PERFORMANCE OF THE CROWBAR OF THE LHC HIGH POWER RF SYSTEM

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Abstract

The counter-rotating proton beams in the Large Hadron Collider (LHC) are captured and accelerated to their final energies by two identical 400 MHz Radio Frequency (RF) systems. The RF power source required for each beam comprises eight 300 kW klystrons. The output power of each klystron is fed via a circulator and a waveguide line to the input coupler of a single-cell superconducting (SC) cavity. Each unit of four klystrons is powered by a -100kV/40A AC/DC power converter. A fast protection system (crowbar) protects the four klystrons in each of these units.

Although the LHC RF system has shown has very good performance, operational experience has shown that the five-gap double-ended thyratrons used in the crowbar system suffer, from time to time, from auto-firing, which result in beam dumps.

This paper presents the recent results obtained with an alternative solution based on solid state thyristors. Comparative measurements with the thyratron are shown.

INTRODUCTION

The two LHC counter-rotating proton beams are captured and then accelerated by two identical 400 MHz RF systems. Eight superconducting cavities per beam, operating at 4.5 K, provide the required accelerating field for increasing the beam energy up to 7 TeV.

The RF power is generated by sixteen 300 kW/400 MHz klystrons, powered by four -100 kV/40A AC/DC power converters.

The klystrons and their four high voltage (HV) equipment interfaces, consisting of the modulators, the crowbar systems, the 4 μF smoothing capacitors and the HV switches are installed in fire proof bunkers that are located in the LHC underground cavern, about 400 meters away from the power converters which are at the surface [1].

In case of an arc occurring inside a klystron, which is operated at -58 kV and 9 A, the high voltage energy has to be removed from the tube within less than a few microseconds in order to avoid damage.

The diversion of the HV energy is achieved by triggering the thyratron which then becomes conducting and acts as a short circuit of the HV power supply to the ground.

The double ended thyratrons currently being used require very fine adjustment and are very sensitive to noise. Although they proved to be reliable, from the point of view of protecting the klystron, from time to time they suffer from auto-firing that results in LHC beam dumps.

A solid state solution, based on a stack of thyristors, has been designed and adapted for a direct thyratron replacement and has recently been implemented in the HV bunker.

THE LHC RF HIGH VOLTAGE INTERFACE

The schematic diagram of the LHC RF high voltage interface is shown in Figure 1. It comprises of a HV switch (not shown), a 4μF smoothing capacitor, a 5 gap thyratron, a modulator, protection resistors, insulation transformer, and long high voltage coaxial cables. This equipment is housed in fire-proof bunkers located in the LHC underground cavern.

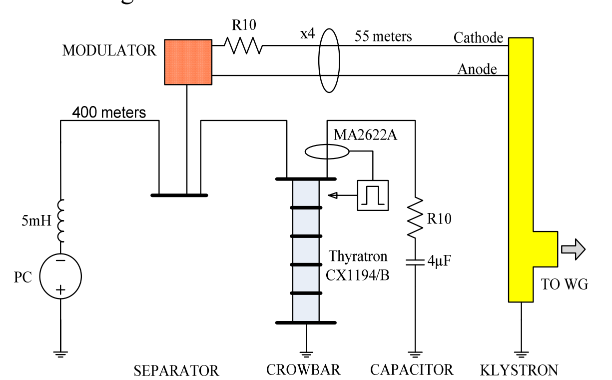

Figure 1: Schematic diagram of one LHC klystron, power supply and protection circuit.

The high power klystrons to be supplied with cathode, filament and modulation anode voltage are installed at a distance of about 55 meters from the HV bunkers, whereas the distance to the HV power converters at the surface is about 400 meters.

In the event of crowbar operation, one has to deal with the fast discharge of the 4 μF capacitor and the long coaxial cables (≈6000 A, 200 μs), followed up by the slower discharge of the 5 mH coils of the power converter (≈ 60 A, 340 ms).

THYRATRON PERFORMANCE

The current transformer (MA2622A – see Fig.1) detects the discharge of the capacitor provoked by an arc occurring inside the klystron. The generated signal triggers the thyratron via an electronic interface. Figure 2 shows the 4 μF capacitor discharge through the 10 Ω resistor. The damped oscillations are explained by the discharge of the coaxial cables that behave like an unmatched delay line (Pulse Forming Line). The cables are indeed short-circuited on the klystron side and open-circuited on the power converter side.

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The slow current discharge generated by the 5 mH inductance of the power converter is shown in figure 3.

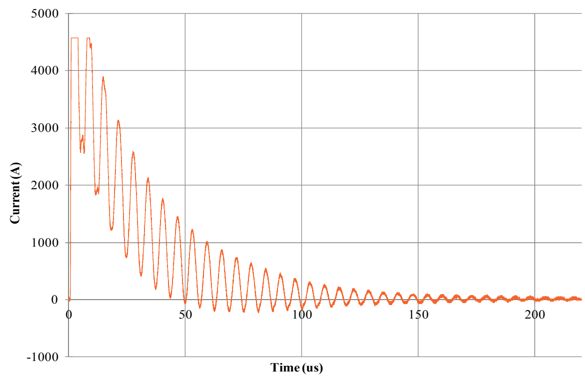

Figure 2: Thyratron crowbar current at -60 kV.

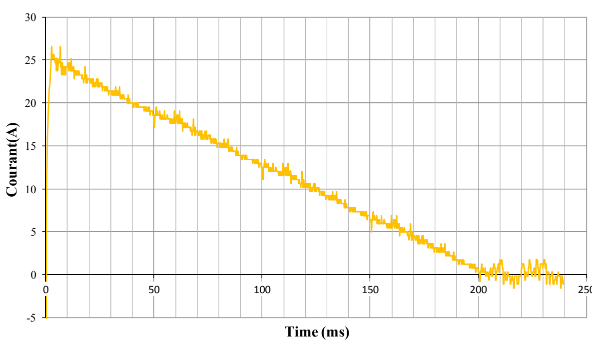

Figure 3: Current slow part -58 kV.

In order to test the performances of the system, a spark gap has been used to generate arcs and thus trigger the thyratron. The current flowing through the arc has been measured with a current transformer (Pearson 150). The result obtained limited by the maximum spark gap voltage capability of 37 kV is displayed in Figure 4. The current reaches a maximum of about 1500 A after 0.8 µs, and then rapidly decreases to zero in about 2.5 µs.

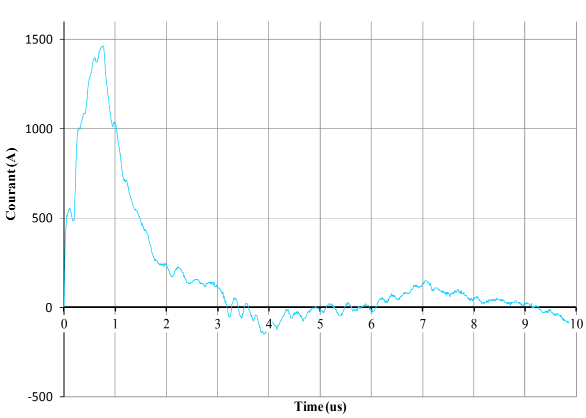

Figure 4: Spark current at -37 kV.

Figure 5 shows the measurements of the spark gap current, the capacitor discharge current (thyratron trigger signal) and thyratron current.

The onset of the 4 µF capacitor discharge (green curve) is observed about 150 ns after the arc is initiated. This delay is due to the length of the HV electrical coaxial cables. The thyratron starts to be conductive about 550 ns after having being triggered. This delay corresponds to the thyratron turn on-delay. Nearly simultaneously the arc current starts to decrease and the capacitor current increases significantly.

The coexistence of the arc and the thyratron current demonstrates that the arc is not immediately killed. It stays alive for another 2.5 µs.

It is also interesting to note that the thyratron rise time is about 1.2 µs.

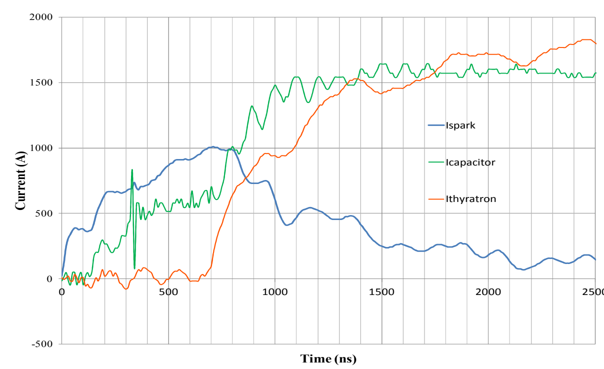

Figure 5: Thyratron crowbar currents delays.

Experience gained with the LEP and LHC machines has proved that the thyratron performances are sufficient to guarantee safe operation.

SOLID STATE DEVICE PERFORMANCE

The measurements described above have been repeated with the solid state device APP S56A-18-E, made up of 18 single thyristors stages, which can handle 40 kA/µs, 14 kA peak, damped-oscillating currents.

The results and the comparison with the performances of the thyratron are shown in table 1. We observe that the turn-on delay of the thyristors stack is 200 ns shorter than the turn-on delay of the thyratron. The rise time of the thyristors stack is however more than twice as long as the rise time of the thyratron.

Table 1: Thyratron & Thyristors Delays Comparison

CROWBAR	Turn ON Delay (ns)	Rise Time (ns)
Thyratron (CX1194B)	550	1200
Thyristor (S56A-18-E)	350	2500

The analysis of the spark current measurements (i.e.: current flowing through the arc) gives interesting and additional information to compare the two devices.

ARC ENERGY DISSIPATION

Figure 6 shows the integral of the arc current as a function of the spark gap firing voltage. This corresponds to the evolution of the energy dissipated in the electric arc. We observe that the performances of the thyratron (black curve) are better than the performance of the thyristors stack (green curve).

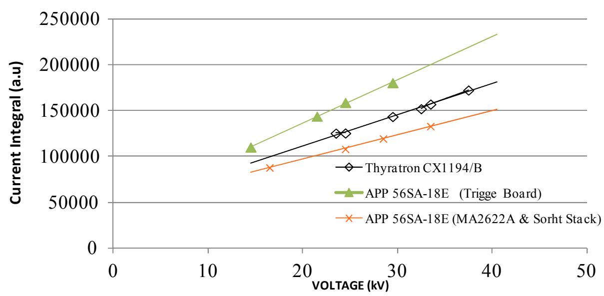

Figure 6: Spark current integral.

Several tests have been made to improve the performance of the thyristors stack:

- The turn-on delay was reduced by shortening the trigger cable, removing the trigger board, and using the output signal from the current transformer (MA2622A) to directly trigger the thyristors.
- The rise time of the device was also improved by shortening the semiconductor stack electrical length and by decreasing the inductive effect by using a better adapted coaxial assembly.

The combination of these modifications made it possible to reduce, by about 25%, the energy lost in the arc (orange dots in figure 6), and thus improve the efficiency of the thyristors stack.
With better performance than the thyratron under all circumstances, the solid state device is considered safe for machine operation [2].

Further complementary measurements are planned to be made with a newly designed motorized electric spark-gap, equipped with voltage and current measurements of the arc. This setup will allow characterizing the energy dissipated in the arc at the nominal operating voltage of -58 kV.

CONCLUSIONS

The fully validated upgraded thyristors stack has been installed in LHC in February 2012. It equips one of the four HV bunker. Until now the device has proven to be very reliable and give full satisfaction. Five other thyristors based crowbars are in production to equip the three other bunkers and the test areas. Contrary to the thyratron, the solid state device excludes the need for any control electronics that are also a source of potential problems. A long reliability run as well as complementary measurement of the energy lost into the arc will be made in the near future.

Figure 7 shows both, Thyratron (left) and Thyristors (right) crowbar.

Figure 7: Thyratron and Thyristors crowbar.

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[1] O. Brunner, H. Frischolz, D. Valuch "RF Power Generation in LHC" 0-7803-7739-9 (2003)
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