

# MEASUREMENTS ON A FAST 66 KV RESONANT CHARGING POWER SUPPLY FOR THE LHC INFLECTORS

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## Abstract

The injection kicker systems for the two LHC beams will each consist of two fast resonant charging power supply (RCPS) systems, four travelling wave type kicker magnets and four pulse forming networks (PFNs), discharged by thyratron switches. Each RCPS system, located with the switches and PFNs in a gallery parallel to the LHC tunnel, will be employed to simultaneously charge two  $5\ \Omega$  PFNs within 1 ms to 60 kV. The stability and pulse to pulse reproducibility of the PFN voltage must be maintained to a precision of better than  $\pm 0.1\%$ . Each RCPS consists of a 2.6 mF primary capacitor bank, charged to 2.5 kV, and connected via a Gate Turn-Off (GTO) thyristor to the primary of a 1:23 step-up transformer. Each PFN will have an effective capacitance of  $0.96\ \mu\text{F}$ . The RCPS systems include several new developments. The prototype, which is the first of six units, has been constructed and tested at TRIUMF in collaboration with CERN as part of the Canadian contribution to the LHC project. Measurements were performed for both normal and abnormal operating conditions. A charge time of 825  $\mu\text{s}$ , and a pulse to pulse reproducibility of the output voltage of better than  $\pm 0.02\%$  have been attained.

hours, consists of 12 pulses with a repetition period of 16.8 s.



Figure 1: 66kV RCPS.



Figure 2: Dummy

Each RCPS will simultaneously charge two  $5\ \Omega$  PFNs to 60 kV, before thyratron power switches are triggered. The stability and pulse to pulse reproducibility of the PFN voltage must be maintained to a precision of better than  $\pm 0.1\%$ . A complete description of the RCPS design, is presented in[1,2]. Accompanying Pspice calculations are given in[5].

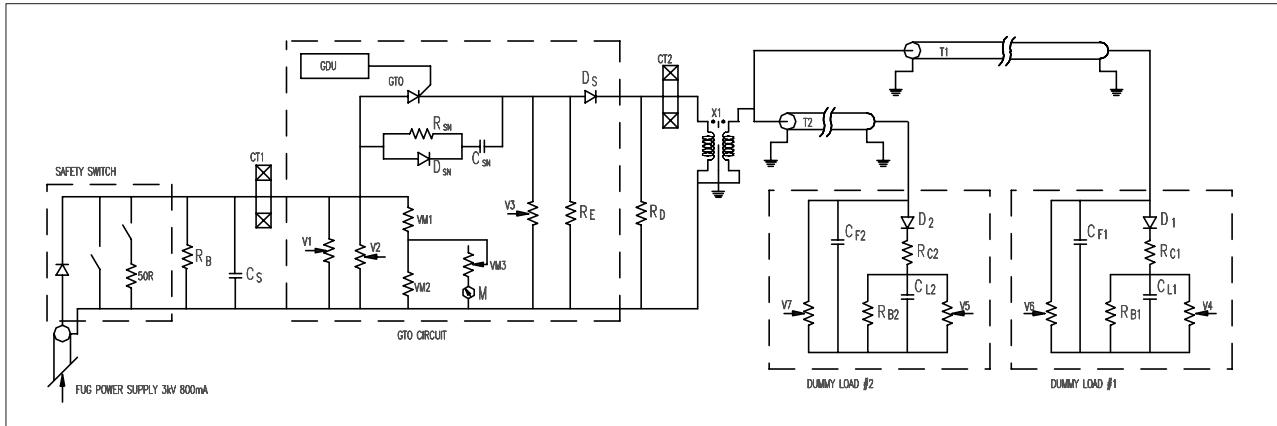


Figure 3: Schematic diagram of 66kV RCPS.

## 1 INTRODUCTION

The LHC will be equipped with two fast injection kicker systems[3], each consisting of two pulsed systems, 2 resonant charging power supplies (RCPS)[1,2], four kicker magnets and pulse generators[4,8] respectively. The injection sequence, repeated approximately every ten

## 2 MEASUREMENTS

Fig 1 and Fig 2 are photographs of the RCPS and the dummy loads respectively. Fig. 3 shows a schematic of the RCPS and dummy loads and the notation utilised for component names. The 2.6 mF storage capacitor bank ( $C_s$ ) in the RCPS (Fig 3) is charged up to 2.69 kV, for a

maximum output voltage of 66 kV. A GTO thyristor[7] is used to switch the energy onto the primary of a 1:23 step-up transformer of low leakage inductance ( $87 \mu\text{H}$ )[9]. GATT mode is initiated at a threshold of 100 A[2]. The transformer output is connected via high voltage cables[10] rated for 160 kV operation, to two dummy loads representing the pulse generators. Each load consists of a  $5.2 \text{ nF}$  filter capacitor ( $C_{F1}, C_{F2}$ ), a stack of 36 diodes ( $D_1, D_2$ ) with a total blocking voltage of 72 kV, a  $70 \Omega$  charging resistor ( $R_{C1}, R_{C2}$ ), and a load capacitor ( $C_{L1}, C_{L2}$ ) of  $0.96 \mu\text{F}$ . The  $0.96 \mu\text{F}$  capacitors each represent one  $5 \Omega$  PFN. A  $500 \text{ k}\Omega$  resistor is used to discharge each dummy load between pulses with a 0.5 s time constant, as there are no thyratrons switches installed in the dummy loads.

## 2.1 Normal operation; two dummy loads

During the charge cycle the voltage on the capacitor bank swings from 2.69 kV to 1.51 kV. The capacitor is then re-charged at a constant current to 2.69 kV in a few seconds. Fig 4 shows the voltage waveforms for 66 kV test operation.

Normal operation at the LHC is planned for 60 kV with each RCPS charging two PFNS. Contingencies were included into the design such that the system pass acceptance tests at 66 kV operation.

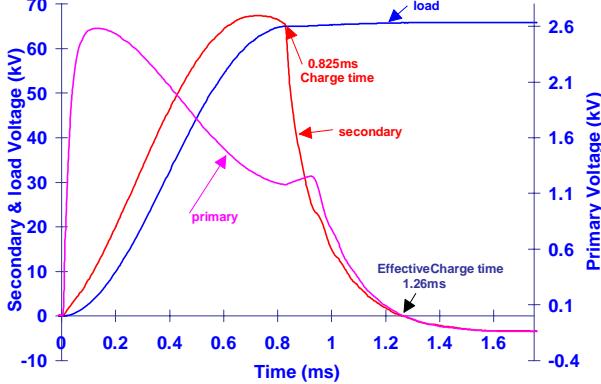


Figure 4: Voltage waveforms for 66 kV operation with two dummy loads.

The dummy loads are equipped with voltage dividers: one on the anode of each diode stack and one on each  $0.96 \mu\text{F}$  load capacitor. The voltage on the anode of the diode stack overshoots 66 kV due to the current in the  $70 \Omega$  charging resistor. The charge time with two  $0.96 \mu\text{F}$  load capacitors is approximately  $\pi\sqrt{LC}$ , neglecting the effect of the damping ( $R_D$ ) resistor and conduction losses.  $L = 87 \mu\text{H}$  is the pulse transformer leakage inductance referred to the primary and  $C$  is the connection of the  $2.6 \text{ mF}$  primary capacitor in series with two load capacitors, referred to the primary ( $23^2 \times 2 \times 0.96 \mu\text{F}$ ). The measured charge time is  $825 \mu\text{s}$ , at the point where the primary current drops to zero (Fig 5) and the load voltage has reached the maximum of 66 kV (Fig 4). The secondary voltage then swings negative crossing zero

volt at 1.26 ms (effective charge time). The primary voltage crosses zero at the same time. This zero crossing time is important because for PFN operation the thyratrons must not be triggered before this instant otherwise the diode stack will become conducting and distort the PFN voltage and also cause a fast transient on the transformer. The filter capacitors are on the anode of

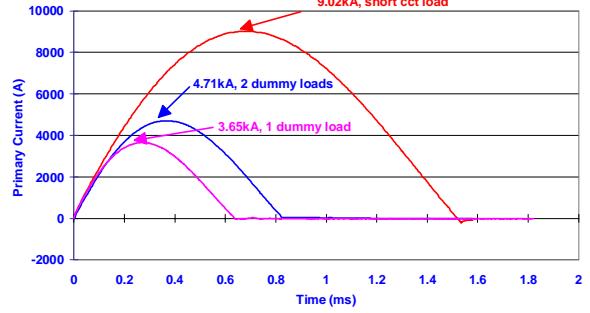


Figure 5: Storage capacitor bank current for different operating conditions for a voltage of 2.24 kV on  $C_s$

the diode stack and thus do not disturb the PFN voltage provided the diode stack is not in conduction.

The damping resistor has several advantages:

- reduces the back-swing time from 1.3 ms to  $435 \mu\text{s}$ .
- reduces the voltage reversal on the capacitor bank relative to the forward voltage from 80.6 % to 5.66 %.
- reduces the volt-time integral by a factor of 2.1 and thus allows for a smaller transformer design.

## 2.2 Short Circuit Operation

A short circuit test was conducted to ensure that the system could withstand a short circuit fault condition on rare occasions. The RCPS was set up for 55 kV operation. A short circuit was placed at the end of a 13m cable, connected to the output of the transformer

For this test the voltage on the storage capacitor bank swings from  $+2.24 \text{ kV}$  to  $-1.7 \text{ kV}$ . The primary current for a short circuit load is shown in Fig 5. The pulse duration is approximately  $\pi\sqrt{LC}$ , where  $L$  is the transformer leakage inductance, referred to the primary, and  $C$  is the storage bank capacitance. The short circuit test was performed for 4 single shots and a peak current of 9.02 kA was recorded, with GATT mode enabled at 100 A.

## 2.3 One Dummy Load

Tests with only one dummy load simulate a fault where one PFN becomes open circuit. The current waveform for operation at 55 kV with one dummy load is shown in Fig 5. The measured charge time is  $636 \mu\text{s}$  and the effective charge time as defined in section 2.1 is 1.08 ms.

## 2.4 Transformer Volt-Time Integral

The saturation of the transformer was measured by charging the capacitor bank to 1.5 kV and pulsing the GTO on and holding it on until the transformer saturated.

The measured saturation volt-time integral, to the point where the primary current begins to increase rapidly, was 60 V.s as compared to the design specification of 47 V.s.

## 2.1 Pulse Amplitude Stability

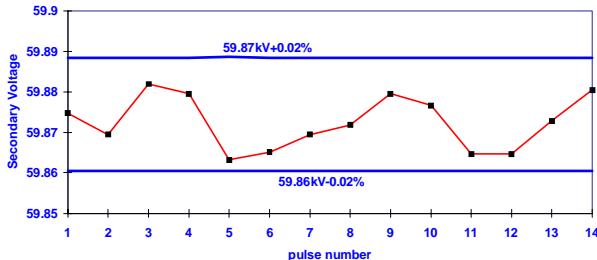


Figure 6: Stability of RCPS for 14 consecutive pulses from a cold start for 60 kV operation.

The pulse to pulse stability of the RCPS is required to be within  $\pm 0.1\%$  [3,4,6]. Fig 6 shows the measured amplitude of 14 consecutive RCPS pulses for an average voltage of 59.87 kV, with a cold start, ie: the RCPS had not been operated for 18 hrs previous to the measurements. The sequence corresponds approximately to a normal injection sequence for one beam into the LHC. The horizontal lines in Fig 6 are at  $\pm 0.02\%$  and the measurements are within this range with a maximum excursion of  $\pm 0.016\%$ . The relative measurement precision on the amplitude of each pulse was achieved by

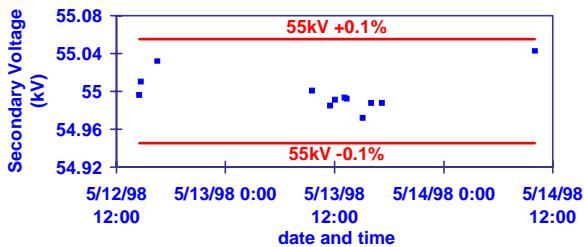


Figure 7: Stability at 55 kV for 2 day test.

using a digital oscilloscope[11] and averaging the flat top voltage amplitude on one  $0.96 \mu\text{F}$  test capacitor during a  $400 \mu\text{s}$  window at a digitising rate of 1 GHz.

An endurance test was also performed over 46 hrs of continuous operation at 0.1 Hz and 55 kV. The stability of the RCPS was checked periodically over the two days and the results are shown in Fig 7. The total spread of the measured RCPS voltages is  $\pm 0.085\%$ .

## 3 CONCLUSION

The prototype RCPS has been successfully commissioned at TRIUMF and operates reliably at 66 kV. The charge time of  $825 \mu\text{s}$  and the effective charge time of  $1.26 \text{ ms}$  are well within the design goals of  $1 \text{ ms}$  and  $2 \text{ ms}$  respectively. The pulse stability over 46 hrs is better than  $\pm 0.1\%$  and satisfies the requirement for  $1\%$  stability over 24 hrs. The pulse to pulse stability over 14 consecutive pulses is better than  $\pm 0.02\%$ , easily

satisfying the  $\pm 0.1\%$  stability requirement for the injection sequence of the LHC.

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