Injection Optics for Fast Mass Switching for Accelerator Mass Spectrometry

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Abstract. Accelerator Mass Spectrometry (AMS) measures the ratio of extremely small amounts of a radioactive isotope in the presence of ~ 10^{15} times more stable ones. The isotopes are injected sequentially over a repeated period and observed at the exit of the accelerator. so any fluctuations in ion source output or transmission through the accelerator over a time comparable to the measurement time, will reduce the accuracy of such measurements. This compromise in accuracy can be lessened by reducing the switching time between isotopes from several seconds to a few milli-seconds. New AMS systems accomplish fast switching by modifying the beam energy though the 90 injection magnet by pulsing the voltage by several kV on the flight tube in the magnet. That requires that the flight tube be electrically insulated which competes with having the flight tube as large as possible. At the ANU, insulating the magnet flight tube would not only have reduced the acceptance of the injection system, but conflicted with a beam chopper attached to the flight tube, that would also have had to be insulated from the ground. This was not practical so the novel alternative of pulsing the voltage on the high voltage ion source deck is being implemented. Beam optics calculations have been performed and beam tests conducted that demonstrated that, in addition to pulsing the voltage on the 150 kV ion source deck, a pulsed Einzel lens in front of the following electrostatic quadrupole triplet lens is required to maintain isotope-independent transmission through the 14UD Pelletron accelerator. The high voltage rise time performance of the components of the system has been shown to be satisfactory.

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INTRODUCTION

The accelerator at the ANU in Canberra is a NEC Pelletron, 14UD built in 1973 for nuclear structure physics. It has been improved continuously since then achieving voltage performance up to 15.75 MV. This work describes the enhancement of accelerator mass spectrometry (AMS) capability by the development of a fast mass switching system with the goal of improving the precision of the measurements of the isotope ratios from the present 2-3% to 0.5%. The apparatus will be described along with computer simulations of the effects on beam transmission. First high voltage rise time tests have been successful but performance with beam is yet to be done.

FAST MASS SWITCHING

Why it is Necessary

The basic AMS measurement involves comparing the number of atoms of the radioactive isotopes to the number of stable ones of the same atomic number. Any part of the beam production, acceleration and detection process that is different for different masses will confound the result. Such differences can occur due to variations in ion source output over time scales of a few seconds. This challenge is addressed by switching between the isotopes on a time scale much smaller than the time variation of the equipment and if possible, detecting them after they have all experienced the same path to the detector. Because the intensity of the stable isotope can be as much as 10^{15} greater than the radio isotope [1], it must be precisely attenuated but nevertheless measured in a Faraday cup rather than by ion counting as is done for the unstable isotope. Figure 1 shows the entire 14UD accelerator system and the components of the fast mass-switching system.

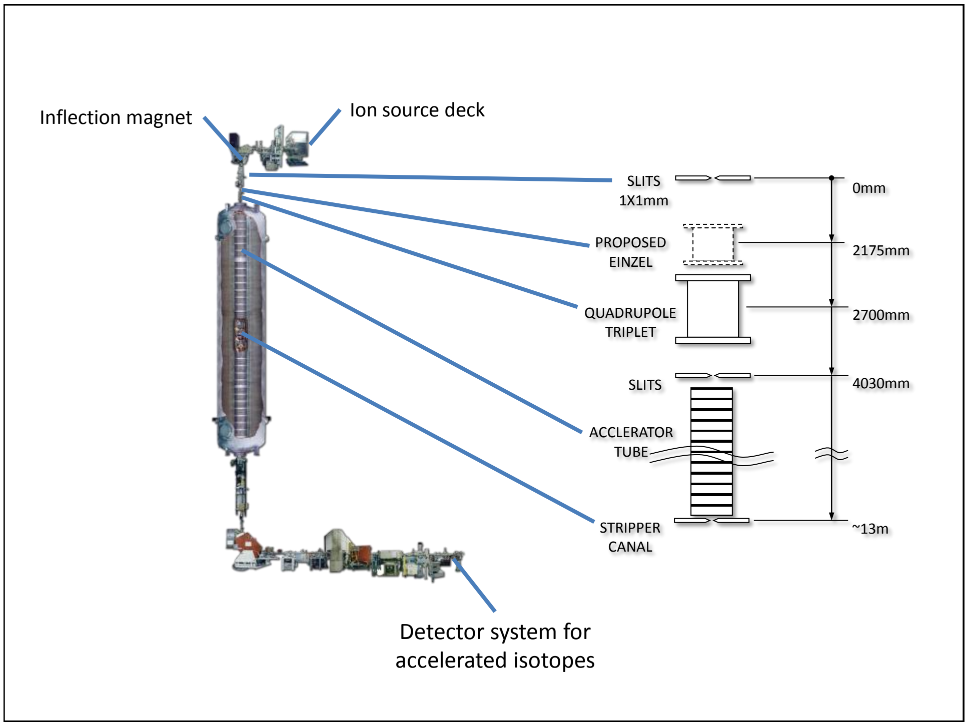

FIGURE 1. The 14UD AMS system from ion source to detector. The components of the fast mass switching system for which beam optics calculations were performed are displayed on the right.

How Fast Mass Switching is Done

In the case of ^{36}Cl measurements, all three isotopes are transported through the accelerator to either a Faraday cup, for ^{35}Cl and ^{37}Cl, or to an ion counting detector for

^{36}Cl. At present, the isotopes are injected sequentially by changing the magnetic field in the injection magnet. The settling time of this large magnet imposes a complete cycle time for the three isotopes of about 6 minutes. Unfortunately, changes in ion source output cause ratio errors of the order of 2-3% [2].

Modern, purpose built AMS facilities greatly reduce this source of error by cycling though the three masses in much less than a second [1, 3]. This is accomplished in the case of ^{36}Cl by increasing the energy of the ^{35}Cl ions while in the injection magnet so that they take the same path as ^{36}Cl had taken. Similarly, the energy of the ^{37}Cl ion is reduced. Both energy changes are accomplished be changing the voltage to ground of the magnet vacuum chamber which is electrically insulated. At the gaps between ground and the magnet vacuum chamber, there is an unavoidable gap-lens effect so the beam focusing optics is different for the different masses which, in principle ,could introduce a confounding mass selectivity. This focusing effect however, is adequately minimized by locating the gap-lenses where the beam is small, i.e. at the beam waists at the object and image points of the magnet.

The injection magnet in modern AMS systems is especially designed with a gap large enough to accommodate insulation around the vacuum chamber as well as not to intercept any of the ion source output. In the ANU installation, two factors worked against adopting such a solution. Firstly, the beam optics of the injection dipole magnet was optimized for a 32 mm gap leaving just enough room for the ion beam. Any reduction in the free gap for insulation would compromise beam transmission.

The second impediment would not be overcome even with a new larger gap magnet. The ANU installation employs an electrostatic chopper directly attached to the exit of the magnet vacuum chamber. The chopper sweeps the beam across the image slits of the double focusing injection magnet. This device includes the fast transistor switches which would have to be raised up to high voltage along with the vacuum chamber. There is no clear technical solution to this problem. It is also likely that any solution would impose large capacitance to ground thereby slowing the cycle time of the mass switching system. Shifting or deleting the chopper, which is used for AMS as well as other experiments, would be too disruptive to the overall operation of the facility.

Switching the Beam Energy

For the reasons above, we have chosen to rapidly change the injection energy to switch between masses. The most obvious way would be to change the injection power supply voltage. However the power supply manufacturer, Glassman™ advised that the settling time for the 200 kV power supply is 1.5 seconds. Since we are seeking a sub-second cycle time, this option must be rejected.

An alternative has been adopted, that interposes a fast TREK™ amplifier between the output of the 200 kV power supply and the ion source deck, in order to change the energies of the beams entering the injection magnet. Figure 2 is a schematic of the system. The amplifier is model 1040A, ±10 kV, capable of delivering a peak current of 120 mA with a rise time of 30 µs every 3 ms. The measured capacitance to ground that the amplifier must drive is 1.5 nF. The measured rise time is 50 µs which is adequate, although there is some interaction with the 200 kV power supply that requires further study.

An additional device provided by TREK is attached to the output of the amplifier and is intended to protect it from sparks on the ion source deck.

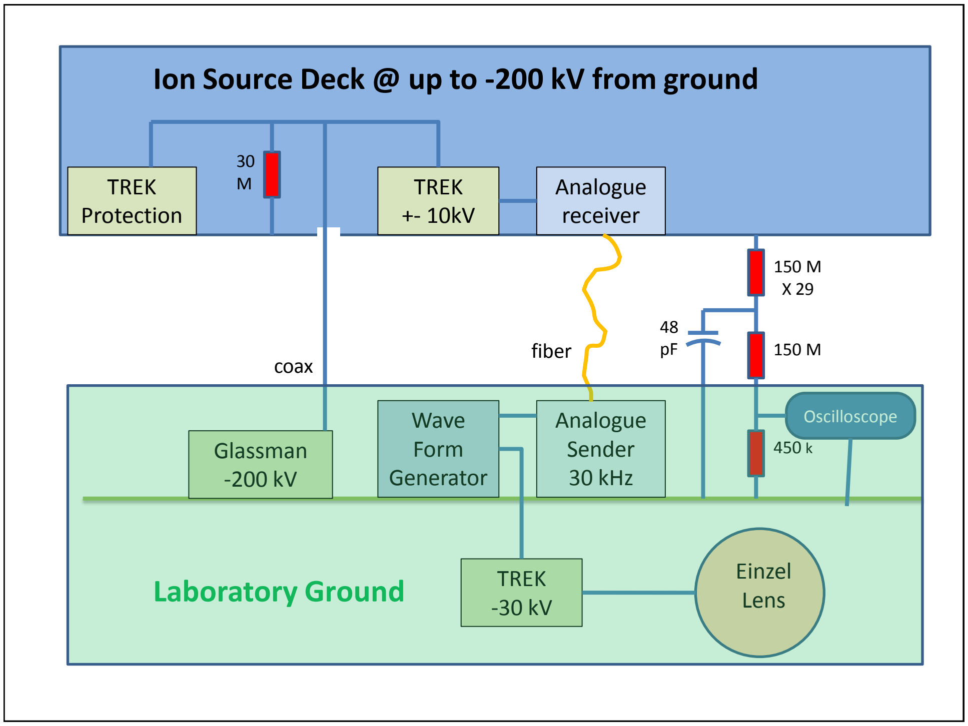

FIGURE 2. Schematic of the Fast Mass Switching System for the ion source deck. The devices in the upper box are connected to the ion source deck local ground. The 30 mΩ resistor provides a current load to the TREK +- 10 kV amplifier. The devices in the lower box are connected to the laboratory ground. There is a string of 30 resistors, 150 mΩ, each, connecting the ion source deck to laboratory ground. The 450 kΩ resistor at the laboratory ground end of the resistor chain samples 10^{-4} of the ion source deck voltage.

The wave form of control voltages is delivered across 150 kV to the ion source deck via fiber optic cable using AA Lab Systems™ AFL-500, 30 kHz sender and receiver. The voltage response of the ion source deck was measured by the oscilloscope across a 450 kΩ resistor at the ground end of the resistor chain on the pre-acceleration tube. The 48 pF capacitor partially compensates for the x10 oscilloscope probe. The first test of this system is shown in Figure 3.

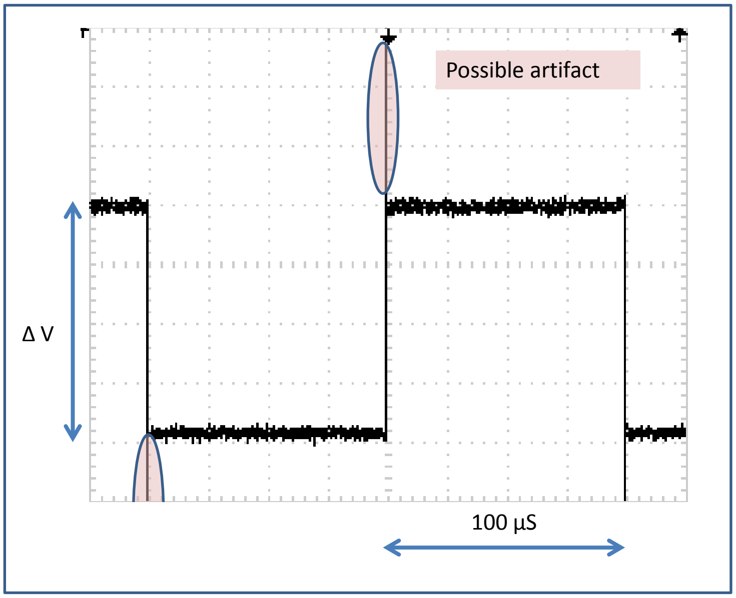

FIGURE 3. Ion source deck driven by the TREK 1040A amplifier from 0 to -4 kV with the ion source platform at -100 kV measured at the ground end of the resistor chain on the pre-acceleration tube. The spikes at the leading edges of the square wave are possibly measurement artifacts or real overshoots.

Switching the Lens Strength

Since the energy of the beam traveling between the injection magnet and the accelerator is now different for the different masses, the lenses may also need to track the energy changes. Tests were performed to quantify this effect.

There is an energy sensitive adjustable lens at the entrance to the pre-acceleration tube between the ion source deck and the inflection magnet. With 150 kV on the deck, changes of ±4 kV in the voltage on the ion source deck had no noticeable effect on the beam intensity at the output of the inflection magnet. Thus no additional focus compensation for this lens is necessary.

There are two additional lenses between the injection magnet and the terminal of the 14UD and both will change focal length as the beam energy is changed for the various isotopes. The first lens is an NEC™ electrostatic quadrupole triplet. The second lens effect is due to the voltage gradient of the accelerator tube entrance [4]. Together, they focus the beam through the stripper in the terminal of the 14UD. In order to ascertain the effect on transmission of the changes in beam energy, tests were performed at fixed settings of the electrostatic quadrupole triplet and fixed terminal voltage of 14 MV typically used for ^{36}Cl AMS experiments. The strength of the tube entrance lens is determined by the ratio of the voltage gradient on the acceleration tube, to the injection beam energy [5].

A ^{28}Si beam was used to simulate the ^{36}Cl beam. The 14UD terminal voltage was 14 MV and charge state 6+ from a gas stripper was selected. The transmission through the accelerator was optimized using the electrostatic quadrupole triplet lens near the accelerator entrance. This lens has steering capabilities which were also optimized. The injected beam energy was 155 keV with 5 kV from the ion source and 150 kV on the ion source deck.

The injection energy was first increased by 4 keV to 159 keV by raising the ion source deck to 154 kV to simulate the ^{35}Cl case. The transmission reduced by 23% and there was little change in the shape of the beam at the accelerator tube entrance as observed on an NEC™ beam profile monitor. The ion source deck voltage was then reduced to 146 kV to simulate the ^{37}Cl case. The transmission decreased by 65% from the standard 150 kV case. In both cases, full transmission could be restored by small changes in the electrostatic quadrupole lens strength only. This change in triplet strength also covers the change in the entrance lens strength which is not separately adjustable. There was no noticeable improvement by readjusting the steering.

The six power supplies for the electrostatic lens are of a similar type to the one supplying the ion source deck potential and so would not have the rise time necessary to support fast mass switching. Instead, we have considered an alternative approach in which a fast-switching Einzel lens is added at the entrance to the quadrupole triplet lens to compensate for the changes in lens strengths of both the electrostatic quadrupole triplet and the 14UD accelerator tube entrance lens for the different energy beams.

The voltage on the additional Einzel lens is driven by a TREK™ model P0621N, -30 kV amplifier. Since an Einzel lens can only increase the focus strength of the combined lenses, one must set it at an intermediate value, in this case near -15 kV, for the ^{36}Cl when optimizing the quadrupole triplet lens. The Einzel voltage is then reduced to ~-2 kV for the ^{37}Cl case and increased to ~-20.5 kV for ^{35}Cl.

Beam optics calculations were performed using the electric field calculation code SIMION [6]. These calculations confirm that adding the Einzel lens could restore equal transmission through the accelerator for all three masses. Figure 4 shows the calculated beam envelopes for the three masses using the Einzel system. It shows that the beam shape could be maintained sufficiently to achieve equal beam transmission for the three isotopes. The Einzel lens, an NEC EL44-40, 40 kV, has a capacitance of ~40 pF and so can be rapidly switched in voltage. The 44 mm diameter lens was chosen because it provides adequate focal strength with a maximum amplifier voltage of -30 kV. It is expected that the aberrations caused by filling 25 mm of the 44 mm diameter will be small since the lens strength is small yielding a focal length of ~ 10 m.

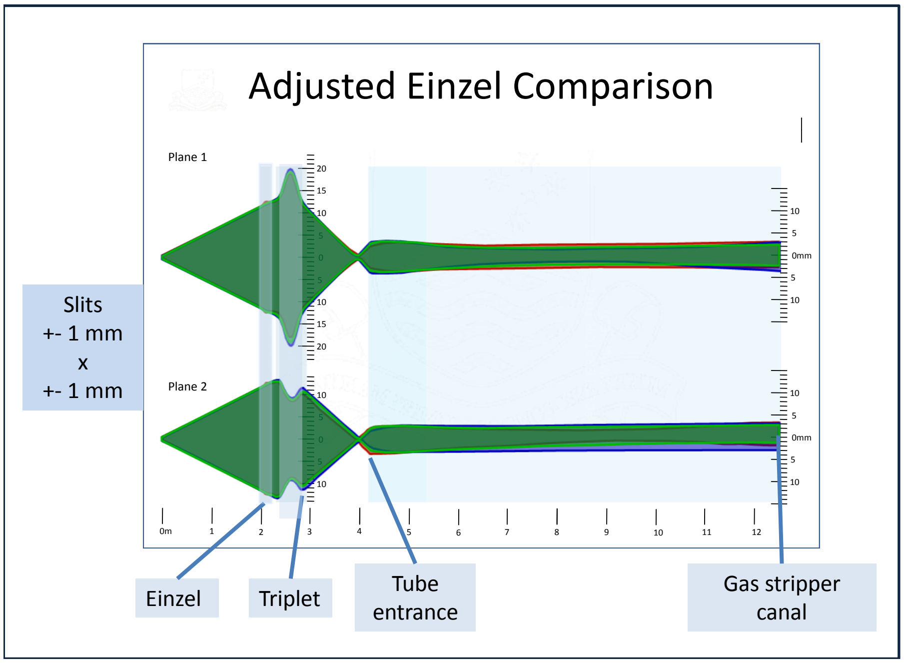

FIGURE 4. SIMION [6] beam envelopes for ^{36}Cl in green, ^{35}Cl in red and ^{37}Cl in blue. The Einzel has been adjusted to minimize the diameter of the beam at the entrance to the terminal stripper for each isotope.

The amplifier for the Einzel lens is driven by the second channel of the wave-form generator serving the amplifier on the ion source deck. The measured rise time for the Einzel is shown in Figure 5.

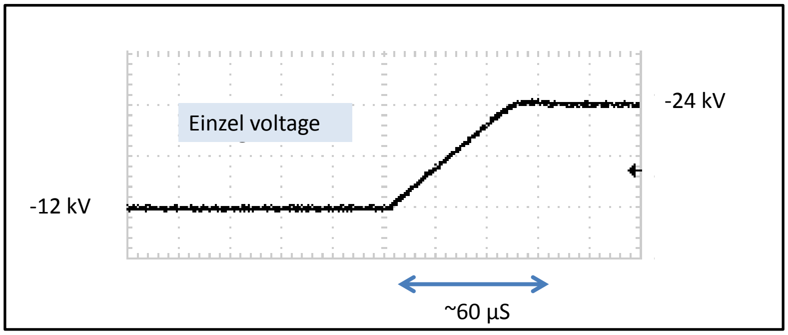

FIGURE 5. The rise time for the additional Einzel lens corresponding approximately to the case of changing from ^{36}Cl to ^{35}Cl.

The rise time of the Einzel system has been measured to be <100 µs. Beam tests to demonstrate equal transmission for the three chlorine isotopes have yet to be done.

CONCLUSION

The fast mass switching system has been modeled using SIMION [6] simulations. Preliminary measurements with DC test beam confirm that the transmission decreased more when the injection voltage was reduced by 4 kV than when it was increased by 4 kV from the nominal 150 kV. The beam measurements confirm that minor correction of the triplet voltage should be able to be approximated by the additional Einzel lens. . The electrical test with the TREK amplifiers confirm high voltage rise times of less than 100 µsec are consistent with the measured capacitances of the ion source deck and Einzel lens and the specifications of the amplifiers. Tests with beam using the amplifiers are yet to be done. These measurements should show if the spike at the edge of the ion source deck wave form is real or an artifact.

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