Increased Post-Excitation Ion Cyclotron Radius by Use of a Novel Grid Cell Design

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Overview

Purpose: Reduced axial ion ejection in FTICR.

Methods: Novel cell design with grids as excitation electrodes.

Results: Improved detection sensitivity and mass accuracy.

Introduction

In Fourier transform ion cyclotron resonance (FTICR) mass spectrometry, high post-excitation cyclotron radii are beneficial in terms of both detection sensitivity and mass accuracy. However, in conventional ICR cells the maximum attainable post-excitation radius usually is limited by axial components of the excitation field causing the loss of ions due to axial ejection. Various ICR cell designs have been introduced over the past several years to compensate for this unwanted effect (1-5). In this work, we show an alternative approach which uses grids as excitation electrodes, extending past the region in which ions are trapped.

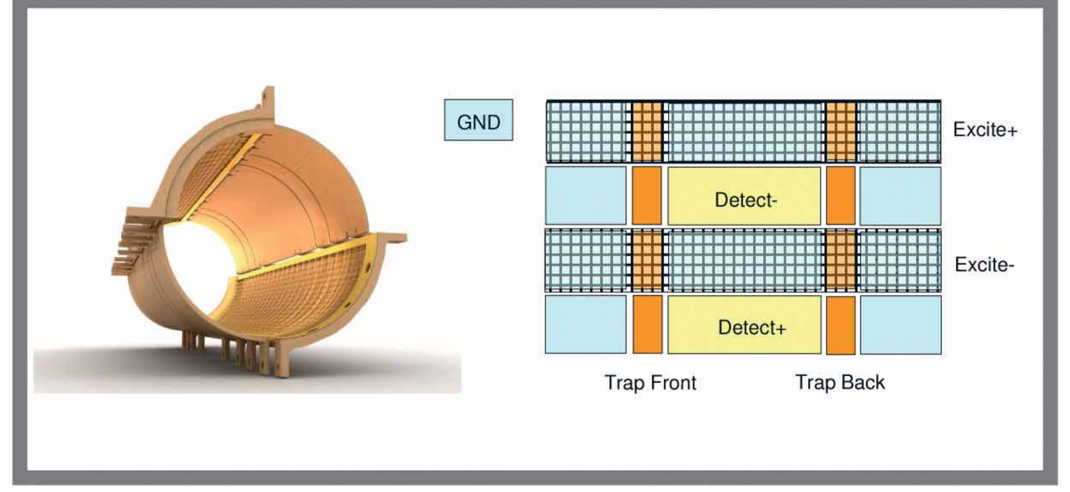
Methods

Experiments were performed on a standard Finnigan™ LTQ FT™ mass spectrometer, first with the original ICR cell and then with the newly designed grid cell.

The grid cell is an open cylindrical ICR cell with two opposing grids clamped inside the cylindrical electrodes over the entire length of the cell. Figure 1 shows a three-dimensional view of the grids within the cell, as well as an unrolled view of the whole grid cell, where the electrodes are labeled as trapping, excitation and detection electrodes, respectively. The grids were etched from 100 µm thick copper sheets. The gap between the grid and the cylindrical cell electrodes is 1.4 mm.

Excitation waveforms are applied to the grid electrodes, resulting in an excitation field which extends well past the region where ions are trapped. Thus, ions are less exposed to the fringe fields with their increased axial components. In order to compensate for the partial shielding of the trapping electrodes by the grids, each trapping electrode is radially segmented into four sections, where increased potentials are applied to those segments covered by the grids.

FIGURE 1. Three-dimensional and unrolled view of the grid cell.



Results

Reduced Axial Components of the Excitation Field

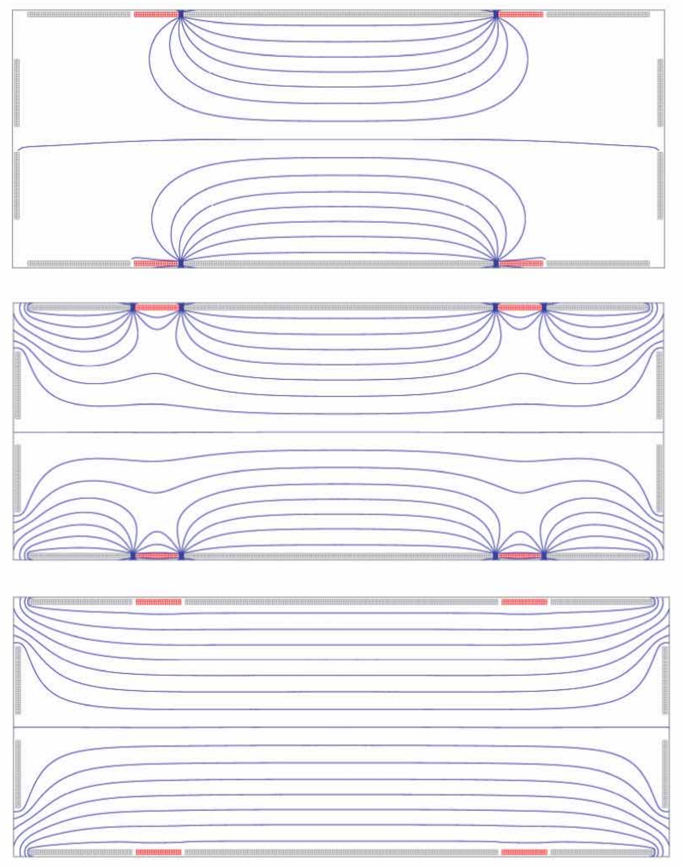
Figure 2 shows a comparison of the computed (SIMION 3D™ 7.0) iso-potential contours of the electric excitation field for three different ICR cell designs.

(a) ICR cell with central excitation electrodes only: All iso-potential lines meet at the gap between the excitation and trapping electrodes. Thus, ions are heavily exposed to axial components of the excitation field.

(b) Original cell of the Finnigan LTQ FT: Within the trapping region, axial components of the excitation field are reduced by additionally applying the excitation waveforms to the outer electrodes positioned adjacent to the trapping electrodes. Nevertheless, axial components do still exist.

(c) Grid cell: The excitation field extends well past the region where ions are trapped. As a result, virtually no axial components of the excitation field exist within the trapping region.

FIGURE 2. SIMION generated iso-potential contours for three different cell designs. Trapping electrodes are marked in red, defining the region where ions are trapped.



(a) ICR Cell with central excitation electrodes only. The outermost electrodes are grounded.

(b) Original LTQ FT cell with the excitation waveforms additionally applied to the outermost electrodes.

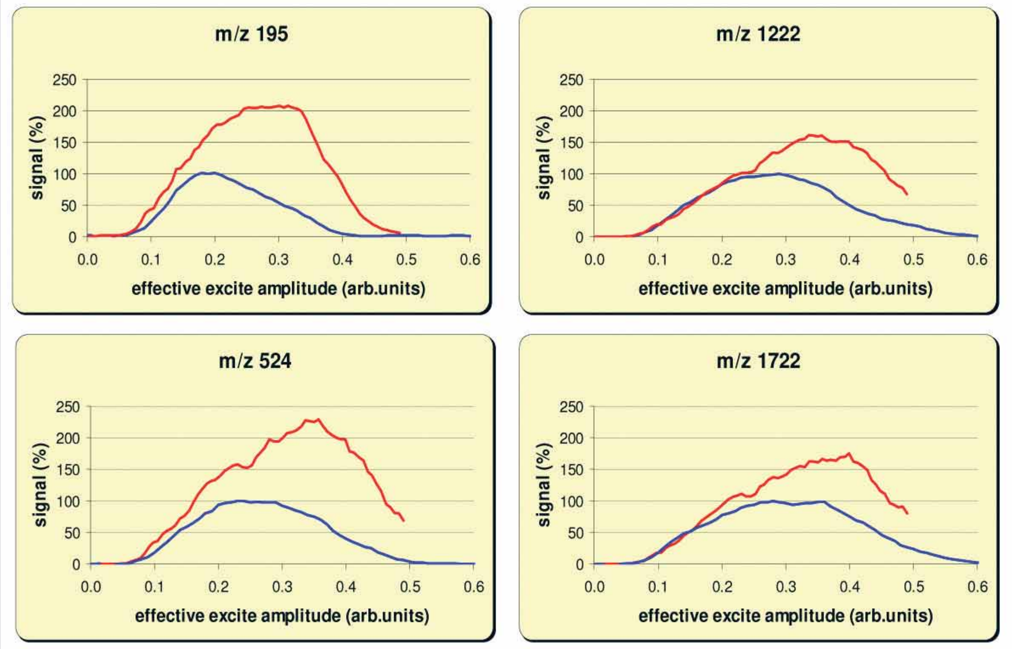
(c) Grid cell.

Enhanced Detection Sensitivity

Figure 3 shows a comparison of excitation profiles (ICR signal vs. excitation amplitude) for four different values of m/z, obtained with the original LTQ FT cell as well as with the grid cell. The profiles were acquired on the same instrument with only the cells being exchanged. An effective trapping voltage of 600 mV was used in each case.

From the excitation profiles it clearly can be seen that the grid cell allows the use of higher excitation amplitudes, resulting in a significantly increased ICR signal. We ascribe this to the reduced axial components of the excitation field allowing higher post-excitation cyclotron radii in the grid cell with respect to the original LTQ FT cell. The corresponding beneficial effect on the signal-to-noise ratio becomes the more pronounced the lower the value of m/z. This can be understood from the fact that the cyclotron energy increases with decreasing value of m/z, resulting in an increased fraction of axially ejected ions in the original LTQ FT cell. The overall improvement in detection sensitivity at optimum excitation amplitude approximately averages out to a factor of 2.

FIGURE 3. Excitation profiles obtained with the grid cell (red) compared to those obtained with the original LTQ FT cell (blue), at four different values of m/z.



Improved Mass Accuracy at External Calibration

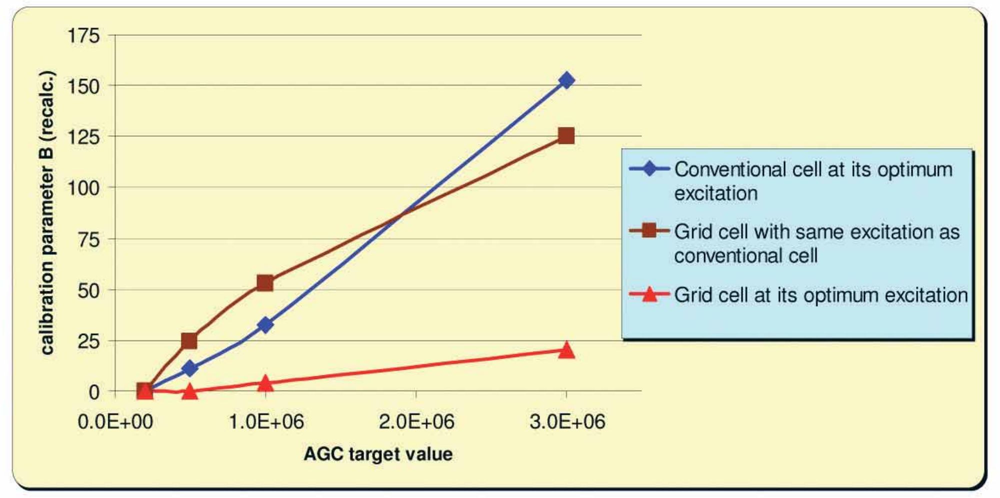
FTICR mass spectra are calibrated by the well known formula

$$m/z = \frac{A}{f} + \frac{B}{f^2} \quad ,$$

where f is the cyclotron frequency and A and B are calibration parameters which depend on the magnetic and electric field, respectively. The electric field is not solely determined by the potential applied to the trapping electrodes but additionally is modified by the space charge of the trapped ions. Thus, the calibration parameter B as well depends on the number of ions. This in general imposes a limit on the attainable mass accuracy.

Figure 4 shows the change of parameter B with increasing number of ions for both the original LTQ FT cell as well as the grid cell, where the number of ions is represented by the target value of the automatic gain control (AGC™). The experiments were performed on the same instrument with only the cells being exchanged.

FIGURE 4. Calibration parameter *B* as a function of the AGC target value for both the original LTQ FT cell as well as the grid cell.



In Figure 4, the slope of the graph "B vs. target value" is reduced significantly in case of the grid cell (red curve) compared to the original LTQ FT cell (blue curve), where each cell was operated at its optimum excitation amplitude. This is a direct consequence of the increased post-excitation cyclotron radius attainable with the grid cell which is equivalent to an increase in mean distance between the ions, i.e. reduced space charge effects. In case where the grid cell was operated at the same effective excitation amplitude as the original LTQ FT cell (brown curve), the slopes are virtually the same for both cell types.

FIGURE 5. Slope of the graph "B vs. target value" for the grid cell (see Figure 4) as a function of excitation amplitude.

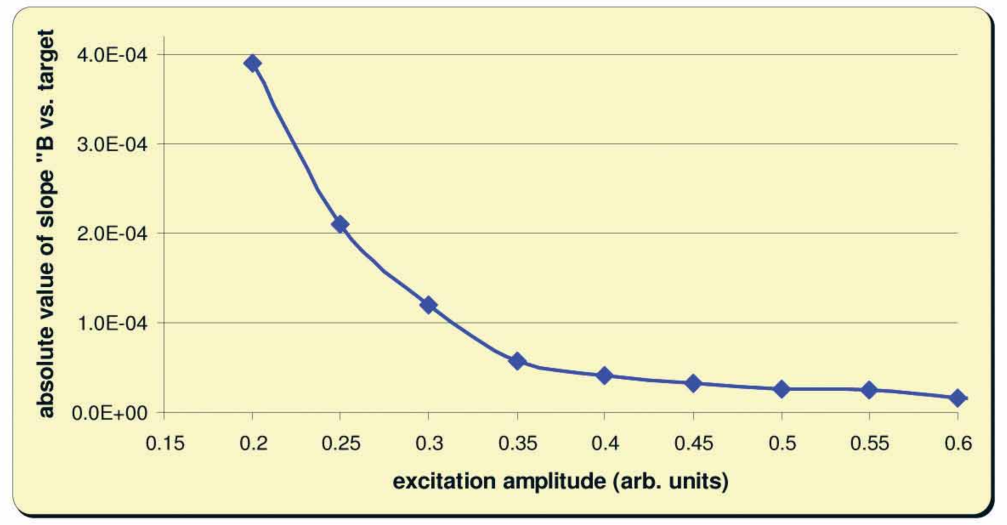
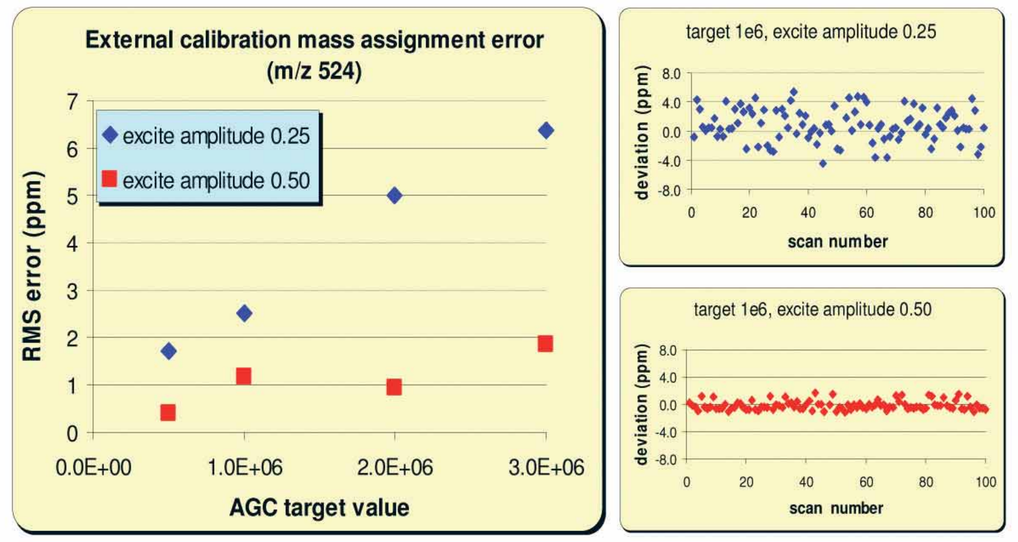


Figure 5 shows the decrease in slope of the graph "B vs. target value" (see Figure 4) with increasing excitation amplitude in case of the grid cell. It should be noted that the grid cell typically is operated at an excitation amplitude of 0.40 (arbitrary units) and higher, whereas the original LTQ FT cell typically is operated at an excitation amplitude of 0.25.

Figures 4 and 5 show that variations due to space charge in parameter B can be decreased by approximately a factor of 4 using a grid cell in place of the standard LTQ FT cell. From the reduced sensitivity of the grid cell with respect to space charge, an improvement in mass accuracy at external calibration is expected since residual fluctuations of ion number (despite automatic gain control) will have a smaller impact on mass position.

The direct effect of the increased post-excitation cyclotron radius on mass accuracy at external calibration is demonstrated by Figure 6. In this figure, mass assignment errors of MRFA (m/z = 524) at external calibration are shown for different AGC target values as well as different excitation amplitudes, obtained from full scans of a mixture of caffeine, MRFA and Ultramark 1621. Accordingly, RMS errors can be drastically reduced by increasing the excitation amplitude from 0.25 to 0.50 (arbitrary units), which especially is true for high AGC target values.

FIGURE 6. Mass assignment errors of MRFA (m/z 524) at external calibration for different AGC target values and excitation amplitudes.



Equivalent magnetic field necessary for an equal improvement in mass accuracy

In FTICR mass spectrometry, the mass accuracy at external calibration in general is limited by the variation of ion numbers in the ICR cell. In particular, the mass assignement error Δm is related to the error ΔB in calibration parameter B (see above) by

$$\Delta m = \frac{\Delta B}{f^2}$$

Thus, in order to increase mass accuracy one either has to reduce the error ΔB or increase the cyclotron frequency f by means of a higher magnetic field. The grid cell reduces ΔB and thus Δm by a factor of approximately 4. An equal reduction in mass assignement error Δm could be also achieved by increasing the cyclotron frequency f by a factor of 2, i.e. by changing the 7 Tesla magnet for a 14 Tesla magnet.

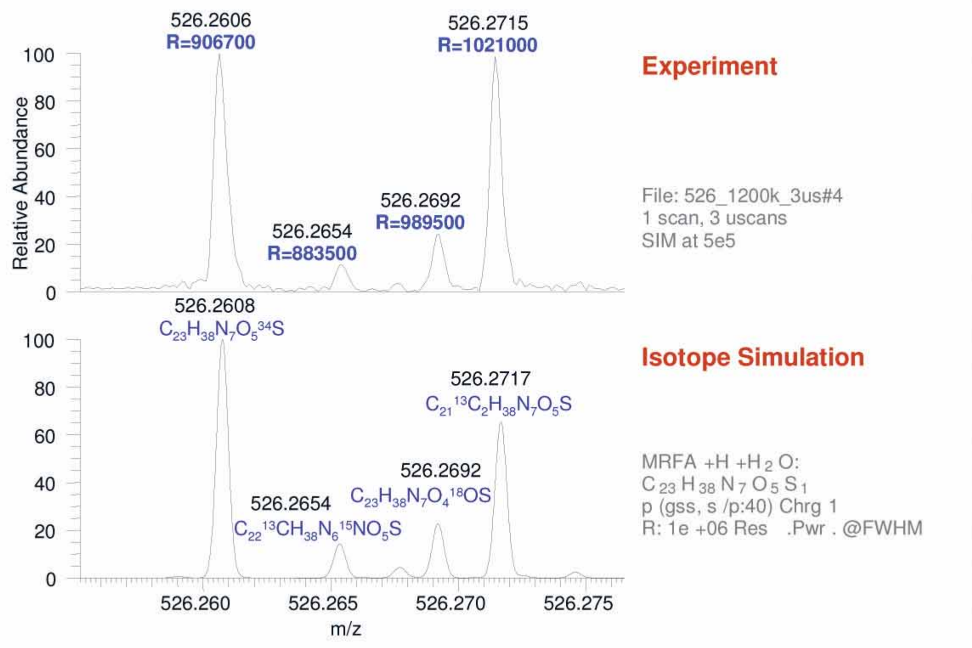
Further performance parameters of the grid cell

The improvements shown in detection sensitivity and mass accuracy, achieved with the grid cell, do not compromise other instrument performance parameters. In particular:

a) The use of the grid cell did not show an increase of the noise band or the number of discrete noise peaks in the FTICR mass spectra.

b) With the grid cell it was also possible to obtain FTICR mass spectra with very high mass resolution. As an example, Figure 7 shows a SIM spectrum of the isotopes around m/z = 526 of the peptide MRFA, acquired with a transient length of 12.3 s which leads to a mass resolution of 1,000,000 at m/z 526. The spectrum was averaged over 3 scans.

FIGURE 7. FTICR spectrum of the peptide MRFA (SIM spectrum of the isotopes around m/z = 526) obtained with the grid cell at a transient length of 12.3 s, compared with an isotope simulation at a resolving power of 1,000,000.



Conclusion

The novel ICR cell design described here which uses grids as excitation electrodes represents an effective way to reduce axial ion ejection. The linearized excitation field allows to excite ions to significantly higher post-excitation cyclotron radii. This results in

- **enhanced detection sensitivity**

as well as reduced space charge effects and thus

- **improved external calibration mass accuracy**.

As a result of these improvements which are achieved without adding significant complexity, the grid cell was chosen as the new standard cell of the successor of the Finnigan LTQ FT instrument which is named LTQ FT Ultra™.

References

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Acknowledgements

We would like to thank the other members of the LTQ FT Ultra project team, Kai Meyer, Wilko Balschun, Oliver Hengelbrock, Frank Czemper, Stefan Beissner, and Oliver Lange. We would also like to thank Michael W. Senko (Thermo Electron, San Jose, CA) for fruitful discussions.