High-stability, high-voltage power supplies for use with multi-reflection time-of-flight mass spectrographs

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Achieving the highest possible mass resolving power in a multi-reflection time-of-flight mass spectrometer requires very high-stability power supplies. To this end, we have developed a new high-voltage power supply that can achieve long-term stability on the order of parts-per-million. Herein we present the design of the power supply and bench-top stability measurements up to 1 kV. The stabilization technique can, in principle, be applied up to 15 kV or more.

Keywords: High-voltage, High-stability, Atomic Masses, MR-ToF

I. INTRODUCTION

A multi-reflection time-of-flight mass spectrograph (MRTOF-MS) consists of a pair of electrostatic ion mirrors separated by at least one electrostatic lens and a field-free drift region. The ions oscillate between the mirrors, thereby experiencing a very long flight path. In principle, each reflection produces a time-focus, where the ion cloud has a maximally short duration, somewhere in the system. By choosing operational parameters such that after the final reflection the time focus is placed at an ion detector, the MRTOF-MS can achieve extremely high mass resolving powers.

Although the MRTOF-MS was first proposed in the 1980’s, the technology to make the idea useful for reliable, accurate, high-precision mass measurements only became readily available in the past decade. These devices require efficient ion traps producing maximally low-emittance ion pulses with small energy spread, time-to-digital converters (TDC) with sub-nanosecond accuracy and maximum duration exceeding 10 ms, fast-settling high-voltage switches, and high-stability high-voltage power supplies. The power supplies remain to be a performance-limiting technical difficulty.

As ions spend much of their time near the turning points of the electrostatic mirrors, variations in the potentials applied to the electrodes near the ion turning points can have a very strong affect on an ion’s time-of-flight (ToF). We have observed that a 4 parts-per-million (ppm) change in the voltage of a single electrode can produce a 1 ppm shift in an ion’s time-of-flight. Such drifts can limit the maximum achievable resolving power by artificially broadening the spectral peak width, while also introducing systematic errors by distorting the peak shape. Post-processing techniques have been developed to minimize such degradation, but these techniques still require the power supplies to be fairly stable for the duration required to produce a suitable reference measurement – typically \( \gg 1 \) s.

In addition to mass analysis, these devices will also be used as online isobar separators for radioactive ion beam facilities. There are plans to use them for even delivering isomerically pure beams. Voltage stability will present a pressing concern when using these devices as isobar separators to provide high purity beams. The techniques used to

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mitigate the affect of ToF drift on spectroscopic analyses are based on post-processing of the spectra and will not be useful to correct drifts in such a high-precision isobar or isomer separator. While one may envision hourly inspection of the ToF signals and adjustment of the separator, such operation would certainly not be ideal.

Presently, some high-voltage power supply companies have begun to bring to market high-stability supplies for use with MRTOF-MS. However, even the most expensive high-end units offer \(\sim 10\) ppm long-term stability, temperature coefficients of \(\geq 10\) ppm/K, and several millivolts of noise in the \(0.1\) Hz – \(10\) Hz range.

We have designed and made initial tests of an inexpensive new high-voltage power stabilization circuit capable of ppm-level long-term stability, exhibiting low noise and a temperature coefficient \(<5\) ppm/K. These power supplies utilize recently available 20-bit DACs and extremely stable voltage references, along with zero-drift, low-noise op-amps. The heart of the design utilizes commercially available photodiodes and high-flux infrared LEDs to emulate transistors with \(15\) kV breakdown voltage.

II. PERFORMANCE CRITERIA

When considering the performance of MRTOF-MS power supplies attention must be given to the short-term (<\(1\) s) stability, intermediate-term (1 s – \(\sim 10\) minutes) stability, and long-term (>10 minutes) stability. If the power supplies exhibit large fluctuations with frequency components greater than \(\sim 0.1\) Hz, the aforementioned post-processing techniques will be unable to correct for the induced ToF drift. To maximize the effectiveness of these post-processing techniques, it is desirable to keep the power supply fluctuations below the level which would result in a statistically significant ToF shift for durations of minutes, to allow ample time to accumulate each reference spectrum (intermediate-term stability). If the device will be used for isobar (moreo with isomer) separation, it is desirable for the supplies to be sufficiently stable as to preclude the ToF peak moving by more than, perhaps, 50% of the time-of-flight separator resolution in the course of days (long-term stability).

Since the mass resolving power is only half the time resolving power in an MRTOF-MS, achieving a mass resolving power of \(R_m=10^5\) requires a time resolving power of \(R_t=2 \times 10^5\). The most sensitive electrode in our system exhibits \(\Delta t=0.26\) ppm time drift from a 1 ppm voltage drift. Assuming all other voltages were perfectly stabilized and further assuming the MRTOF had an infinite inherent resolving power, the voltage applied to the most sensitive electrode could not exceed a voltage variance \(\sigma(V)/V<19\) ppm in order to achieve \(R_m=10^5\). Achieving \(R_m=5 \times 10^5\) would require \(\sigma(V)/V<3.8\) ppm. The fact that fluctuations in the bias applied to each electrode independently contribute to the width, and the inherent resolving power is not infinite, makes the stability requirements even more stringent.

One strategy for limiting voltage fluctuations is to use an RC low-pass filter. This has some limitations, however. Without resorting to large, oil-filled capacitors one is limited to \(10\) nF by the available capacitance of high-voltage capacitors. The resistor must be chosen so as to not create large Johnson noise (\(\approx 4\) \(\mu\)V/\(\sqrt{\text{Hz}}/\text{M} \Omega\) at room temperature). In the case of a 5 kV potential, such a criterion would permit the use a 1 G\(\Omega\)//10 nF low-pass filter to achieve a time constant \(\tau=10\) s while keeping the contribution of Johnson noise below 1 ppm. Unfortunately, the leakage current of high-voltage capacitors can readily fluctuate on the level of nanoamp\(\text{M}^\text{a}\). A fluctuation of \(\Delta I_{\text{leak}}=10\) fA would already cause a 1 mV variation in voltage drop across a 1 G\(\Omega\) resistor – corresponding to 1 ppm at 1 kV.

On the other hand, a 1 M\(\Omega\)//10 nF low-pass filter would not be so affected by these deleterious effects, but has only a \(\tau=10\) ms time constant. Of course, larger capacitors could be implemented, however achieving \(\tau=10\) s or more can only be accomplished with large, oil-filled capacitors, which are available with capacitances exceeding 10 \(\mu\)F but also pose a serious safety hazard.

In addition to the dangers posed by high-capacitance high-voltage capacitors, very long time constant low-pass filters have other downsides, too. During the initial tuning of an MRTOF-MS, the potentials applied to each electrode should be scanned within a few volt
range in order to find the optimal parameters. Stabilization based on long time constant RC low-pass filtering can require a pause of as much as 10 minutes between each step in such a scan, to allow the voltage to sufficiently stabilize. This makes initial tuning of the MRTOF-MS a laborious task.

III. HIGH-VOLTAGE STABILIZER DESIGN

In order to achieve a fast-settling, high-precision, long-term stable high-voltage power supply for driving our MRTOF-MS, we have extended the concept laid out in the Voltage Multipliers, Inc. application note “AN-0300 - High Voltage Op-Amp Application Using Opto-Couplers”\(^1\). The application note describes the use of infrared LEDs and high-voltage photodiodes to emulate an operational amplifier with up to 15 kV power supply span. AN-0300 describes the use of a complimentary transistor pair to drive LEDs and induce complimentary currents in a pair of photodiodes – essentially producing a phototransistor-based amplifier. As described in AN-0300, an op-amp implemented as an error amplifier, with the non-inverting input grounded, drives the bases of the complimentary transistor pair. The output is programmed by applying a set voltage to the inverting input via a gain-setting resistor \(R_g\). By further connecting a high-resistance feedback resistor \(R_f\) from the high-voltage output to the inverting input of the error amplifier op-amp creates the positive feedback loop which regulates the output, producing something of a bootstrapped inverting op-amp with gain \(g=-R_f/R_g\).

![Conceptual design of the high-voltage stabilizer](image)

FIG. 1. Conceptual design of the high-voltage stabilizer. A precise, low-noise reference voltage is achieved with four units of LTC6655-5 in parallel. Analog Devices AD5791 has been used for the 20-bit DAC. A micro controller unit (MCU) programs the 20-bit DAC and monitors the system temperature. The gain adjust is used to change the full-scale output range of the voltage stabilizer; see text for more details. D1 and D2 are high-flux infrared LEDs. D3 and D4 are high-voltage photodiodes from Voltage Multipliers, Inc. The precision voltage divider (Caddock HVD5 series, 1000:1 divider) is the only galvanic connection between the high-voltage and low-voltage components. The feedback capacitor \(C_{fb}\) prevents oscillations.

Starting from this basic premise of a bootstrapped high-voltage op-amp and utilizing high-precision components it has been possible to produce a programmable high-voltage power supply...
supply with ppm-level stability. A conceptual circuit diagram of the design is given in Fig. 1. A 20-bit DAC (Analog Devices AD5791) is used to provide the set voltage. A very stable $V_{\text{ref}}=5$ V reference potential, produced using four parallel units of LTC6655-5 to reduce the inherent noise level and limit the thermal response, is used to ensure the stability of the DAC output. Using an AD8675 precision op-amp with the internal gain-setting resistors from the AD5791 allows a bipolar output range of $V_{\text{set}} \in \pm V_{\text{ref}}$. The output is then buffered by a voltage follower before being rescaled using a high-precision op-amp in an inverting configuration ("Gain adjust amplifier" in Fig. 1), with the inverting gain determined by a pair of low temperature-coefficient metal film resistors to produce a modified set voltage $V'_{\text{set}}$. The modified set voltage is similarly buffered with a voltage follower. The gain and feedback resistors for the bootstrapped op-amp system are made using a high-precision voltage divider (Caddock HVD5 series), with $R_g=50$ kΩ and $R_f=49.95$ MΩ. To prevent oscillations, a 1 nF ceramic disc capacitor ($C_{\text{fb}}$ in Fig. 1) rated for 10 kV DC (Murata DHRB34A102M2BB) is placed in parallel to $R_f$, making an $f_c=200$ Hz low-pass filter.

![Photograph of the prototype printed circuit board used in this work. The photodiodes, covered by brown paper to shade them from ambient light sources, are mounted atop high-flux infrared LEDs.](image)

The high-precision voltage divider provides a gain of $g=999$ with a gain temperature coefficient of $\pm 5$ ppm/K, while allowing safe functioning with $V_{\text{out}} \in \pm 5$ kV, which would be difficult to achieve with discrete resistors. However, such a large gain is not always desirable. The optimal potential which should be applied to many of the MRTOF-MS electrodes is much smaller than 5 kV. At a gain of $g=999$ the minimum output step size is
9.5 mV, which may be inconveniently large in cases where \( \approx 500 \, \text{V} \) is desired. By adding an op-amp stage with \( g \leq 1 \) (“gain adjust amplifier” in Fig. 1) the full-scale range can be adjusted to an optimal range for each electrode. At the same time, selecting the resistors such that the gain temperature coefficient of the gain adjust amplifier balances that of the Caddock HVD5 can greatly reduce the effective temperature coefficient of the device.

To remove any fluctuations at frequencies far exceeding our ability to precisely measure, a 1 MΩ//20 nF low-pass filter has been added to the output. While the large output impedance may introduce some extra Johnson noise, and fluctuation in the capacitor’s leakage current may produce some voltage fluctuations, this was determined to be an acceptable compromise. Additionally, the inclusion of such a low-pass filter simplifies the optional addition of large, oil-filled high-voltage capacitors for long time-constant low-pass filters in the future, if yet higher intermediate-term stability becomes necessary.

A 16-bit digital thermometer (Analog Devices ADT7310) was installed near the DAC to monitor the local temperature. Monitoring the temperature allows for indication of failures, such as e.g. oscillations that can cause the LED driving system to dramatically heat up. It also is foreseen that such thermal monitors could be useful in a future active thermal stabilization of the power supplies.

IV. TESTING PROCEDURES AND RESULTS

A number of benchtop tests were performed with the voltage regulator. These included reproducibility, linearity, settling time, long-term behavior, and medium-term stability measurements. For these measurements, a minimal setup was utilized. An Agilent 3458A 8.5-digit digital multimeter was used to digitize the output voltage. A GPIB-to-Ethernet interface (Prologix, LLC) allowed interfacing with the 3458A using TCP/IP. Rather than \( \pm 5 \, \text{kV} \), the supply rails were initially set to +1 kV and 0 V to protect the 3458A from possible damage due to overvoltage.

A Raspberry Pi Model 3 computer was implemented as the micro controller unit (MCU) of Fig. 1, while also serving as a rudimentary data acquisition and control system. The Raspberry Pi’s GPIO interface was used to communicate with the power supply, both setting the DAC output and reading from the thermometer. Similarly, a computer code running on the Raspberry Pi was used to set the digitization rate of the 3458A and record the digitized data, interfacing via TCP/IP.

A. Long-term stability

The primary motivation for development of the new power supply being to provide extremely stable voltages for MRTOF-MS, the intermediate and long term stability were studied. To exclude thermal effects, the device was placed in a temperature controlled room. The DAC was programmed so as to produce a 400.000 V output. The Agilent 3458A was set to average for 30 power cycles (600 ms at 50 Hz mains power) resulting in a digitization rate of \( \approx 1.7 \, \text{Hz} \). After allowing the device a few hours to achieve thermal equilibrium, the digitized output was recorded along with the temperature of the digital thermometer over a multiple day period.

As shown in Fig. 3a, across a 3 day period the temperature varied by \( \Delta T \approx 0.4 \, \text{K} \). The voltage exhibited a peak-to-peak fluctuation of \( \Delta V \approx 6 \, \text{ppm} \). No correlation between voltage and temperature could be determined.

A histogram of measured voltage, Fig. 3b, shows a fairly Gaussian distribution indicative of true noise. The full-width at half-maximum variation was 2.28(4) ppm over the entire 3 day measurement, while the standard deviation across the entire 3 day period was \( \sigma(V) = 1.22 \, \text{ppm} \). Based on our MRTOF-MS, the mass resolving power achievable using such voltage stability would be limited to \( R_m < 7.4 \times 10^5 \). This is compatible to even the most stringently demanding isobar separation applications.
FIG. 3. (a) Stability of one voltage stabilizer during 3 days of operation at \( V_{\text{out}} = 400 \) V. The voltage digitization rate was 1.7 Hz, while the temperature was recorded every 5 s. (b) Histogram showing the voltage stability over the course of the measurement. A Gaussian fit (red curve) shows a full-width at half-maximum stability of 2.28(4) ppm. (c) Histogram of standard deviation across all consecutive 10 minute intervals within the data shown in the top panel. The standard deviations averaged 0.88(21) ppm.

For use as a mass analyzer, the application of drift correction methods makes the intermediate term (~10 minutes) stability the limiting factor. Figure 3 shows the measured voltage variance histogram for all consecutive 10 minute intervals within the 3 day measurement. The average full-width at half-maximum variation across all consecutive 10 minute intervals was 2.08(51) ppm. Thus, the long-term and intermediate-term performance are not very dissimilar. With this level of intermediate stability, the mass resolving power achieved by an infinitely-high-resolution device would be limited to \( R_m < 8.4 \times 10^5 \).

B. Settling time

In order to tune the MRTOF-MS in a reasonably finite duration, as previously noted, it is valuable for the power supply to settle reasonably quickly following a step change in the output. To test the settling time, the output was first set to 200 V and left to equilibrate for several minutes. The data acquisition was started with a digitization rate of 1.7 Hz. After approximately one minute of data acquisition, while continuing the signal digitization, the DAC output was changed to produce a 300 V output from the power supply. The result, shown in Fig. 4 zoomed to show detail of the final 20 ppm of the transition, is that the system settles on the ppm-level within approximately 1 minute. Within 10 s, the system having settled to within \( \approx 5 \) ppm of the new set value, it would be reasonable to begin production of a ToF spectrum for MRTOF-MS tuning.

C. Reproducibility and linearity

Two further characterizations of a precision power supply are the linearity and reproducibility. These qualities determine the accuracy which can be anticipated when e.g. scaling the voltages in the MRTOF-MS. With a high degree of accuracy, the potentials
should be able to be scaled to change the ion energy without need for a time-consuming retuning of the voltages. Additionally, it is useful to understand the linearity.

To test the reproducibility of the system, the DAC output was switched between values appropriate to produce 200 V and 300 V. In light of the measured settling time, the power supply was given 60 s to stabilize after each transition, after which 20 consecutive digitizations of the output were made at 1.7 Hz and the average and standard deviation recorded.

Over an ≈8 hour period, 180 transition cycles were made. Histograms showing the measured deviation from desired outputs are shown in Fig. 5. For reasons unknown the reproducibility appears to be better following a falling transition (“V_out=200 V”). The reproducibility in either case is on the ppm-level, indicating that it should be able to reliably reproduce the desired voltages with the level of accuracy that would be desired for MRTOF-MS systems of the highest conceivable resolving powers.

The linearity was tested in increments of 200 in the DAC code. After sending a new DAC code, the system was allowed 10 s to stabilize, after which 10 consecutive digitizations of the output were made at 1.7 Hz and the average and standard deviation recorded. Upon reaching the maximum DAC code, the measurement was repeated in reverse.

Figure 6 shows the result of the linearity measurement. The integral non-linearity was determined by dividing the residual of the best-fit line of V_read as a function of V_set by the least significant bit (LSB) voltage. In this measurement the LSB voltage was 715 µV.

### D. Thermal effects

There are several thermal effects which could degrade the performance of the device. The Seebeck effect, whereby voltages are induced by thermal gradients at an interface of dissimilar materials (e.g. solder joints), as previously mentioned, is rather difficult to evaluate in such a device where multiple components may exhibit self-heating. However, the effect should be below the 100 µV level based on the components used, and should not produce dynamic changes in the output once the device has achieved thermal equilibrium. It is possible that these effects will noticeably inhibit reproducibility between extended powered off periods.

The temperature coefficients of the voltage reference and of the gain-setting resistors will combine to produce a gain temperature coefficient affecting the output, which will produce a similar relative shift at all output voltages. The data sheet for the LTC6655-5 voltage reference lists the typical temperature coefficient to be 1 ppm/K, while the Caddock HVD5-series 1000:1 voltage divider has a stated ratiometric temperature coefficient of ±5 ppm/K.
FIG. 5. Results of reproducibility test. The output was switched between 200.000 V and 300.000 V. Histograms of the deviation from the desired voltage after 60 s of settling time shows that the desired output can be reliably obtained within a few parts per million.

A passive measurement of the temperature coefficient was performed by placing the device in an environ without temperature stabilization and setting the output to 300.000 V. The temperature and voltage were then measured over the course of 2 days. From the result, shown in Fig. 7, a temperature coefficient of $\Delta V / \Delta T = -1.6$ ppm/K could be ascertained.

However, in addition to the multiplicative effects from such temperature coefficients, a
temperature-dependent voltage offset is possible. The most likely source of such an offset in this device would be the AD8676 op-amp used to drive the $g = 1000$ photodiode-based amplifier (see Fig. 1).

In order to determine the temperature coefficient of the voltage offset, the DAC output was slowly scanned – similar to the linearity test, but in smaller steps – over a one day period without thermal stabilization. The thermometer reading decreased by 6 K and then recovered again during the measurement. The resultant data is plotted in Fig. 8.

In Fig. 8 it can be seen that the maximum deviation from initial temperature is well-aligned with the maximum absolute deviation between $V_{\text{set}}$ and $V_{\text{read}}$, near $V_{\text{set}} = 80$ V. By plotting the absolute voltage deviation as a function of the temperature, as shown in Fig. 8b, a linear correlation is seen, with a slope of $-307(2) = \mu V/K$. This is the voltage offset temperature coefficient.

At $V_{\text{set}} = 300$ V the temperature offset coefficient would be responsible for $\Delta V/\Delta T = -1.0$ ppm/K. As such, we can infer that the true gain temperature coefficient is a mere $\Delta V/\Delta T = -0.6$ ppm/K.

E. Intermediate-term stability as a function of gain and output voltage

In order to further evaluate the performance of the device, stability measurements were made using three gain values at output voltages up to 1 kV. The tests were limited to 1 kV by the maximum allowable voltage of the Agilent 3458A digital multimeter. As can be seen in Fig. 9 the intermediate-term stability seems to be unrelated to the gain value. The intermediate-term stability performance seems to degrade for output voltages below $\approx 400$ V. This could in part be due to occasional ($\sim 1$/minute) single-bit glitches observed in the output, which produce a larger relative effect at lower voltages. However, were that effect to be dominant we would expect to observe a gain dependence, which does not seem to be present. An alternative explanation is some constant noise in the system, which would make a large effect at low output voltages. A noise level of $\approx 100 \mu V_{\text{rms}}$ in the output would account for the observed effect. Within the framework of this design, it is unlikely that this can be improved, as it would be difficult to reduce the noise in the error amplifier output significantly below 100 nV_{rms}. However, if a lower maximum output were desired, reducing the final gain ratio from $g = 1000$ may improve the intermediate-term stability.

V. CONCLUSION AND OUTLOOK

We have designed and bench-tested a voltage regulation circuit which settles on the ppm-level within one minute and has proven capable of maintaining $\sigma(V)/V \approx 1$ ppm for several days. The device uses high-voltage photodiodes and high-flux infrared LEDs in combination

![FIG. 7. Measured temperature response of the voltage regulation system showing a temperature coefficient of -1.6 ppm/K.](image)
FIG. 8. (a) Result of a slow scan of the DAC output during which the temperature of the room changed. (b) A plot of the difference between set and read voltages. The red line is the line of best fit, which indicates the existence of a $-307(2) \mu V/K$ temperature dependent offset voltage. This is consistent with the listed offset voltage of the AD8676 (typically 0.2 $\mu V/K$, maximum 0.6 $\mu V/K$) used to drive the $g=1000$ photodiode-based amplifier.

FIG. 9. Intermediate-term stability as functions of output voltage for multiple total gain values.

with a high-voltage 1000:1 resistive voltage divider and low-noise op-amp IC to produce a high-voltage, $g=1000$ op-amp. A 20-bit DAC with extremely low-noise voltage reference drives the op-amp. The high-voltage output was measured to have an integral linearity comparable to the 20-bit DAC itself.

Over the course of 3 days evaluation at 400 V output, the maximum relative deviation was observed to be $\approx 6$ ppm, while the standard deviation was 1.22 ppm across the evaluation period. Thermal effects were determined to be very low, with a temperature dependent offset voltage of $-307(2) \mu V/K$ and an inferred gain temperature coefficient of $-0.6$ ppm/K. While limitations in test equipment precluded characterization of outputs exceeding 1 kV,
the flat response in the stability as a function of output voltage gives us some confidence that the device will provide ∼1 ppm stability up to the design limit of ±5 kV.

From these results, based on the previously described effects of voltage stability, we can estimate that the maximum fluctuation in time-of-flight across several days could be limited to ∆t/t ≤ 2 ppm, which should be acceptable in even the most stringent ToF separator applications. Using a ToF drift correction technique, the intermediate term stability of typically ∆V_{FWHM}=2 ppm full-width at half maximum during 10 minute intervals indicates that ToF spectral width induced by voltage instability would be limited to ∆t/t=0.5 ppm. In such circumstances, achieving R_m≈10^6 would be technically feasible.

Moreover, the capability to settle to the ppm level within one minute of a 100 V step in output will allow ease in tuning the MRTOF-MS potentials. In the near future we will test the power supply with an MRTOF-MS.

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1Hermann Wollnik, Deutches Patentamt #DE 3025764 A1, 28 January 1982
2H. Wollnik, M. Przewloka, International Journal of Mass Spectrometry and Ion Processes 96 (1990) 267
3P. Schury, M. Wada, Y. Ito, F. Arai, S. Naimi, T. Sonoda, H. Wollnik, V.A. Shchepunov, C. Smorra, C. Yuan, Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms, 335 (2014) 39-53
4Paul Fischer, Stefan Knauer, Gerrit Marx, Lutz Schweikhard, International Journal of Mass Spectrometry, Volume 432 (2018) 44-51
5P. Schury, Y. Ito, M. Rosenbusch, H. Miyatake, M. Wada, and H. Wollnik, International Journal of Mass Spectrometry, Volume 433 (2014) 40-46
6Plaß, W.R., Dickel, T., Czok, U., Geissel, H., Petrick, M., Reinheimer, K., Scheidenberger, C., Yavor, M.I., Nucl. Instrum. Methods B 266 (2008) 4560-4564
7Hirsh, T.Y., Paul, N., Burkey, M., Aprahamian, A., Buchinger, F., Caldwell, S., Clark, J.A., Levand, A.F., Ying, L.L., Marley, S.T., Morgan, G.E., Nystrom, A., Orford, R., Galván, A.P., Rohrer, J., Savard, G., Sharma, K.S., Siegl, K., Nucl. Instrum. Methods B 237 (2016) 229-232
8Chauveau, P., Delahaye, P., France, G.D., Abir, S.E., Lory, J., Merrer, Y., Rosenbusch, M., Schweikhard, L., Wolf, R.N., Nucl. Instrum. Methods B 237 (2016) 211-215
9T. Dickel, W.R. Plaß, S. Ayet San Andres, J. Ebert, H. Geissel, E. Haettner, C. Hornung, I. Miskun, S. Pietri, S. Purushothaman, M.P. Reiter, A.K. Rink, C. Scheidenberger, H. Weick, P. Dendooven, M. Diwisch, F. Greiner, F. Heiße, R. Knöbel, W. Lippert, L.D. Moore, I. Pohjalainen, A. Prochazka, M. Ranjan, M. Takechi, J.S. Winfield, and X. Xu, Physics Letters B 744 (2015) 137-141
10Paul Horowitz and Winfield Hill, "The Art of Electronics", Cambridge University Press, ISBN 0-521-37095-7
11“AN-0300 - High Voltage Op-Amp Application Using Opto-Couplers”, Voltage Multipliers, Inc, http://www.voltagemultipliers.com/pdf/High-Voltage-Op-Amp-and-Linear-Regulator-App-Notes.pdf
12https://www.raspberrypi.org/