New Design of a Compact Fourier-Transform Quadrupole Ion Trap for High Sensitivity Applications

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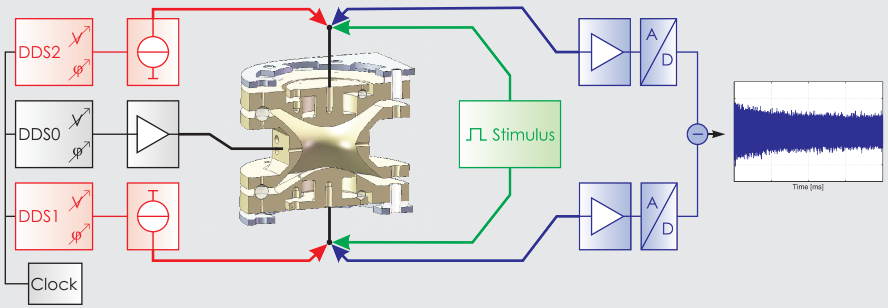
Introduction

The fourier-transform quadrupole ion trap is used to measure the influence charge of stored ions. This method, which is similar to magnetic ICR, allows multiple measurements of the same ion population and features high dynamic range and high mass resolution in combination with a compact design and low power consumption. The trap was now improved for high ion sensitivity applications.

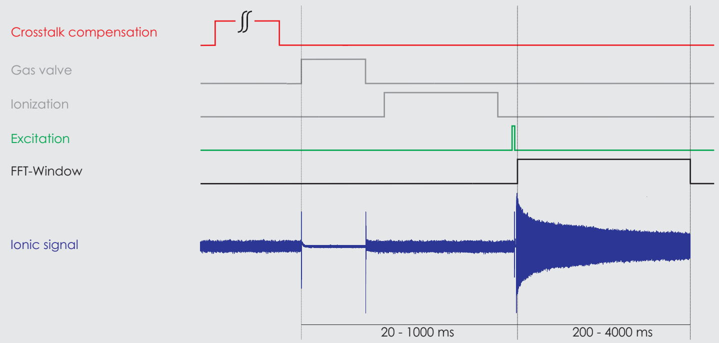
Novel Aspects and Applied Methods

- New mechanical trap design to reduce field distortion, reduce crosstalk-signals, and allow easy mechanical assembly
  This is done by separating the cap electrodes into two parts, using crystal balls as bearing of cap and ring electrode
- New electronic system with improved crosstalk-compensation, improved charge-amplifiers for better ion sensitivity
  This was archived by utilizing ultra low noise electronic parts and circuitry
- Theoretical models allow to estimate the number of ions stored in the trap
- The new system was tested with aromatic compounds (mass-range 78 - 120 amu), ionized by a UV-Laser

Block Diagram of the Ion Trap System

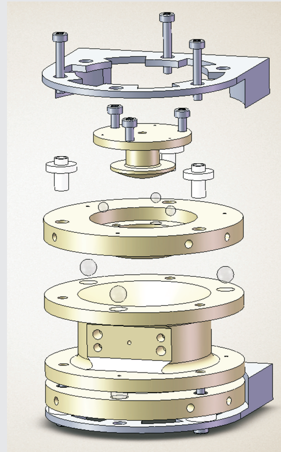


Measurement Timing Diagram

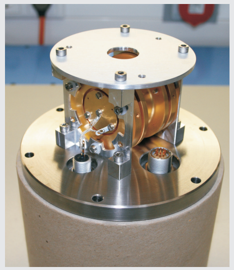


Quadrupole Ion Trap

The trap is designed with a ring electrode and two cap electrodes, which are split into an active inner part and a passive outer part. The splitting is optimized for optimal signal detection and minimal rf crosstalk. The remaining crosstalk is compensated inside the charge amplifier. The cap electrodes and ring-electrode are beared by crystal balls. This allows easy assembly and narrow mechanical tolerances, which reduce field distortions.



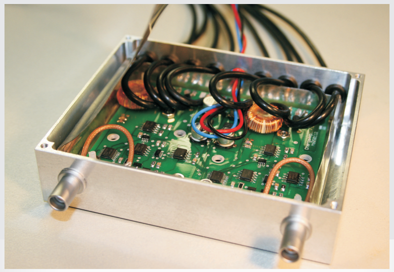
The hole trap features its own ground domain and is electrically isolated from the housing to prevent noise coupling from other parts in the system. A gold plated surface prevents surface charges which reduce mass resolution.



Key parameter of the quadrupole ion trap:

trap dimension:	60 x 60 x 40 mm^3
core radius r_0:	10 mm
cutoff-radius r_{cut}:	20 mm

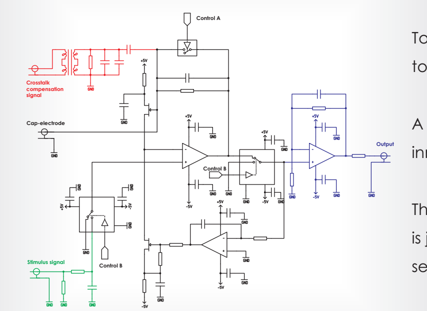
Charge amplifier



The charge amplifiers pick up the influence charges that are induced onto the inner cap-electrode by the oscillating ions inside the trap. This is done by a low noise JFET in combination with a low noise OP.

An output-buffer (blue) amplifies the ion signal before it is fed to a filter amplifier (not shown).

The charge amplifiers are also used for applying the compensation (red) and stimulus signals (green) to the inner cap-electrodes.



To prevent saturation switches allow to disable the amplifier output and to modify the amplifier gain in the feedback loop.

A servo loop circuit controls the operating point and precisely defines the inner cap-electrode to 0V DC-level..

The supply voltage is ±5 V, the power consumption of the charge amplified is just 600 mW. The entire electronic system (including HV amplifier and sequence control system) has a power consumption of less than 3 W.

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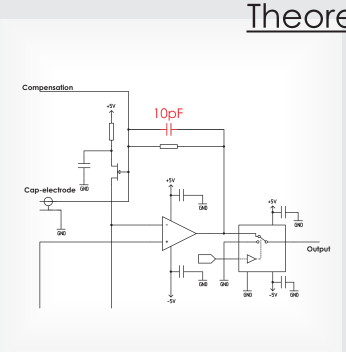
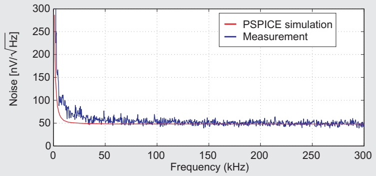
Theoretical considerations



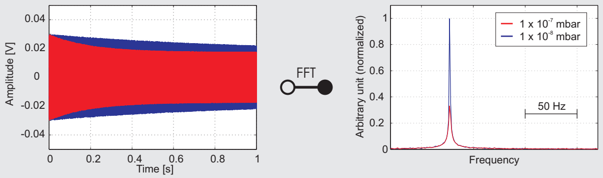
During the ion oscillation the ions induce an influence current in the charge amplifier. This current will be integrated by the capacitor in the feedback loop. As a result the electric charge stored in the capacitor corresponds to the charged particles inside the trap (e.g. the number of ions). Because of the Q-V-conversion characteristic of the capacitor we are able to compute the number of ions inside the trap by measuring the ion signal amplitude at the beginning of the ion transient:

$$N_{ion} = \frac{C_{conv}}{V_{ion} \times e \times A}$$

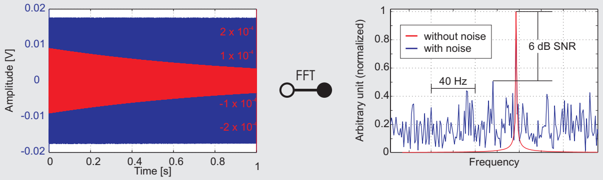
e: unit charge, 1,6 x 10^{-19} C; V_{ion}: measured signal amplitude in V; C_{conv}: conversion capacitor, 10 pF;
A: post amplification factor of measured signal amplitude; N_{ion}: Number of ions stored inside the trap



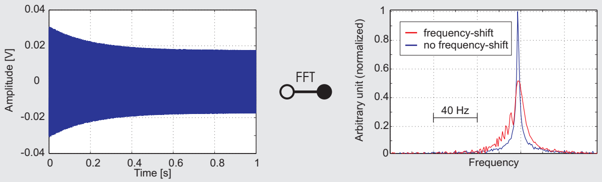
The measured output noise of the charge amplifier is about 50 nV/√Hz and fits to the simulated (PSPICE) noise performance results.
The equivalent input noise level is round about 3 ions/√Hz .



Simulations show that the residual pressure is an important factor for ion sensitivity. Because of more ion-residual gas-collisions the ion transient will be shorter and the energy in the signal is lower.

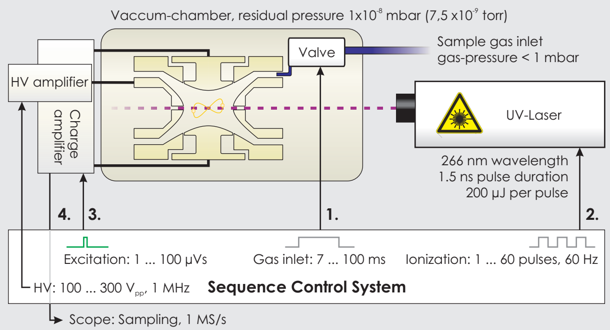


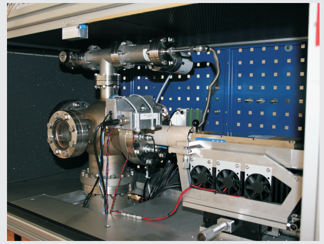
It is possible with the given noise level to detect down to 65 ions at low residual pressures (blue). The red curve shows the transient and spectra for a noise-free system.



Stored ions inside the trap cause space charges which cause a frequency-shift over time. This will reduce mass resolution.

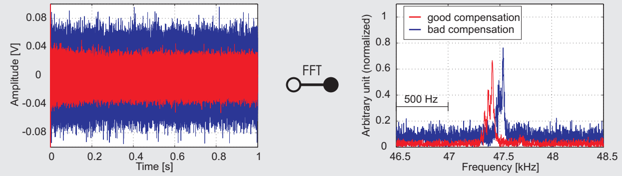
Measurements



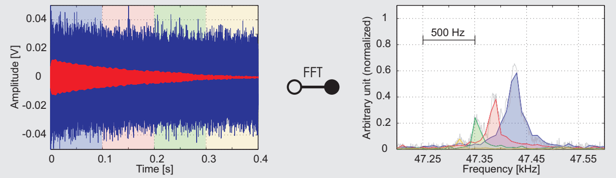


All measurements were carried out with toluene ($C_6H_5CH_3$).

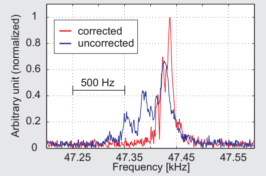
Good rf crosstalk compensation is essential for high ion sensitivity. The noise level can be orders of magnituides smaller compared to a bad compensated system.



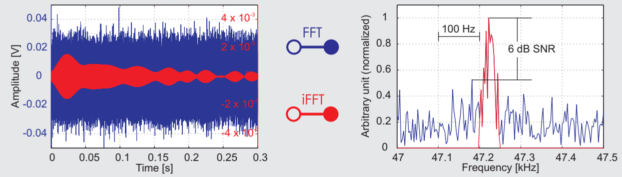
High ion densities result in space charges which cause a frequency-shift in the spectra.



The frequency-shift can be corrected afterwards by determining the frequency-shift-function and suitable time-signal resampling. This method can improve mass resolution and also increase ion sensitivity.



The figures show ion transient and spectra of about 650 ions. Because of the low ion transient amplitude we utilize frequency spectra filtering and inverse FFT to get the shape of the ion transient and its maximum amplitude.



Conclusions & results

- The number of ions trapped can be computed by measuring the maximal ion transient amplitude
- Lower residual pressure leads to higher ion sensitivity, because of longer signal transients
- Frequency resolution depends on transient signal shape and record length
- Space charge effects lead to blured mass spectra (low mass resolution)
- Bad crosstalk compensation causes a high noise level and therefore a decreased ion sensitivity
- Space charge effects lead to time-dependent frequency-shift
- These effects can be partially corrected by signal processing
- The measured results correspond with the simulation data