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An Accurate Low Current Measurement Circuit for High-Resolution Energy Spectroscopy Systems

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ABSTRACT--- ***With the development of radioactive ion beam physics, heavy-ion beams have been applied to the treatment of deep-seated inoperable tumors in the therapy terminal of the Heavy ion Research Facility in Lanzhou (HIRFL) located at the Institute of Modern Physics, Chinese Academy of Sciences (IMP, CAS). An accurate low current measurement circuit was developed to monitor the beam current at 10fA range. The circuit consisted of a low current high sensitivity I/V converter with a dynamic bandwidth. A low offset voltage precision amplifier and new guarding and shielding techniques were used in the I/V converter circuit which allowed as to measure current up to 10fA with a current gain of 0.43 V/fA and noise less than 50 fA. This paper will also show a T-network configuration which was used for boosting bandwidth.***

Keywords--- Low beam current, I/V Converter, Operational amplifier, Bandwidth

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1. INTRODUCTION

The main works in CSR IMP Lanzhou are heavy ion beam accumulation, experiments related to cancer therapy, patients' treatment, mass measurement and prophase experiments on recombination [1, 3]. The main function of electron cooler in CSR was heavy ion beam accumulation. The accumulation efficiency was related with a lot of parameters of storage ring and electron cooler, such as the work-point setting, closed-orbit, electron density, and angle between electron beam and ion beam. At the beginning, the electron beam alignment was done to maximize the accumulated ion beam intensity. Since November 2006, up to 2012, 106 patients have been irradiated in the therapy terminal of the heavy ion research facility in Lanzhou (HIRFL) at IMP, where carbon-ion beams with energies up to 100 MeV/μ can be supplied and a passive beam delivery system has been developed and commissioned. A number of therapeutic and clinical experiences concerning heavy-ion therapy have been acquired at IMP. To extend the heavy-ion therapy project to deep-seated tumor treatment, a horizontal beam line dedicated to this has been constructed in the cooling storage ring (CSR), which is a synchrotron connected to the HIRFL as an injector to be analyzed by detectors, and is now in operation. A beam current monitor (BCM) was needed to calibrate these detectors. Beams applied to treatment are less than 1pA. These low beams current are modulated because of operating modes of a synchrotron and also suffer from poor accuracy. The previously therapeutic techniques in terms of beam delivery system developed for measurement of currents in this order of magnitude are limited in their bandwidth [2, 4].

This paper contains a description of an accurate ultra low current measurement circuit for the beam current monitor system. In detail the paper will describe the structure of femtoammeter based on noise analysis, offset voltage technique of the amplifier and introduction of a T-network with high sensitivity transimpedance for unlimited bandwidth. It also shows that the sense amplifier can sense currents and convert them to voltage while speeding up the time constant.

2. VERY LOW CURRENT MEASUREMENT CIRCUIT IN THE BEAM MONITOR SYSTEM

Fig.1. Shows the block of the heavy ion beam current monitor system. The accurate very low current measurement circuit consists of an I/V Converter and a GI. The current signal from the FC, which was pulsed for 3s a period of 20s, was converted into a voltage signal through a transimpedance amplifier, the output of which was integrated by the GI in order to measure the charge of the beam [2], [5]. Outputs of I/V Converter and GI were acquired by a data acquisition system based on PXI. The signals were processed by the local computer.

Compared to conventional current integrators [2], [6], which integrated the current from the FC by a GI directly, the novel circuit (I/V Converter) avoided many disturbances like leakage current of the feedback capacitor and charge injection of switches.

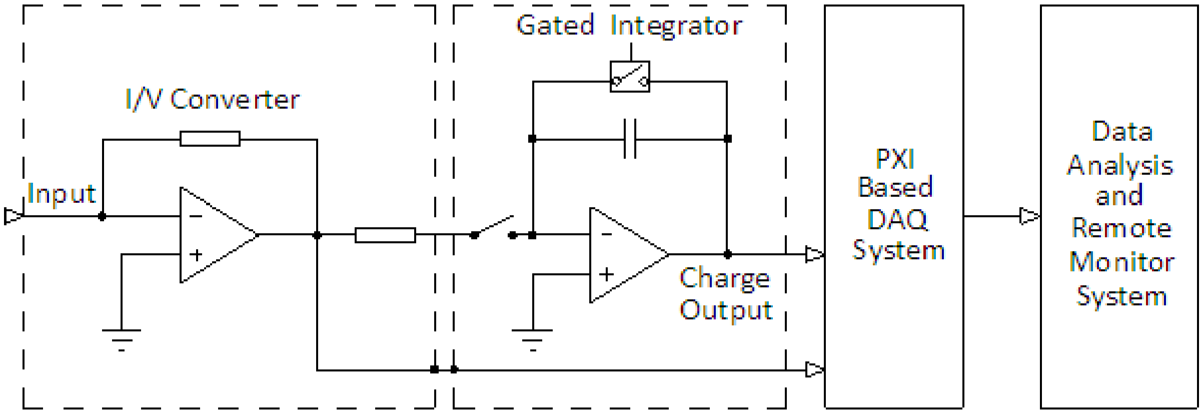

Fig.1. Block diagram of the heavy ion beam monitor system

3. THE DESIGN OF THE I/V CONVERTER WITH ULTRA LOW NOISE

3.1. Noise analysis of the I/V Converter

If we take into consideration disturbances shown in figure 2. The output voltage of the femtoammeter can be described by Eq. (1)

$$U_0 = -I_s R_f - (I_t + I_{na} - I_b - I_{nR}) R_f + \left(1 + \frac{R_f}{R_s}\right)(U_{oa} + U_{na}) = -I_s R_f + U_n \tag{1}$$

Where: I_b is the input bias current of the amplifier; I_{na} is the instantaneous value of the input noise current of the amplifier; I_t is the current coming from constructing and circuit elements (i.e. leakage of insulators, cables; printed circuit board) in transmission; I_{nR} is instantaneous value of thermal noise current of the scaling resistor; U_{na} is the instantaneous value of input noise voltage of the amplifier; also U_{oa} is the input offset voltage of the amplifier [7, 8].

The ideal solution is to be capable to neglect the effect of noise equation shown in the Eq. 2 from the Eq. 1.

$$U_n = -(I_t + I_{na} - I_b - I_{nR}) R_f + \left(1 + \frac{R_f}{R_s}\right)(U_{oa} + U_{na}) \tag{2}$$

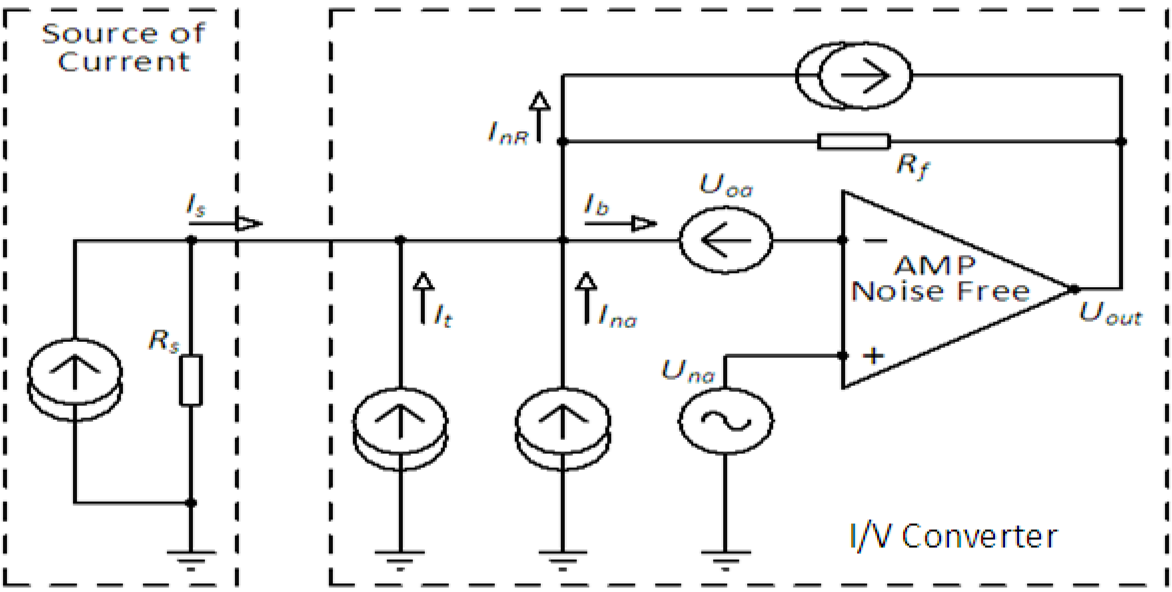

Fig.2. Schematic diagram of the low current I/V Converter including the dominant sources of noise

3.2 Structure of the I/V Converter

As can be seen in eq. (1) a low bias current, a low noise current, a low noise voltage and a low offset voltage are needed in order to minimize the noise figure of the femtoammeter. In order to address those issues, we developed a novel femtoammeter whose block diagram is shown in fig.3.

Fig.3 shows a current/voltage converter with that provides an open-loop unity gain bandwidth 250MHz. A precision amplifier with guaranteed bias current 1pA was used as the input stage and the equal input impedance was addressed for each input of amplifier (inverting and non inverting input amplifiers), to meet the tight design specification related to the input bias current.

Due to the stable open-loop gain of the amplifier, a compensation circuit which is based on the injection of an adjustable voltage or current into the circuit to compensate for the offset error worked well. This scheme does not introduce any additional imbalances in the input stage, so there is no degradation in drift, CMRR (Common-Mode Rejection Ratio), or PSRR (Power-Supply Rejection Ratio). With this circuit, the output offset voltage could be adjusted to less than ±65mV. The potentiometer, R_P, was used to drive the input guard ring.

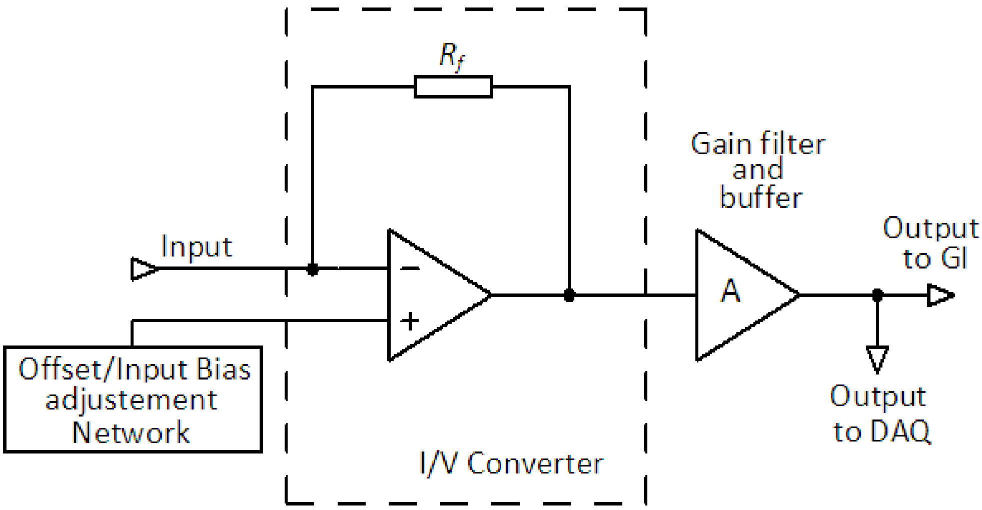

Fig.3. Block diagram of a transimpedance with a T-Network I/V converter

For measurement of current up to *10fA*, the transimpedance, which was equal to the feedback resistor, R_f, at low frequency, must be in the range of $10^{12}\Omega$. It is apparent that high-sensitivity applications may require unrealistically large resistances. Unless proper circuit fabrication measures are adopted, resistors with high resistance value and at the same time with small temperature resistance coefficient and voltage resistance coefficient will decrease the net feedback resistance and degrade the accuracy of the circuit. Figure 4 shows a widely used technique to avoid this drawback. For this reason the single feedback resistor R_f, was replaced by the circuit a T-network to achieve a current gain as high as 4.3mV/pA (or 4.3V/fA) with *1MΩ* high sensitivity without requiring unrealistically large resistance.

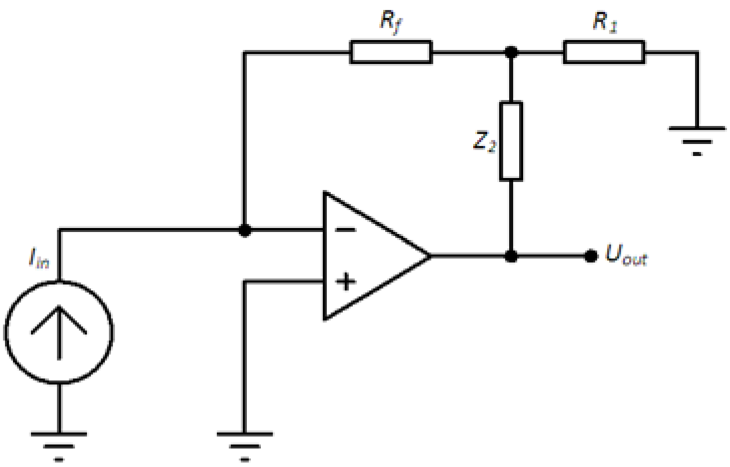

Fig. 4. High sensitivity I/V converter

3.3. Guarding and shielding techniques

Compare to the conventional structure, the figure 4 is realized with reasonable size of resistances, R_f and R_2, R_1 is made by a circuit of transistor MOS 2N7000, where the transistor is operating in the strong-inversion and deep triode region. The circuit in effect increases R_f by the multiplicative factor *k*. We can thus achieve a high sensitivity by starting out with a reasonable value of R_f and then multiplying it by the needed amount *k*, as can be seen in eq.3.

$$k = 1 + \frac{Z_2}{R_1} + \frac{Z_2}{R_f} \qquad (3)$$

$$U_{out} = -kR_f I_{in}$$

To meet the tight design specification related to the very low current I/V Converter, the chosen transistor MOS and the capacitor placed in parallel to resistance R_2 guard a new precision amplifier with a dynamic bandwidth, as can be seen in equation 4.

$$\omega_{c_0} = \sqrt{\frac{\omega_c(Z_2+A_0R_1)}{Z_2R_fC_i}} \qquad (4)$$

Thus, the sense amplifier can sense currents and convert them to voltage while speeding up the time constant for sensing from R_fC_{in} to $R_fC_{in}/(1+A_0R_1/Z_2)$ such that rapid changes in the input current are not filtered out. Such changes would be filtered out if we merely used R_f to directly convert I_{in} to V_{out}.

4. THE DESIGN OF THE NEW I/V CONVERTER

To get the total charge of the beam, we realize an offset voltage compensation circuit which introduced an offset in none inverting input of the amplifier, the schematic of this circuit is shown in figure 5.

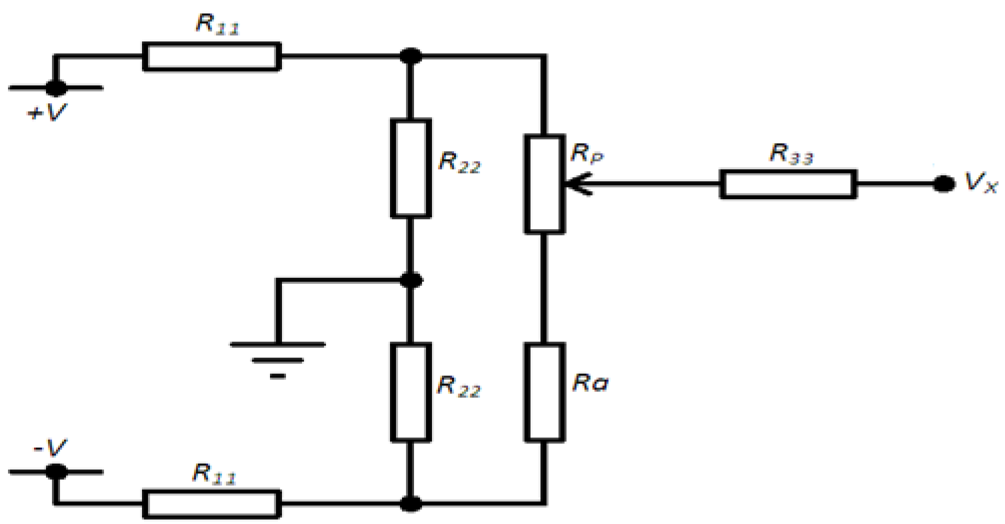

Fig.5. Circuit for compensation offset voltage

4.1. External offset-error nulling circuit for current-to-voltage converter

The most convenient point of injection of the correcting signal depends on the particular circuit. For current-to-voltage converter configurations of figure 4, we simply lift R_{33} off ground and return it to an adjustable voltage *Vx*. By the superposition principle, we now have an apparent input error of e_{off} + *Vx*, and we can always adjust *Vx* to neutralize e_{off}. *Vx* is obtained from a dual reference source, such as the supply voltages if they are adequately regulated and filtered. In the circuit shown, we impose $R_{22} << R_P$ to avoid excessive loading at the wiper, and $R_P >> Ra$ to avoid perturbing the existing resistance levels.

When the state of switches used in none inverting input of the amplifier is changed from the ground level to the output of the external offset error nulling circuit via the resistance R_{33}, the output of the current-to-voltage converter changed. Since it is known that the presence of the external offset error nulling circuit allows an adjust voltage to neutralize e_{off} (offset voltage). Thus by changing the adjusting output of external offset error circuit, the error of the output voltage caused by offset voltage of the transimpedance was reduced to less than $10\mu V$.

4.2. T-network to achieve high sensitivity I/V converter

It is known that resistors with high resistance value and at the same time with small temperature resistance coefficient and voltage resistance coefficient are difficult to obtain and very expensive. It is also apparent that high-sensitivity applications may require unrealistically large resistances. Unless proper circuit fabrication measures are adopted, the resistance of the surrounding medium, being in parallel with R_f, will decrease the net feedback resistance and degrade the accuracy of the circuit. Figure 4 shows a widely used technique to avoid this drawback. The circuit utilizes a *T*-network to achieve high sensitivity without requiring unrealistically large resistances.

Real-life op amps do draw a small current at their input terminals, called the input bias current, it may degrade the performance of high-sensitivity *I/V* converters, in which I_{in} itself is quite small. This drawback can be avoided by using op amps specifically rated for low-input bias current, such as JFET-input and MOSFET-input op amps. The OPA357AIDBV was chosen as op amp in the *I/V* converter with external offset-error nulling circuit which allows equal impedance for each input of amplifier, to meet the tight design specification related to the input bias current, R_1 is made by the transistor MOS 2N7000, which is operating in the strong-inversion deep triode region, R_f and R_2 are reasonable values. Due to the capacitor C_2 in parallel with R_2, R_2 becomes Z_2, the transimpedance, *I/V* converter stands as the second-order low-pass filter, which is given by

$$H(s) = -\frac{H_0}{\left(\frac{s}{\omega_{c0}}\right)^2 + \left(\frac{s}{\omega_{c0}}\right)\frac{1}{\varphi_0} + 1} \qquad (4)$$

$$H_0 = R_f\left(1 + \frac{Z_2}{R_1}\right) \; ; \quad s = j\omega \; ; \; \omega_{c0} = \sqrt{\frac{\omega_c(Z_2 + A_0 R_1)}{Z_2 R_f C_i}} \; ; \; \varphi_0 = \frac{\omega_{c0} R_f C_i}{1 + R_f C_i \omega_c}$$

Where H_0 is called the dc gain, $s=j\omega$ is the complex frequency (ω is the angular frequency), in radians per second, ω_C is called the cutoff frequency of the op amp, ω_{C0} is called the cutoff frequency of the transimpedance *I/V* converter, A_0 is called the voltage gain factor of the op amp. Such a configuration can allow the dynamic range rapid changes in input current to be maximized. Eq. (3) shows that rapid changes in the input current are not filtered out.

5. MEASUREMENTS

The measurements were performed in the lab in order to characterize AC and DC performances of the circuit. The streaming signal generator XLV1 associated with voltage controlled current source was selected to supply input current signal to the femtoammeter on the software program Multisim. The output was connected into the four channel oscilloscope XSC2.

Specification of the I/V Converter is shown in table 1. Parameters were measured when the source current was in DC mode. All DC test results presented here, including linearity shown in fig.6, were based on the average of 128K points which was around 7s. The -3dB bandwidth of the I/V converter was obtained when the current source operated in AC mode.

Table 1

Parameter	Value
Full scale output	±3V
Current conversion gain	4.3mV/pA (0.43 V/fA)
Linearity error	<0.10%
Output voltage noise	<0.2mV(rms)
Equivalent input current noise	<0.01pA(rms)
-3dB bandwidth	dynamic
Output offset voltage	<±0.22mV
Temperature range	-40°C to 125°C

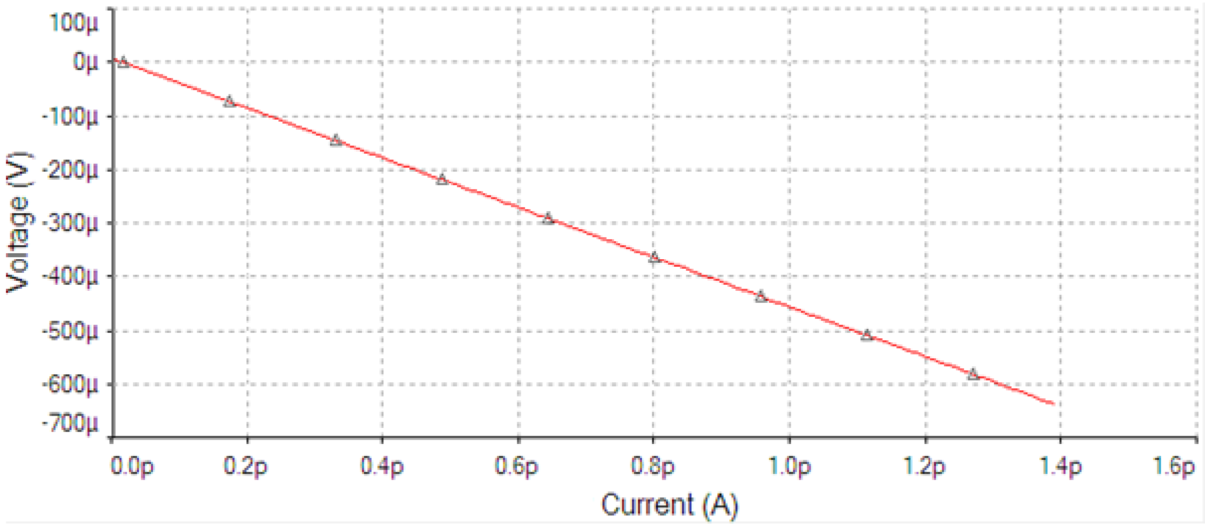

Fig. 6. I/V Converter transfer curve and linearity errors.

6. CONCLUSIONS

The very low current I/V Converter had been developed and test. The high degree of linearity was achieved by using a novel technique high sensitivity I/V converter. The results of the test of a very low current measurement circuit show that it had a high accuracy and stability. Because of the circuit design techniques used for high event rate capability insured that the circuit would perform well in high-resolution energy systems.

7. ACKNOWLEDGEMENTS

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