"Mass Spectrometry Fundamentals"
A STEM Education Lab Course

Design, Build and Test Your Own Original Mass Spectrometer

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Ceramitron

Mission Statement

To present the fundamentals of mass spectrometry and ion optics through a hands-on approach to the design, fabrication and testing of original prototypes by students in a secondary school or university STEM laboratory setting.

Why Mass Spectrometers?

- Practical application of classical electrodynamics
- Blends physics, chemistry, mechanics, electronics
- Enhances understanding of materials/construction
- MS is the most versatile analytical technique
- Lessons learned in lab directly transfer to the widest range of real-world applications (industrial, medical, energy, military…)
- Students with hands-on experience gain a distinct edge in the job market!

A Novel Approach

Our insight was recognizing that the precision machined metal elements typically found in mass spectrometers could be replaced by the very inexpensive surface metallization now used on standard printed circuit boards (PCBs)—*without any significant loss in performance!*

Fabricating MS units from PCBs *saves >90% of prototyping cost*, eliminates manual alignment of elements, and drives down the cost of large scale production.

MS Lab Course Highlights

- Lab has 8-12 students: 4 teams of 2-3 students
- Each team designs it own original MS prototype using SIMION software
- SIMION designs transferred to printed circuit boards (PCBs) using CadSoft's EAGLE software
- PCB .dxf artwork emailed to quick-turn fab shop
- Finished PCBs assembled into working MS units
- Designs tested and evaluated against original specifications, with analysis of errors, etc.
- Final report write-ups
- Teams demonstrate their designs to the class
- Designs archived for future classes

MS Lab Infrastructure

Equipment
- 2 complete vacuum stations serve 4 design teams
- Electronics and power supplies for 2 MS units
- LabView control/data capture/presentation of spectra
- Lecture bottles of pure gas samples and mixtures

Other
- 4 PCs with Simion and EAGLE (CAD) software
- Student Manual (in digital download format) showing MS and vacuum fundamentals, PCB design methods, examples of ion optics experiments, etc.

MS Lab Budget

One-time investment of $26,000 can purchase all capital equipment, software and other items to set up the lab program.

Estimated useful lifetime: 10 yrs.

A consumables budget of $2,000 per class covers fab shop costs to produce 4 complete units of each team's MS design, as well as sample gases, construction materials and miscellaneous parts.

MS Fabrication using PCBs

- PCB fabrication accommodates a wide range of mass spectrometer types and geometries
- PCB layout is homeomorphic with MS geometry
- Photolithographic metallization creates the same electric fields as discrete metal components
- Stacking PCBs to create MS enclosures provides very precise geometric alignment
- Stacked PCBs, sealed together, form vacuum enclosures that eliminate stainless steel vacuum chambers and fittings!

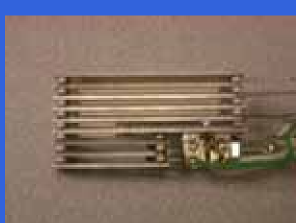
MS Fabrication using PCBs

- PCBs eliminate high NRE/retooling costs
- Unit cost drops dramatically for larger run size
- Easy scaling of designs using PCB CAD software
- Standard (.dxf) CAD format allows devices to be fabricated anywhere in the world
- PCBs may be fab'd in PEEK, polyimide, Vespel, ceramics to meet demanding performance specs
- Inexpensive PCB MS devices are *disposables!*

Flexibility of PCB Design

- Accommodates virtually *any* MS geometry
- Minimizes cost of prototype development
- Vertical-wall metallization can fabricate
  - Ion traps, ICRs…
  - Electric-sector energy analyzers
  - Lenses
  - Ion source volumes
  - TOF reflectrons
  - Faraday cup detector arrays
  - Shielded component enclosures (EMs…)

MS Examples: Discrete vs. PCB

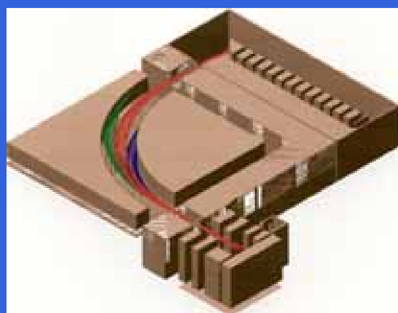


Cycloidal MS Prototype, ca. 1985

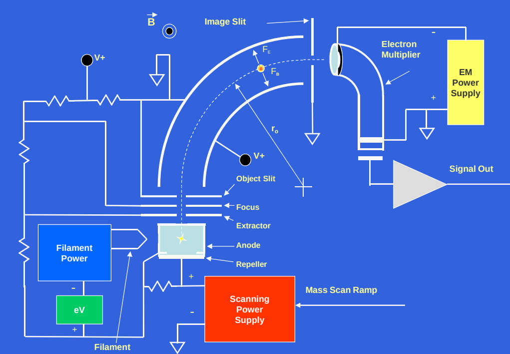
3-PCB design ca. 2012

Ceramic Photolithographic Cycloidal MS, ca. 1989

SIMION™ 90° Double-Focusing MS Geometry

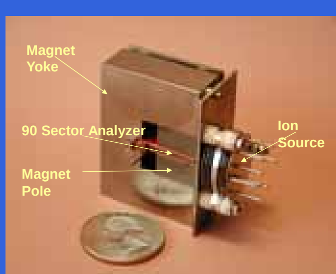


Simion model of Univ. of Minn. DFMS. Diaz, et al (1998)



Simplified Electrical Block Diagram

Discrete-Element Sensor



Courtesy Mass Sensors, Inc.

Mass range: 1-50 amu

Resolution: 45

Ionization: electron impact

Sensitivity: 1-5 ppm

Weight: 150g

Construction:

-- machined elements

-- manual assembly

-- precision alignment

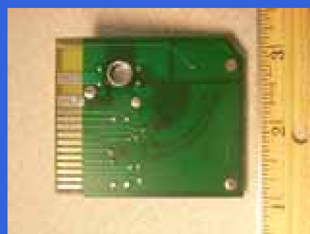
-- requires vacuum chamber

Courtesy Mass Sensors, Inc.

Sensor mounted on standard vacuum flange

MS Examples: Discrete vs. PCB

90-degree Double-Focusing Magnetic Sector MS analyzer, (1998) Univ. of Minnesota Diaz, et al, US Patent 6,501,074

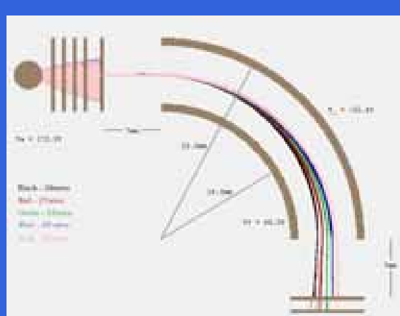


3-PCB DFMS in vacuum-tight enclosure (2009) Berger, et al US Patent 6,831,276

SIMION™ Model: 90° Double-Focusing MS Geometry

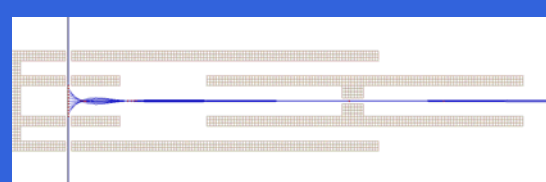
Simion model using discrete element ion source ca. 2013

SIMION™ Model: 90° Double-Focusing MS Geometry

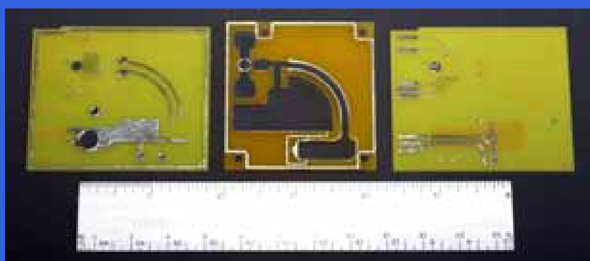


Simion model using photolithographic lenses and resistive film electric-sector analyzer, ca. 2013

Simion Model: Ion Source with Two Discrete Elements



Fiberglass Mass Spectrometer



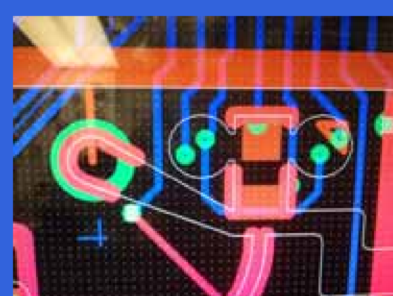
Elements With Solder-Seal Rings

Fiberglass Sensor Prototype

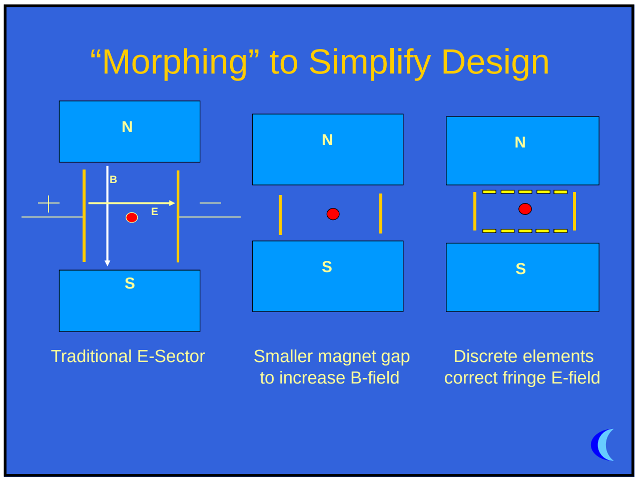
Stand-Alone Operation

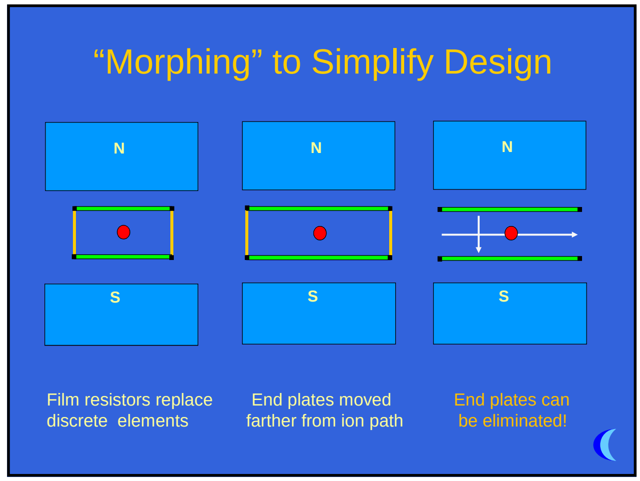
Fully-Outboard Operation—Without Vacuum Chamber!

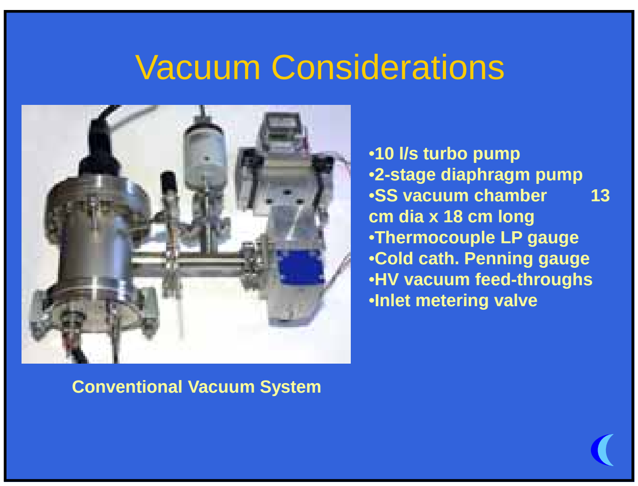
EAGLE CAD Drawing Detail of PCB DFMS

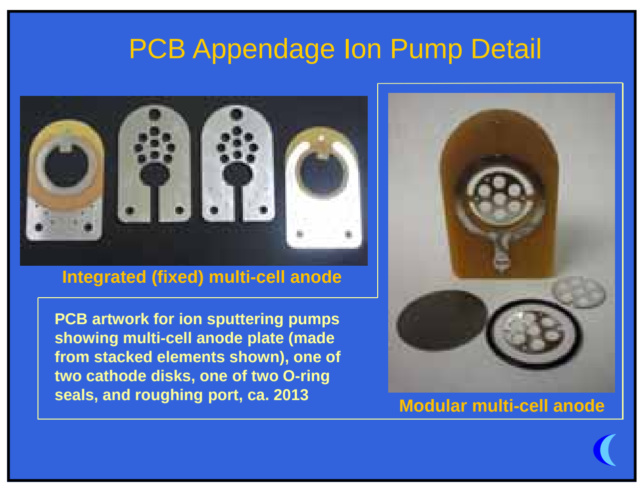


PCB artwork for DFMS prototype showing ion source volume, dual-filament enclosures, electric sector energy analyzer and vacuum roughing port, ca. 2013


"Morphing" to Simplify Design
N
S
B
E
Traditional E-Sector
N
S
Smaller magnet gap to increase B-field
N
S
Discrete elements correct fringe E-field


"Morphing" to Simplify Design
N
S
Film resistors replace discrete elements
N
S
End plates moved farther from ion path
N
S
End plates can be eliminated!


Vacuum Considerations
•10 l/s turbo pump
•2-stage diaphragm pump
•SS vacuum chamber 13 cm dia x 18 cm long
•Thermocouple LP gauge
•Cold cath. Penning gauge
•HV vacuum feed-throughs
•Inlet metering valve
Conventional Vacuum System


PCB Appendage Ion Pump Detail
Integrated (fixed) multi-cell anode
PCB artwork for ion sputtering pumps showing multi-cell anode plate (made from stacked elements shown), one of two cathode disks, one of two O-ring seals, and roughing port, ca. 2013
Modular multi-cell anode

Sorption Pump Alternative

90-degree DFMS (left half) with multi-cell ion pump anode (right half), vacuum roughing port and card-edge I/O connector, ca. 2013

MS with self-contained ion sputtering vacuum pump

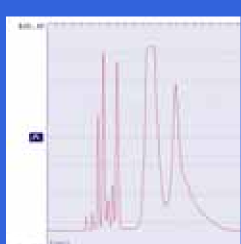
Ti and Ta cathode plates are positioned externally to form sandwich with multi-cell anode

Non-evaporable getter (NEG) not shown

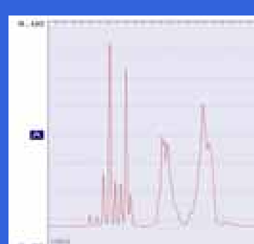
Requires only one pump-down event to achieve and maintain 3E-6 Torr pressure

PCB Integrated Ion Pump Detail

PCB artwork for ion sputtering pump showing multi-cell anode plate and one of two cathode disks (2013)



Acetone in air



Isopropanol in air

Spectra generated using FR4 fiberglass PCB DFMS with 2 cm energy analyzer and 1-Tesla NdFeB magnet

Other Concerns

- How might additive manufacturing (3-D printing) contribute to easy prototyping?
  - Relative cost?
  - Speed?
  - Surface characteristics, hermeticity?
  - Metallization?
- How does material outgassing affect performance?
- Identify initial applications to drive use and interest.
- Should we consider selling “kits” of successful MS?

Conclusions

- "MS Fundamentals" integrates physics, chemistry, electronics, materials into a practical teaching experience
- Simion, EAGLE CAD and LabView provide an easy-to-learn method for investigating novel MS designs and implementing prototypes in an academic setting
- Quick-turn PCB fabrication is highly cost-effective and accommodates a wide range of MS design geometries
- Student teams can produce several original MS designs that benefit the entire class
- This pedagogical, hands-on approach can significantly improve university Chem/Physics curricula and raise student knowledge and competency.

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