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An ion beam guidance control tool proposal

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Abstract: A versatile tool for ion beam line up is proposed. This tool will be used at the CERN-ISOLDE facility in negative ion experiments. Apertures in the ion optics are used to guide the beam and traditionally the current is measured on the apertures in order to detect the presence of an ion beam. By slitting the aperture into four separate pieces, the aperture current can also be used to determine the direction of the misalignment and the size of the ion beam diameter. A 4-channel pico ammeter with optical LED indication of the ion beam position is suggested in an analog/digital hybrid design. The design utilizes two charge/current-to-digital chips in a microcontroller design.

Keywords: Ion optics, aperture, pico ammeter, guarding technique, microcontroller

1. Introduction

In ion-beam experiments, the process of lining up the ion beam is typically a long-suffering and tedious job since it requires guiding the ions through a long range of ion optics [1]. Fig. 1 illustrates an example of the kind of ion optics that is frequently used.

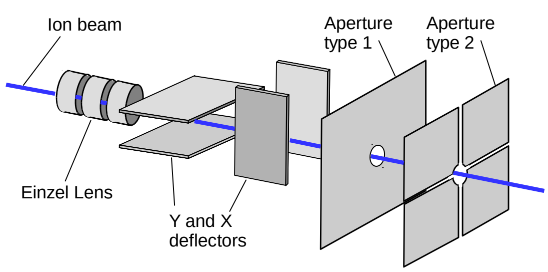

Fig. 1. Ion beam optics example

Enzel lenses are used to focus the beam and deflector plates are used to control the beam trajectory in the X and Y directions. Apertures are used to narrow the beam diameter but are also useful indicators of the beam quality and direction. Ideally, the current registered on any aperture plate should be zero. The apertures' current is a crucial parameter to monitor during ion beam line-up.

Ion beam currents are of the order of nano amps at best and sub-pico amps at worst and hence this requires sensitive ammeters with careful design layouts.

Commercial sub-pico ammeters are very expensive; a desktop instrument could cost as much as $5,000 [2] and in order to line up an ion beam, multiple ammeters are required. For these reasons, a versatile, non-expensive multi-channel ammeter with pico ampere capability has been requested.

There are in principle two basic ammeter circuits; the shunt ammeter and the feedback ammeter [3]. This work is based on the DDC112 chip from Texas Instruments [4] which contains two capacitive-feedback ammeters [5]. The instrument should primarily be used to line up the ion beam through the ion optics to the target. Hence the accuracy, resolution and absolute values are not crucial but the tool should be able to indicate ion currents of the order of 1 pA or less.

1.1. Problem description

A typical aperture plate has a circular hole in the center (left side of Fig. 2). This aperture design will narrow the ion beam and by tapping off its current an indication of misalignment is achieved but it will not reveal the direction of the misalignment. For that reason, the aperture is slit into four separate pieces, see Fig. 2, right side.

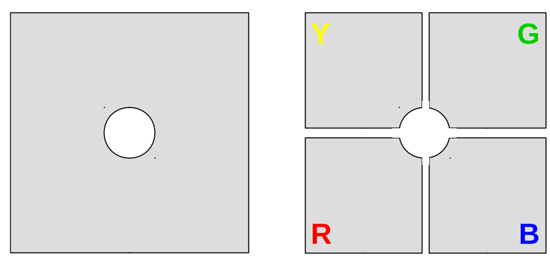

Fig. 2. Ion optics apertures

By measuring the current separately on all four aperture plates, it is possible to determine the direction of the misalignment and also draw some conclusions about the beam quality; a large current on one plate indicates a misalignment in that direction and a current on all plates indicates a wide beam. The disadvantage is that in order for the quad-aperture to be really useful, it requires that the four currents are measured simultaneously; an inexpensive four-channel pico ammeter is required.

1.2 Proposed solution

An analog/digital hybrid 4-channel picoamp tool will be designed. Each one of the four aperture plates will be color-coded (Yellow, Green, Red and Blue). Four pico ammeters will be implemented on the same pcb based on two DDC112 chips. The digitized current is transferred to a microcontroller via a synchronous serial interface (SPI compatible) and can optionally be relayed to a host computer, but this is primarily a stand-alone desktop instrument intended as an ion beam guiding tool. The instrument panel will have four sets of four colored LEDs as illustrated in figure 3.

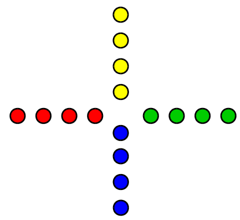

Fig. 3. The instrument panel has four arrays of LEDs

Each colored LED array corresponds to the ion current on the corresponding aperture plate. This will offer a convenient optical indication of the ion beam (mis)alignment. Some examples are illustrated in figure 4 through 6. Notice that a high degree of activity on the LEDs indicates a misaligned or broad ion beam and a low activity (or no activity) indicates a clean passaged through the aperture.

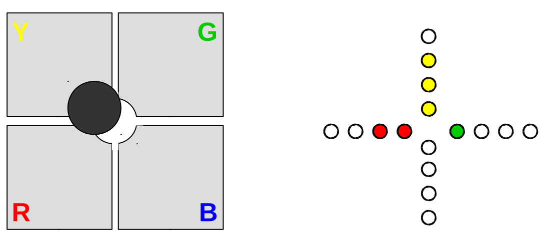

Fig. 4. Ion beam too broad and too far to the upper left

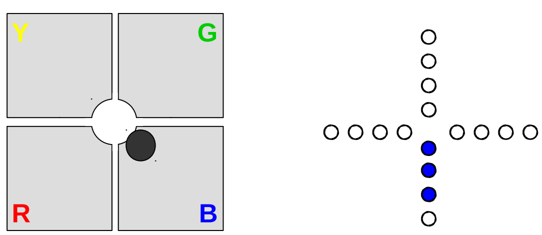

Fig. 5. Ion beam too far to the lower right (but size is probably ok)

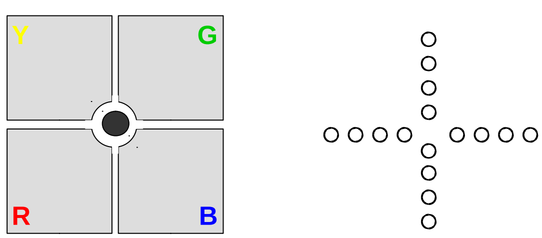

Fig. 6. No LEDs turned on indicates that the ion beam passes the aperture in the center of the Z direction (unobstructed)

2. Design

2.1. Hardware

At the core of the design are two DDC112 chips from Texas Instruments [4]. This 28-pin SO-chip has two charge input channels (sharing the same 20-bit ΣΔ ADC) and each channel comprises two classical analog charge integrators; while one is being digitized, the other one is being charged. Hence, the input charge/current is seamlessly monitored. The range depends on the feedback capacitor and the integration time. Internal feedback capacitors are available but external capacitors can also be used. The integration time is provided by the user by toggling the CONV pin. Figure 7 illustrates the pin layout and figure 8 is a (simplified) model of input channel 1.

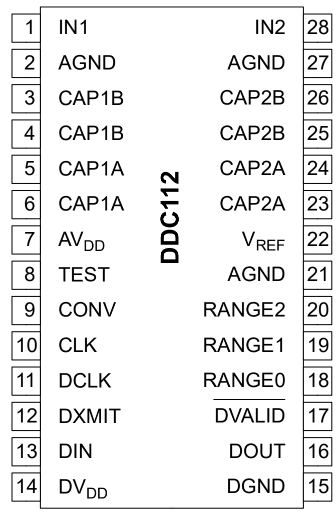

Fig. 7. Current-to-digital converter (DDC112)

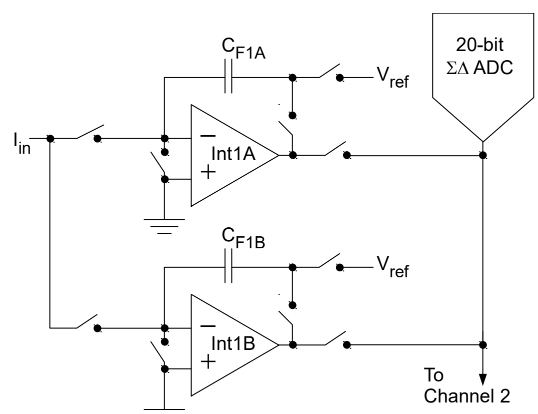

Fig. 8. Charge-input integrator

The switches in figure 8 alternately charges/ discharges the feedback capacitors and forward the integrators' outputs to the ADC for digitalization. The switches are controlled by an internal synchronous state machine in order to charge/discharge the capacitors and to relay the two integrator outputs to the ADC alternately. Figure 9 illustrates the timing diagram; input integrators A (on both channels) are integrated simultaneously while integrators B are being digitized by the AD converter. The $\overline{\text{DVALID}}$ signal indicates when both channels have been digitized and data is stored in a 40-bit shift register.

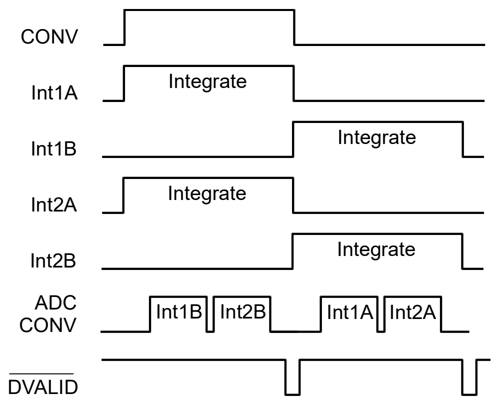

Fig. 9. Integration timing diagram

The user retrieves data through the synchronous serial interface (pins DCLK and DOUT). This is illustrated in figure 10 [6].

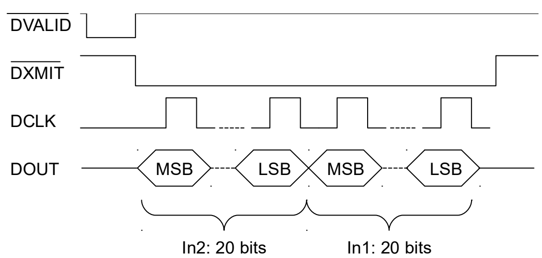

Fig. 10. Timing diagram of data retrieval

Transmission is initiated by the user setting the $\overline{\text{DXMIT}}$ signal low and data is shifted out on the DOUT pin synchronous to the rising edges on the DCLK pin. Notice in figure 10 that the $\overline{\text{DVALID}}$ signal is automatically reset when transmission is initiated.

The primary concern in this design is to detect negative ion currents or electrons. However, sometimes positive ion experiments are conducted and for that reason the instrument needs to be able to detect both positive and negative currents. The DDC112 chip can easily be converted to a bipolar ammeter by adding an offset current to the input, see figure 11 [7].

The ADC in the DDC112 chip has a resolution of 20 bits; if the input current equals the full scale current (I_{FS}), the ADC output will be 0xFFFFF (2^{20} -1). V and R in figure 11 will produce an offset current V/R and this current is added to the sensor current. In order to make the instrument bipolar, V and R are dimensioned so that $V/R = I_{FS}/2$.

The two currents from the sensor and the offset branch are added in the junction and the sum of the two currents are fed to the DDC112 chip. The consequence of that is that when the sensor input current $I_{SENS} = -I_{FS}/2$, the input current to the DDC112 chip is zero. Table 1 illustrates the consequence of the offset current. From table 1 it is obvious that the instrument is now bipolar.

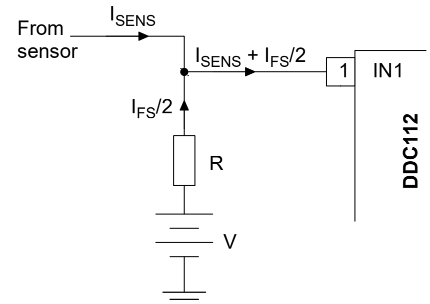

Fig. 11. Bipolar input

Table 1. ADC output vs sensor current

I_{SENS}	Input current	ADC output
$I_{FS}/2$	I_{FS}	0xFFFFF
0	$I_{FS}/2$	0x7FFFF
$-I_{FS}/2$	0	0x00000

2.2. Current range calculations

The aim is to create a bipolar instrument with a full-scale range of ±50 nA. Due to the bipolar circuitry in figure 11, this means that the maximum input current to the DDC112 chip is 100 nA. With a 20-bit ADC resolution, the current resolution will be

$$\frac{100\text{ nA}}{2^{20}} = 95\text{ fA} \quad (1)$$

which is less than the expected noise level (≈ 2 pA).

If we choose internal feedback capacitors 87.5 pF, the required integration time for a full-scale range of 100 nA is [4]

$$T_{int} = \frac{0.96 \times V_{ref}}{I_{FS}} \times C_F \quad (2)$$

$$T_{int} = \frac{0.96 \times 5.0}{100 \times 10^{-9}} \times 87.5 \times 10^{-12} = 4.2\text{ ms}$$

This time is important not only for the integration; from figure 10 we can see that in order to retrieve the old data before the next data is digitized, 40 clock pulses must be generated during this time. Hence, the minimum clock rate on the synchronous serial interface is

$$f_{DCLK,min} = \frac{40}{0.0042} = 9523\text{ Hz}$$

In order to allow for some overhead, the DCLK clock rate will be at least 20 kHz.

2.3. The microcontroller design

The two DDC112 charge integrating chips are connected to an 8-bit PC16F1779 microcotroller [8] as described in figure 12.

Notice in figure 12 how the two DDC112 chips have been cascaded; the data of the first one will be shifted through the second chip. The data is transferred to the microcontroller via a synchronous serial interface and from figure 10 it is clear that signals DXMIT, DCLK and DOUT complies with a standard SPI interface (or a clocked USART interface).

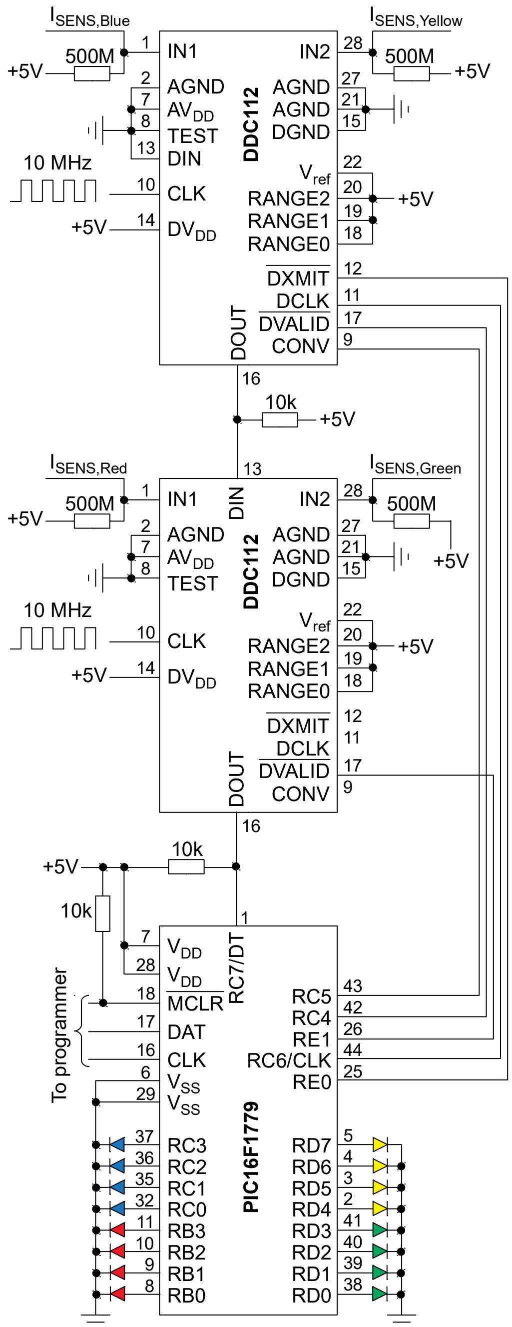

Fig. 12. 4-channel pico ampmeter

In this first prototype, data will be translated to different diode levels, four on each collimator plate, and the high-resolution DDC112 chip may appear to be an overkill. However, the use of the DDC112 chips makes the design easier (compared to using op amps) and since they make the absolute current values available (high-resolution), it would be easy to modify the design to either display them locally on an LCD or transfer them to a host computer. Primarliy, knob will be added to allow for at least three different full-scale ranges (50 nA, 5 nA and 1 nA).

In all sub-nano current designs, it its important to protect the inputs from stray wire capacitances. In order to facilitate an expedient pcb layout for this purpose, the two analog inputs are located at the top of the DDC112 chip and the next two pins are analog ground [3]. This makes it easy to surround the analog inputs by a shielding copper layer on the pcb [4] as illustrated in figure 13.

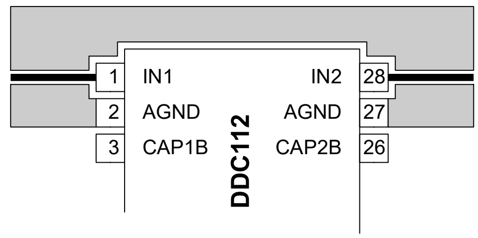

Fig. 13. Input signals are protected from stray capacitances

3. Related/previous work

The DDC112 chip is a common solution to low-current/low-charge problems. It has been used in precise current integrators in scanning tunneling microscopes and atomic force microscopy [9], measuring sub-picoamp currents from Faraday cup detectors [10], ion beam monitoring in deep proton lithography [11] and as photometric analysers in optical telescopes [12]. The idea explored in this work, where an ion optics collimator plate is split into four symmetric pieces, was first suggested by Snowden and Barber [13] but their application was for microamp currents and used shunting resistors in a bridge to detect the current. The main difference of this work is that it utilizes the versatile DDC112 chip (based on charged integration), the option to transfer absolute current values to a host computer and the convenient visual indication of the beam position fascillitated by the front panel LEDs.

4. Conclusions

A microcontroller based, 4-channel pico ammeter is being developed for the purpose of facilitating convenient line up of ion beams in particle physics experiments at the GANDALPH setup at the CERN-ISOLDE facility. Instead of devolving to discrete feedback opamp solutions, two, 2-channel charge integrating chips are employed. This solution is less expensive, more roubst, simplifies pcb layout and facilitates a digital interface for retrieving the absolute current value.

A prototype will be presented in October 2019 and beta testing will be performed in the Atomic Physcis Laboratories in Gothenburg during the fall before the instrument is shipped to the CERN ISOLDE facility later this year.

5. Acknowledgement

The author has no conflict of interest to report.

References

[1] D. A. Skoog and J. J. Leary, Principle of Instrumental Analysis, 4th ed., Orlando, Florida: Saunders College Publishing, 1992, pp. 429-432.

[2] Tektronix Inc., "Keithley Series 6400 Picoammeters," Tektronix, Inc., 19 March 2018. [Online]. Available: https://www.tek.com/keithley-low-level-sensitive-and-specialty-instruments/keithley-series-6400-picoammeters. [Accessed 19 March 2018].

[3] Keithley Instruments, Inc., Low Level Measurments Handbook, 6th ed., Cleveland, Ohio: Keithley Instruments, Inc., 2004.

[4] Texas Instruments, Burr-Brown, "DDC112: Dual Current Input 20-bit Analog-to-Digital Converter," Texas Instruments, 2004.

[5] A. A. Mortuza, F. Pervez, K. Hossain, S. K. Sen, N. H. Mia, M. K. Basher and S. Alam, "Pico-current Measurement Challenges and remedies: A Review," *Universal Journal of Engineering Science,* vol. 5, no. 4, pp. 57-63, 2017.

[6] J. Todsen, "Retrieving data from the DDC112," Burr-Brown Corporatino, Tucson, Arizona, 1998.

[7] J. Todsen, "Creating a bipolar input range fo rthe DDC112," Burr-Brown corporation, Tucson, Arizona, 1999.

[8] Microchip Technology Inc., "PIC16(L)F1777/8/9" Tucson, Arizona, 2015-2016.

[9] K. Raczkowski, T. Piasecki, M. Rudek and T. Gotszalk, "Design and evaluation of precise current integrator for scanning probe microscopy," *Measurement Science and Technology,* vol. 28, no. 3, pp. 1-9, 2017.

[10] S. Agosteo, E. Borsato, F. Corso, A. Fazzi, F. Gonella, M. Intrioni, I. Lippi, M. Lorenzoli, L. Modense, F. Montecassiano, M. Pegoraro, A. Pola, V. Varoli and P. Zotto, "Performance of a proton irradiation chamber," *Nucl. Instr. and Methods in Phys. Res. Sec. A: Accelerator, Spectrometers, Detectors and Associated Equipment,* vol. 664, no. 1, pp. 193-202, 2012.

[11] P. Vynck, B. Volckaerts, M. Vervaeke, H. Ottevare, P. Tuteleers, L. Cosentino, P. Fincchiaro, A. Pappalardo, A. Hermanne and H. Thienpont, "Beam monitoring enhances Deep Proton Lithography: towards high-quality micro-optical components," in *Porceedings of Symposium IEEE/LEOS Benelux Chapter*, Amsterdam, 2002.

[12] R. S. Romaniuk, "Space and High Energy Experiments Advanced Electronic Systems 2012," *Int. J. Electron. Telecomm.,* vol. 58, no. 4, pp. 441-462, 2012.

[13] K. Snowdon and C. Barber, "Simple accelerator beam position monitor," *J. Phys. E: Sci. Instr.,* vol. 12, no. 10, p. 923, 1979.

[14] Analog Devices, Inc., "Ultralow Input Bias Current Operational Amplifier, Rev. H," Analog Devices, Inc., Norwood, Maine, 2008.

[15] Analog Devices, Inc., "Monolithic Precision, Low Power FET-Input Electromieter Op Amp, Rev. A.," Analog Devices, Inc., Norwood, Maine, 1997.

[16] Microchip Technology, Inc., "PIC16(L)F1516/7/8/9," 2016. [Online]. Available: http://ww1.microchip.com/downloads/en/DeviceDoc/40001452F.pdf. [Accessed 23 March 2018].