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Differential Capacitive Trans-Impedance Amplifier for Ion Detection in Ion Mobility Spectrometry

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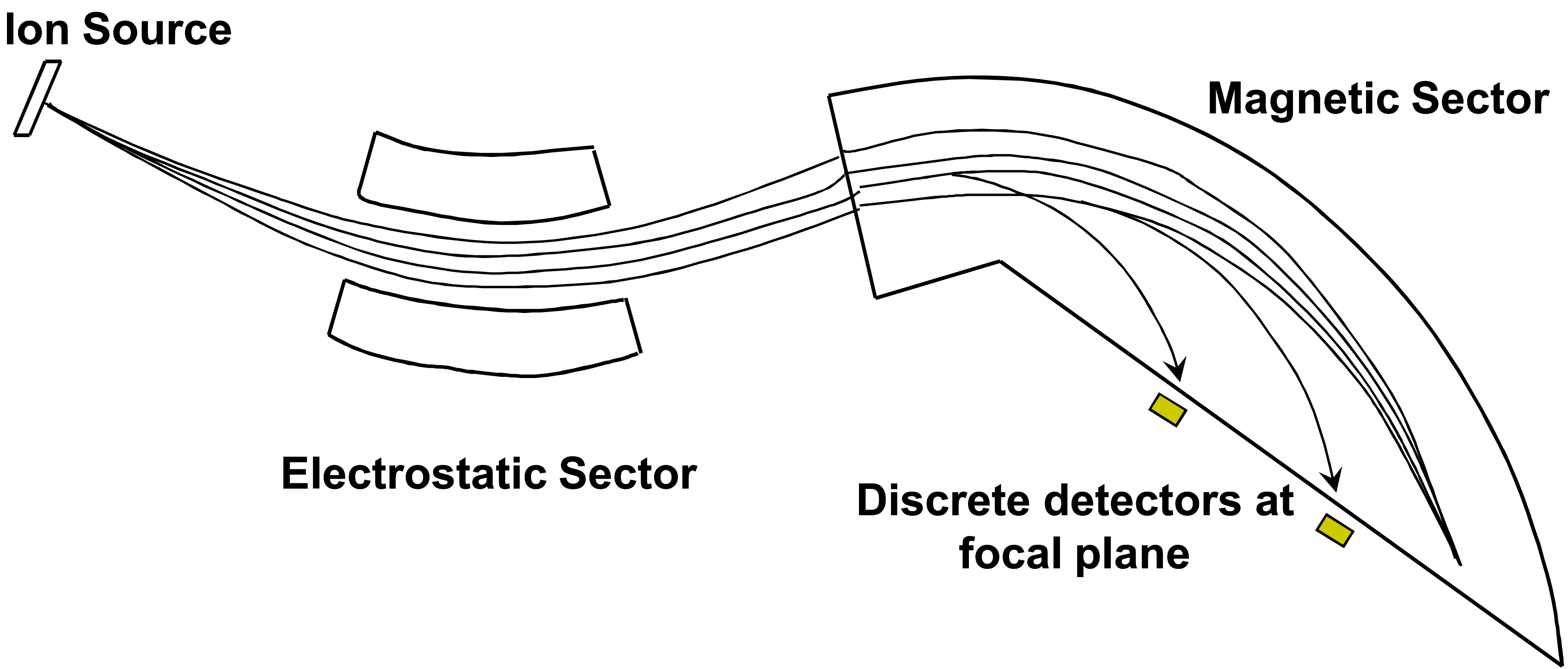
Common Ion Detectors in Mass Spectrometry

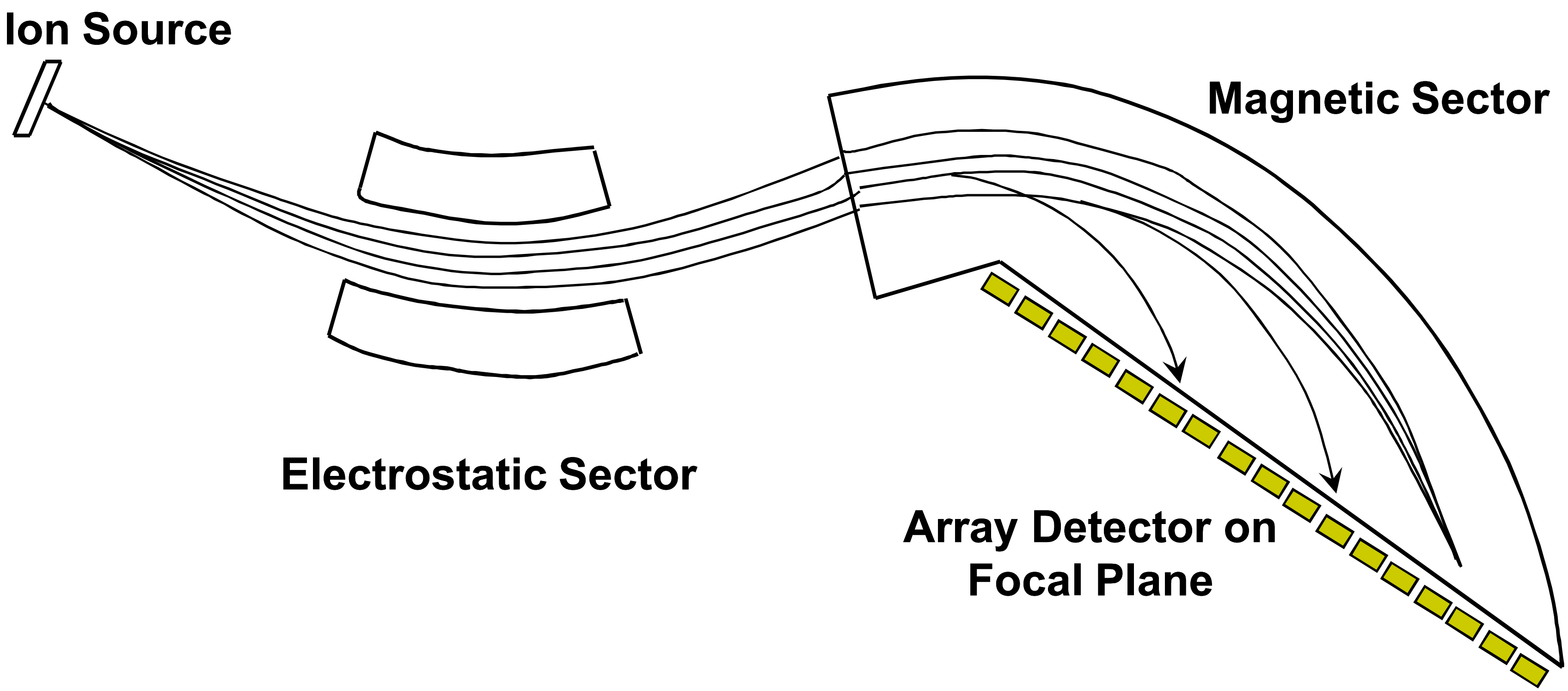
- **An ion-neutralization electrode (Faraday cup) followed by a current-to-voltage converter.**
  - Relatively poor ion sensitivity
  - Requires 6000 ionic charges/s (1fA)

- **An ion-to-electron converter followed by an electron multiplier.**
  - Ions require large kinetic energies to eject an electron from the ion-to-electron conversion surface.
  - Must be operated under vacuum

Discrete Detectors in Mass Spectrometry
Mattauch-Herzog Geometry



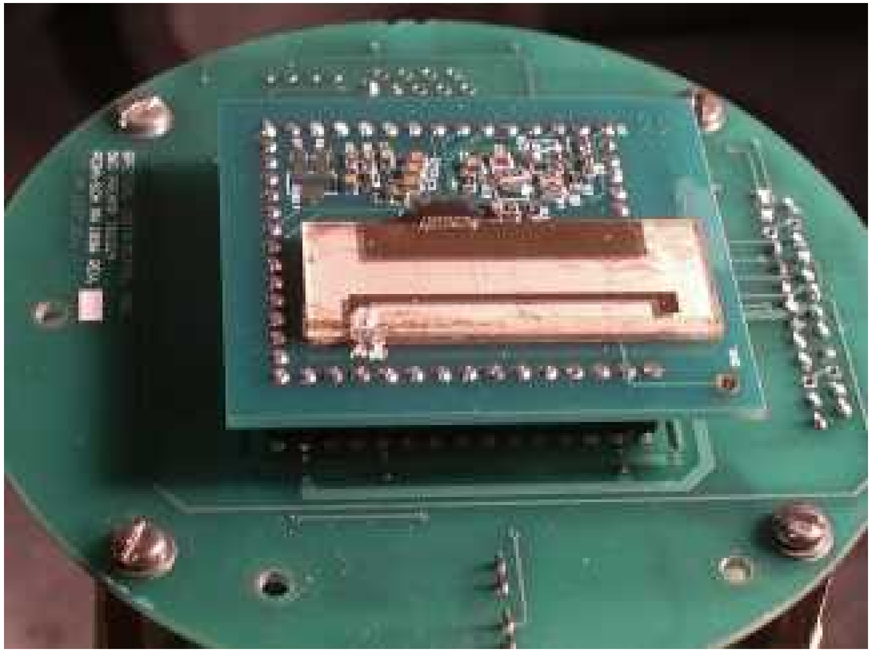
Array Detector in Mass Spectrometry
Mattauch-Herzog Geometry



Array detectors provide a multiplex advantage in dispersive mass spectrometers.

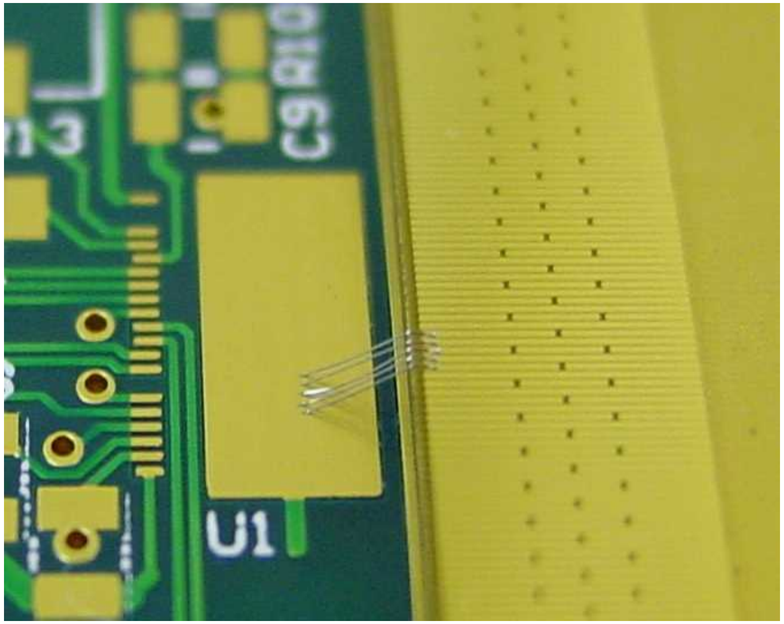
CTIA Array Detector

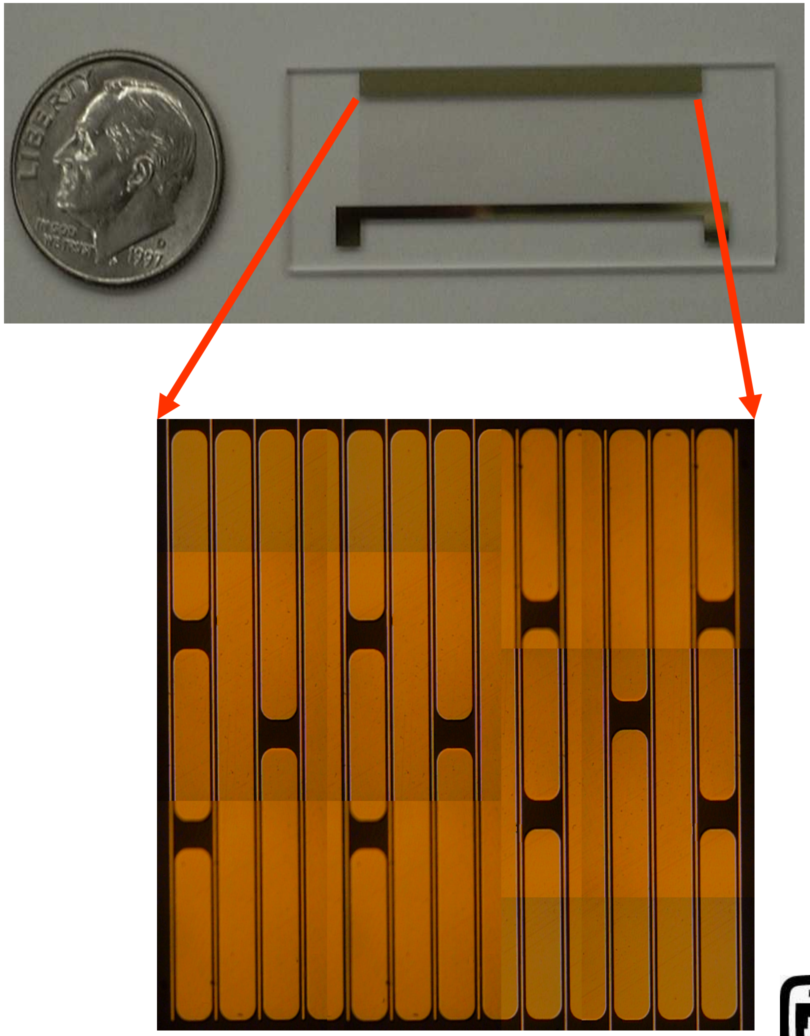
Detector configured for magnetic sector mass spectrometer



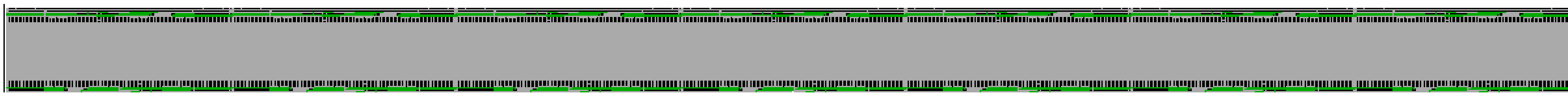
Top view of micro-Faraday finger ion detector array (32 pixels)

Micro-Faraday Finger Array

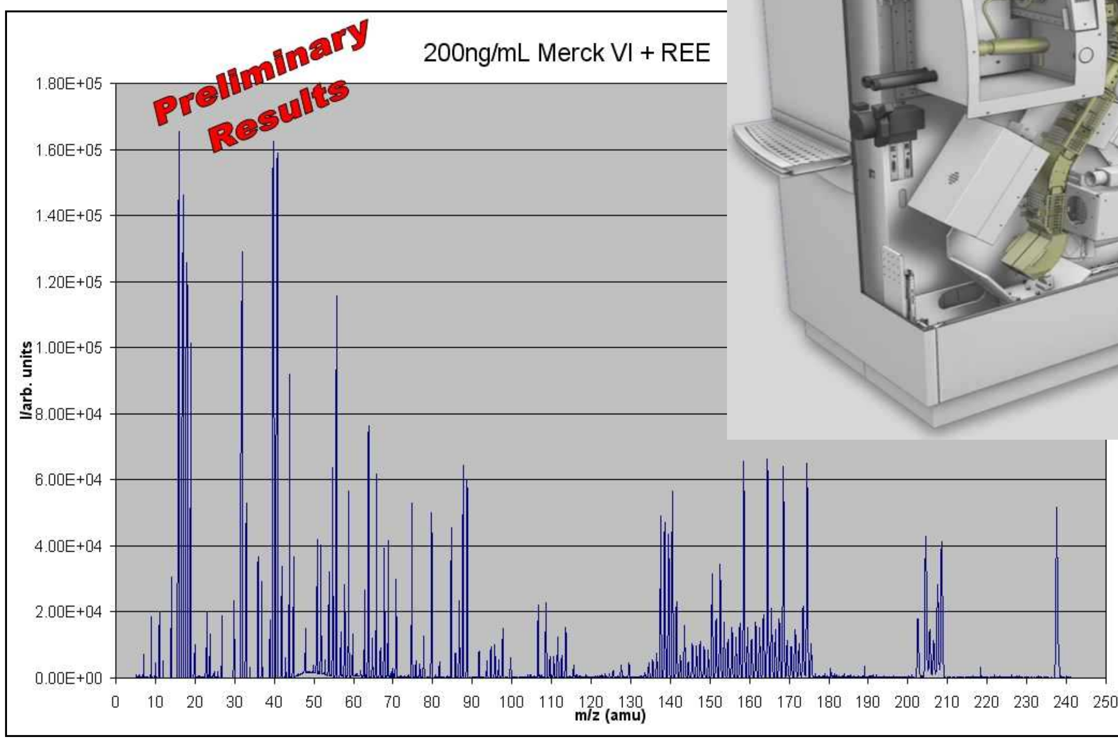




World First Commercial CTIA Array MS

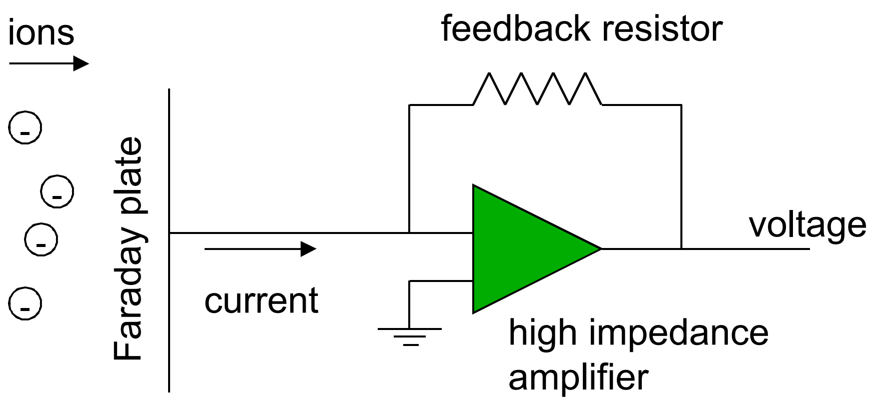


- ICP-MS with a 9600 pixel, monolithic, "stitched" array
- Continuous mass coverage from 0-250 m/z



Faraday Plates as Ion Detectors

Current-to-voltage converter



A Faraday plate uses a current-to-voltage converter to measure the number of incident ions.

A small ion flux requires high gain to produce a detectable voltage. The gain is determined by the magnitude of the feedback resistor (V = I R).

Advantages

- Produces a 1:1 signal.
- Simple to build and operate.
- Rugged; not easily contaminated.

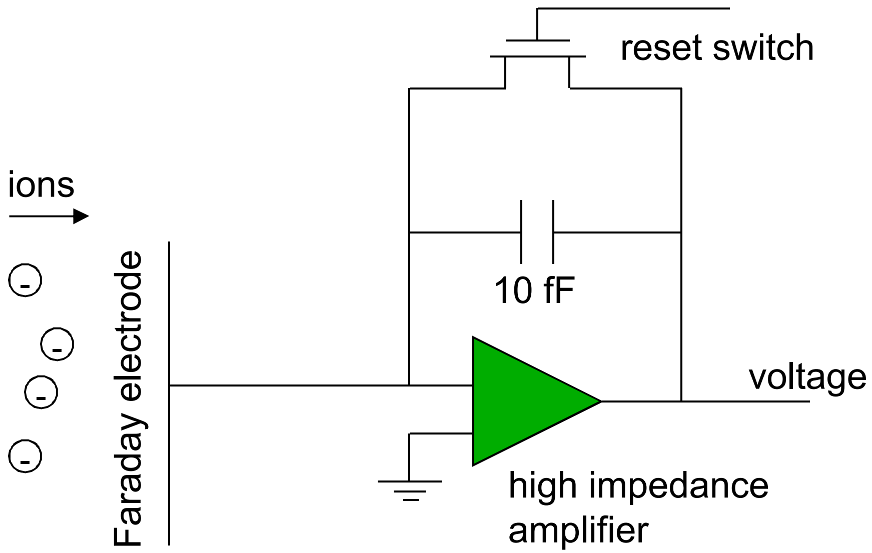
Disadvantages

- State-of-the-art Faraday plate requires a minimum of 6,000 ions/s.
- Large feedback resistor introduces substantial Johnson noise

$$\nu_{rms} = (4\ k\ T\ R\ \Delta f)^{1/2}$$

- Wire used to connect the Faraday plate to the amplifier is inches long and acts as an antenna and picks up noise.

Capacitive Transimpedance Amplifier (CTIA)



Output voltage is determined by the amount of incident charge and the magnitude of the feedback capacitor (Q = V C).

The output voltage is *inversely* proportional to the feedback capacitor. Smaller capacitors result in a larger signal.

Advantages

- Integrating detector; total charge is quantified, not current.
- Capable of detecting ***tens*** of ions.
- Readout is located millimeters away from electrodes; low antenna noise.
- Johnson noise is insignificant compared to Faraday plates.
- Uses double correlated sampling; no switching noise.

Disadvantages

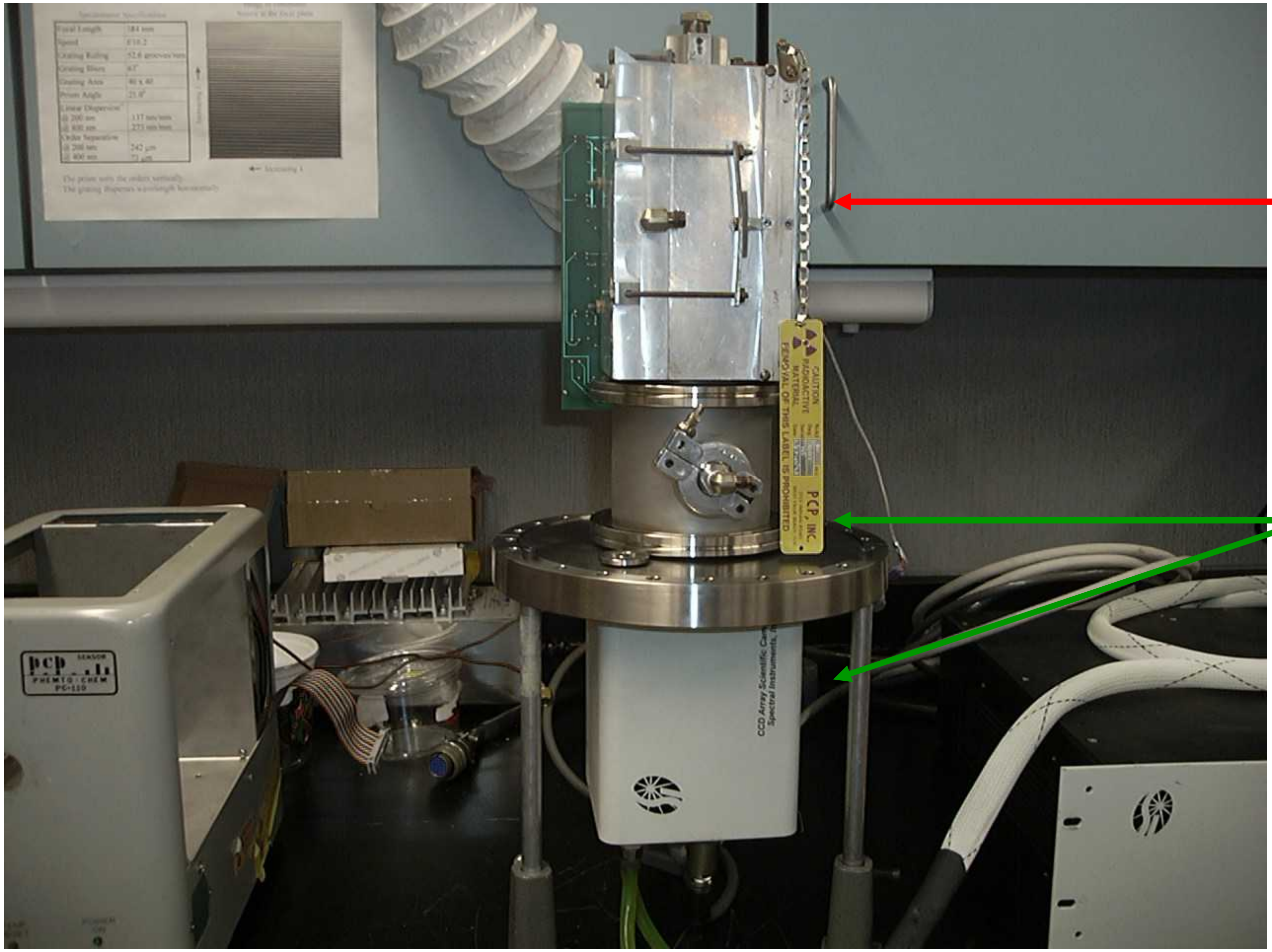
- As the electrode size increases, the capacitance increases and the sensitivity decreases.
- Micro-Faraday array is more complex than Faraday plates.

CTIA Performance Parameters*

	High Gain	Low Gain
Dark current (attoAmp)	200	1900
Transimpedance (μV/e^-)	16	0.16
Full well capacity (e^-)	1.8×10^4	1.8×10^6
Linear dynamic range	10^5	10^5
Read noise (e^-)	29	310
3σ Detection limit (charges)	90	900

*Detector temperature = -40 °C

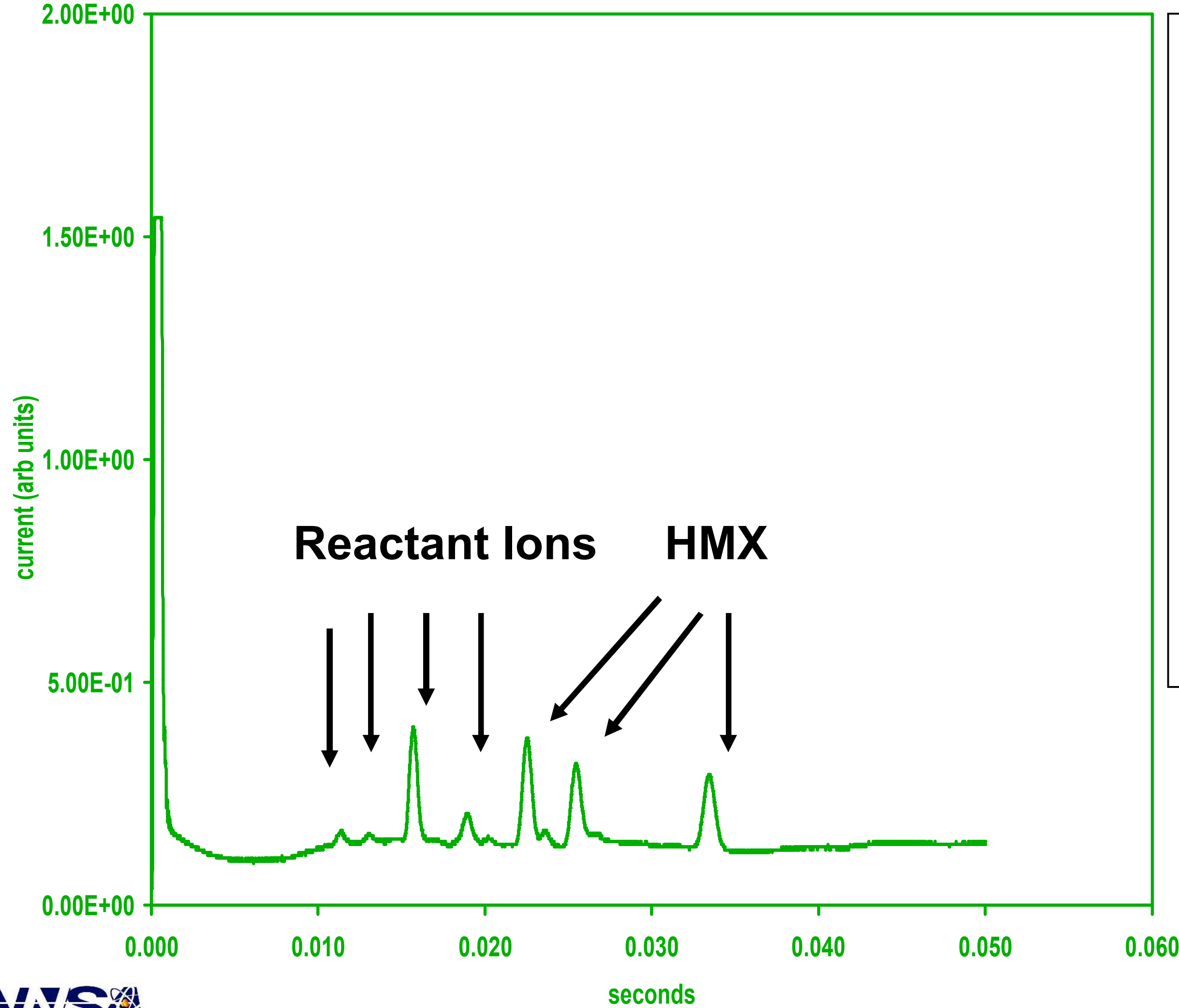
CTIA Array Detector Couple to IMS



Modified ion mobility spectrometer

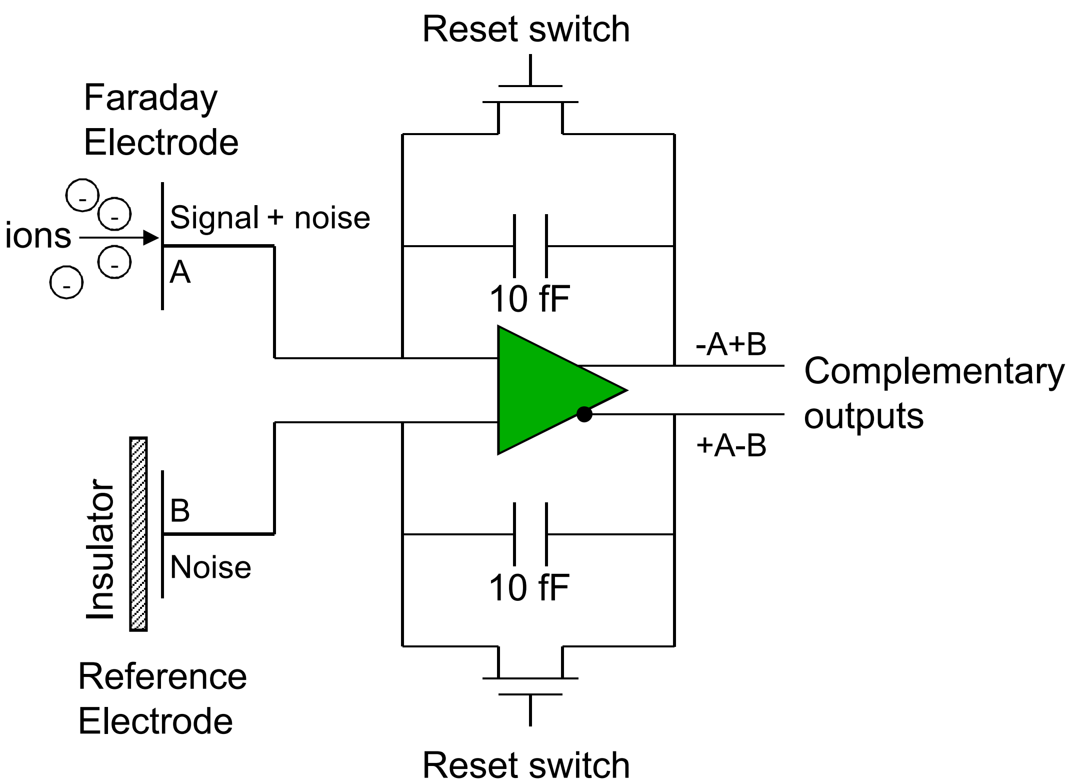
Mass spectrometry camera (CTIA array detector)

HMX Spectra - PCP 110 IMS/Faraday Plate



- 200 scans averaged
- N_2 used as drift and carrier gas
- CH_2Cl_2 introduced via permeation tube
- Operating in (-) mode
- Drift region kept at 80 ºc
- 500 μs pulse width at 10 Hz
- S/N 10:1

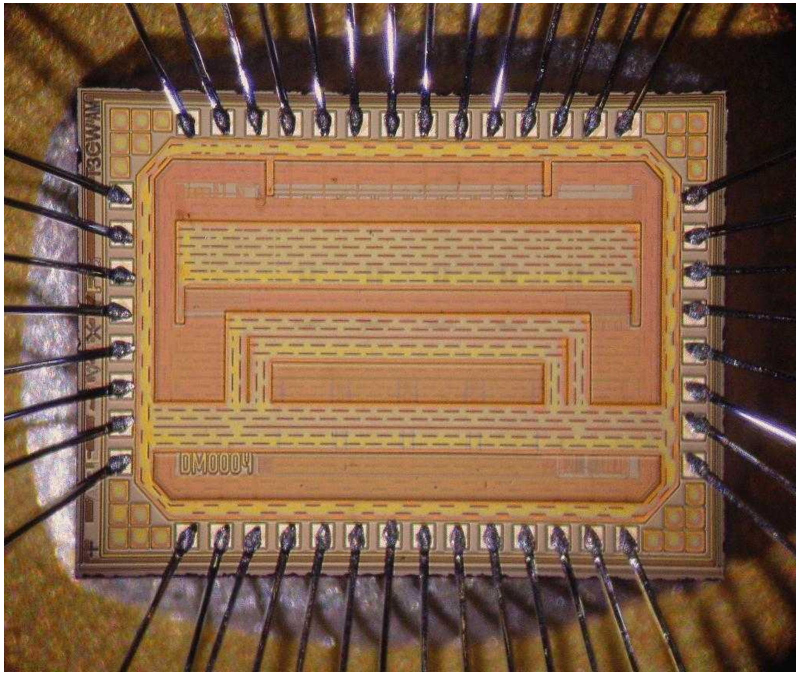
Differential Capacitive Transimpedance Amplifier



Advantages

- Outputs are the difference between the signals on the Faraday and reference electrodes.
- Input noise is cancelled before high amplification.
- Reduces the influence of time-correlated noise features.
  - Environmental electromagnetic interference (EMI)
  - Power supply noise and ripple
  - Common mode rejection ratio (CMMR) ≈ 30
- Complementary outputs allow time-correlated noise picked up by transmission wires to be cancelled. (+A-B) - (-A+B) = 2A-2B

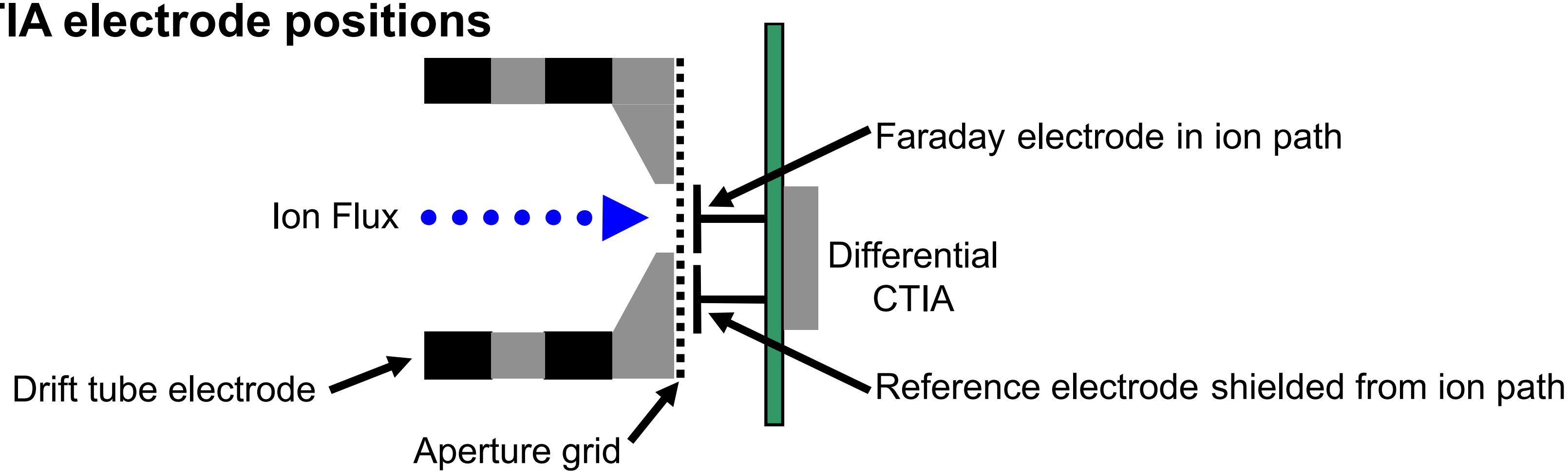
Differential Capacitive Transimpedance Amplifier



- 4 differential channels per device.
- Modern integrated circuit design and fabrication techniques allow very small feedback capacitances.
- The two integrators must have identical responsively for perfect external noise cancelation.
  - Fully symmetric topology allows FETs and capacitors to be placed close together and fabricated under almost identical conditions.

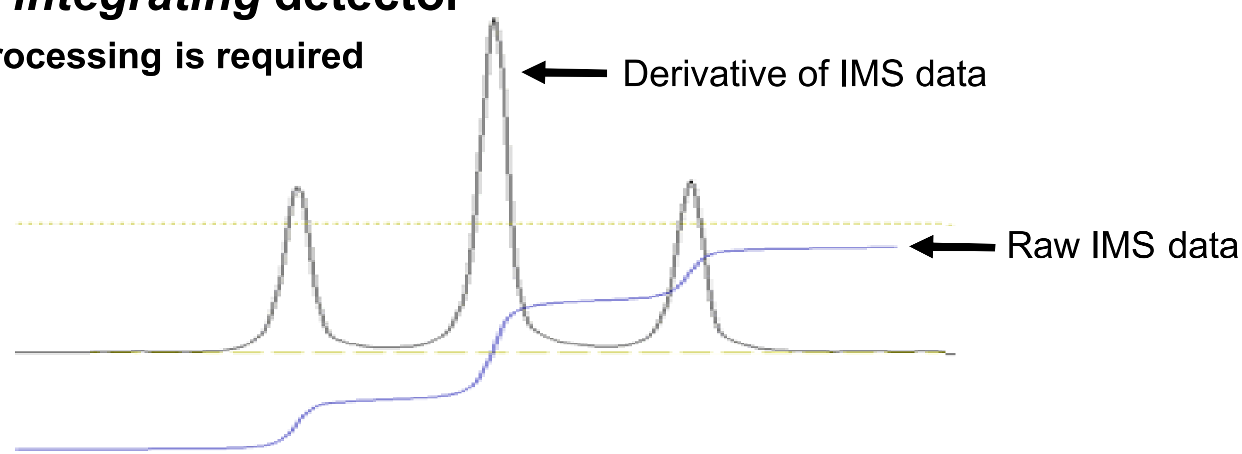
Implementing the Differential CTIA in IMS

CTIA electrode positions



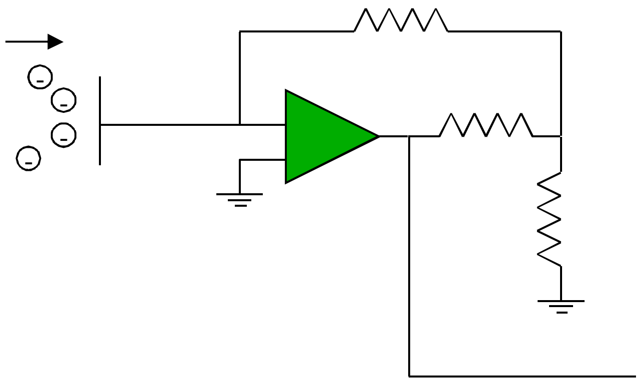
The CTIA is an *integrating* detector

- **Additional processing is required**

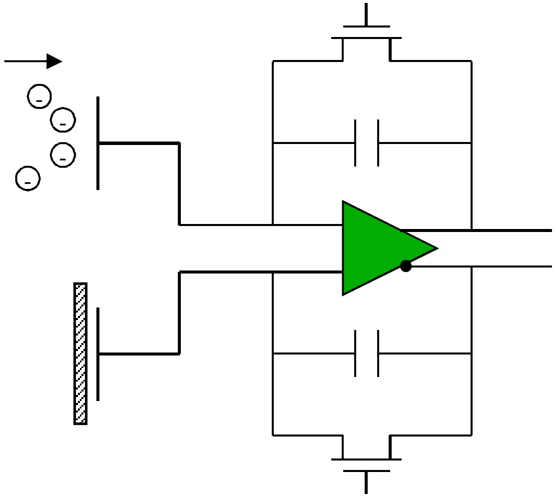


Comparison of Detector Technologies

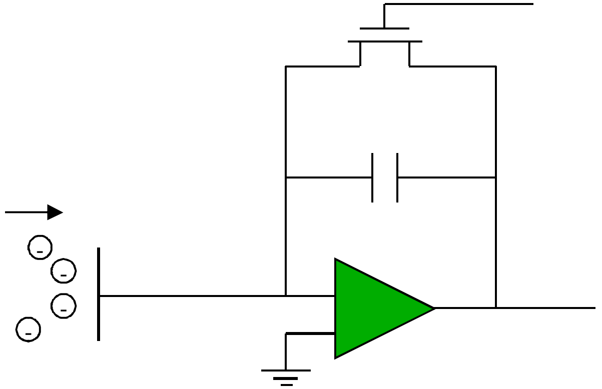
OPA129 (Texas Instruments) Electrometer



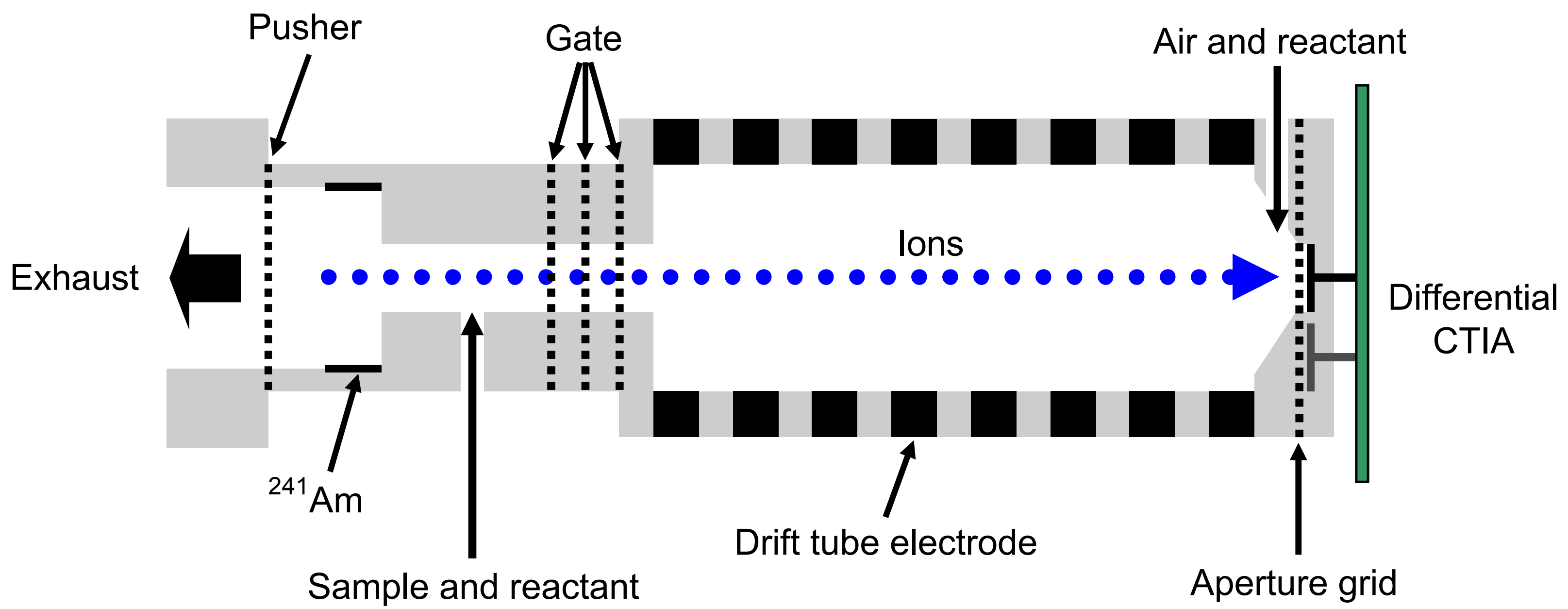
DM04 Differential CTIA



IL002 Single-Ended CTIA

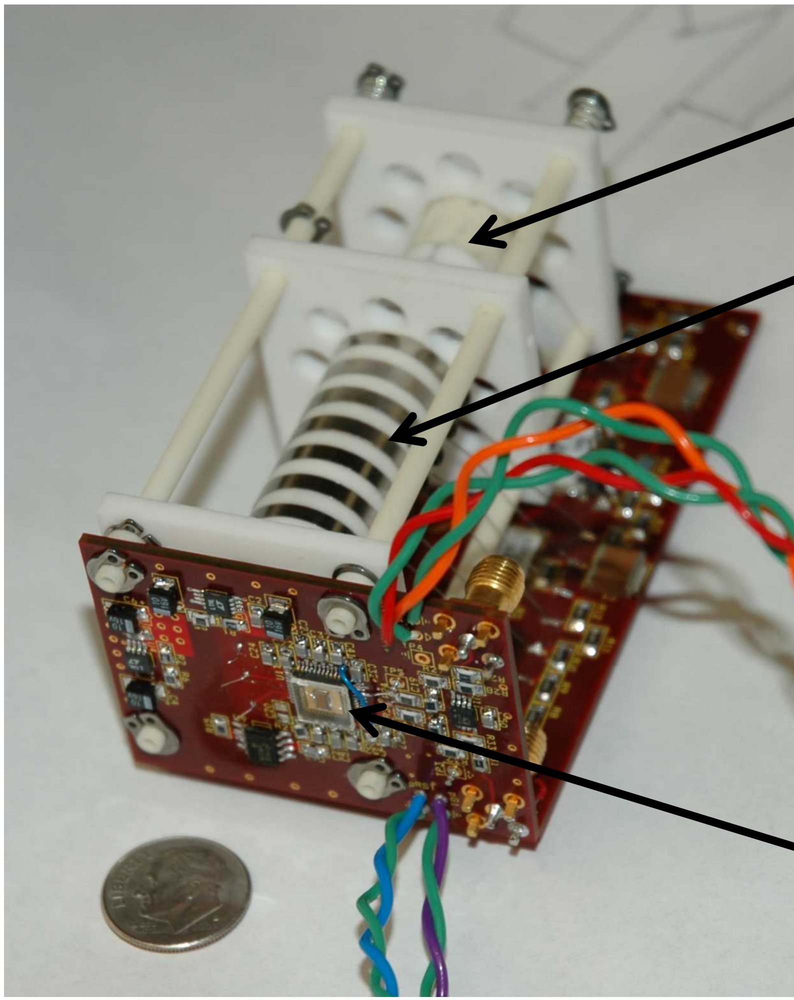


University of Arizona Miniature IMS Drift Tube Schematic



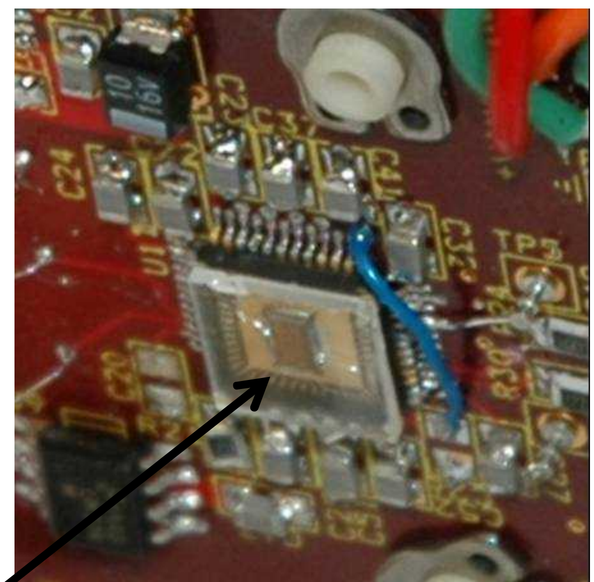
Same IMS miniature IMS instrument was used for detector comparisons.

University of Arizona Miniature IMS with Differential CTIA Detector



Ionizer

Drift Tube



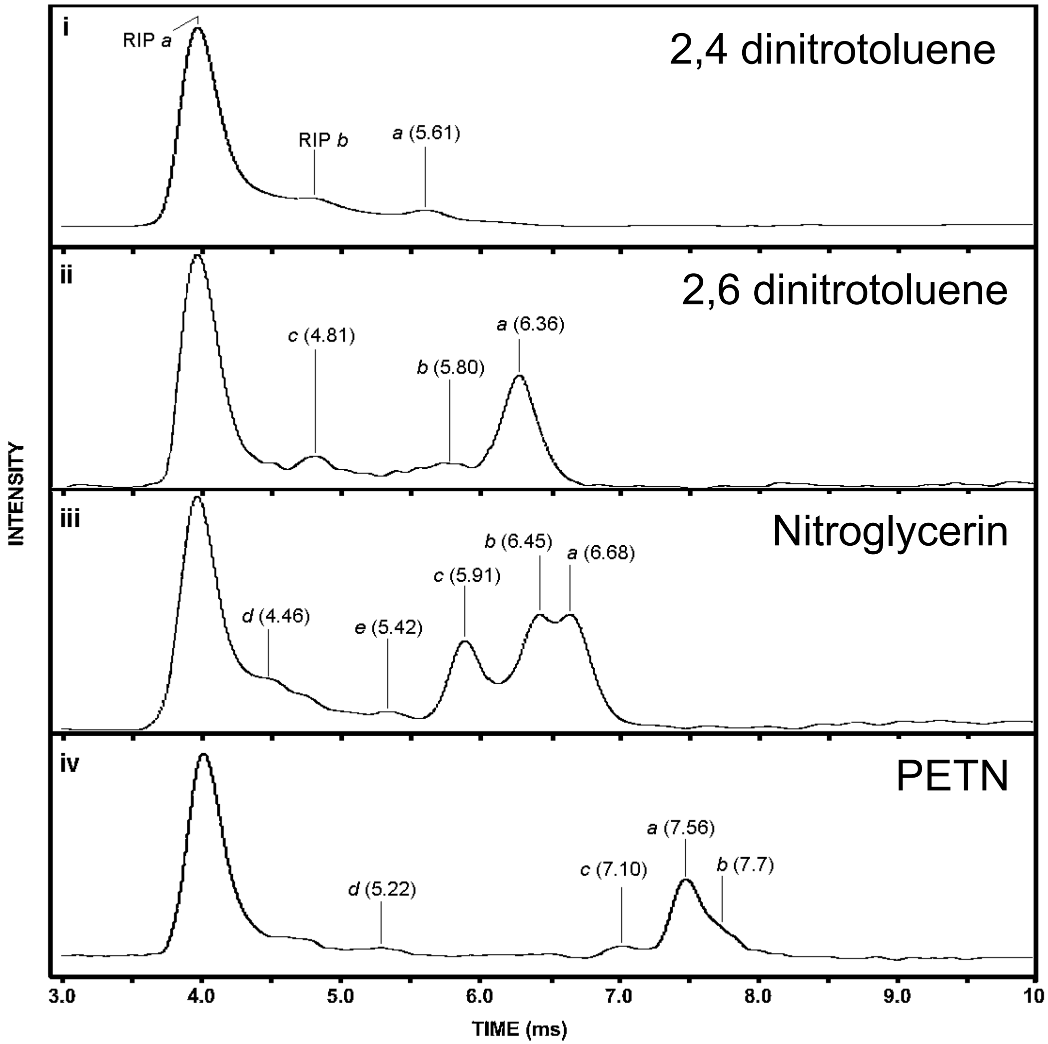
Detector

M. Bonner Denton and Roger Sperline, University of Arizona, Tucson, AZ

Detector Comparison Results

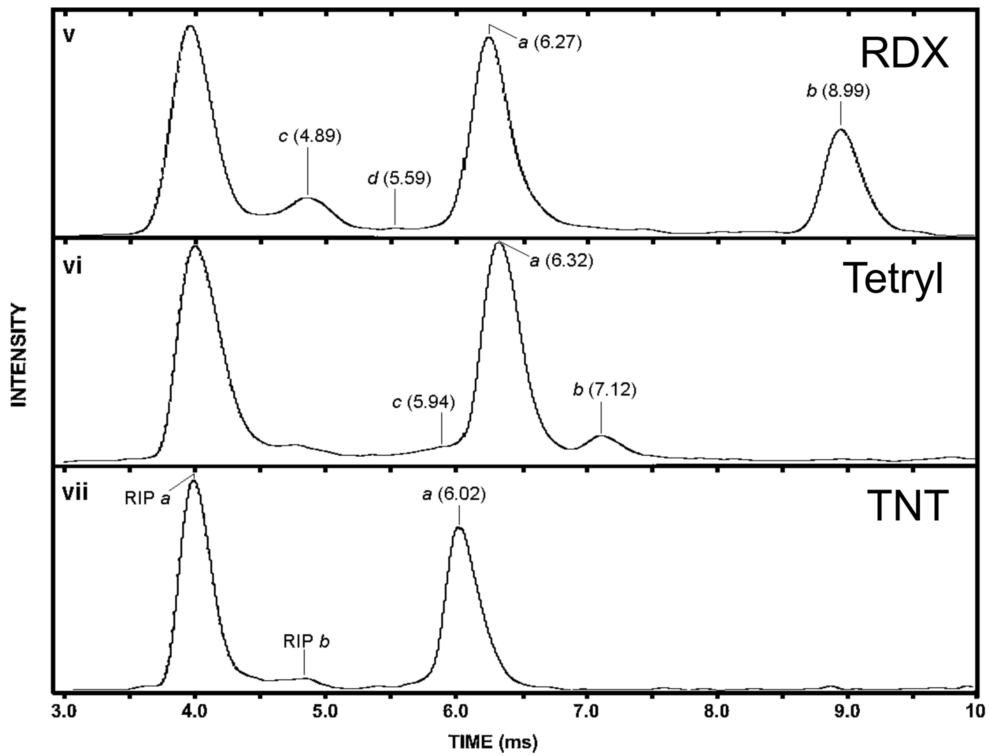
	Limit of Detection (3σ/slope)	Relative Sensitivity
OP129A	1.5 ng	1
Single-ended CTIA	1.4 pg	1100
Differential CTIA	790 fg	1900

Miniature IMS Plasmagrams



Babis, J. S.; Sperline, R. P.; Knight, A. K.; Jones, D. A.; Gresham, C. A.; Denton, M. B. *Analytical and Bioanalytical Chemistry* **2009**, *395*, 411-419.

Miniature IMS Plasmagrams



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Pocket IMS – Handheld Explosives Detection System

Specifications

- Dimensions = 3 3½ 12¾ in.
- Weight = 2.8 lb
- Battery life = ~2.5 hr
- Desiccant life = 12+ hr
- Warm-up time < 15 min
- Sampling rate ~1 liter/min

Features

- Visible alarm
- Audible alarm option
- Single handed, one-button operation
- Custom software for OS and data interpretation
- Onboard desiccant, temperature, and battery-life sensors
- Metal foam preconcentrator for high-efficiency vapor sampling

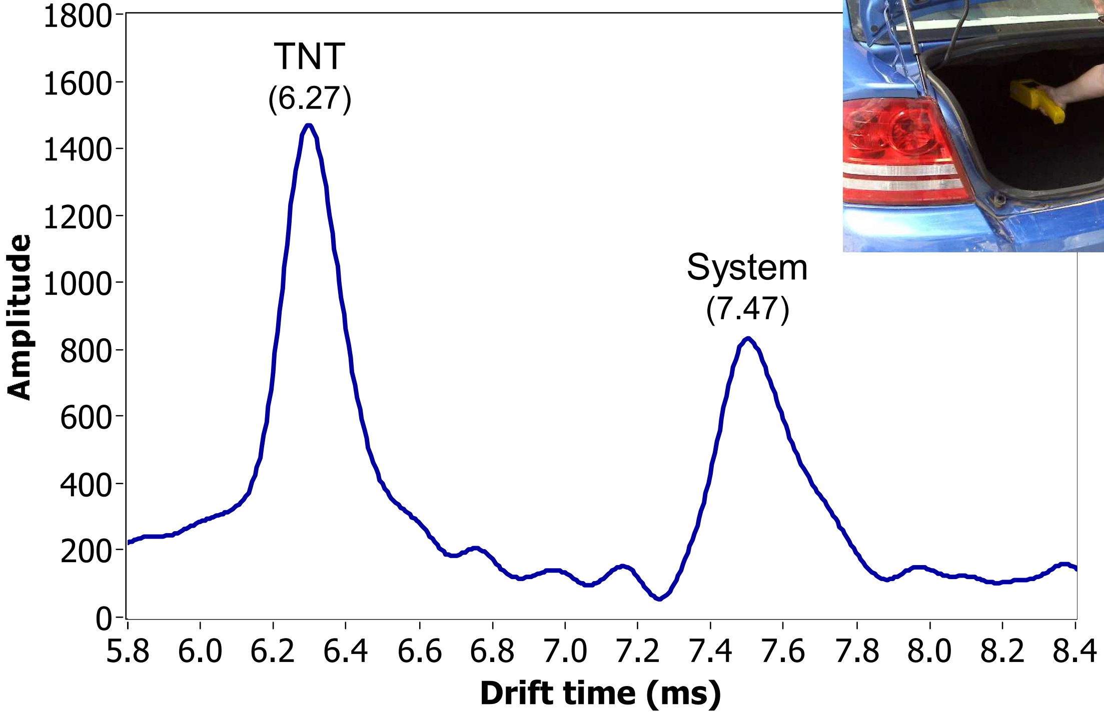
Detection of Trace Explosives from a Simulated Vehicle Bomb

- 200 lb of TNT were loaded into the trunk of a car to simulate the explosives contamination generated during the preparation of a simulated vehicle-borne improvised explosive device (VBIED).
  - TNT was in a cardboard box that was double-bagged in plastic.

- Opportunity to test Pocket IMS under "real-world" conditions.
  - All sampling by the Pocket IMS was non-contact air sampling.
  - Air samples were acquired for 15 seconds.

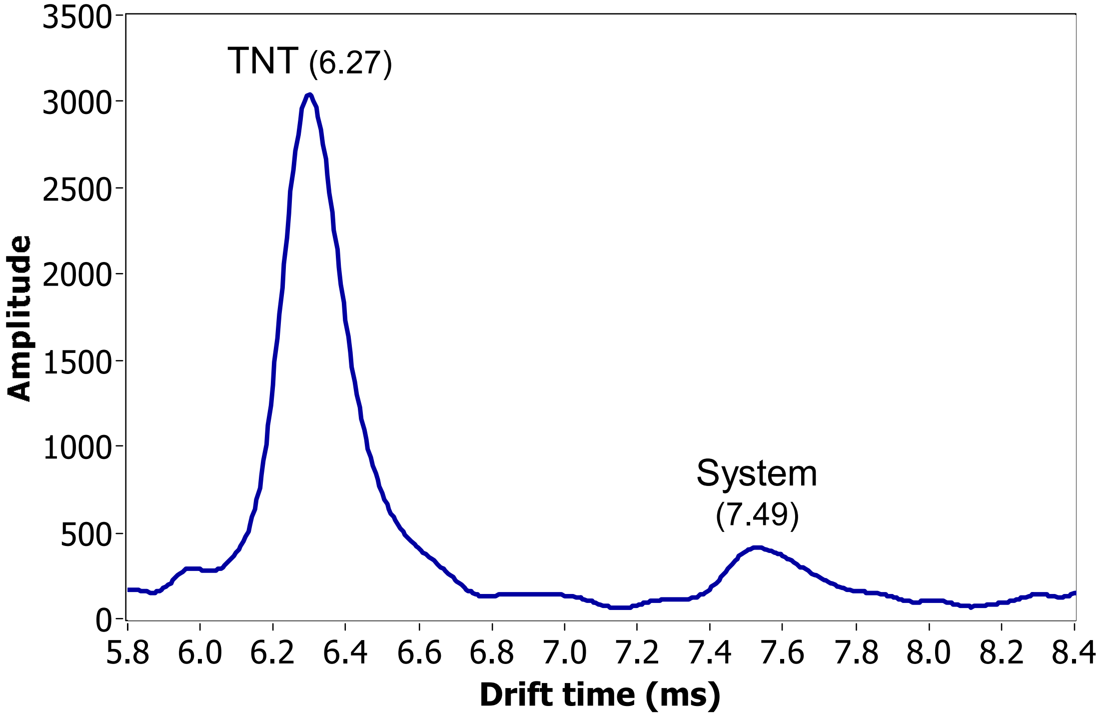
Air in Middle of Trunk

- Sampling air in middle of trunk after TNT was removed.



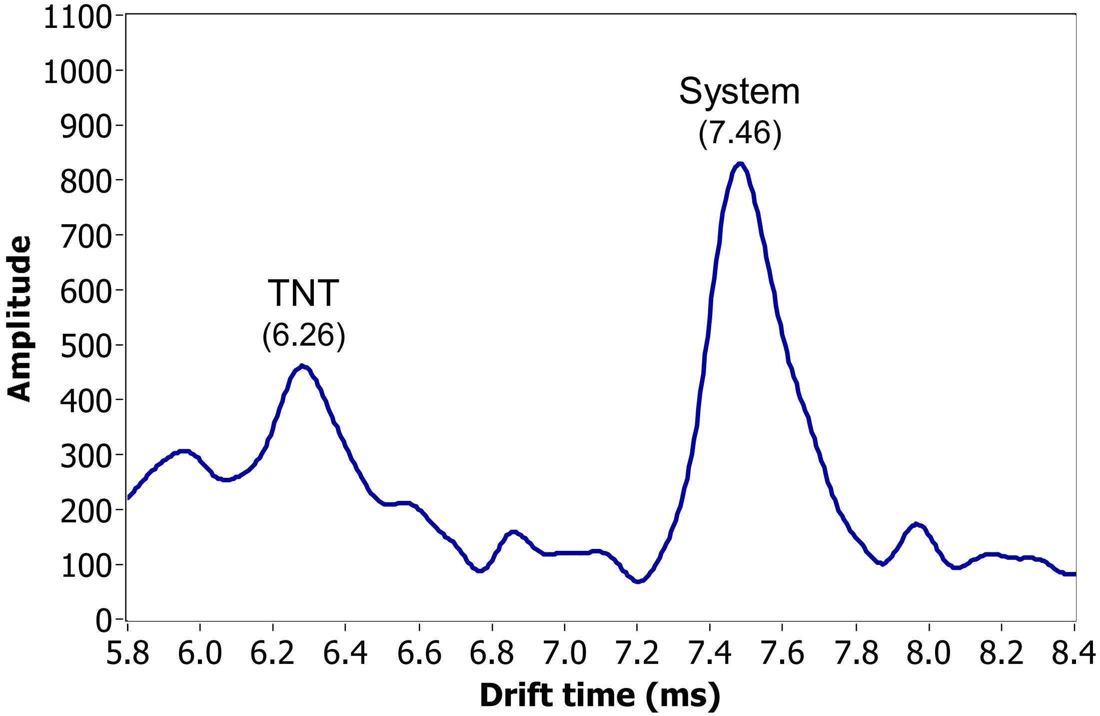
Near Trunk Wall

- Sampling near carpeted trunk wall after TNT was removed.



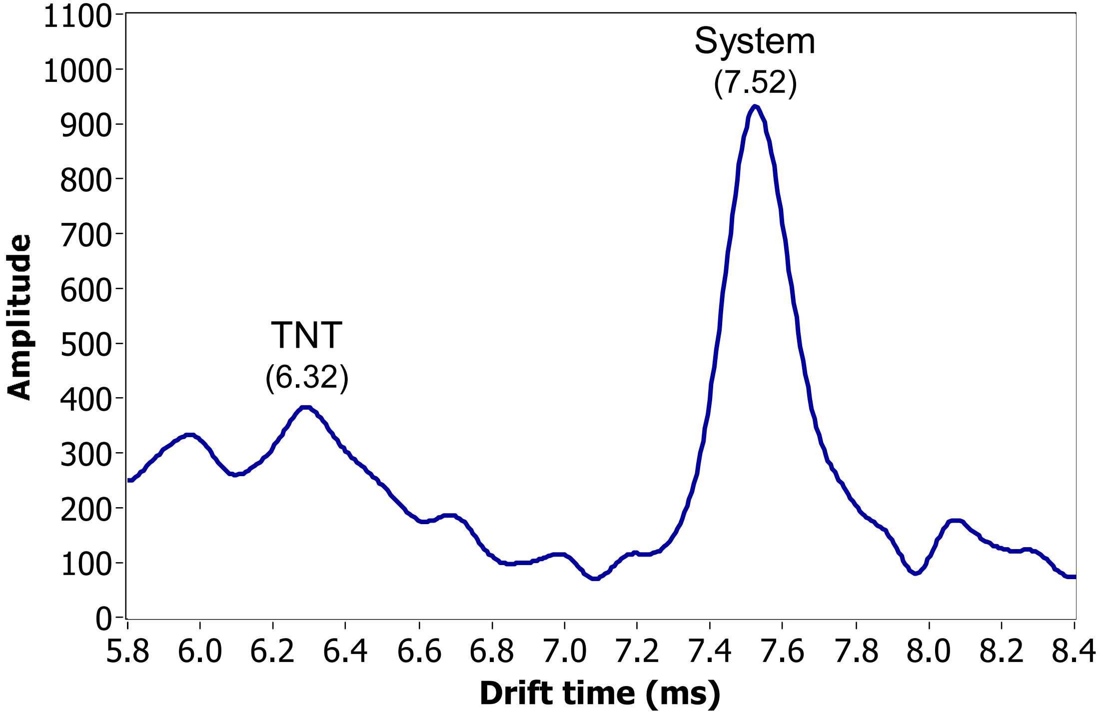
Driver's Side Interior Door Handle

- Sampling near interior door handle on driver's side after TNT had been loaded into the trunk.
  - Contact transfer from the explosive handler.



Driver's Seat Belt Buckle

- Sampling near drivers seat belt buckle after TNT had been loaded into the trunk.
  - Contact transfer from the explosive handler.



Conclusions

- A differential charge transimpedance amplifier (CTIA) as been developed for ion detection in ion mobility spectrometry.
- The differential CTIA has demonstrated a ~2000-fold increase in sensitivity compared with conventional electrometer-based Faraday plate detectors.

Acknowledgements

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