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## Laser spectroscopy with an electrostatic ConeTrap

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**Abstract** A compact electrostatic trap has been designed and installed as part of the recent upgrades to the IGISOL IV facility. The ConeTrap provides an in vacuo optical pumping site for low energy (800 eV) ionic ensembles available for interaction periods of 10–100 ms. At present, 6.7(3) % of injected mass  $A=98$  ions can be trapped, stored for 5 ms, extracted and transported to a laser-ion interaction region. This fraction represents those ions for which no perturbation to total energy or energy spread is observed. Proposed enhancements to the trap are designed to improve the trapping efficiency by up to a factor of 5. Differential pumping and reduction in background pressure below the present  $10^{-6}$  mbar will extend storage times beyond 100 ms.

**Keywords** Electrostatic · Ion · Trap · Laser · Spectroscopy

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## 1 Introduction

At the laser-IGISOL facility JYFL, there has been an increased, experiment driven, desire for a field free, high vacuum, trapped ion interaction region in which to perform long interaction (10–100 ms) laser spectroscopy. A ConeTrap, pioneered by Schmidt *et al.* [1], would provide such a location. These electrostatic traps can successfully contain 30 000 ions for in excess of 100 ms [1, 2], and are thus ideal for the purpose of laser spectroscopy.

ConeTraps comprise of two (or more) conical, reflecting electrodes that are used to provide multi-reflection based containment of ions. Simple conical electrodes at voltage create potentials which internally are harmonic in both the  $z$  and  $r$  directions (specified in cylindrical coordinates). When two facing cones are partitioned with a grounded aperture electrode then electrostatic potentials such as those shown in Fig. 1 can be formed. It is observed that, even with extended central sections, stable ion trapping can be achieved (Fig. 2) for a range of potentials and various reflections in the ConeTrap.

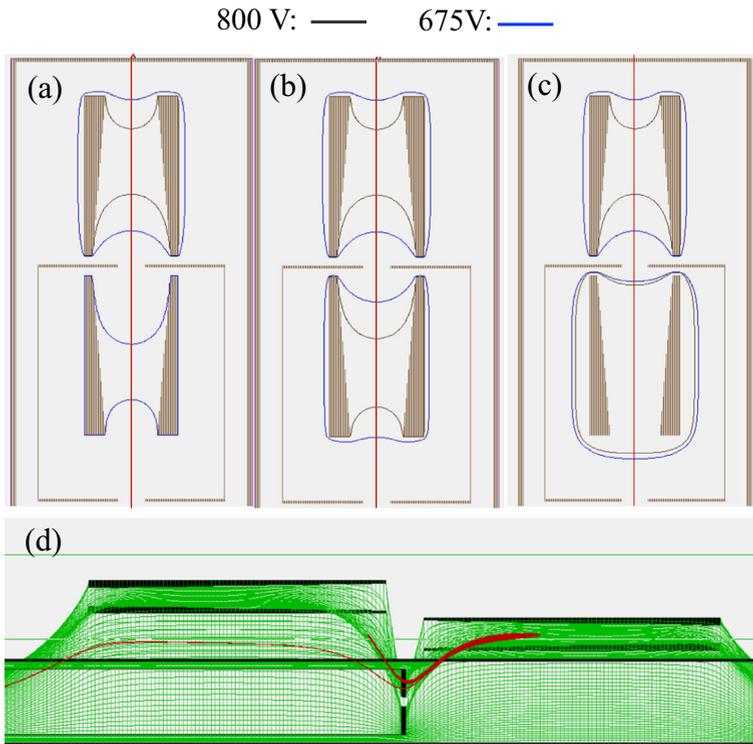
The ions in the ConeTrap have a maximum axial velocity in the central region, determined by the electrode voltages. Each ion will momentarily have a net axial velocity of zero at each end of the trap electrodes. These extremes, the turning points and the trap centre, are associated with extremes in Doppler-shifted frequency where optical resonance can be induced in trapped ions. In the centre, velocity spread compressed, collinear laser spectroscopy can be attempted, albeit at modest total energy (800 eV). At the turning points a laser-ion interaction perpendicular to the direction of motion is achieved irrespective of energy (given a sufficiently narrow laser beam).

## 2 Description and basic operation of the ConeTrap

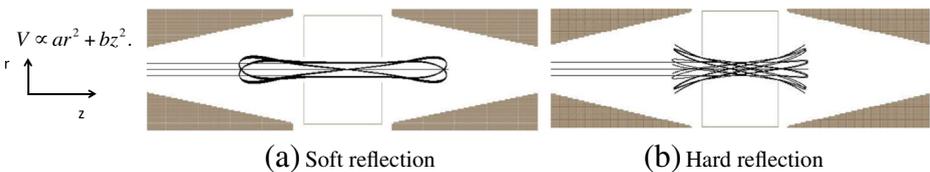
Initially, the ConeTrap implemented at the IGISOL IV laboratory was comprised of two conical electrodes separated by a grounded central chamber, following the designs outlined in reference [3]. The conical electrodes were made with open ends, allowing laser light to pass through the ConeTrap and interact with ions in the central region. The restricted stability and critical alignment dependencies led to design changes that resulted in the removal of the grounded central region and development of a ‘collapsed’, two cone only, trap. The final design is highly compact and electrostatic simulations (described below) reveal broad stability regions achievable in a range of trapping modes. The device is shown in Fig. 3. The ConeTrap is constructed from high purity (deoxygenated) copper and PEEK insulators, with the stainless steel supporting rods and meshes external to the trap. The copper electrodes are each 74.0 mm in length, the smaller aperture,  $\phi_1 = 23.0$  mm and the larger aperture,  $\phi_2 = 34.0$  mm, creating an opening angle of  $8.46^\circ$ . The two electrodes are separated by 4.0 mm of insulation and a grounded central aperture 2.0 mm thick with opening diameter 8.0 mm.

At the IGISOL, the ConeTrap is situated on the high voltage platform that houses the RFQ cooler. At this point, ions have a kinetic energy of approximately 800 eV, thus moving with a lower velocity than any other section of the high vacuum beamline. Only modest trapping potentials and fast switching (50 ns) of voltages less than  $\sim 2$  kV are required to operate the device. When positioned on one face of a switchable quadrupole bend, a laser-ion interaction region covering the full injection path of the ConeTrap can readily be achieved.

To enable ions to enter the trap the front electrode is switched to an ‘injection’ voltage and then back to a ‘trapping’ voltage, prior to the reflected bunch returning to the front cone.



**Fig. 1** Plots showing equipotential contours for: (a) Front cone at injection/extraction potential (680 V) and rear at 805 V, (b) symmetric ConeTrap with both electrodes at 805 V, (c) asymmetric ConeTrap with the front and rear electrodes set to 1350 V and 805 V respectively. Also included is, (d) a 3-D projection of the harmonic potential created in the  $z$  direction for the asymmetric regime, as shown in (c)

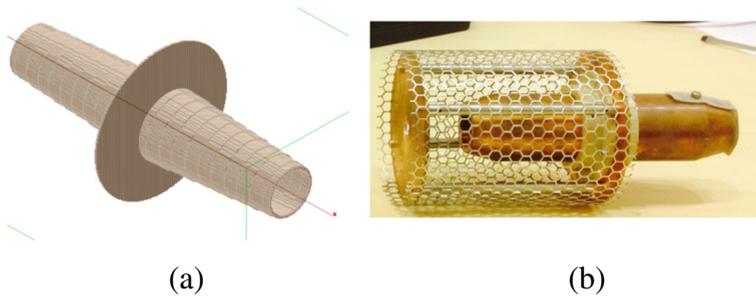


**Fig. 2** Trajectories of ions within the ConeTrap in two different trapping modes

After a desired trapping time, switching down the front electrode permits extraction and secondary acceleration. At the IGISOL, the ions that exit the trap are guided to the ‘Light Collection Region’ (LCR) in the collinear laser beamline.

In the absence of collisions with residual gas, or ion-ion interactions, an ionic ensemble can be indefinitely trapped in either of two symmetric trapping modes, denoted *soft* and *hard* reflections here. A *soft* reflection is established, at  $E_{ion} = 800$  eV, when both electrodes are set to a voltage of  $\sim 810$  V. *Hard* reflection is achieved at potentials of 1250–1400 V. It is also possible to achieve stable modes using an asymmetric combination of these reflections.

The soft reflection results in ions spending significant time,  $>10 \mu s$  at  $A=100$  and 800 eV, transiting within the electrode compared to that,  $<2 \mu s$ , characteristic of a hard reflection. A



**Fig. 3** Two depictions of the ConeTrap installed at the IGISOL IV beamline. Panel **a**) shows the electrode structure as in SIMION [4], panel **b**) shows the manufactured component, plus fore-line ion injection Faraday cage

soft reflection in the back cone and a hard reflection in the front causes ions to spend a significantly longer time away from the switching potential of the front electrode. An asymmetric ConeTrap, with respect to potentials, provides the optimal solution for injection and extraction through the same electrode, and was employed in all testing of the ConeTrap.

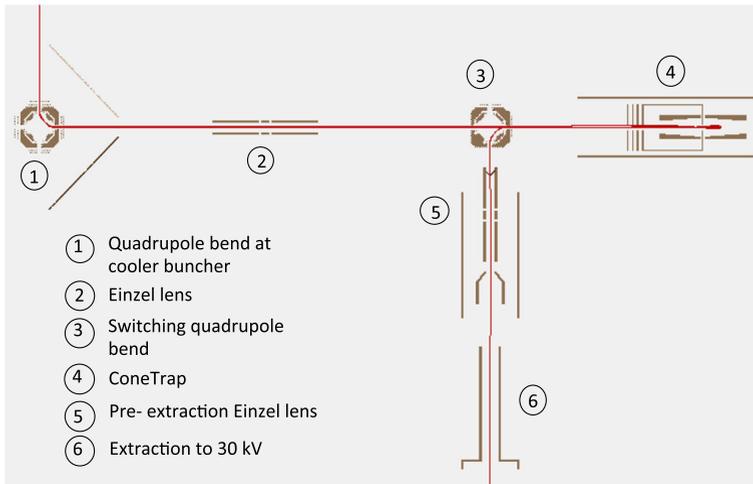
### 3 Intra trap optical pumping

For 800 eV ensembles with energy spreads of 0.6 eV, typical for the JYFL cooler-buncher [5], reduced Doppler widths of <100 MHz would be expected for  $A=100$  ions at 300 nm. An efficient ConeTrap thus provides an ideal interaction region for optical pumping of transitions in ionic species. At the IGISOL such optical pumping has already been used to permit spectroscopy of, previously inaccessible, short-lived radio isotopes [6, 7]. In references [6, 7] pumping was performed within the gas-filled cooler buncher and was limited in linewidth by the macro motion within the RFQ trap (corresponding to 10's of GHz of line broadening). More critically, the spectroscopy was limited in the excitation energy of the populated excited state due to non-photonic relaxation processes in the trapped volume. A ConeTrap would readily overcome these limitations and permit post trapping spectroscopy if extracted ensembles could be recovered with minimal perturbation of the energy and energy spread. Each has been explored at the IGISOL and the results are discussed here.

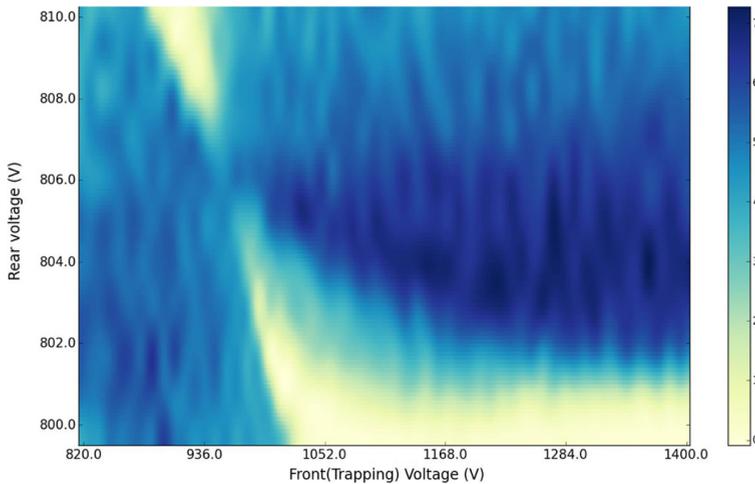
### 4 ConeTrap parameters

Full simulation of the ConeTrap has been conducted using the ion-optic simulation package SIMION [4], in which the potential is initially evaluated (in cylindrical geometry) by numerically solving the Laplace equation for finite grid elements (with 1 mm resolution). Particle trajectories are then evaluated using a fourth order Runge-Kutta method in three dimensions [8]. Particle-particle and particle-gas interactions were neglected in the simulations (but explored experimentally). Figure 4 shows the electrostatic model of the post-cooler environment (referred to as a workbench in SIMION). The behaviour of ions can be modelled, and the survival as well as energy and temporal spread predicted for the full trapping period.

The simulation was set such that the ConeTrap would trap the ions after a user defined time, replicating realistic operating conditions including temporal and energy spread of the



**Fig. 4** The SIMION workbench for the ConeTrap and all post-cooler elements used in guiding and focussing the ion beam. Shown in the right hand corner is a cross section of the asymmetric ConeTrap employed at typical operating conditions



**Fig. 5** Stability plot for the collapsed ConeTrap, showing the survival percentage of ions that are contained for 5 ms, then released to the LCR (as modelled in SIMION). Negligible losses to buffer gas or ion-ion collisions are assumed

bunched ion plume. ConeTrap parameters that maximise the trapping efficiency were found, as functions of the trapping, rear and injection voltages. Injection and extraction voltages were found to optimise at the same value, reducing the complexity encountered in switching potentials in the ConeTrap. The region shown in Fig. 5 focuses on rear cone voltages of 800 – 810V, corresponding to  $>6 \mu\text{s}$  transit in the rear cone (the minimum storage time for the efficient capture of ion plumes from the IGISOL cooler-buncher) and extend to 1400 V for the front cone beyond which trap stability is rapidly lost. The observation of a relatively

narrow stability region near symmetric potentials and broader stability region for higher potentials (separated by a region of instability) closely follows the behaviour predicted and observed in other ConeTraps [3].

## 5 On-line results

Experimental testing of the collapsed ConeTrap guided by the SIMION modelling was undertaken at a range of masses and trapping potentials. With the trapping time of the ConeTrap set to 5 ms, the released plumes were deflected to micro channel plates (MCPs) at the LCR (and viewed on an oscilloscope). To ensure count rates free of saturation, ion fluxes were limited to 0 – 5 ions per bunch.

Ion plumes arriving 5 ms after cooler-buncher release were evident as (shown in Fig. 6). The temporal spread of the ion plume no longer reflects the 10–15  $\mu\text{s}$  characteristic release of the JYFL cooler buncher [9] and instead reflects the cycle time in the ConeTrap, dominated by the orbit time in the rear cone electrode. Figure 7 shows that the bunch width decreases with an increasing rear voltage in a manner entirely consistent with the SIMION simulation predictions.

At rear voltages of 805 – 808 V >60 % of the typical ion plumes can be captured by the device ( $V_{\text{front}}=1350$  V). Measurements of trapping efficiencies were made using radioactive ions around mass  $A=100$ . The ions were produced in fission using 25 MeV protons incident upon a natural uranium target. At mass  $A=98$  a range of strontium, yttrium and niobium systems could be investigated by directly monitoring decay gamma emission with and without storage in the ConeTrap (overcoming saturation issues with the channel plates). A direct comparison between count rates with and without storage in the ConeTrap were made using spectra such as those shown in Fig. 8. The ConeTrap extraction efficiency showed no dependence on chemical species and could be estimated using data from multiple photopeaks (highlighted in Fig. 8) to be 6.7(3) % survival from cooler-ejection to end of laser line detection. Whilst clearly demonstrating that the ConeTrap is operational the result, an order of magnitude less than our expected (simulated) maximum, suggests significant losses and potentially significant improvements can be made to the device (Section 6).

Collinear laser spectroscopy was performed on re-accelerated ionic ensembles (previously stored in the ConeTrap) under off-line conditions. A full a description of the laser spectroscopy experimental procedure can be found in reference [10]. For these tests the  $^{180}\text{Hf}$  ion was studied (which can be efficiently explored on transitions from its ionic ground state without optical pumping). The 0 – 33180.92  $\text{cm}^{-1}$  resonance in  $^{180}\text{Hf}$  was inspected using direct bunched beam spectroscopy and compared to that observed following 5 ms storage in the ConeTrap. The spectra are displayed in Fig. 9. A total of 197 scan (corresponding to 1.955 s/channel) were taken with ions bypassing the ConeTrap, while 2007 scans (corresponding to 30.1 s/channel) were recorded for ion ensembles having been stored for 5 ms in the device.

The linewidth of the resonances (Fig. 9) corresponding to those of trapped ions and those guided directly to the LCR were found to be 29(6) MHz and 35(3) MHz respectively. No shift in centroid within errors was detected, suggesting that the mean energy of the transported bunch had remained constant. The possibility that only an energy analysed fraction of the total ensemble has been transported to the LCR can only be excluded once higher overall injection-storage-extraction efficiency has been achieved (and the linewidth and centroid investigated at those conditions). At present only the 6.7(3) % transported fraction can be confirmed to maintain energy and energy spread.

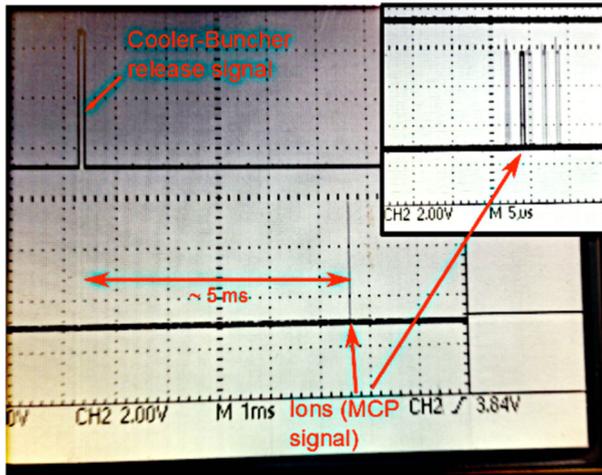


Fig. 6 Ion plumes arriving at 5 ms after cooler release signal

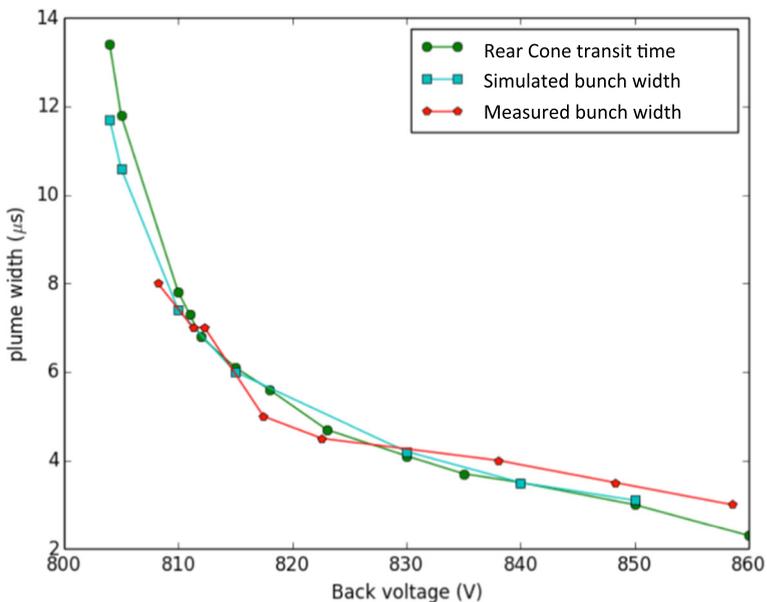
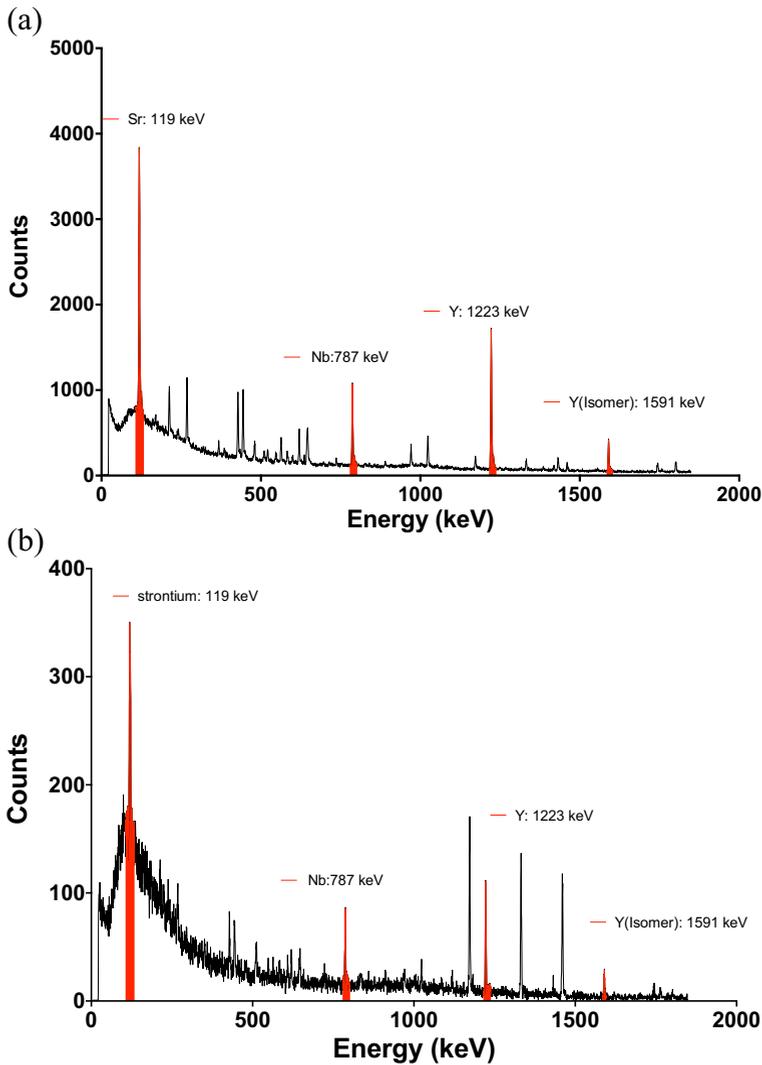


Fig. 7 Plot comparing the measured and simulated temporal plume width on release and the transit time in the rear electrode

## 6 Improving the yield

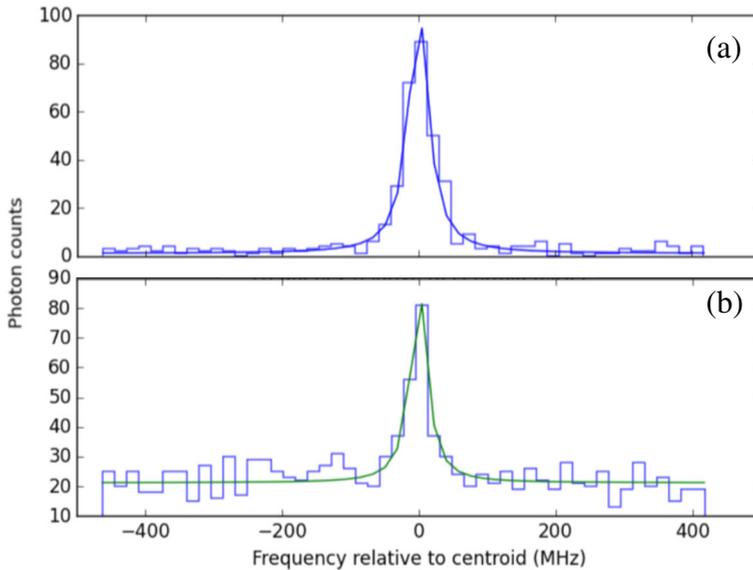
To improve on the 6.7(3) % efficiency presently achieved on-line further, critical, focussing ion optics are needed. Simulations run at the *experimentally determined* optimum trap parameters (with realistic plume widths of 10 μs and 0.6 eV energy spread) suggest the



**Fig. 8** Germanium detector spectra from  $A=98$  fission fragment isobars detected at the LCR collected over 300 s (peaks highlighted in red indicate those used in storage efficiency estimates) with the (a) ConeTrap bypassed and (b) 5 ms ConeTrap storage

ConeTrap to presently optimise close to the edge of trap stability and at parameters that do not provide efficient post-trap transport conditions. Significant losses are predicted to occur at the first quadrupole switching bend (see Fig. 10) and changes to ion optical elements have been explored. The full workbench simulation suggests that an additional applied Einzel lens at the injection/extraction electrode can simultaneously permit both optimised trapping efficiency and optimised downstream transport. Figure 10 shows the suggested optical changes and ray traces at optimised conditions.

Following commissioning of the new ion-optics further optimisations including faster switching HV supplies will be explored. During these tests it is intended that single in-out



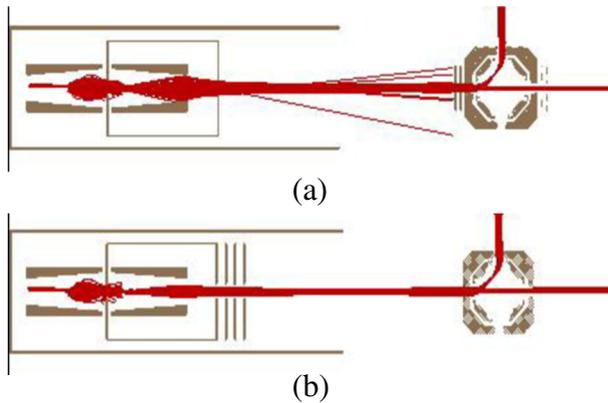
**Fig. 9** Resonance spectra of  $^{180}\text{Hf}$  observed for (a) ions passing directly to the LCR and (b) for those following 5 ms storage in the ConeTrap

reflections of the open ConeTrap will be explored such that the losses arising from injection, extraction and transport may be quantified separately and addressed appropriately. A major redevelopment of the rear cone electrode will then be explored. Simulations including misalignments and increased spatial ion beam size have shown losses to be significantly reduced on increasing the size of the rear trap electrode. Figure 11 shows the SIMION model of a new electrode, presently under construction.

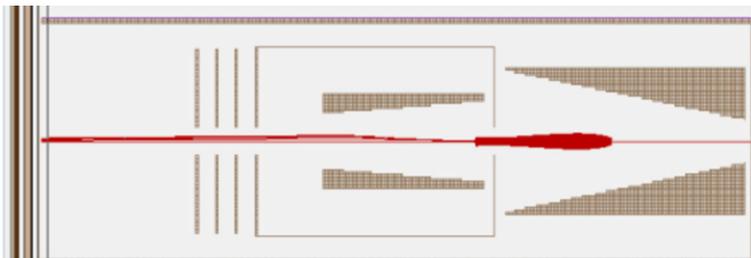
## 7 Prospects for laser spectroscopy using the ConeTrap

Once fully optimised for transport, losses in the ConeTrap arise from charge exchange collisions with neutral background gas and from ion-ion interactions as the space charge limit is approached. The latter has experimentally been confirmed to be negligible at typical IGISOL conditions ( $\sim 1000$  ions per bunch) consistent with the behaviour reported in [1]. The former, charge-exchange collisions, occur with probabilities dependent on ionic electron configuration and a straight-forward but highly efficient spectroscopy can be explored in which ion survival as a function of excited state population is monitored during optical pumping. The spectroscopy, which may be considered a variant of that developed and fruitfully exploited in reference [11], can be attempted by pre-pumping ionic ensembles in the cooler buncher, facilitating broad-band spectroscopy, or within the ConeTrap itself, providing spectroscopy at  $\sim 100$  MHz linewidth (for medium mass nuclei).

When fully commissioned, defined by the device reaching the specifications described above and further, being operated at a pressure of  $< 10^{-8}$  mbar, losses to charge exchange collisions should be minimal ( $< 10\%$ ) at 100 ms storage. When achieved, optical pumping in vacuo coupled to fast beam collinear spectroscopy can be performed and the original objectives of the ConeTrap realised. The interaction time is envisaged to facilitate efficient



**Fig. 10** Comparison of ion trajectories on exit from the ConeTrap at the same operating conditions, with (b) and without (a) an Einzel lens present



**Fig. 11** A cross section, taken from the SIMION simulation, of the new proposed ConeTrap with large rear electrode

spectroscopy on the weakest of allowed spectroscopic transitions and to enable intra-trap 2-photon spectroscopy.

## 8 Summary

An electrostatic ConeTrap, developed from that described in reference [1], has been constructed and tested at the IGISOL facility, JYFL. The trap is presently operational but improvements in total injection-storage-extraction efficiency, of close to an order of magnitude, are being sought. The JYFL ConeTrap is designed for laser spectroscopic use. Long duration,  $>100$  ms, laser-ion interaction studies using the trap are to be developed during the next commissioning phase.

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