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A compact linear Paul trap cooler buncher for CRIS

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Abstract

A gas-filled linear Paul trap for the Collinear Resonance Ionisation Spectroscopy (CRIS) experiment at ISOLDE, CERN is currently under development. The trap is designed to accept beam from both ISOLDE target stations and the CRIS stable ion source. The motivation for the project along with the current design, simulations and future plans, will be outlined.

Keywords: Ion trapping, Laser spectroscopy, 3D printing

1. Introduction

Gas-filled linear Paul traps are used at a variety of radioactive beam facilities to provide bunched beams with low emittance to a range of experimental setups [1, 2, 3]. Bunched beams are essential to Collinear Resonance Ionisation Spectroscopy (CRIS) [4, 5, 6] because the required high-power lasers are only available with repetition rates of the order of 100 Hz, meaning the ion beam must also be pulsed to remove duty-cycle losses. The pulsed-time structure also reduces optical pumping to atomic dark states, further increasing ionisation efficiency [7]. Minimising the ion beam energy spread via in-trap buffer-gas cooling reduces the Doppler broadening of the resonant excitation steps, leading to higher precision in extracted hyperfine structure and isotope shifts. For more information on the CRIS technique, see the contributions from Á. Koszorús et al. and A.R. Vernon et al. in these proceedings [8, 9].

CRIS at ISOLDE [10] currently utilises the ISCOOL gas-filled linear Paul trap (RFQcb). ISCOOL has been essential to the success of the CRIS experiment, providing bunched beams with <1 eV energy spread and <5 μs width. When fully optimised the transmission efficiency of ISCOOL can reach 70%, however for lower masses the usable efficiency decreases significantly [11]. This article describes the development of an independent RFQcb for the CRIS beamline, to be placed after the CRIS ion source (CRISIS) [12]. Installing a dedicated RFQcb would decouple the CRIS beamline from the rest of ISOLDE; ions injected into the trap from ISOLDE and from CRISIS would have the same properties when they reach the CRIS interaction region. This would allow for continual optimisation of trapping parameters and efficiency with stable isotopes, improving beam quality and transport efficiency for radioactive beam experiments. Frequent reference measurements,

performed by extracting a stable reference isotope from ISOLDE, are required during experiments on radioactive atoms to keep track of slow drifts in wavenumber readout. Switching masses on the ISOLDE separator for this purpose is time consuming (approximately 6 minutes per mass change); during recent CRIS campaigns, between 5% and 10% of the total beamtime was spent cycling the magnets. In addition, more than 33% of the remaining time was spent adjusting bending and focussing electric potentials to maximise ion beam transmission through CRIS. A dedicated trap would allow CRISIS to be used for the reference measurements, and would almost entirely eliminate the beam transport optimisation required at the start of radioactive beam experiments. This period is when the yield of radioactive cases is at its maximum and additional data collection at this point would have a disproportionate effect on the overall signal significance. As the majority of background counts at CRIS scale with the beam current, for example non-resonant laser ionisation of isobaric contamination, the total background observed is proportional to the interaction region atom throughput, hence the signal significance scales with the product of the beam intensity, measurement time and total efficiency.

2. Prototype RFQcb overview

Anticipating the available lab space, the current prototype design uses a short trapping region, 20 cm in length, with four cylindrical rods at 5.3 mm internal radius. Sine or square wave RF driven at frequencies of the order of MHz will be applied to the rods to trap the ions radially, while helium buffer gas (at pressure in the range 10^{-3} to 10^{-1} mbar) will be used to reduce the amplitude of the radial oscillation. The ions will be trapped longitudinally using DC potentials applied to four printed circuit boards inserted between the rods. The rods and PCBs are mounted on two 3D printed endcap pieces.

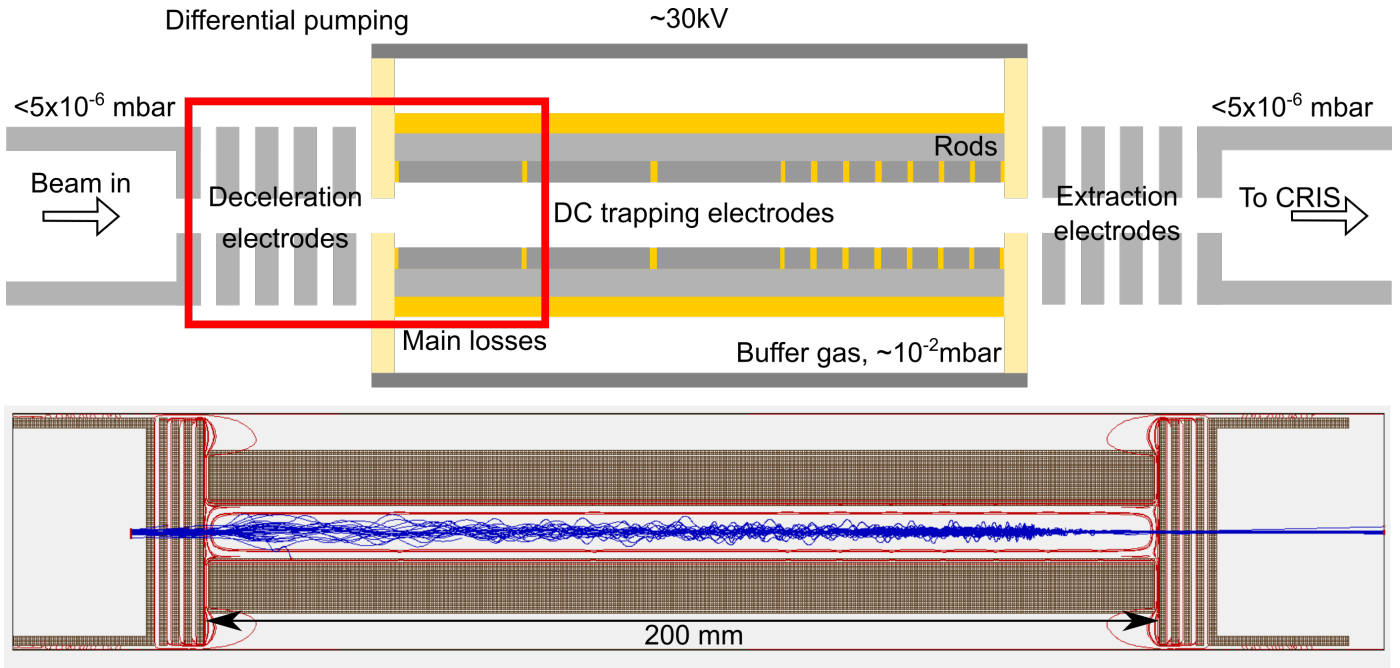*christopher.ricketts@manchester.ac.uk

Figure 1: The current linear RFQ design. Upper - schematic of the trap design including the buffer gas containment cylinder (dark grey) around the trapping region, the 3D printed components (light yellow) and the PCB electrodes (dark yellow). 70% of the losses occur in the region indicated by the red box. Lower - SIMION simulation showing electric potential contours (red) and $A = 70$ ion trajectories starting at the beam waist, at 0.034 mbar buffer gas pressure (blue). The ions travel from left to right. Losses are minimal during extraction.

We have demonstrated that polylactic acid biopolymer (PLA) used in 3D printers is vacuum compatible. Figure 3 shows the pressure over time in a 3-way T-piece vacuum chamber with $440 \, \mathrm{L \, s^{-1}}$ pumping capacity. As the figure shows, when a 20 mm side length cube of 3D printed PLA was placed in the vacuum chamber, the pressure decreased to 2×10^{-7} mbar after 5.5 hours of pumping, equal to the pressure reached by the empty chamber within the same pumping time. This pressure is compatible with the vacuum requirements of the RFQcb. Residual gas analysis was performed at 3.9×10^{-8} mbar with the PLA sample present and at 6.7×10^{-8} mbar when the chamber was empty. No significant change was seen in the composition of the gas after adding the sample, indicating that outgassing of the PLA is not significant at these pressures. The RGA spectra are shown in Figure 4. Flow rate calculations indicate the 4 mm apertures on either side of the trapping region will provide the required differential pumping to reach pressures below 5×10^{-6} mbar outside the trap with two stages of differential pumping and up to 0.1 mbar internal buffer gas pressure.

The entire trap is biased to a potential slightly below 30 kV to decelerate the incoming beam from 30 keV to approximately 100 eV. At 30 keV, the Doppler broadening of the resonant excitation lineshape is comparable to the natural linewidth of many resonant transitions and a larger platform operating voltage is not required. SIMION simulations, shown in the lower part of Figure 1, have indicated that more than 70% of the ion beam losses occur during the injection-deceleration phase due to the narrow input aperture required for differential pumping and collisions with residual buffer gas. To mitigate these losses, a se-

ries of PCB ring electrodes were introduced into the model to produce a longitudinal potential structure of the form $V(z) = V_0(1 - e^{-\alpha z})$. This produces a transverse focussing effect with a focal point at a position proportional to $1/\alpha$ [13]. The results of the simulations are shown in Table 1 and an output emittance plot for $A = 70$ is shown in Figure 2. These used an input 30 keV focussed beam with $20 \, \pi$ mm mrad transverse emittance and a Gaussian radial profile with 0.5 mm standard deviation. The ions were released from the simulated trap after 2 ms. The transmission efficiency at $A = 70$ was 54% and the final simulated emittance of the cooled beam at this mass was $1.5 \, \pi$ mm mrad.

3. Outlook

The benefits of installing an independent gas-filled linear Paul trap at the CRIS beamline have been explained and the design outlined is under development. Simulations have indicated the feasibility of a short trap design and have informed possible design improvements. The design offers a cost effective and high efficiency method to trap ions for radioactive beam studies. This work also illustrates the possible uses of 3D printed parts in vacuum, enabling cheaper and faster methods for design prototyping.

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Mass, A	Pressure / mbar	Transmission probability / %	Acceptance / π mm mrad	Output emittance / π mm mrad
12	0.012	11	10	16
70	0.034	54	20	1.5

Table 1: Simulated RFQ trapping parameters with total ion transmission probabilities, the input beam acceptance and output beam emittance after reacceleration at optimised buffer gas pressures. A 30 keV focussed input beam with $20\,\pi$ mm mrad transverse emittance and a Gaussian radial profile with 0.5 mm standard deviation was used. The ions were released after 2 ms.
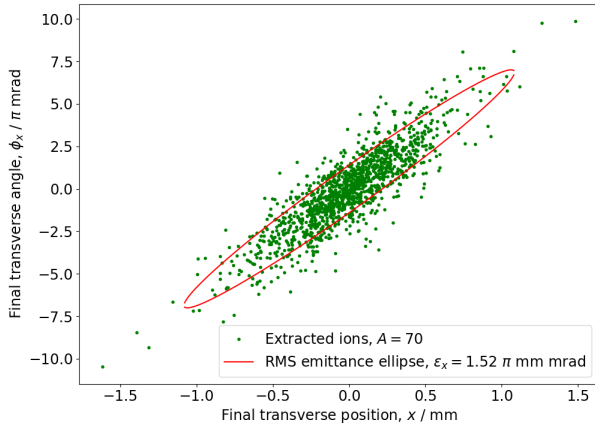

Figure 2: A plot showing the displacement along the transverse x-axis vs the velocity angle relative to the beam axis in the xz-plane, where z is aligned along the beam axis, of the transmitted $A = 70$ ions in a SIMION simulation of the RFQcb (green points). The ellipse showing the RMS transverse emittance in x is also included (red line).

Figure 4: A plot showing the partial pressure at each mass detected by a residual gas analyser of the empty vacuum chamber at 6.7×10^{-8} mbar (red) and the vacuum chamber containing the PLA test cube at 3.9×10^{-8} mbar (black). No significant change in the RGA spectrum is seen after adding the PLA sample, indicating that outgassing from the sample is not significant at these pressures.

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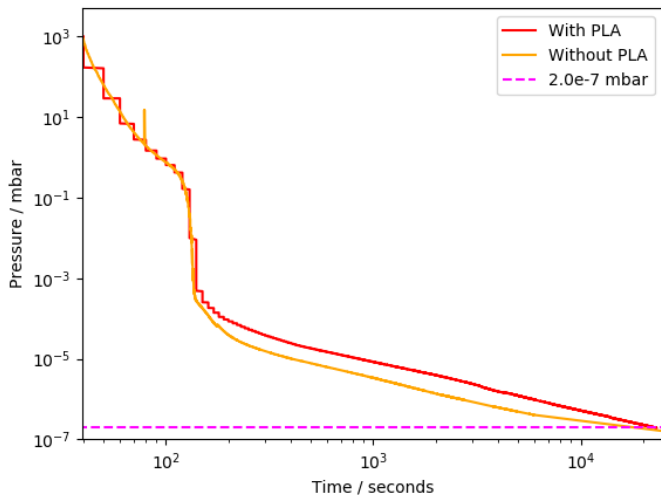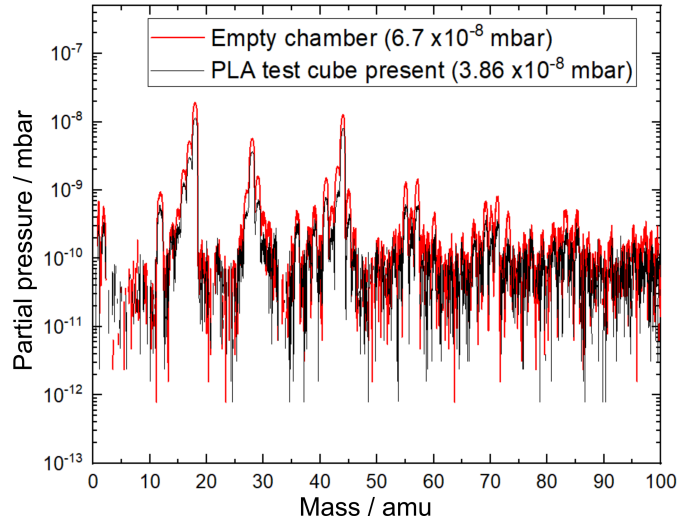

Figure 3: Pump down curves for an empty chamber (yellow) and for the same chamber with a 20 mm side length cube of PLA (orange). The chamber containing the PLA sample reached a pressure equal to that of the empty chamber, 2×10^{-7} mbar, after 5.5 hours of pumping, indicated by the pink dashed line. Features in both curves below the order of 2×10^2 s are related to different pumping stages turning on.