ION BEAM PREPARATION WITH TITAN'S DIGITAL RFQ AT ISAC

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and
the TITAN collaboration

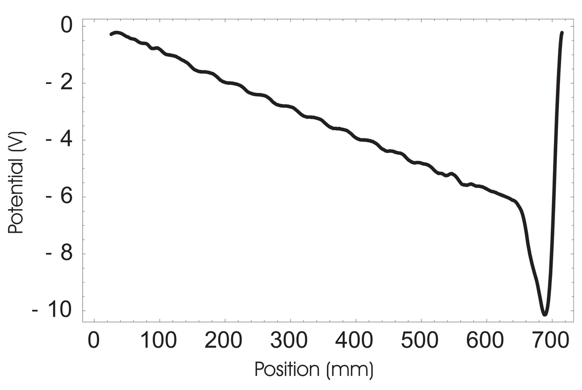
The RFQ Cooler and Buncher

The gas-filled, segmented RFQ is fast becoming a standard piece of equipment at online facilities. Such devices use the combination of a time variant quadrupolar electric field and a longitudinally applied electrostatic field to trap ions in 3-D.

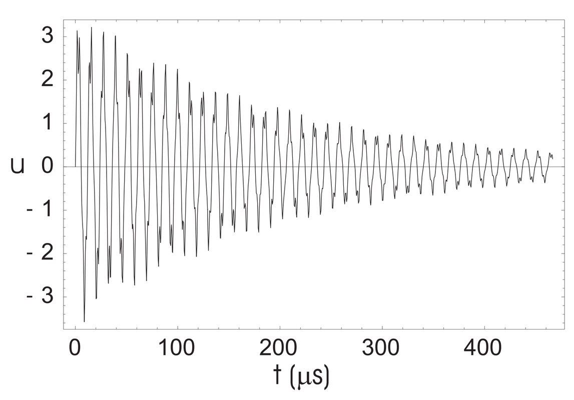
The quadrupolar field is realized by the four-electrode geometry shown. Ions inside the electrode structure can be trapped in the 2-D plane defined by the X- and Y- axes by applying an RF potential. The ion's motion in the radial direction is a combination of a simple harmonic macro-motion, due to the quadrupolar field, coupled with a micro-motion, due to the RF.

An ion beam can be cooled via collisions with an inert buffer gas. However, such collisions cause the beam to diverge. The RFQ provides a force that pushes the ions onto its Z-axis. Hence, an ion beam can be cooled inside an RFQ via collisions with a buffer gas without the beam diverging.

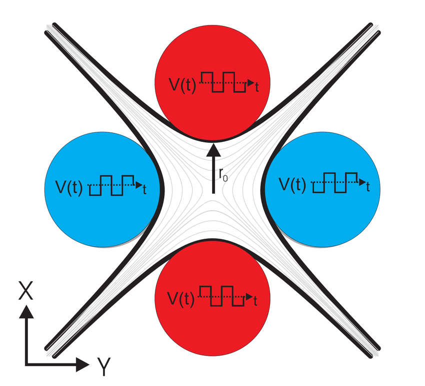
By segmenting the RFQ rods a longitudinal electrostatic potential can be applied such that ions can be trapped in 3-D. This potential can be pulsed such that an RFQ can be used to provide a bunched beam.



The shape of the electrostatic potential used to trap ions longitudinally in the RFQ.

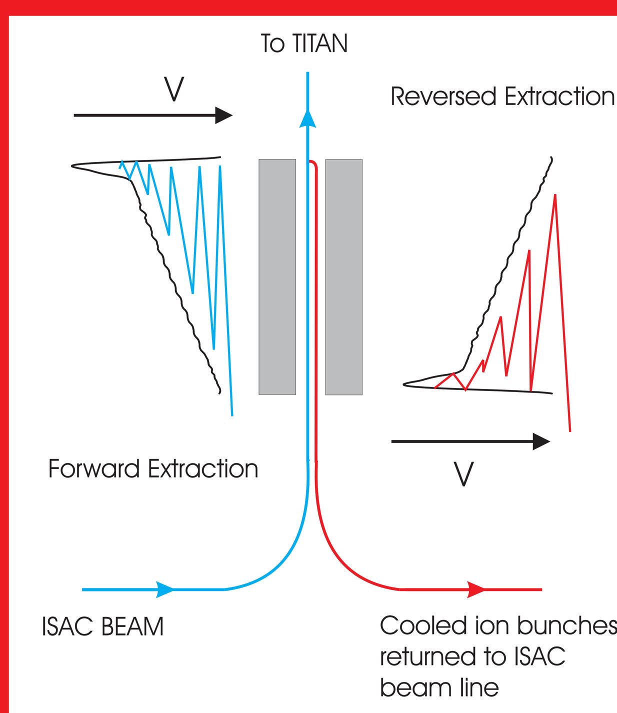


The amplitude, u, of the motion of an ion inside an RFQ as a function of time. The effect of the gas is to remove energy from the beam and hence to damp the ion's motion. To calculate this trajectory a simple viscous drag model for the ion's interaction with the gas was used.



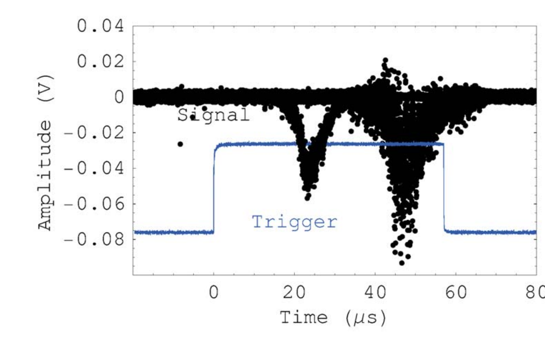
The quadrupolar electrode structure used to generate the trapping field. The corresponding equipotential lines are shown in grey.

Reversed Extraction

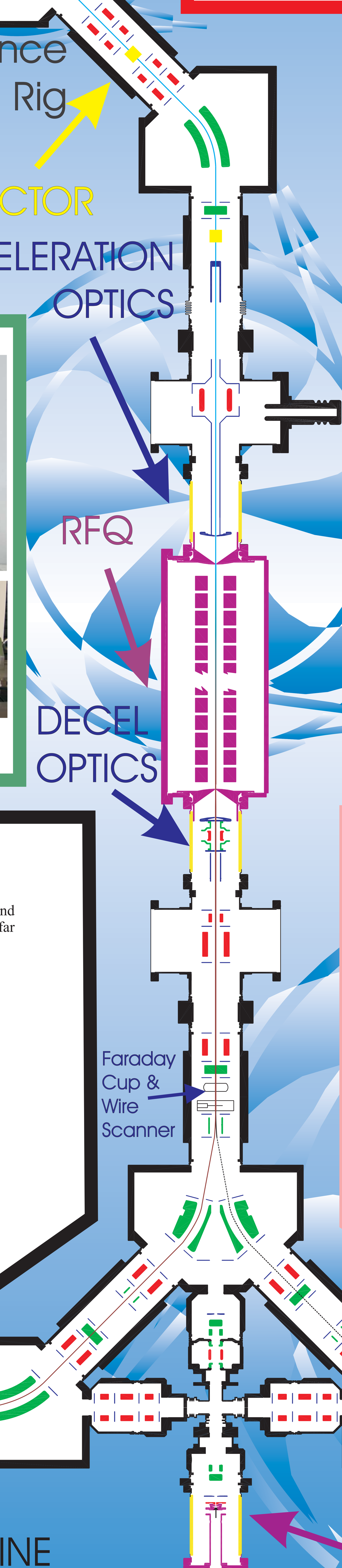


A unique feature of the TITAN RFQ cooler and buncher is the ability to extract ion pulses back into the ISAC line. In this mode the DC potential applied to RFQ rods is reversed such that the ions are trapped and cooled at the bottom of the beam cooler. The bunches can then be delivered to other experiments at ISAC where such beam properties are desirable e.g. collinear laser spectroscopy and beta detected NMR.

Extraction in this mode has been successful demonstrated using both ^{133}Cs ions from a small test ion source mounted below the RFQ and with ^{136}Xe from the ISAC Off-Line Ion



Extracted ^{136}Xe pulses detected on two separate MCPs in the ISAC line. The MCPs were separated by a distance of 3 m. The observed 20 μs time of flight between detectors corresponds to mass 136 ions with 15 keV kinetic energy.

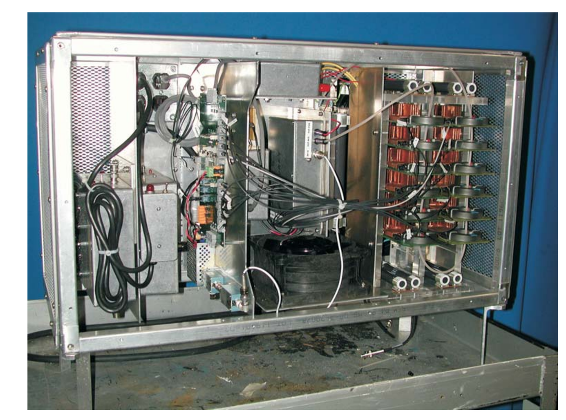


Square-Wave-Driver

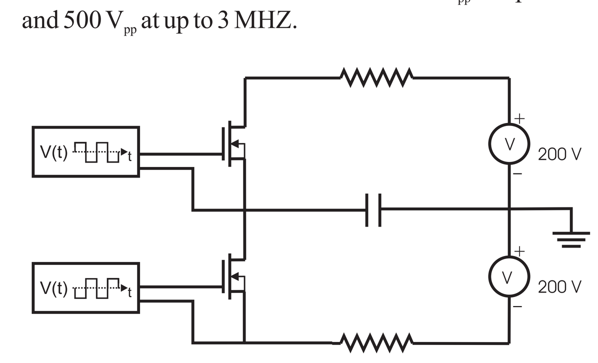
The TITAN RF driver produces a rectangular (digital) waveform of 400 V_{pp} at a frequency of 1 MHz. The elimination of transformer coupling, a mainstay in traditional sinusoidal high power RF systems, enables the TITAN beam cooler to be a truly frequency agile device.

The drive system consists of a series stack of N-channel fast switching Field Effect Transistors (FET). The current system is an X=3 configuration where six boards (three UP and three DOWN) are connected in series and the output is derived from the stack "middle". The top and bottom of the stack are connected to a positive high voltage and ground respectively. An appropriate trigger scheme alternately turns the UP/DOWN stack on/off to generate a rectangular waveform of any duty cycle.

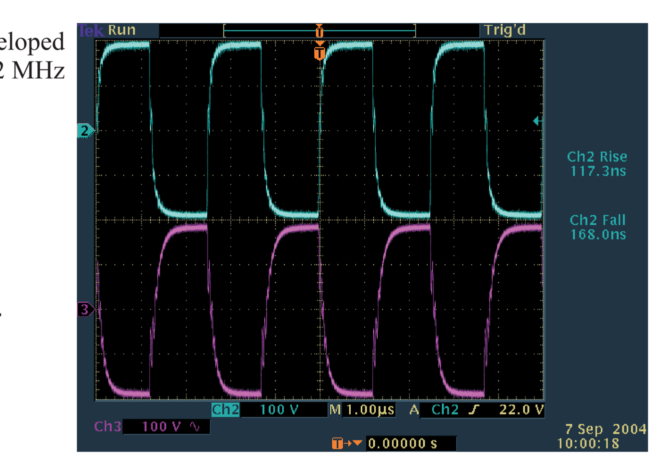
A second version of the square wave driver has been developed with X=4. This version can switch 600 V_{pp} at up to 2.2 MHz and 500 V_{pp} at up to 3 MHZ.



TITAN's square-wave-driver

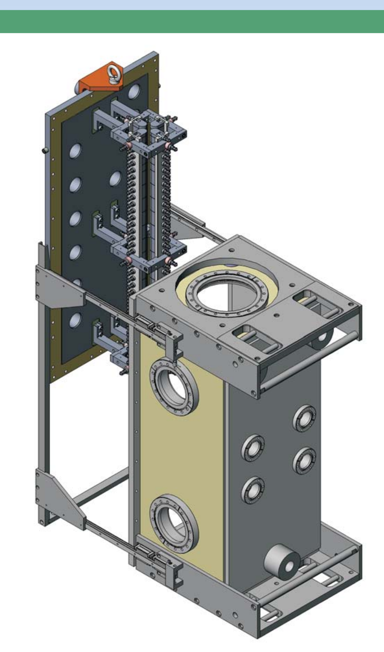


Simplified circuit for the square wave driver. The experimental driver uses a stack of MOSFETs so as to be able to switch higher voltages. The RFQ provides the capacitance in the real system.



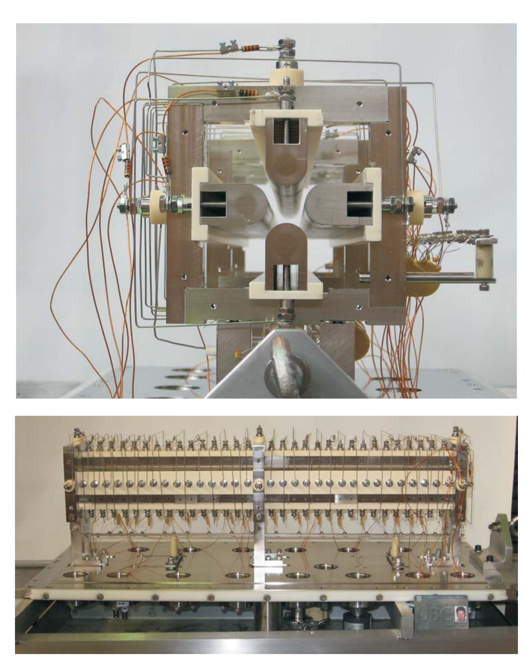
Oscilloscope traces of both phases of the RF taken directly from the RFQ electrodes.

TITAN's RFQ



Solid model of the guide structure designed to insert the RFQ into the vertically mounted vacuum vessel.

- 700mm in length
- Segmented into 24 pieces with 0.5mm spacing
  - 12x20mm pieces (injection and trapping)
  - 11x40mm pieces (central region)
  - 1x9mm piece (end-cap electrode)
- r_0 = 10mm
- 400V applied square-wave (digital) RF at up to 1 MHz
- Filled with a helium buffer gas @ $2.5x10^{-2}$mbar

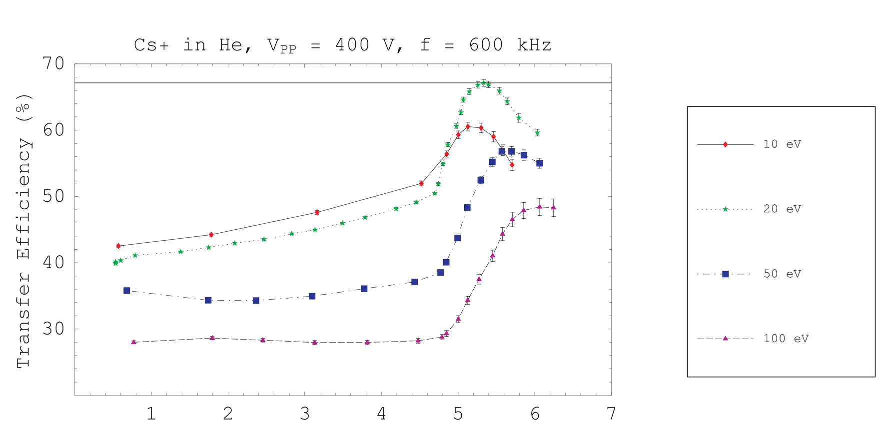


Side and end views of TITAN's RFQ.

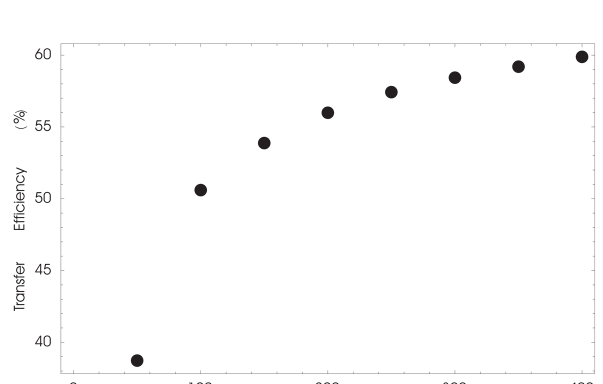
Results

The RFQ has been commissioned using an offline ion source. A stable beam of ^{133}Cs was created using a surface ionization source and accelerated to energies of up to 40 keV. Studies are ongoing with this test source to determine optimum operating parameters but so far we have demonstrated:

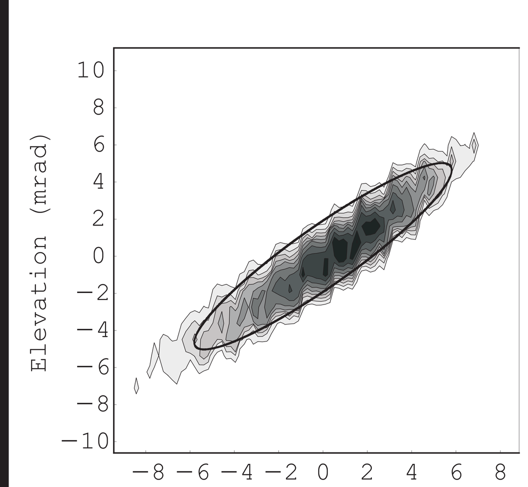
- Successful transport of beam through the digital RFQ in DC and bunched mode
- 68% transfer efficiency for a DC beam cooled with helium at a pressure of 5.5 mtorr
- Ion bunches with $\varepsilon_{2rms} < 15\,\pi$ mm mrad @ 4 keV with approximately $2x10^6$ ions per bunch
- Injection and extraction of a ^{7}Li beam from ISAC in DC mode
- Injection and extraction of a ^{136}Xe beam from the ISAC Off-Line Ion Source (OLIS) in both forward and reversed pulsed mode



DC Transfer efficiency for ^{133}Cs ions in He as a function of gas pressure. An optimum efficiency of 68% has been observed at 5.5 mTorr.



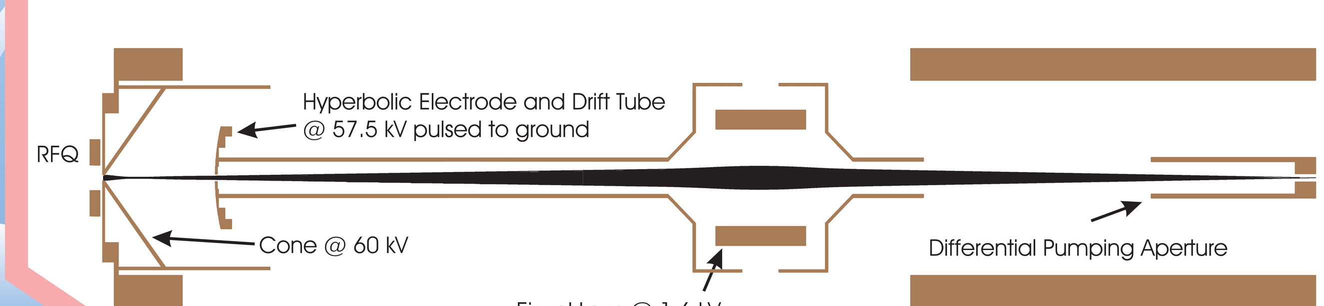
Maximum transfer efficiency as a function of applied peak to peak voltage for ^{133}Cs ions in He at 5 mTorr. As expected the efficiency increases as the depth of the radial trapping potential is increased.



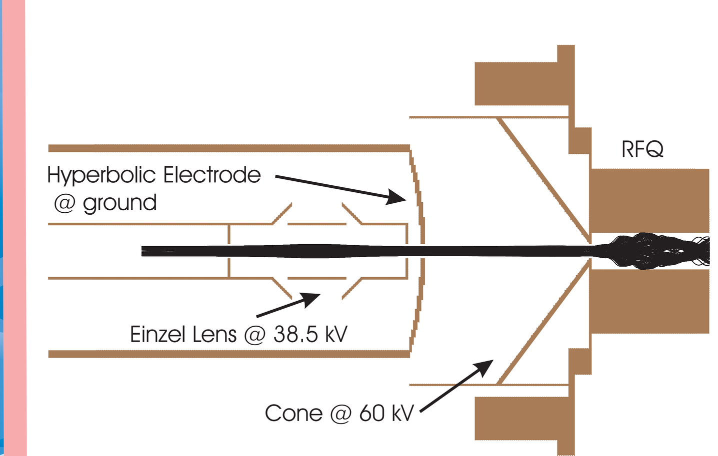
A typical emittance plot for an extracted ion pulse, obtained with an Allison type emittance scanner. A fit to the data gives an emittance of:
$14.8 \pm 0.1\,\pi$ mm mrad @ 4 keV
This emittance is for approximately $2x10^6$ ions in the trap. Work is underway to improve the pulsing electronics that are used to extract the ions from the trap. This should in turn help to further reduce the emittance of the extracted ion bunches. Collimators are also being installed in front of the test ion source. This will reduce the number of trapped ions, which will also help to reduce the observed emittance.

Injection and Extraction

One of the biggest challenges in beam cooler design is efficiently matching the emittance of the incoming beam to the acceptance of the RFQ. This is especially challenging as the incoming beam, at a typical energy of 30-60 keV, must be decelerated to a few tens of electron volts energy. For the installation of TITAN's RFQ in the ISAC hall a new set of deceleration optics has been designed. These optics use the combination of a grounded hyperbolic electrode along with a cone that floats at a potential close to that of the beam energy. The two electrodes create a radially hyperbolic electrostatic potential, the motion of ion's in which traces out a right ellipse in phase space. The optics are designed such that this ellipse matches the first order acceptance of the RFQ as well as the emittance of the beam delivered along the ISAC beam line. The same electrode geometry is also used to extract the beam from the RFQ. This will make it possible to inject/extract beam from both ends of the beam cooler. The new optics have been constructed and installed, testing is currently underway.



SIMION simulation of the new extraction optics. An ion pulse is accelerated to 2.5 keV before being passed through an Einzel lens and focused as it passes through a differential pumping barrier.



SIMION simulation of the new, hyperbolic, injection optics. A 40 π mm mrad beam @ 60.1 keV is decelerated to 100 eV and transmitted into the RFQ (Vpp = 400 V, q = 0.3) with 100% efficiency.

Summary and Outlook

- A digital RFQ beam cooler has been built for use as part of the TITAN project.
- A transport efficiency of 68% in DC mode has been demonstrated
- Cooled bunches of cesium with $\varepsilon_{2rms} < 15\,\pi$ mm mrad @ 4 keV have been extracted
- Reversed extraction from the RFQ has been successful demonstrated
- Further commissioning tests are underway to find the optimum operating parameters
- Laser spectroscopy on ions extracted in reversed mode this summer
- First mass measurement, ^{11}Li, with the TITAN experiment in August

For more information see:

J. Dilling et al., Int. J. Mass Spectrom. **251**, pp 198 (2006)
M. Barnes and G. Wait, Proceeding of the 14th IEEE pulsed power conference vol2, pp 1407 (2003)
M. Smith, A Square-Wave-Driven RFQ Cooler and Buncher for TITAN, Msc Thesis, University of British Columbia (2005)