BEAM COOLING USING A GAS-FILLED RFQ ION GUIDE

S. Henry, I. Martel-Bravo*, M. de Saint Simon,
M. Jacotin, J.-F. Képinski, and D. Lunney†

CSNSM-IN2P3-CNRS, F-91405 Orsay, France

Abstract. A radiofrequency quadrupole mass filter is being developed for use as a high-transmission beam cooler by operating it in buffer gas at high pressure. Such a device will increase the sensitivity of on-line experiments that make use of weakly produced radioactive ion beams. We present simulations and some preliminary measurements for a device designed to cool the beam for the *MISTRAL* RF mass spectrometer on-line at *ISOLDE*. The work is carried out partly within the frame of the European Community research network: *EXOTRAPS*.

For most experiments using weak radioactive beams, for example the MISTRAL project at ISOLDE/CERN [1], it is desirable that the beam emittance be as small as possible. This requires that the beam be concentrated in a small geometrical area, with a small angular divergence, and a small energy spread. The way to reduce the beam emittance is to cool the beam for which several schemes exist: stochastic cooling and electron cooling are generally used in storage rings while ion trapping applications rely on resistive cooling, laser cooling, and buffer-gas cooling. The latter is of great interest as it is relatively simple and more or less universal.

Ions confined in a Paul or Penning trap can be cooled by introducing a light, neutral gas such as H_2 or He. The ion motion is viscously damped, in principle down to the temperature of the gas itself. This scheme was extended to a continuous beam traversing a radiofrequency quadrupole mass filter by Douglas and French [2] who demonstrated a dramatic gain in transmission through a small hole at the end of a tandem mass filter system by introducing buffer gas into the last quadrupole section. The mass filter continuously focuses the ion beam onto the central axis to avoid the diffusion that would otherwise occur as the ion transit the gas. Similar work using sextupole ion guides has also been reported [3,4].

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*Present address: University of Seville, Spain
†Corresponding author (*lunney@csnsm.in2p3.fr*)

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The purpose of the simulation presented here is to design a similar system capable of decelerating the 60 kV ISOLDE beam and cooling it to the buffer gas temperature before re-acceleration. Since radionuclides are generally short-lived, the cooling process must be rapid. Furthermore, any losses incurred must be minimal. In principle, simply increasing the buffer gas pressure will increase the cooling rate however the consequences of operating electric devices at high pressure are obvious. The design of such a device requires detailed simulation of a system of quadrupole rods (which we refer to as an RF ion guide) and a collisional cooling mechanism as discussed below.

Shown in figure 1 is a schematic diagram of the beam cooling system. Taking pumping speeds of 500 l/s, the end pressures are calculated using Knudsen's formula for vacuum impedance assuming a set of enclosed rods 50 cm long with 10 mm apertures and 0.033 torr of gas introduced in the center. The ion trajectories are simulated by the program described below (using the mass filter operating parameters indicated) and show that the ions reach thermal equilibrium with the gas before exiting the guide.

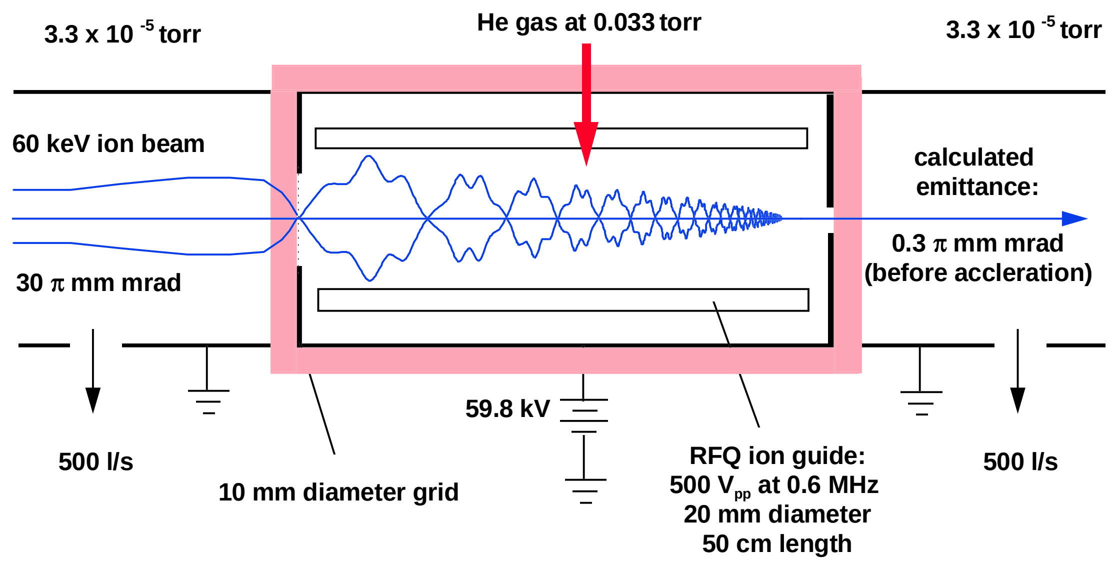


FIGURE 1. Schematic diagram of beam cooling system with optimized design parameters indicated.

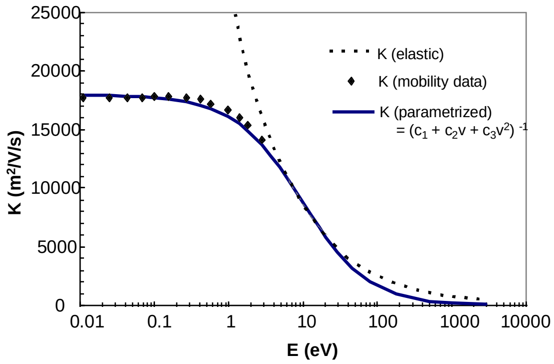
The deceleration system was modeled using the SIMION program in which a 60 keV ion beam is gradually slowed to about 150 eV maintaining a moderate focus into the mass filter aperture. This is done using three electrodes: the first, at ground, with an aperture of 40 mm; the second, 40 mm downstream with a 30 mm aperture, is at 53 kV; a further gap of 40 mm separates the injection aperture grid of 10 mm diameter which floats at 59.9 kV. The grid is necessary to prevent over-focusing. The RF ion guide is located 4 mm further and floats at 59.8 kV thus creating a small potential barrier to stop cooled ions from diffusing back upstream. The beam focus, given the initial emittance of 35 π·mm·mrad at 60 kV (the measured ISOLDE value), is 7 mm in diameter with a divergence of 15° (corresponding to a transverse energy of about 8.5 eV) with a final axial energy of 130 eV, all in accordance with Liouville's theorem.

Due to the phenomenon of RF distortion, the acceptance of an RF ion guide is limited and furthermore, depends on the phase of the RF voltage at injection. Note that though the RF motion is coherent and not affect the ion temperature (in the absence of RF heating), it can cause part of the ion distribution to fall outside the confines of the ion guide. In order to minimize this effect, the operating parameters of the ion guide have to be chosen carefully.

First, reducing the effect of the RF can be done simply by lowering the RF voltage however this has the disadvantage of also lowering the ion guide confining power, or potential well depth D. Therefore, we must minimize the Mathieu parameter q and maximize D which results in choosing an RF voltage as high as possible (*caveat emptor*: high buffer gas pressure!) and an RF frequency such that q remains modest (less than about 0.6). For this simulation we have chosen an RF voltage of 500 V_{pp} and a frequency of 0.6 MHz which results in $q = 0.5$ and $D = 32$ eV. The resulting macromotion frequency ω_0 (for $A = 133$) is 108 kHz.

The effect of RF distortion was studied and indeed, some of the ions are lost before having their motion adequately damped by the buffer gas. However, if we recall that the number of ions actually present in the wings is relatively small (assuming the phase space diagram has a Gaussian distribution), the resulting loss in transmission will be of the order of less than 10%. This loss can eventually be remedied by a simple bunching voltage added to the injection electrode in order to let the ions arrive at an RF phase where RF distortion is minimized.

The viscous damping term is calculated using a parametrization of measurement data from ion mobilities in gases [5] which are tabulated versus ion drift velocity. An example of this parametrization is shown in figure 2 (left) for K^+ ions in He gas at 1×10^{-4} torr. For comparison, the mobility calculated using the gas density and the gas-kinetic cross-section for hard-ball collisions is also shown. At higher energies, one can see that the measured mobility approaches the elastic collision curve and indeed, the fit is tailored to more or less follow this curve at higher energies. There is a preponderance to treat buffer gas collisions as hard-ball collisions which is not correct for ions approaching thermal energies as can be seen from the graph. Evidence for this claim can be found from cooling times observed for ions in Paul traps which are much shorter that what would seem possible from elastic collisions. This is illustrated in figure 2 (right) where the damping time constant is plotted versus energy for mobilities derived from the two approaches discussed above along with an experimental result of the cooling time for K in a He gas-filled Paul trap [6]. Still further support for viscous damping calculated from measured mobilities can be found from measurements with buffer-gas cooled ions in Penning traps [7].



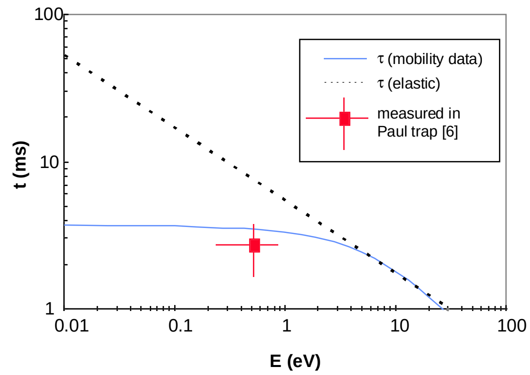


FIGURE 2. (left) K^+ (A = 39) ion mobility in He versus kinetic energy for a pressure of 1×10^{-4} torr (data points from [5]) shown with the mobility calculated using the gas-kinetic cross-section ($\sigma \approx 3 \times 10^{-19}$ m^{-2}). Note that the damping function is parametrized using velocity though energy is shown here for convenience (fit parameters: c_1 = 0.0455, $c_2 = 5\times 10^{-7}$, $c_3 = 9\times 10^{-10}$). (right) Cooling time constant versus energy as calculated from the mobilities shown (left). Also plotted is an experimental cooling time constant measured for K^+ in He gas in a Paul trap [6].

For the trajectory calculations, an acceleration term derived from the Lorentz equation is numerically integrated by a 4th order Runge-Kutta algorithm. From this term is subtracted the parametrized mobility calculation illustrated above which is recalculated using the new velocity after each time step. As the final energy of the cooled ions should be in equilibrium with the gas, the corresponding gas temperature energy is also added to the acceleration term after each step. This is done, for the transverse coordinates, using the macromotion frequency ω_0 which represents the statistical motion of the ions and for the longitudinal coordinate, just the simple thermal "diffusion" velocity.

Using the ion guide parameters in fig.1 and the action diagram calculated by SIMION, it was found that a 50 cm long ion guide operated in a pressure of 0.033 torr cools the ions to the gas temperature in all three dimensions. The calculated ion trajectory for a corner point on the action diagram is shown in fig. 3 (left). While it is interesting to see the trajectory inside the ion guide, it gives us no indication of how much the emittance is reduced as a result of the cooling. For this, we must compare action diagrams at the entrance and exit of the ion guide, as done in figure 3 (right). Here the input and output phase space diagrams - directly proportional to the emittances - are superimposed. When the emittance is calculated from these diagrams ($\pi/4 \times \delta y \times \delta\theta$) and normalized for the beam transport energy, we get a reduction factor of 100 (for each coordinate). In principle this reduction is simply determined by the ratio of the temperature corresponding to the energy spread in the ion source to that of the buffer gas. For an ISOLDE beam, this corresponds to a few eV compared to 0.026 eV if a room-temperature gas is used.

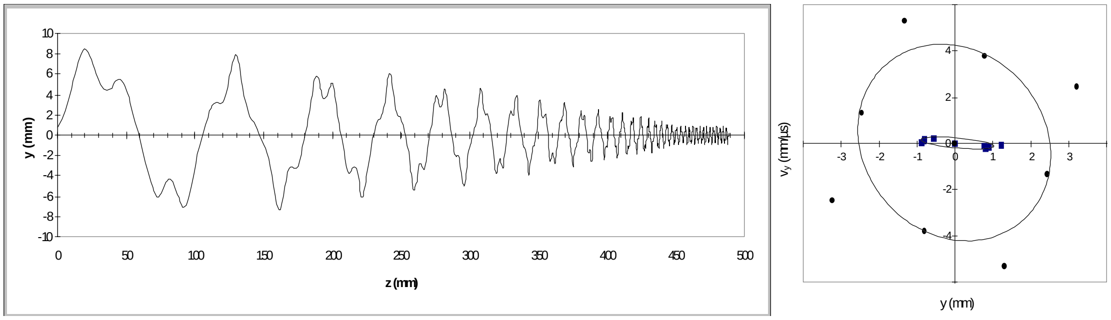


Figure 3. (left) Simulated trajectory of a single ion with an axial energy of 130 eV and a transverse energy of 8.5 eV subject to buffer gas cooling at 0.033 torr in a quadrupole ion guide. (right) Transverse phase space diagrams (for one dimension) of the ion beam before and after transit through the ion guide. The ratio of the corresponding emittance is a factor of 100. Ion guide operating parameters are as in figure 1.

These preliminary results show that such a system is definitely feasible. The critical problem seems to be the transmission loss due to RF distortion and perhaps the gas load on the system. The loss of ions due to charge exchange and other chemical reactions has also not been evaluated. This is sure to play some role as previous results have already shown [4]. Another factor not considered here is the phenomenon of RF heating that occurs in Paul traps. This effect causes an effective increase in temperature (and hence, emittance) when collisions with heavier ions cause a transfer of the coherent RF motion to the statistical (macro) motion. A test system scaled-down (by about a factor of ten) in energy is being built at the *CSNSM* using an existing mass spectrometer set-up. It is hoped that the *ISOLDE* emittance can thus be significantly reduced, corresponding to a similar gain in sensitivity for *MISTRAL* and eventually, other on-line experiments at *ISOLDE* and elsewhere. A similar device, with the added feature of bunching, is being built for the *ISOLTRAP* experiment [8], also at *ISOLDE*. Both projects are part of the European Community research network: *EXOTRAPS* [9] devoted to cooling and purifying radioactive beam.

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