A linear radiofrequency quadrupole ion trap for the cooling and bunching of radioactive ion beams

A. Kellerbauer [a,e,1], G. Bollen [b], J. Dilling [c], S. Henry [d]
F. Herfurth [c], H.-J. Kluge [c], E. Lamour [c,2], R. B. Moore [e],
C. Scheidenberger [c], S. Schwarz [a], G. Sikler [c], J. Szerypo [f]

[a] *CERN, 1211 Genève 23, Switzerland*

[b] *Sektion Physik, Ludwig-Maximilians-Universität München, 85748 Garching, Germany*

[c] *GSI, Planckstraße 1, 64291 Darmstadt, Germany*

[d] *CSNSM-IN2P3-CNRS, 91405 Orsay-Campus, France*

[e] *Department of Physics, McGill University, Montréal (Québec) H3A 2T8, Canada*

[f] *Department of Physics, University of Jyväskylä, PB 35 (Y5), 40351 Jyväskylä, Finland*

Abstract

A linear radiofrequency quadrupole ion guide and beam buncher has been installed at the ISOLTRAP mass spectrometry experiment at the ISOLDE facility at CERN. The apparatus is being used as a beam cooling, accumulation, and bunching system. It operates with a buffer gas that cools the injected ions and converts the quasi-continuous 60-keV beam from the ISOLDE facility to 2.5-keV beam pulses with improved normalized transverse emittance. Recent measurements suggest a capture efficiency of the ion guide of up to 40 % and a cooling and bunching efficiency of at least 12 % which is expected to still be increased. The improved ISOLTRAP setup has so far been used very successfully in three on-line experiments.

Key words: Atomic masses. Ion guide. Ion trap. Buffer gas cooling. Mass spectrometry. Radioactive ion beams.
PACS: 07.75.+h, 21.10.Dr, 27.60.+j, 32.10.Bi

---

[1] Corresponding author. Telephone +41-22-7672780, facsimile +41-22-7678990, e-mail <a.kellerbauer@cern.ch>
[2] Present address: GPS, Université Paris 7 et 6, 2 pl. Jussieu, 75251 Paris Cedex, France

1 Introduction

The ISOLTRAP experiment is a high-precision mass spectrometer which is installed at the on-line isotope separator ISOLDE at CERN [1]. It consists of a beam preparation trap and a tandem Penning trap setup. The tandem Penning trap configuration is made up of a cylindrical Penning trap for the cooling and isobaric cleaning of the ion beam bunch and a hyperbolical Penning trap for the precision mass mesurements [2]. The two Penning traps have resolving powers of about 10^5 and about 10^7, respectively. The masses of more than a hundred radioactive nuclides have so far been measured with the ISOLTRAP mass spectrometer.

It has been a main challenge to develop an efficient deceleration system for the ISOLDE ion beam and a preparation stage for mass measurements in a Penning trap. Originally, the cooling Penning trap also served as the beam deceleration device. The ISOLDE ion beam was deposited on a rhenium foil at its entrance side. After some time, the foil was turned by 180 degrees and heated so that the ions were surface-ionized and once again released from the foil towards the cooling Penning trap. This technique was used successfully for many mass measurements. However, it restricted the applicability of ISOLTRAP to the nuclides of surface-ionizable elements, namely the alkali metals, the alkali earths, and the rare earths. This restriction was removed by the implementation of a very large Paul trap as the beam collection device [3]. The 60-keV ISOLDE beam was electrostatically decelerated to nearly zero energy within a few tens of millimeters and injected directly into the Paul trap filled with a buffer gas. However, it turned out that the acceptance of the Paul trap was not well matched to the transverse phase space of the ISOLDE beam. The Paul trap was therefore replaced by a segmented linear radiofrequency quadrupole (RFQ) ion trap which will be described in some detail in the next section.

2 The RFQ ion trap

An RFQ ion trap is based on the confining properties of an axiperiodic oscillating electrical quadrupole field. These properties have been exploited for many years in so-called "quadrupole mass filters" [4]. The principle of buffer gas cooling in RFQ ion guides was first demonstrated by Douglas and French [5]. The technique was further developed by many groups both in the fields of physics and chemistry. In the context of the guiding and cooling of ion beams from external ion sources, substantial work was carried out at McGill University [6,7]. It was demonstrated that 100-eV beams of ions can be very effectively cooled in a buffer-gas-filled ion guide and that such cooled ions can be extracted from

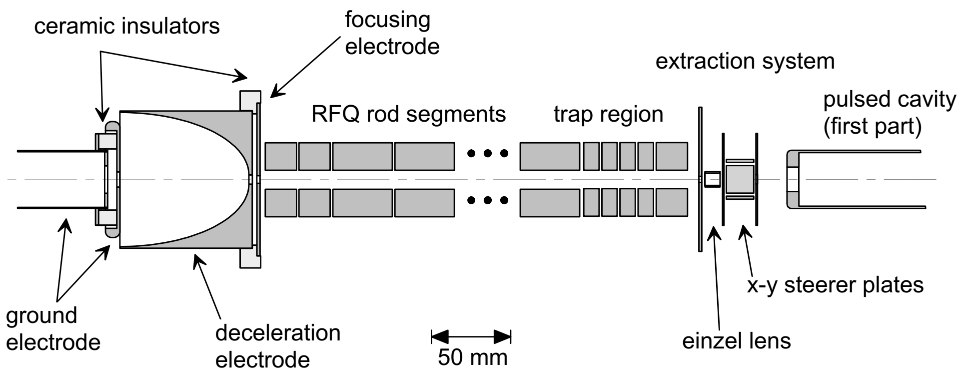

Fig. 1. Cross-sectional view of the injection optics, the RFQ ion trap, and the ejection optics of the ISOLTRAP ion beam cooler and buncher

the cooler as a well-defined beam of very small emittance. Furthermore, an electrostatic deceleration scheme was designed and tested [8]. Its task is the retardation of a 60-keV ion beam to an energy of a few tens of electronvolts while carefully matching its shape in phase space to the acceptance of the RFQ ion guide.

Taking the experience with these prototypes into account, a final system was designed in a collaborative effort between CERN, GSI, and McGill University and installed at the ISOLTRAP spectrometer at ISOLDE. Figure 1 shows the system now in use at ISOLTRAP. The ion guide is composed of four segmented rods about 900 mm in length which are placed in a high-voltage cage that is floated at 60 kV. The potentials that are applied to the deceleration electrodes as well as the axial potential of the ion trap are obtained by applying small negative potentials relative to the potential of the high-voltage cage. The ion trap is maintained at a helium gas pressure of a few pascals. Adequately low pressures in the neighboring regions are obtained by differential pumping through small orifices. The ISOLDE beam enters the structure through the deceleration and the focusing electrodes. In the ion guide, the decelerated beam is radially confined by the pseudo-potential of the RFQ field while it is dragged along the axis of the structure by a small axial DC field. The cooled ions are finally trapped in an axial potential well that extends over a few tens of millimeters near the end of the ion trap. The beam bunch is ejected by lowering the potential of the axial trap on the exit side, and the bunch traverses a pulsed cavity in which its potential energy is adapted to ground potential. Typically, the ion bunch is accelerated to about 2.5 keV as it enters the pulsed cavity. This energy allows the bunch to be transferred to the tandem Penning trap setup for measurement.

3 Performance measurements

For an evaluation of the performance of the beam preparation trap, its efficiency as well as the characteristics of the extracted beam bunch are of particular interest.

When the system is used purely as an ion guide, i.e. without buffer gas and without an axial trapping potential, the combined retardation efficiency and transmission is found to be as high as 40 % for an ISOLDE beam [9]. This is in good agreement with the values obtained from simulations. The total efficiency of the beam preparation system in bunching mode is more difficult to measure. For such a measurement, the current of the incident beam must be carefully chosen to be large enough for a current measurement just before the system, but small enough to still allow the counting of single ions on a multi-channel-plate (MCP) detector on the ejection side just beyond the pulsed cavity. Furthermore, the detection efficiency of an MCP has to be known as a function of the ion energy and mass [10]. For the present measurements with 2.5-keV ions of moderately high mass, a detection efficiency of about 30 % was assumed. It was found that the total efficiency of the beam cooler and buncher is between 12 and 15 % for xenon ions, which were used for this study.

An analysis of the shape of the ion pulse ejected from the beam buncher shows that the ions are cooled to room temperature in the ion trap within a cooling time of only a few milliseconds [9]. From the time and energy spread of the pulse, a longitudinal emittance of about 10 $\mathrm{eV}\cdot\mu\mathrm{s}$ can be extracted. The transverse emittance of the ejected ion pulse at an energy of 2.5 keV was also measured using a beam observation system. It was found to be less than 10 $\pi\cdot$mm$\cdot$mrad. This corresponds to a transverse emittance of less than 2 $\pi\cdot$mm$\cdot$mrad for a 60-keV beam and represents a substantial improvement over the ISOLDE beam with an emittance of typically 35 $\pi\cdot$mm$\cdot$mrad.

4 Summary and outlook

The implementation of the RFQ ion guide beam preparation trap has been a highly successful improvement to the ISOLTRAP facility. The total efficiency of the beam preparation stage was increased by three orders of magnitude as compared with the previously used very large Paul trap. This increase in efficiency, along with the emittance-improving properties of the buffer gas cooling scheme, has made possible the measurement of the masses of radioactive nuclides very far from stability and with very short half-lives [11,12]. Some of these nuclides are delivered by ISOLDE with intensities of only a few thousand ions per second.

Practical experience with the existing system has led to the theoretical development of a novel ion guide design in which the four rods are replaced by a hollow cylinder that is longitudinally cut into wedges [9]. This simpler design whose properties are still being studied in simulations appears to show the same characteristics of the current system but promises to be easier to build, implement, and control.

Acknowledgements

The authors wish to thank J. Bernard, W. Hornung, G. Marx, and W. Quint of GSI who participated in the design and/or the commissioning of the RFQ ion trap for ISOLTRAP.

This work was financially supported by the European Commission within the EXOTRAPS RTD project under contract ERBFMGECT980099 as well as by the Natural Sciences and Engineering Research Council of Canada (NSERC).

References

[1] E. Kugler et al., Nucl. Instrum. Methods B **70** (1992) 41.

[2] G. Bollen et al., Nucl. Instrum. Methods A **368** (1996) 675.

[3] S. Schwarz. Ph.D. thesis, Johannes-Gutenberg-Universität Mainz, 1998.

[4] P. H. Dawson, ed. *Quadrupole Mass Spectrometry and its Applications*. New York: American Institute of Physics, 1995.

[5] D. J. Douglas and J. B. French, J. Am. Soc. Mass Spectrom. **3** (1992) 398.

[6] T. Kim. Ph.D. thesis, McGill University, 1997

[7] A. Kellerbauer et al., to be submitted to Nucl. Instrum. Methods A.

[8] A. Kellerbauer. M.Sc. thesis, McGill University, 1999.

[9] F. Herfurth et al., submitted to Nucl. Instrum. Methods A.

[10] B. Brehm et al., Meas. Sci. Technol. **6** (1995) 953.

[11] F. Herfurth et al., these proceedings.

[12] J. Dilling et al., these proceedings.