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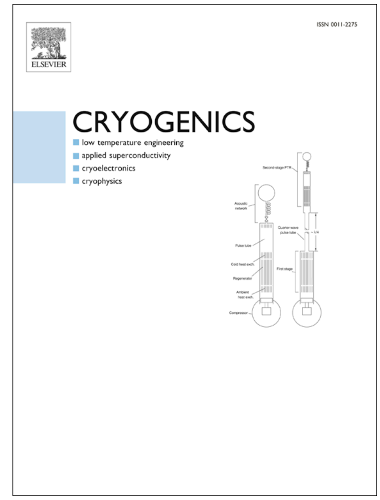


# Cryogenic low-dropout voltage regulators for stable low-temperature electronics

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# Cryogenic low-dropout voltage regulators for stable low-temperature electronics

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**Abstract**

To enable scalable quantum computers, it has been proposed that the quantum–classical interface has to be integrated and operated at deep-cryogenic temperatures. Common to all electronics is the power management and distribution through the system. These systems are currently powered from room temperature supplies, thus requiring long interconnects. This results in a significant and fluctuating voltage drop from the supply to the electronics. Especially sensitive systems, such as analog-to-digital and digital-to-analog converters that are needed for the read-out and control of the quantum processor, are thus limited in performance by the stability of the voltage regulation at room temperature.

In this paper, we propose the design and use of voltage regulators at cryogenic temperatures (down to 4 K), close to the actual load. As no commercial regulator was found to work below 90 K, we implemented an ad-hoc low-dropout regulator with commercially available components that operate at 4 K. Its output voltage varies with less than 0.2% over the complete temperature range and it can regulate loads within 1 mV/A.

*Keywords:* Voltage regulator; LDO; reference; operational amplifier; MOS; cryogenic.

## 1. Introduction

Cryogenic electronics has been studied for the past decades, mainly for space, radio astronomy and physics read-out applications [1–4]. With recent advances in quantum technologies, the use of cryogenic electronics has intensified. Since quantum technologies, in particular quantum processors, rely on extremely low temperatures to exhibit the required quantum phenomena (entanglement and superposition) [5], electronics at low temperatures are required for signal amplification and potentially for the read-out and control of qubits [6].

Operating conventional electronics at deep-cryogenic temperatures as low as 4 K is challenging, as the properties of active and passive components are significantly altered. For example, CMOS transistors exhibit a higher mobility, a higher threshold voltage and a steeper subthreshold slope, though they remain functional even at temperatures as low as 100 mK [7, 8]. Bipolar transistors, on the contrary, suffer from silicon freeze-out at low temperatures and cease operation between 70 K and 90 K [9].

Several electronic systems have been demonstrated at deep-cryogenic temperatures: low-noise amplifiers [10, 11], analog-to-digital converters [12] and even complete field-programmable gate arrays [13, 14]. For all these devices, the voltages are supplied and regulated at room temperature. As the distance into a cryogenic system is usually not infinitesimal (compared to room temperature with on-board regulators), and with cryogenic cabling with non-negligible impedance, there can be a significant voltage drop. Moreover, this drop constantly fluctuates with the activity of the electronics. Especially for sensitive applications, this limits the performance, as the parameters of the electronics are continuously changing. These problems have been demonstrated in [15] for a cryogenic FPGA-based ADC system. A better solution would be to use cryogenic regulators, close to the actual load.

In the past, several attempts were made to implement cryogenic voltage regulators, but none were shown to operate at deep-cryogenic temperatures. [16] demonstrated that simple shunt regulators based on Zener diodes operate stably down to 100 K. Furthermore, low-dropout (LDO) regulators were shown to operate down to 77 K [17]. [15] has not found any commercial regulator to operate below 90 K.

In this article, we implement and characterize low-dropout regulators operating at temperatures as low as 4 K, built from commercially available devices. First, in Section 2, a study of commercial voltage regulators is undertaken, and our proposed LDO is introduced. In Section 3, several discrete components required for the LDO are characterized over temperature. We then highlight the results of our LDO in Section 4 over a wide range of temperatures, but focussing on operability at 4 K. Conclusions are drawn in Section 5.

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