm$10% (voltage signal higher than 90%), while the Marx generator's pulse will be 5 μs $\pm$ 5%. Table 1 shows the main parameters for both generators. The big fall time for the voltage signal generated with the HRR circuit (130 μs from 90% to 10% voltage signal amplitude at 4 kV from sending 5 μs signal to the switch) led to the requirement to change the circuit.

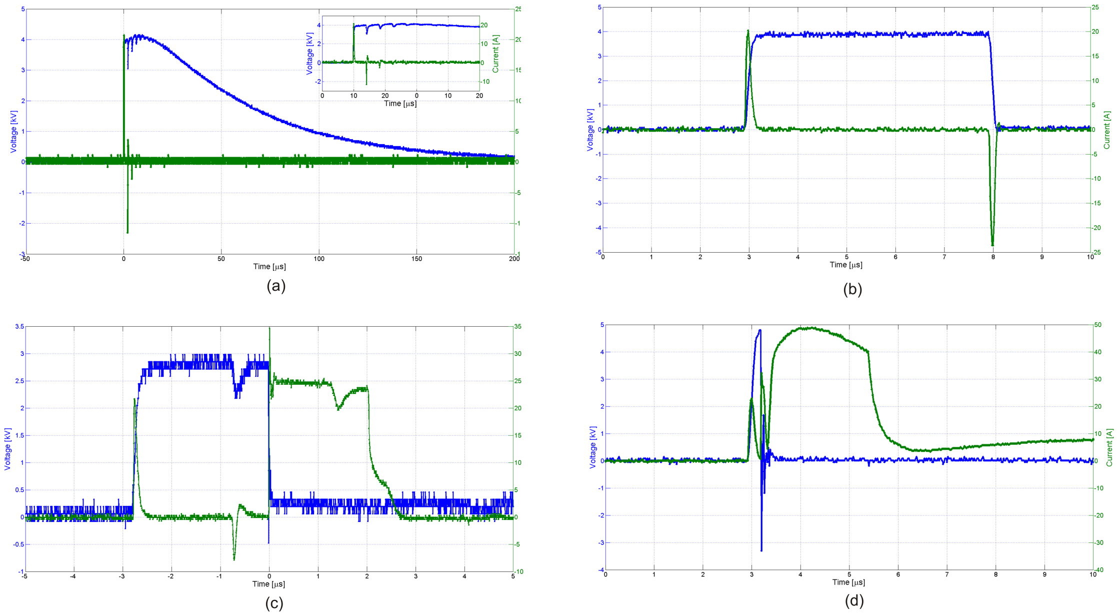


Fig. 4: Typical waveforms taken with the Large Electrodes System and: (a) HRR circuit without breakdown at 4 kV and 5 μs pulse signal sent to the controller, (b) Marx generator without breakdown at 4 kV and 5 μs pulse signal to the controller, (c) HRR circuit with breakdown at 2.9 kV; (d) Marx generator with breakdown at 5.12 kV. Current signals are shown in green, voltage signals are shown in blue.

Table 1: Comparison of main parameters HRR circuit and Marx generator.

Parameter	*HRR circuit*	*Marx generator*
Maximum voltage	12 kV	10 kV
Maximum frequency	1 kHz	6 kHz
Pulse length (switch control signal)	3 - 7 μs	400 ns - 100 μs
Delay after breakdown	2 μs	600 ns - 2.3 μs
Stored energy (for 10 kV)	~1.4 J	~1.4 J
Rise time (for 4 kV)	200 ns	180 ns
Fall time (for 4 kV)	130 μs	100 ns

3 Results and conclusions

Pulsed dc systems are being used at CERN for studying breakdown phenomenon. A comparison of data from RF and d.c. conditioning experiments is shown at Fig 5. The scaled gradient is the value taken for better comparison the results from pulsed dc system and RF measurements. It is:

$$E_{scaled} = \frac{E(MV/m) \cdot t_p^{1/6}(ns)}{BDR^{1/30}} \tag{1}$$

where E is the electric field in MV/m, t_p the pulse length taken in ns, BDR the breakdown rate (or breakdown probability) defined as:

$$BDR = \frac{Breakdowns}{Pulses} \tag{2}$$

For d.c. tests the copper electrodes followed the same heat treatment procedure as in RF accelerating structures. Also the algorithm for conditioning tests in a pulsed dc system was adapted to RF measurements to make it more similar [10]. The pulsed dc system's data shown in Fig. 5 were taken with the HRR circuit. Results from d.c. tests have similar behavior as from RF measurements. Experiment in the pulsed dc system with a pulse shape and length similar to the RF pulse will produce data for understanding the difference in magnitude of the scaled electrical field between RF and d.c. results.

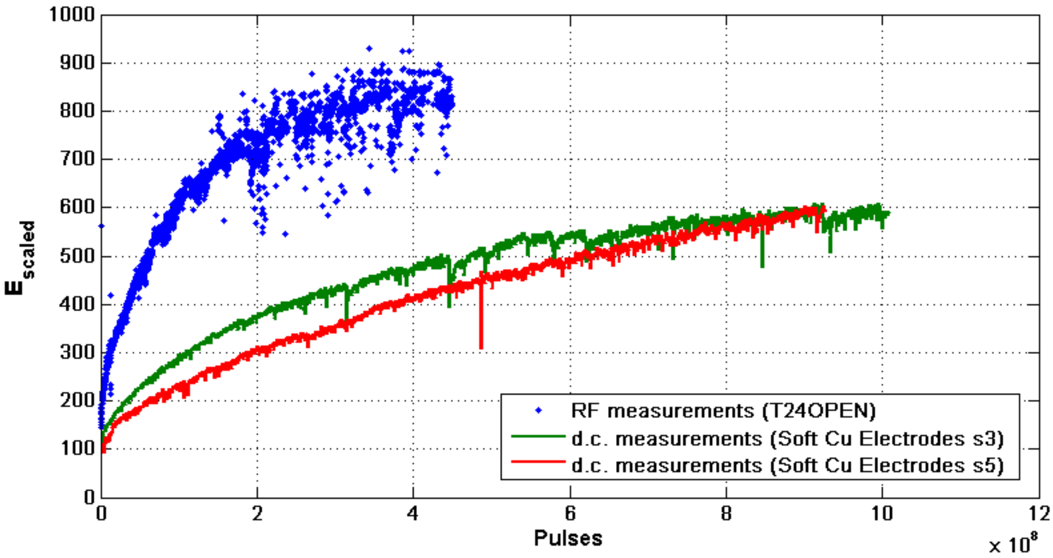


Fig. 5: Comparison of the scaled electric field versus the accumulated number of pulses for d.c and RF results [10]

Two high repetition circuits used as generators for applying high voltage pulses are described and compared in this paper. The Marx generator is a significant improvement of the system for studying breakdown phenomena. It produces a pulse shape and pulse length range closer to the RF case. Also the Marx generator provides more variables for possible future tests with pulsed dc systems.

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