Design of High Dynamic Range Preamplifiers for a Diamond-based Radiation Monitor System

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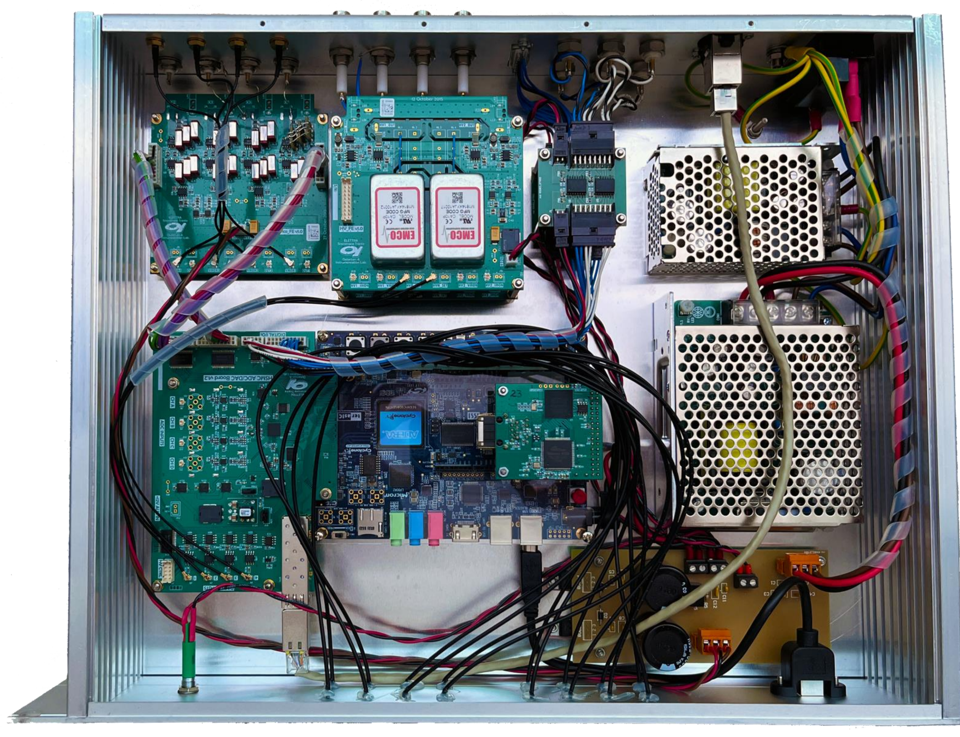
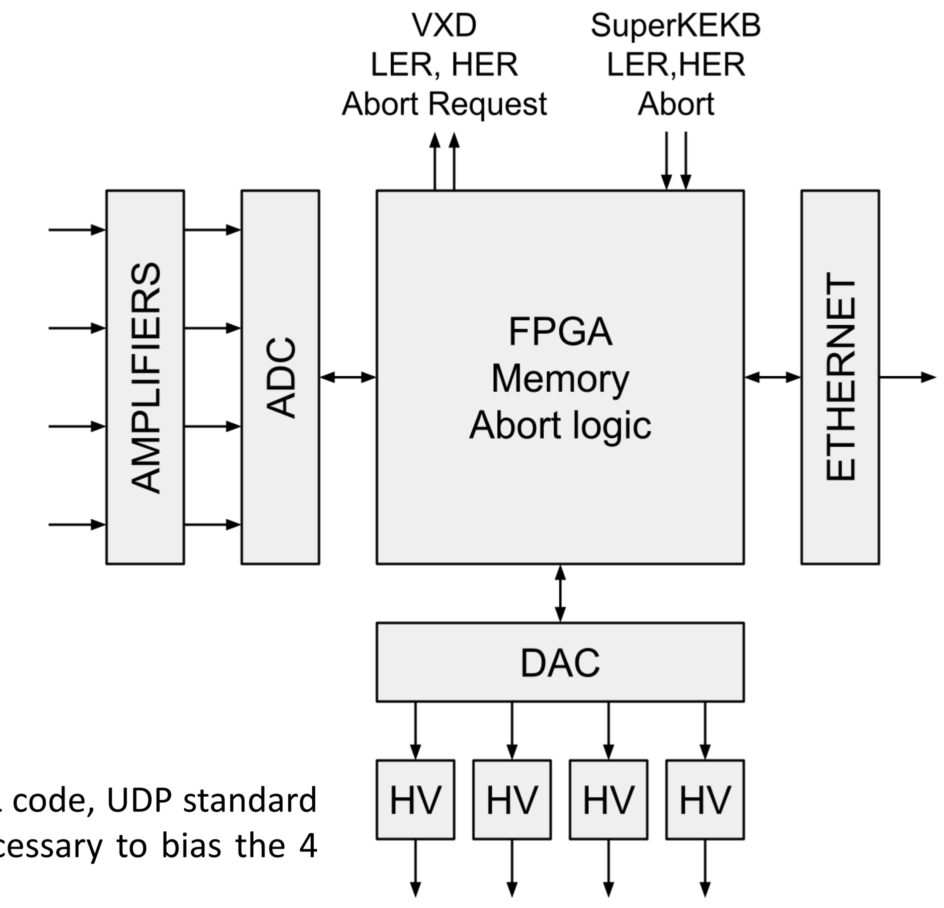
Introduction

SuperKEKB hosts Belle II, the first super B-Factory experiment, designed for precision measurements of weak interaction parameters for finding New Physics beyond the Standard Model of particle physics. The inner Belle II employs two types of detectors, namely microstrip and pixel sensors, which are silicon based. The main concern is to reduce their performance degradation caused by radiations exceeding 20 Mrad (MGy). Indeed, the absorption, in short time intervals, of significant dose rates from the inner detector parts can cause their irreversible damage. To reduce these risks, continuously monitoring radiation levels throughout the experiment and signaling abort requests is fundamental. The main abort signal is generated by the central control room after receiving abort requests from the local control rooms, indicating abnormal accelerator and/or beam conditions.

Diamond Control Unit



The current monitoring instrument named DCU (Diamond Control Unit) is an FPGA based system capable of handling up to 4 Diamonds Sensors for both electron and positron monitoring. Currently there are 7 DCUs (Diamond Control Unit) with 4 diamonds each, that are monitoring the High Energy Electron Ring (HER) and the Low Energy Positron Ring (LER).
Figure on the right shows the block diagram of the system, and figure on the left is a picture of the assembled unit.
The amplifiers convert the input current in a voltage and filters the signals for each of the 4 channels. One important aspect of the transimpedance stage (TIA) is the variable gain obtained, by switching between different feedback networks which are selected by FPGA controlled relays. The TIA's operational amplifier is a LTC 6268, a low noise 500 MHz FET input amplifier with low input capacitance and low bias current. The filtering stage is implemented with an OPA211, low power, low noise density precision amplifier. The bandwidth is selected with the same technique as gain switching. For the analog to digital conversion the AD9653 is used. It is a quad, 16-bit, 125 MSPS ADC with an on-chip sample-and-hold circuit. It is also equipped with an SPI user control interface for different features.



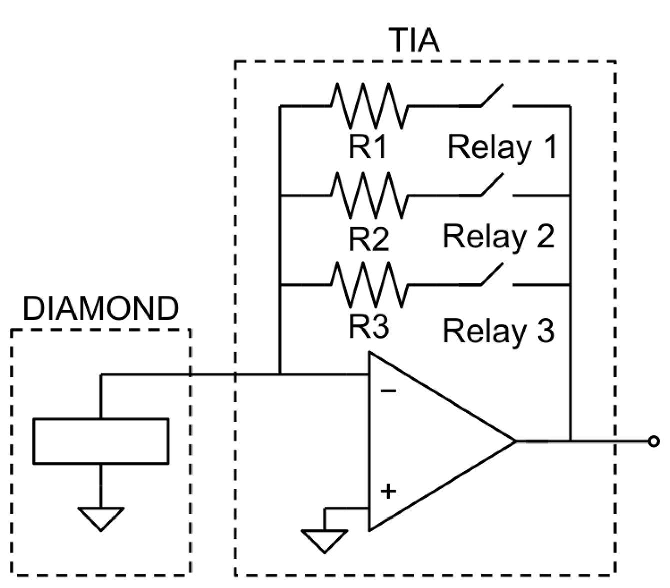
To provide an ethernet connection to the DCU a SFP interface was installed. This transceiver supports the Ethernet Gigabit Protocol; with a specific Verilog HDL code, UDP standard was implemented for the exchange of data and commands to and from the DCU. The HV Bias board is responsible for the generation of the 4 voltages necessary to bias the 4 diamonds. The control signals are driven by the DACs, situated on the ADC/DAC board which are in turn configured by the FPGA.
Assuming a sampling frequency of the current to voltage signal of 50 MHz, the sum of 125 samples is available every 2.5 us. These sums are defined "400 kHz Data" and are stored in a circular DDR memory.
The stored data are further accumulated in groups of 40000, to obtain the sum of 5000000 values defined as "10 Hz Data". In the event that "400 kHz Data" value is greater than a predetermined threshold value for a predetermined duration, "Alarm" signals are generated and the data storing is stopped. These signals are sent to the control unit which can decide to switch off the beam. When this happens the control unit generates a proper interrupt signal which is sent to all of the machine systems. "10 Hz Data" can continuously be read at 10 Hz with the possibility of detecting a portion of these with a proper flag. The diamond-based system has been providing useful information on beam losses in the interaction region, used for accelerator tuning (injection, collimators), estimates of beam-induced background composition, and integrated radiation doses in the VXD (Vertex Detector) region. However there are some evident limitations of the system. In this paper we will focus mainly on two of the most important ones: the dynamic range and speed of gain switching.

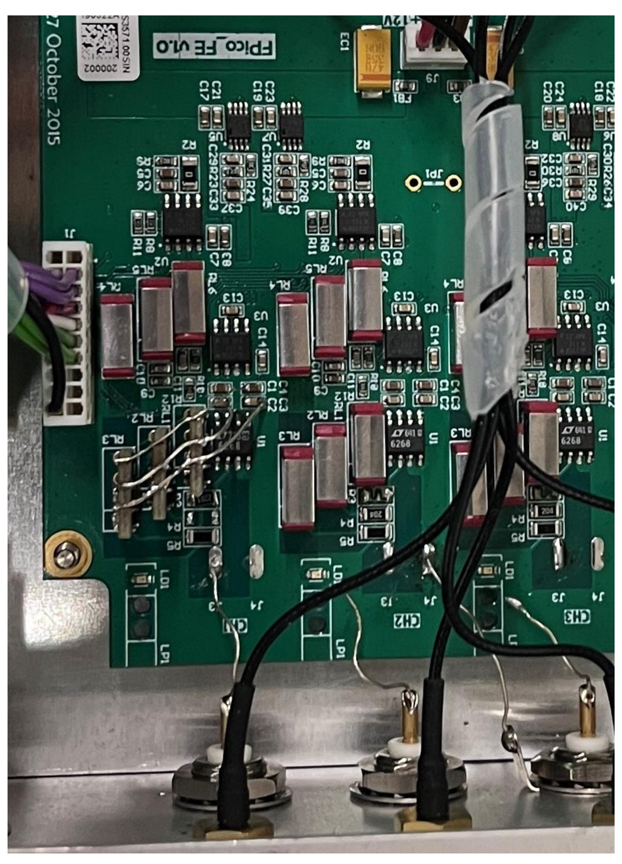
Proposed Circuit

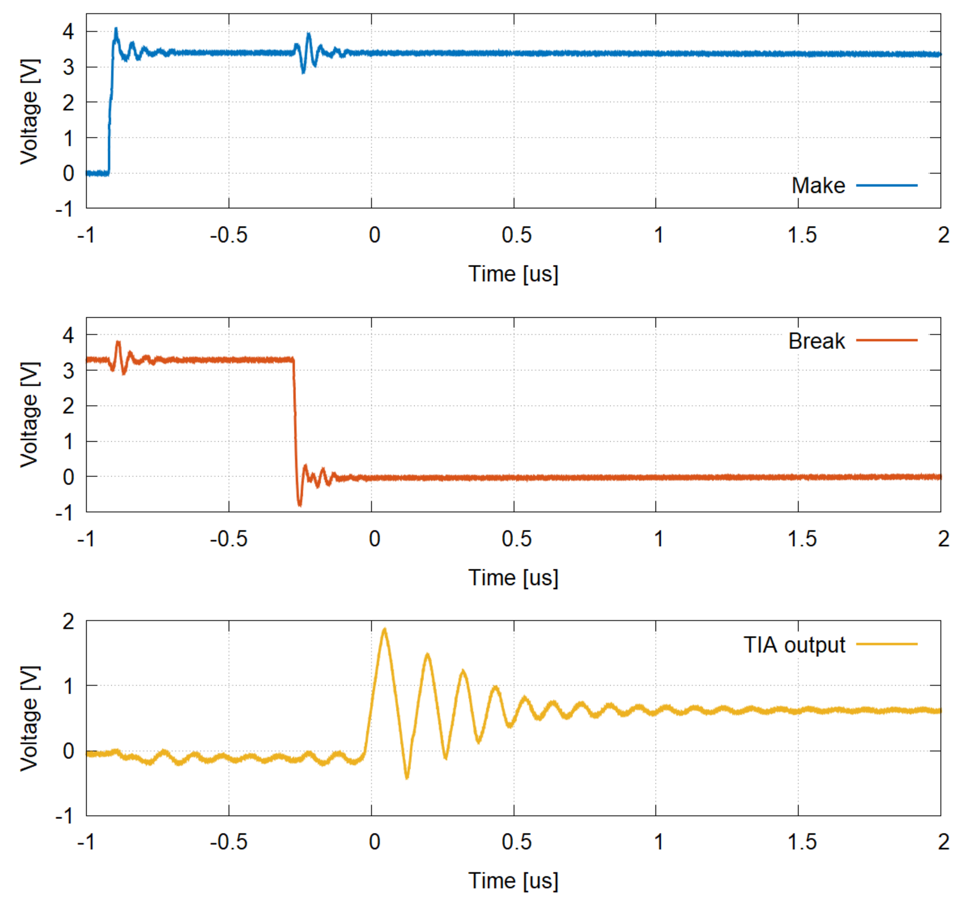
The DCU dynamic range is not sufficient to accommodate all of the requirements. In particular:

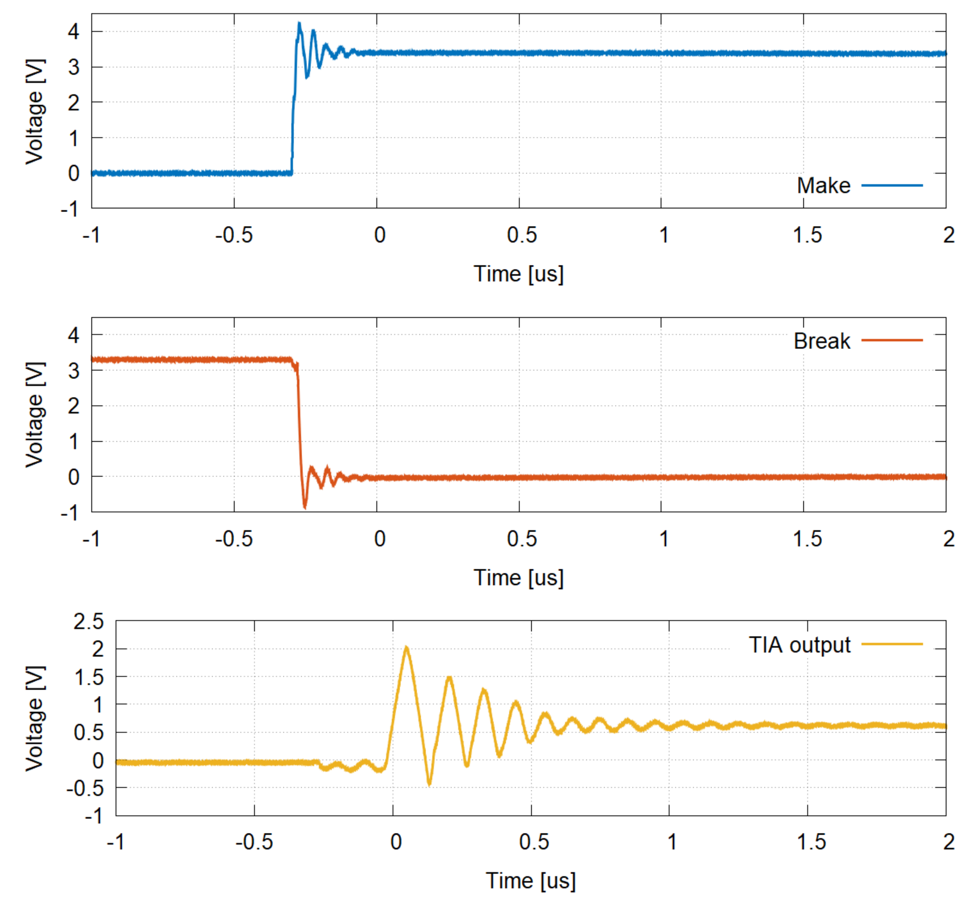
1. accelerator tuning needs measurements of dose-rates down to the order of 1 mrad/s, with a 10% precision of about 0.1 mrad/s, corresponding on average to about 3 pA;
2. beam losses correlated with aborts can reach or exceed 10-100 krad/s, corresponding to currents of the order of several milli-ampere;
3. in continuous injection mode, the beam-losses peak during short time intervals at values exceeding the average losses by more than two orders of magnitude.

The separation of the functions of 20 detectors (6 DCUs) dedicated to monitoring smaller currents in range 0, and four detectors (one DCU) dedicated to generate beam aborts on large signals in range 2, is a compromise solution, working only to some extent; in particular, injection spikes still saturate range 0. A wider dynamic range is needed.
To satisfy the request an extra range was added, by increasing the number of resistors. The ranges were recalculated to provide a higher dynamic range, reducing both the possibility of front end saturation and the smallest input current detectable. To address the second limitation the analysis of which component contributes mostly to the time necessary to switching gains has been performed. Due to their electromechanical working principle the commutation time for relays is the main cause that contributes to the switching duration. In addition, it is mandatory to take into account the fact that a gain switch requires a two step process known as "make before break" to avoid an open feedback. This process consists in enabling the relay of the desired gain (make) before disabling the relay of the undesired gain (break), increasing the switching time. This means that the times to pass from one range to another are of the order of several milliseconds, which prevents the continuity of following the temporal evolution of the current when it takes place on several ranges. The adopted solution replaced the relays with high-speed analog switches (TS5A 1066). These single-pole single-throw (SPST) switches have an on time of 4.8 ns maximum and an off time of 3 ns maximum. Comparing the switching time between the current and past solution it is evident how much time is saved.
Figures below show the "make" and "break" signal and the corresponding TIA output; the two images differ in the duration of the make-break process. Analyzing the TIA's output some damped oscillations can be detected. This phenomena can be assigned to two main factors: charge injection from the switch and the frequency response of the closed loop system to the make (break) step. These factors contribute to extend the duration of the gain transient to about 1.5 microseconds, still more than 1 order of magnitude lower than that of the previous solution.
Finally, thanks to the high speed switches, this approach allows to identify (and therefore give an alarm) much more quickly a sudden increase of the current. In fact, when a DCU is monitoring very low currents (pA order), it necessarily works in a very low analog bandwidth configuration (kHz order). In this situation the problem is not given by the speed of the switches, but by the limited rise time of the front end: a possible rise in the current would be filtered by the amplifier, so identifying alarming values too late. The architecture proposed here would allow periodical sampling (for example every few tens of us, depending on the maximum expected current rise times) of the current in the least sensitive range (and therefore with the highest analog bandwidth): thus any reading other than 0 pA in that range would indicate a sudden increase in the current, since - given the dynamics of the system - even the values relating to the least significant bits in the maximum range are several times greater than the full scale of the lower ranges. This periodic reading would only affect the number of accumulated samples ("400 kHz Data") which, once every "N" would be only 50 instead of 125, introducing a small increase in noise on that single sample (being averaged over a lower number of values), however almost negligible. Although the proposed solution is definitely better, it needs further investigation to better characterize the charge injection and its effects on the system.









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FUTURE WORK

- Fully characterize the proposed circuit and charge injection issues
- Development of appropriate Verilog HDL code
- Investigate current integration approach