

MULTI-CHANNEL HEATERS DRIVER FOR SIRIUS BEAMLINE'S OPTICAL DEVICES

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Abstract

Thermal management of optomechanical devices, such as mirrors and monochromators, is one of the main bottlenecks in the overall performance of many X-Rays beamlines, particularly for Sirius: the new 4th generation Brazilian synchrotron light source [1]. Due to high intensity photon beams some optical devices need to be cryogenically cooled and a closed-loop temperature control must be implemented to reduce mechanical distortions and instabilities. This work aims to describe the hardware design of a multi-channel driver for vacuum-ready ohmic heaters used in critical optical elements. The device receives PWM (Pulse-Width Modulation) signals and can control up to 8 heaters individually. Interlocks and failure management were implemented using digital signals input/outputs available at device rear panel. The driver is equipped with a software programmable current limiter to prevent load overheating and it has voltage/current diagnostics monitored via EPICS (Experimental Physics and Industrial Control System) or an embedded HTTP (Hypertext Transfer Protocol) server. Enclosed in a 1U (rack unit) rack mount case, the driver can deliver up to 2A per channel in 12V and 24V output voltage versions. Performance measurements will be presented to evaluate functionalities, noise, linearity and bandwidth response.

INTRODUCTION

The optical devices design for synchrotron facilities is clear to be one of the most discussed topics to ensure state-of-art beamlines and perform complex experiments, especially for Sirius, the new low-emittance 4th generation Brazilian synchrotron light source [1]. These devices are highly stable thermo-mechanical solutions equipped with cryocooling schemes via cryostats and heaters for temperature control. This work aims to describe the hardware design of a multi-channel heaters drivers for Sirius custom high-performance mirrors [2] and monochromators [3-4]. The driver is also allocated at experimental stations with cryogenic setups, such as Taramã [5], a sub-microprobe station at CARNAUBA (Coherent X-Ray Nanoprobe Beamline) beamline.

The multichannel driver was designed to simultaneously deliver up to 1.5A at 12V to eight ohmic vacuum-compatible heaters. Each channel can be individually controlled by a TTL (Transistor-Transistor Logic) compatible PWM (Pulse-Width Modulation) signal. Optocoupled interlock inputs were implemented for safety purposes and failure outputs for open load and short-circuit signaling. A current

limiter scheme has been included to protect both heater and driver from overload and short-circuits.

Figure 1 shows the internal block diagram and interfaces. Voltage, current and duty cycle are monitored by two multi-channel 12-bit ADC (Analog-to-Digital Converter) AMC7812B [6], also responsible to set current limiter threshold over an internal DAC (Digital-to-Analog Converter). The AMC7812B are connected via SPI (Serial Peripheral Interface) to a NXP LPC1768 [7], an ARM[®] Cortex-M3 microcontroller.

Ethernet connection is provided to remotely access diagnostics data via an embedded HTTP (Hypertext Transfer Protocol) webserver and a TCP (Transmission Control Protocol) socket for EPICS integration. The current limiter threshold and a software enable control are available remotely. An USB (Universal Serial Bus) connector is provided at front panel for firmware update purpose.

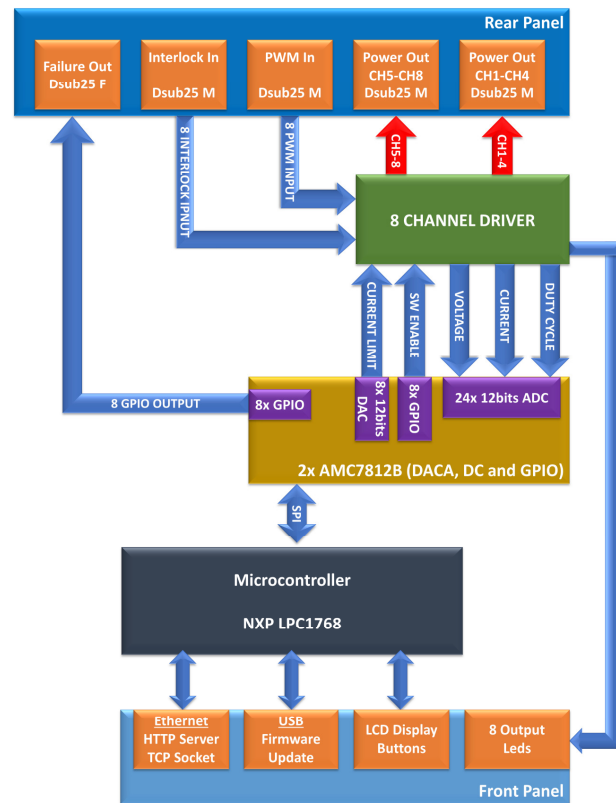


Figure 1: 8-Channel Heaters Driver Block Diagram.

This paper is organized as follows: Section II deals with hardware design details and concepts; Section III presents the embedded firmware architecture; Section IV discuss the mechanical design; Section V presents general results including performance parameters and Sirius'

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monochromator case study. Finally, Section V outlines the main conclusions of this work.

HARDWARE DESIGN

Power Driver Topology

The power driver is based on a simple buck DC-DC voltage regulator [8], which has its output voltage controlled by an input voltage (V_C) applied to a series resistor (R_C) at the feedback node, as shown in Fig. 2:

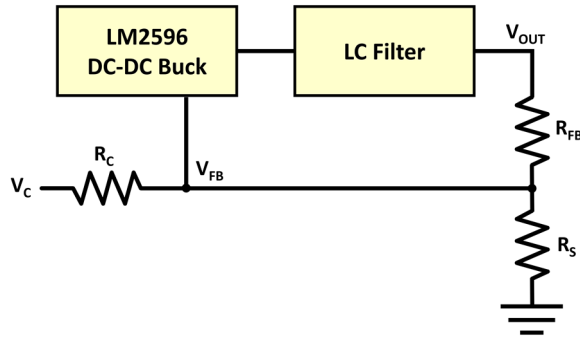


Figure 2: LM2596 Control Principle.

Assuming a DC-DC stable control loop, the feedback node voltage (V_{FB}) is fixed at 1.3V [8]. Considering the current drawn by the regulator feedback node (I_{FB} 10nA typical [8]) can be neglected, the output voltage is a linear function of control voltage (V_C) described by Eq. (1):

$$\frac{V_{OUT}-V_{FB}}{R_{FB}} = \frac{V_{FB}}{R_S} + \frac{V_{FB}-V_C}{R_C} \quad (1)$$

The maximum output voltage can be obtained by Eq. (2), assuming V_C at 0V and LM2596 input voltage higher than V_{OUT_MAX} :

$$V_{OUT_MAX} = V_{FB} \left(1 + \frac{R_{FB}(R_S+R_C)}{R_S R_C} \right) \quad (2)$$

Similarly, assuming 0V the desired minimum output voltage, solving Eq. (1) at this condition, the maximum control voltage can be obtained, as shown in Eq. 3:

$$V_{C_MAX} = V_{FB} \left(1 + \frac{R_C(R_S+R_{FB})}{R_S R_{FB}} \right) \quad (3)$$

These equations were used to determine resistors values to 12V maximum output voltage at 15V power supply. The control voltage is generated by a PWM signal applied to a Sallen-Key second-order low-pass active filter [9] ($C_1=C_2=100nF$ and $R_1=R_2=100k\Omega$) designed to limit bandwidth at 16Hz, transfer function shown by Eq. (4):

$$H(s) = \frac{1}{1+2RCs+(RCs)^2} = \frac{1}{1+0.02s+10^{-4}s^2} \quad (4)$$

The control bandwidth is expected to be limited by this filter, once the internal control loop response of the bulk regulator is considerably faster than 16Hz.

A current limiter is designed based on an analog comparator switching a PNP transistor that injects current directly at LM2596 feedback node. Since the load current overcomes the configured DAC threshold, the transistor turns on, dropping the LM2596 output voltage.

The power driver has been designed to provide 12V output voltage, however the hardware can be easily adapted to provide 24V output. This modification allows each channel to deliver up to 36W (1.5A at 24V) for higher power heaters, as used in Tarumã cryogenic experimental station [5].

Signal Acquisition

Multiple channel 12-bit ADCs (AMC7812B) acquire 24 analog voltages. Conditioning circuits with rail-to-rail single supply operational amplifiers were designed for ADC protection and signal conditioning. Therefore, the device perform 3 measurements per channel:

- The voltage across a shunt resistor, measuring the output current indirectly.
- The output voltage.
- The control voltage (Fig. 2 V_C), inversely proportional to the PWM input duty cycle.

Passive anti-aliasing filters are included at ADC inputs.

Additional Features

Optocoupled normally open enable inputs were designed to prevent power deliver in critical failure situations. These inputs are tied directly to LM2596 enable pins, that is, they are not firmware dependents.

Based on voltage and current diagnostics is possible to deduce open-load and short-circuit failures, triggering 5V TTL compatible optocoupled outputs at the rear panel.

FIRMWARE ARCHITECTURE

The microcontroller LPC1768 is programmed using Mbed framework [10], running Mbed Os 2 as real-time operating system, arranging tasks in 4 separate threads:

- **Main thread:** running at normal priority, responsible for Ethernet reconnection in case of failure, device startup configuration and save persistent data into internal Flash.
- **Sampling thread:** running at real-time priority, this thread samples ADCs at 100 samples per second and applies a digital filter.
- **Webserver socket thread:** running at normal priority, a TCP socket server is available at port 80, in which a HTTP server is implemented for quick diagnostics.
- **TCP socket thread:** running at normal priority, this thread implements a TCP socket server at port 6767 with a question/answer protocol command list to configure the device and read diagnostics data. The IOC (Input/Output Controller) makes use of this connection to integrate the device with EPICS control system.

The sampling thread performs an exponential moving average IIR (Infinite Impulse Response) filter, as shown in Eq. (5).

$$y[n] = (1 - \alpha)y[n - 1] + \alpha x[n] \quad (5)$$

Considering 100 samples per second and α equals to 0.17, the cutoff frequency is 3Hz, as shown by Eq. (6):

$$f_{3dB} = \frac{F_s}{2\pi} \cos^{-1} \left(1 - \frac{\alpha^2}{2(1-\alpha)} \right) \cong 3Hz \quad (6)$$

MECHANICAL DESIGN

The driver is enclosed in a 1U 19" rack mount metallic case, as shown in Fig. 3. Two power supplies provide board voltages:

- 15V up to 13.4A (200W) to power drivers.
- 5V up to 5A (25W) to logic and I/O's (Inputs and Outputs).

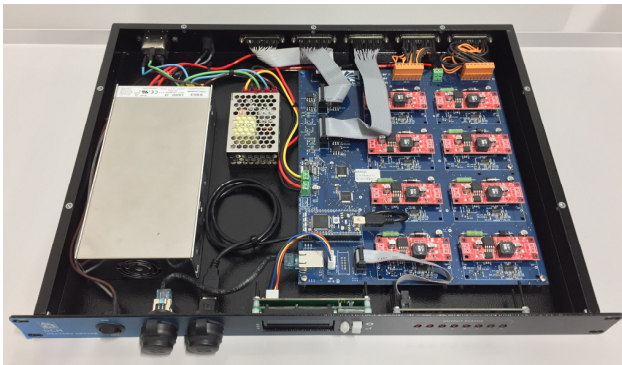


Figure 3: Mechanical Assembly.

The front panel, shown in Fig. 4, displays channels status, provides a main switch, ethernet input and USB input for firmware updates.



Figure 4: Front Panel.

At the rear panel, shown in Fig. 5, the AC line input and 2A fuse are connected to power supplies and 5 25-pin Dsub connectors provide output power to heaters and I/O's to controller: Control Input, Failure Output, Interlock/Enable Input, Power Output (2x).

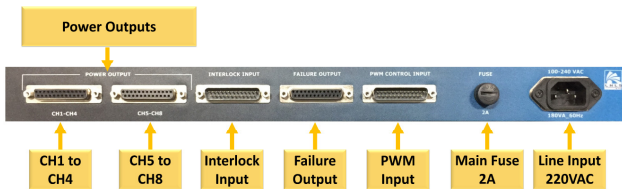


Figure 5: Rear Panel.

RESULTS

Electronics characterization

Due to hardware limitations, the output response is linear from 10% to 85% PWM duty cycle, as shown in Fig. 6, obtained delivering power to 20Ω loads. PWM frequency has been adjusted to 1kHz.

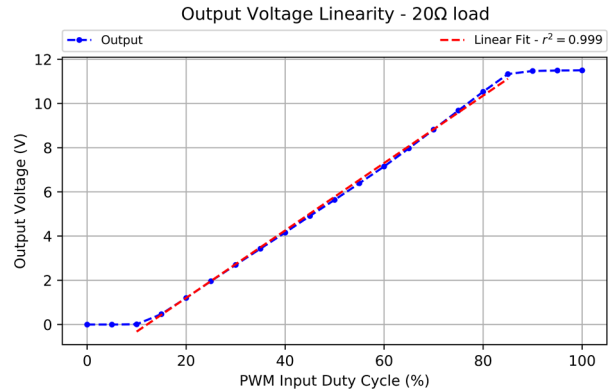


Figure 6: Output Linearity.

As mentioned in Hardware Design section, the driver bandwidth is limited by the Sallen-Key filter, designed to cut-off over 16Hz. Figure 7 shows driver frequency response, that has been obtained using a sinusoidal modulated 1kHz PWM signal delivering power to 20Ω loads. The sinusoidal signal modulates from 20% to 80% duty cycle with 100mHz to 100Hz variation. The normalized output refers to peak-to-peak AC load voltage at a given frequency.

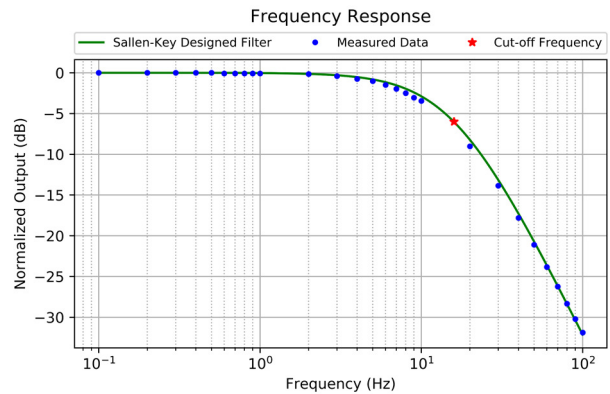


Figure 7: Single-channel Frequency Response.

The null-input output noise presents 100kHz 60mVpp spikes, shown in Fig. 8. At this condition, 31.75mV DC voltage is applied to 20Ω loads.

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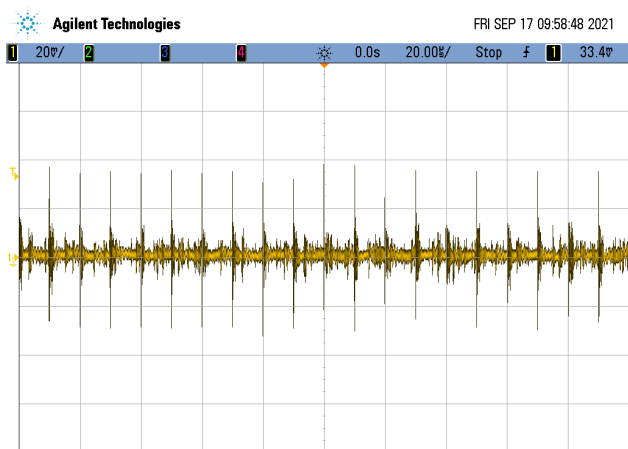


Figure 8: Output Voltage (Shorted-input and 20Ω load, AC coupling).

The output noise worst case occurs at 50% duty cycle input, 20mVpp spikes at 1kHz PWM frequency are shown in Fig. 9. In this condition, the driver delivers 5.89V to a 20Ω load.

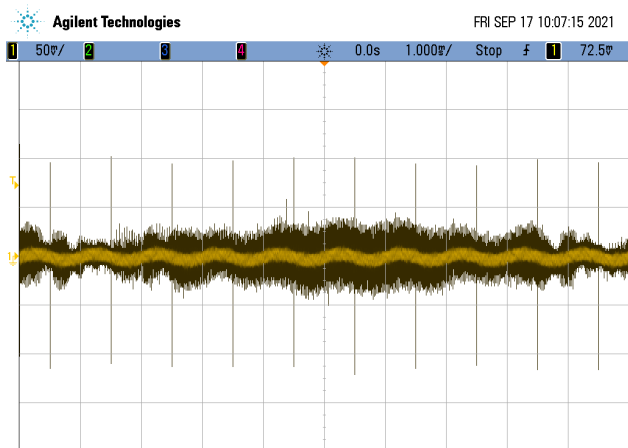


Figure 9: Output Voltage (1kHz 50% PWM Input delivering 5.89V to 20Ω load, AC coupling).

Temperature variations involved in thermal systems are usually long-term changes, thus tens of mV spikes at kHz frequencies does not affect overall performance.

The enable input is necessary to avoid unexpected over-temperatures in case of controller's failure. The output rise and fall times have been obtained by adjusting 100% duty cycle PWM inputs and applying a 5Hz square wave to enable inputs. Results are shown in Table 1.

Table 1: Enable Input Timing Performance

Enable	95% Settling Time
Rise edge	44ms
Fall edge	51ms

Field Application Results

The heaters driver is employed in several optical devices at Sirius beamlines. The simplified block diagram of the Double Crystal Monochromator (HD-DCM) [3] thermal management control system is presented in Fig. 10, using a NI CompactRIO [11] as main controller:

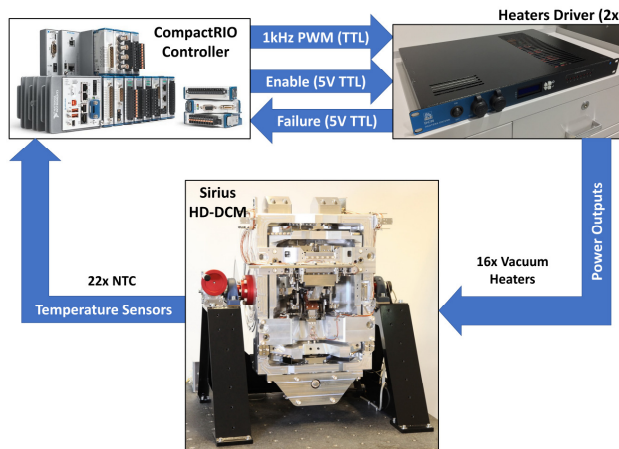


Figure 10: Sirius HD-DCM heaters driver application simplified block diagram.

A closed loop 24-hour long-term thermal stability is shown in Fig. 11, spotting DCM crystals temperature sensors during a regular user shift at EMA (Extreme condition Methods of Analysis) beamline [12]:

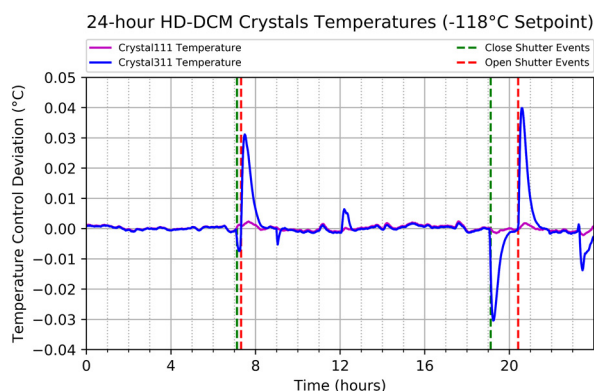


Figure 11: 24-hour HD-DCM crystal temperature measurements.

There is a strong correlation between variations and gamma shutter events, nevertheless crystals temperatures remain below 0.05°C deviation over 24 hours.

The HD-DCM thermal system characterization and control loop tuning are not intended to be presented at this paper, however related works [4, 13] discuss this subject in-depth.

CONCLUSION

This work presented the hardware design concepts and results about a multi-channel heaters driver, intended to be used at beamlines optical devices, such as mirrors and monochromators. The driver is capable to deliver up to 18W per channel at 12V (36W per channel at 24V) simultaneously to eight ohmic heaters. The output power is controlled by 5V PWM signals that can be easily integrated to any digital controller.

In addition, 5V TTL failure outputs signalize malfunction heaters and enable inputs turn off power outputs 51ms afterwards a falling edge. An embedded webserver is

implemented to allow fast diagnostics and a TCP socket is available for EPICS infrastructure integration.

Power outputs noise levels have not significant influence for thermal systems, typically characterized with long-term variations.

The first 20 units production set currently being used in first 6 Sirius` beamlines were manufactured in 2018. In 2021, 12 additional units have been produced for upcoming beamlines. Driver hardware failures have not been reported in the past years, supporting driver high reliability, usually an essential requirement for thermal management systems.

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