thermoscientific

How Mass Spectrometer Model and Electrode Temperature Determines FAIMS Separation

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ABSTRACT

Purpose: The effect of changing FAIMS gas velocity on an ion's compensation voltage position, compensation voltage peak width, and residence time within the FAIMS electrodes is described.

Methods: FAIMS gas velocity was varied by using multiple heated transfer tubes of different conductances.

Results: As the conductance of the heated transfer tube is increased, the FAIMS gas velocity is increased leading to wider compensation voltage peak widths and faster compensation voltage switching times.

INTRODUCTION

FAIMS separates gas phase ions by subjecting them to tens of thousands of cycles of alternating high and low electric fields generated by applying an asymmetric waveform to an inner electrode counter to a grounded outer electrode.[1] Ions are carried through the gap between the electrodes, perpendicular to the electric field, within a flow of gas and are selectively transmitted into a mass spectrometer by scanning a DC potential called compensation voltage, or CV. FAIMS resolution is determined by the electric field strength, the amount of time ions reside in the field, and the temperatures of the two electrodes. Here, the effects of ion residence time and electrode temperature on resolution are discussed.

MATERIALS AND METHODS

A new FAIMS instrument comprised of an electronics control box, a transformer box, and cylindrical electrode set was designed to operate on a Thermo Scientific™ TSQ Quantiva™ triple quadrupole mass spectrometer, shown in Figure 1. The electrodes, shown in Figure 2, are independently temperature controlled and sealed to the high capacity transfer tube (HCTT) of the mass spectrometer.[2] A dispersion voltage (DV) of -5000V is applied across the 1.5mm electrode gap and nitrogen is supplied to the entrance of the electrodes to carry the ions through the FAIMS device and into the mass spectrometer.

The HCTT, with a 2.0 mm x 0.6 mm slotted orifice, draws approximately 7.0 L/min of gas through the FAIMS electrodes. In order to change the velocity of the gas flowing through the electrodes, two heated transfer tubes of different conductances were modified to fit on the mass spectrometer. The first, with a 1.6 mm x 0.6 mm slotted orifice, draws approximately 5.5 L/min and corresponds to gas flows used on the Thermo Scientific™ Orbitrap Fusion™ Lumos™ Tribrid™ mass spectrometer and the Thermo Scientific™ TSQ Altis™ triple quadrupole mass spectrometer. The second, with a 0.58 mm circular orifice, draws approximately 1.5 L/min and corresponds to gas flows used on the Thermo Scientific™ TSQ Endura™ triple quadrupole mass spectrometer, the Thermo Scientific™ TSQ Quantis™ triple quadrupole mass spectrometer, and the Thermo Scientific™ Orbitrap Fusion™ Tribrid™ mass spectrometer.

Data were acquired, by infusion of Thermo Scientific™ Pierce™ Triple Quadrupole Extended Mass Range Calibration Solution (EMRS), with each heated transfer tube and with both electrodes heated to 100ºC for standard analysis. In addition, data were taken with the inner electrode cooled to 70ºC, while the outer electrode remained at 100ºC, to study the effect of FAIMS gas velocity and electrode temperature on CV peak width and resolution. Finally, the amount of time that an ion resides within the FAIMS device was studied for each heated transfer tube.

Figure 1. FAIMS Mounted on TSQ Quantiva MS

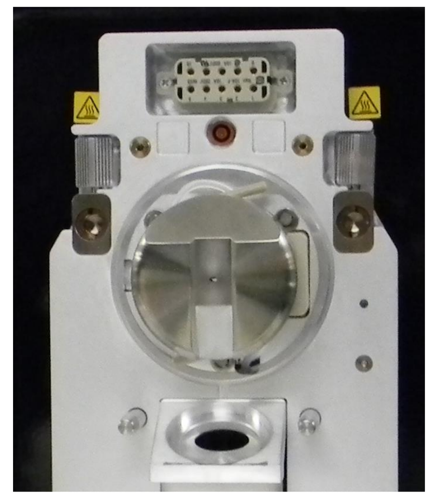
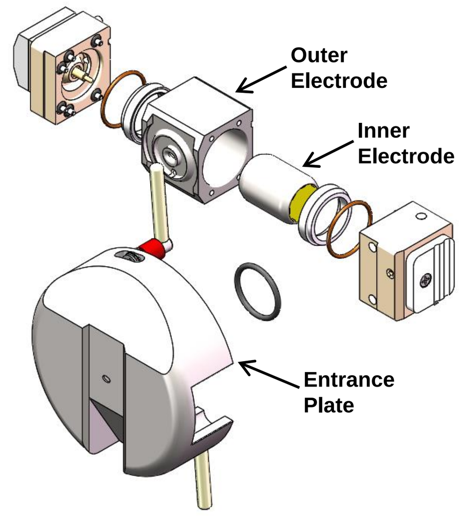


Figure 2. FAIMS Electrode Set



CV PEAK POSITION

Electrode temperature affects FAIMS separation by changing the number density of the ion population, denoted n, within the electrode gap. Thus, the separation field can be reduced to E/n, where E is set by the DV. When the inner electrode is cooled with respect to the outer electrode, the delta in separation field across the gap is reduced and requires a narrower compensation field to transmit the ion packet.[3] Figures 3 and 4 show CV scans for an infusion of EMRS into a FAIMS system mounted onto the TSQ Quantis equivalent transfer tube with the electrodes both set to 100ºC (Figure 3) versus one with an inner electrode cooled to 70ºC (Figure 4). Note the reduction of CV peak widths when the inner electrode is cooled. In addition, the hotter inner electrode creates a higher E/n within the gap compared to the cooler inner electrode. This requires a higher compensation field to draw the ion back to the center of the electrode gap, resulting in a CV shift for each ion.

Although changing the temperature of the electrodes results in shifts in CV peak position, changing the velocity of the FAIMS gas does not. To demonstrate this, the TSQ Altis equivalent ion transfer tube was installed and CV scans for EMRS were collected (Figures 5 and 6). Note that each ion's CV peak lines up with its corresponding peak in the TSQ Quantis equivalent experiments. This is because the FAIMS gas flows orthogonally to the separation field and holds no bearing on CV peak position. To further demonstrate this effect, CV scans were also acquired using the TSQ Quantiva ion transfer tube (Figures 7 and 8). Once again, an increase in FAIMS gas velocity results in comparable CV peak positions relative to previous experiments using comparable electrode temperatures. However, gas velocity does show an effect on CV peak width and intensity and will be discussed later.

Figure 3. TSQ Quantis Equivalent Transfer Tube With T_{inner} = 100ºC and T_{outer} = 100ºC

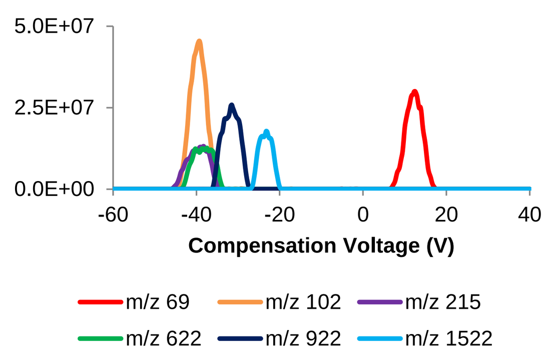


Figure 4. TSQ Quantis Equivalent Transfer Tube With T_{inner} = 70ºC and T_{outer} = 100ºC

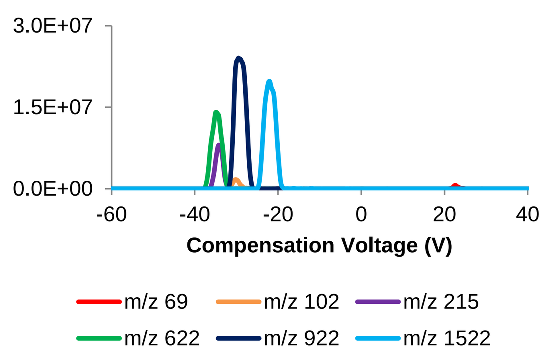


Figure 5. TSQ Altis Equivalent Transfer Tube With T_{inner} = 100ºC and T_{outer} = 100ºC

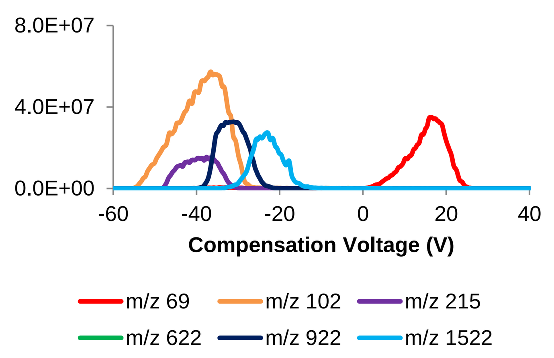


Figure 6. TSQ Altis Equivalent Transfer Tube With T_{inner} = 70ºC and T_{outer} = 100ºC

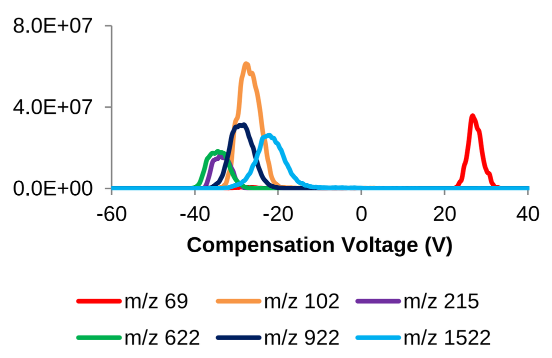


Figure 7. TSQ Quantiva Equivalent Transfer Tube With T_{inner} = 100ºC and T_{outer} = 100ºC

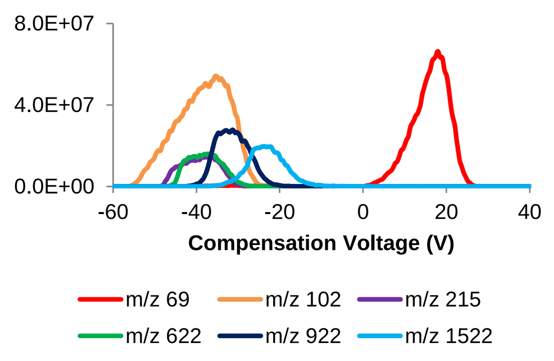
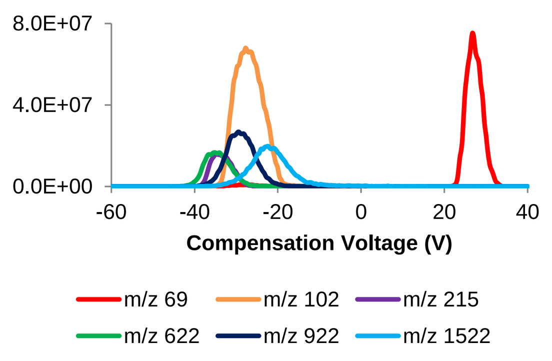


Figure 8. TSQ Quantiva Equivalent Transfer Tube With T_{inner} = 70ºC and T_{outer} = 100ºC



ION RESIDENCE TIME

The amount of time required for an ion to flow through the electrodes is the rate limiting parameter for FAIMS-MS analysis. On the original commercial FAIMS system, this ion residence time was approximately 100ms due to the large volume of the electrode gap and the fact that the outer electrode was not sealed to the mass spectrometer inlet. Here, the electrode's gap volume has been reduced and sealed to the ion transfer tube. Since the conductance of the ion transfer tube determines the gas flow rate through the gap, this means the residence time can be changed by changing the transfer tube.

The ion residence time was determined experimentally for each of the three ion transfer tubes and the data are shown in Figures 9, 10, and 11. This was accomplished by first blocking the ion beam by applying a large CV offset and then switching to the optimized CV and measuring the ion current after a short period of time. This process was repeated many times while slowly increasing the waiting time before current measurement and the resulting data were plotted. The ion residence time was defined as the period of time after which no further increases in the ion current were detected. As the transfer tube conductance is increased, the ion residence time decreases. As the ion residence time is decreased, the time required to wait after switching CVs is decreased. This allows the user to interrogate more discrete CV values in the same analysis time.

Figure 9. CV Switching Time Plot for TSQ Quantis Equivalent Transfer Tube

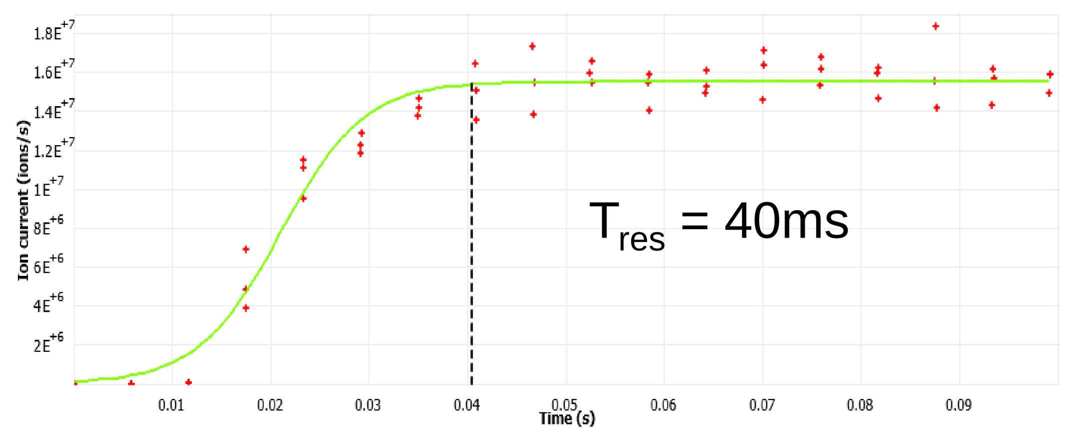


Figure 10. CV Switching Time Plot for TSQ Altis Equivalent Transfer Tube

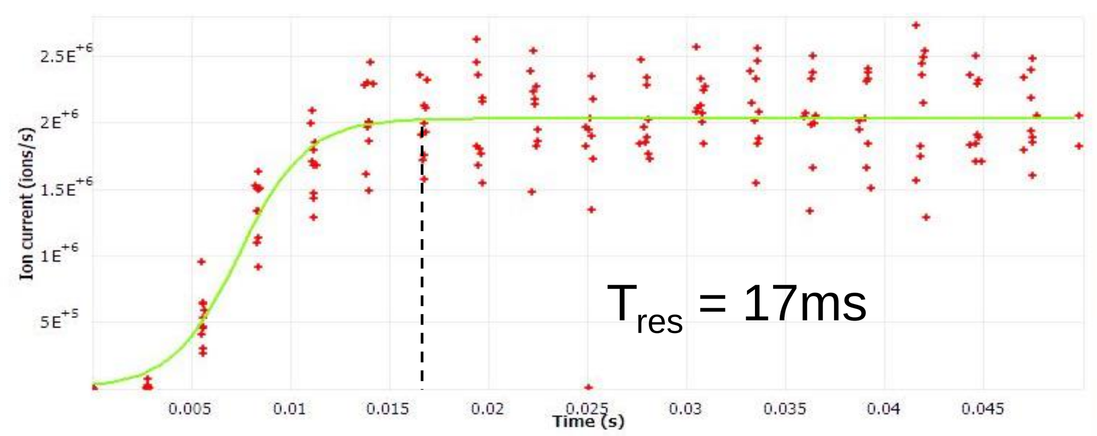
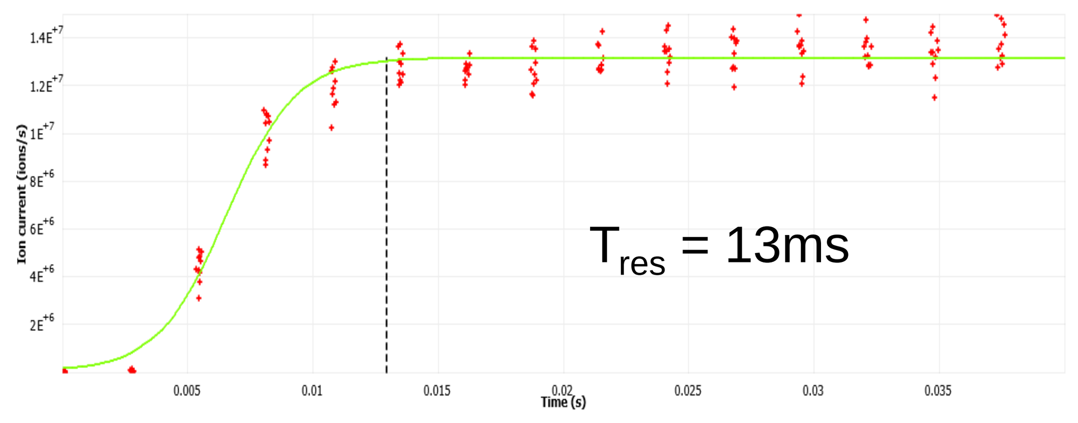


Figure 11. CV Switching Time Plot for TSQ Quantiva Equivalent Transfer Tube



SENSITIVITY AND PEAK WIDTH

Although changing the ion transfer tube does not affect CV peak position, it does affect other characteristics of the FAIMS experiment. As the conductance is increased, the velocity of the gas passing over the curved entrance orifice of the outer electrode is increased, allowing the incoming gas stream to bend away from its initial angle, following the curve, and flow more efficiently into the electrode gap. Figure 12 demonstrates this effect by comparing CV scans for an EMRS calibration ion, m/z 622, using each of the three ion transfer tubes with the inner electrode set to 70ºC and the outer electrode set to 100ºC. Note the increase in ion signal when using the higher conductance transfer tubes. In fact, this effect is also seen for other ions and electrode temperatures (Figures 13-17). The TSQ Altis equivalent transfer tube gives slightly better signal intensity than the higher conductance TSQ Quantiva transfer tube due to its use in optimizing the curved geometry of the outer electrode inlet.[4]

In addition to sensitivity, CV peak width is also affected by changing the ion transfer tube. As the FAIMS gas flows faster through the electrode gap, CV peak width increases. This is due to ions that have the optimal differential mobility to be passed through the device but are introduced into the gap close to the electrode wall being transmitted before they can be fully focused to the center of the gap. As the gas speed drops, the effects of diffusion dominate and the CV peak width decreases.

Figure 12. CV Peak Width And Sensitivity Effects for m/z 622 (Cool Inner Electrode)

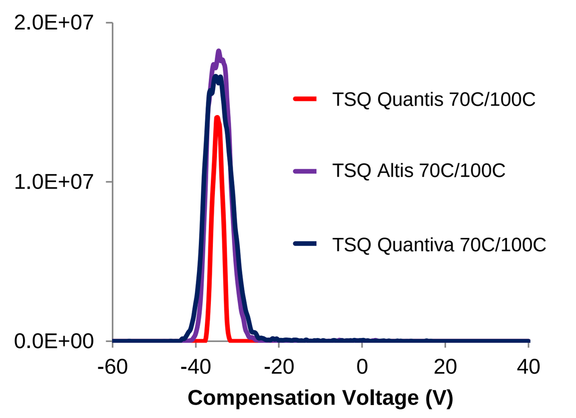


Figure 13. CV Peak Width And Sensitivity Effects for m/z 622 (Hot Inner Electrode)

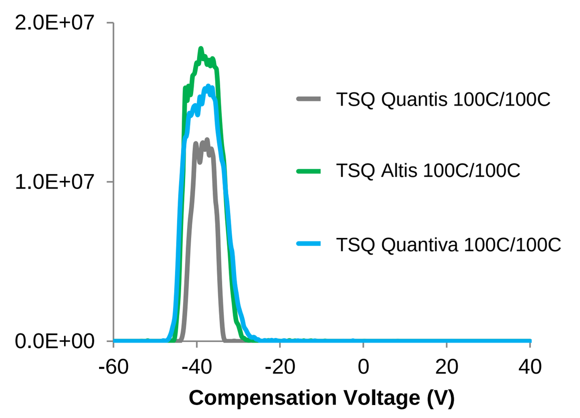


Figure 14. CV Peak Width And Sensitivity Effects for m/z 922 (Cool Inner Electrode)

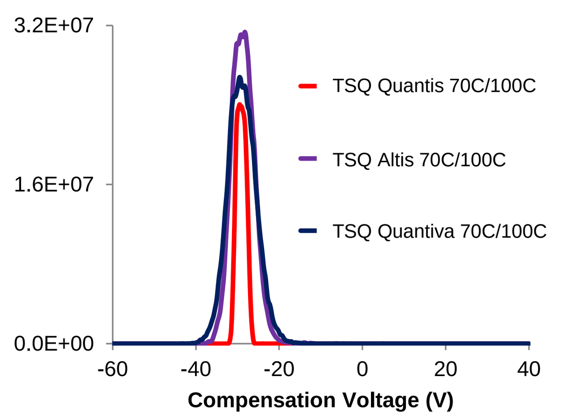


Figure 15. CV Peak Width And Sensitivity Effects for m/z 922 (Hot Inner Electrode)

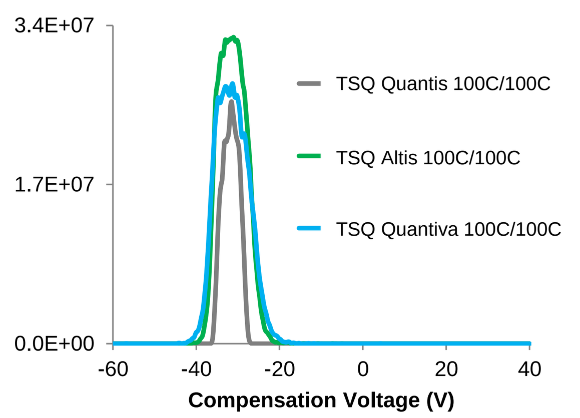


Figure 16. CV Peak Width And Sensitivity Effects for m/z 1522 (Cool Inner Electrode)

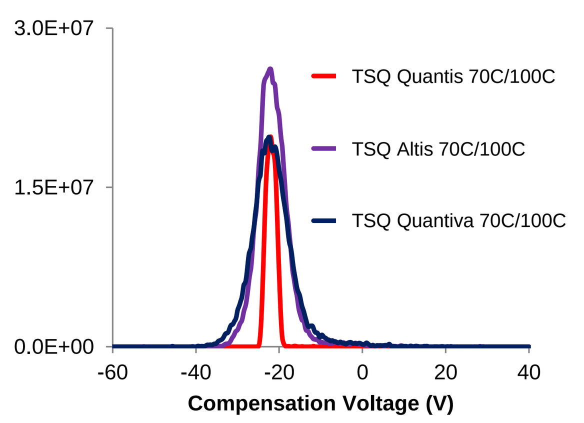
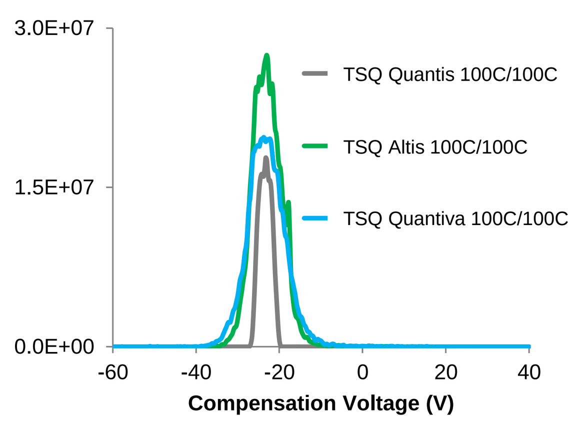
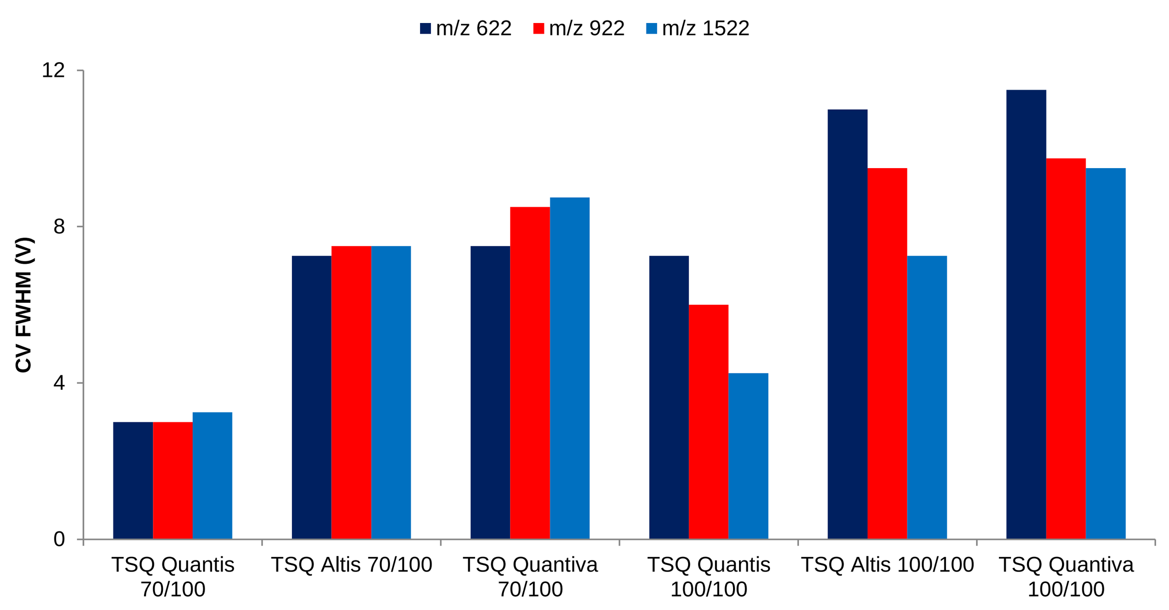


Figure 17. CV Peak Width And Sensitivity Effects for m/z 1522 (Hot Inner Electrode)



The effect of electrode temperature and FAIMS gas velocity is summarized in Figure 18. As the FAIMS gas velocity is increased, the CV peak width is also increased for the analyses with the inner electrode set to 100ºC. However, the CV peak width can be reduced by cooling the inner electrode to 70ºC. This offers the user multiple parameters to optimize for optimal separation and sensitivity.

Figure 18. CV Peak Width Dependence on Electrode Temperature and Transfer Tube Type



CONCLUSIONS

- The conductance of the mass spectrometer inlet and volume of the gap determines the gas velocity through the FAIMS electrodes
- FAIMS gas velocity affects how quickly the compensation voltage can be changed
- FAIMS gas velocity does not affect compensation voltage peak position since the gas flow and separation field are orthogonal
- Electrode temperature does affect compensation voltage peak position because it changes the separation field strength
- Compensation voltage peak width increases as FAIMS gas velocity increases
- Ion intensity is affected by the efficiency of the FAIMS gas wrapping around the curved wall of the outer electrode entrance orifice

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TRADEMARKS/LICENSING

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