# ION PROCESSING: CONTROL AND ANALYSIS

## BACKGROUND OF THE INVENTION

The present invention relates to ion processing systems and, more particularly, to radio-frequency mass spectrometers and ion storage systems. A major objective of the present invention is to provide flexible apparatus for the processing, storage, and analysis of large numbers of ions in parallel.

Mass spectrometry, or more generally the techniques and apparatus for control and analysis of charged particles or ions, has provided important tools for scientific exploration. Traditionally defined, a mass spectrometer is an instrument which produces ions from one or more substances, sorts these ions into a spectrum according to their mass-to-charge ratios and records the relative abundance of each species of ion present. From its beginnings in the early 1900's, mass spectrometry has become a necessary and integral component of modern science and commerce. Many areas of current research depend upon mass spectrometric techniques to perform crucial experiments. For example, mass spectrometry has found use in the analysis of upper atmospheric gases, detecting and studying ozone depletion processes. Medical research and practice routinely use mass analysis instrumentation for the detailed analysis of protein structures and the genetic coding in DNA. These analytical methods require the precise separation and identification of the mass and quantity of each ion extracted from an initial particle mixture. In many experimental regimes, new laboratory processes rapidly create a large range of molecular species in great quantities, placing ever increasing demands on the rate and fidelity with which mass analysis must occur. Current mass spectrometry technology faces difficult challenges in meeting these experimental needs.

The domain of ion processing encompasses more, however, than just the analytical measurement of distributions of ion mass. Other technologies involve the preparative separation and storage of different ion species. One example would be the separation of isotopes, which vary in atomic mass. The accurate isolation of radioactive isotopes finds use in medicine, nuclear energy and pure physics research. Another use for ion processing techniques involves the separation, buffering and long-term storage of charged antimatter. Most large particle accelerator facilities produce antimatter in the form of anti-protons (positronium) and anti-electrons (positrons). Since the annihilation of matter with antimatter results in the most efficient conversion of matter into energy, extensive efforts are being made, as discussed in report AFRPL TR-85-034, from the University of Dayton Research Institute, toward the trapping, storing and annihilating of positronium. New generations of spacecraft capable of harnessing the energy released in controlled matter-antimatter annihilation could achieve extremely high velocities. Antimatter is highly reactive, however, and must be stored in perfect isolation until final use. The current inability to reliably and effectively cool and store significant quantities of charged antimatter in portable systems is a key factor in preventing practical use of antimatter propulsion. The storage methods used to maintain such antimatter ions comprise another example of potential ion processing techniques.

The explosive growth of mass spectrometric applications throughout science and industry rests on the ability of external and easily controlled electrostatic, magnetostatic and electrodynamic fields to precisely and accurately manipulate charged matter, abilities unequaled by other neutral manipulation techniques. However, all such charged-particle devices suffer from the effects of space charge, that is, mutual coulombic repulsion remains a fundamental physical limit. Yet today, industrial and scientific demands for greater amounts of informative and preparative outputs from smaller samples of matter, and in shorter periods of time, have well exceeded the limits imposed by space charge on device throughput.

All mass spectrometers operate as flow systems. Ions, either captured or created by ionization, are guided through or confined within a volume prior to and during their detection. The mutual coulombic repulsion of like charges, however, makes difficult the production or capture of dense ion fluxes. The maximum output (either in analytical information or in preparative ion production) remains directly proportional to the average number of ions (the ion current) passing through the machine per unit time. The coulombic repulsion from space charge limits this average flow per unit volume. Ultimately, the volume governable by precise ion control limits the throughput of a given device.

Various mass spectrometers, or more generally, tools for the processing, control and analysis of ions, remain currently available. Each device combines unique operation attributes together with particular limitations, suffering more or less from space charge restrictions. Early mass spectrometers were what are now termed magnetic (or magnetic and electrostatic) sector instruments. These devices generally use static magnetic, or magnetic and electric, fields to carefully disperse focused beams of moving charged particles. Depending on the charge-to-mass ratio, the particles' paths bend in different amounts. A mass spectrum for a particle group (that is, a numerical analysis of the mass distribution) comprises measurements taken of the numbers of particles at each focus point.

One form of sector spectrometers disperses the mass spectrum onto a strip of photographic film, forming a mass spectrograph. Photographic means can detect minute components of a substance being analyzed, thus providing a means for accurate mass determination. Photographic techniques, however, are less well suited for relative mass abundance measurements. As an alternative method, then, sector instruments scan their magnetic and/or electric fields such that various masses scan across a narrow stationary slit. Ions passing through this slit can then be detected electronically. The simultaneous photographic approach yields the greatest device throughput; relative abundance measurements through sector scanning are gained at the cost of information through-put. Time-averaging techniques can increase the amount of information collected, but only during relatively short periods due to inherent instabilities in the magnetic and electric confinement fields.

While the sector-type mass spectrometer was one of the earliest instruments in widespread use, it has certain inherent problems. The magnetic fields used to focus the charged particles in one direction tend to defocus ions in the perpendicular direction, requiring further focusing elements. The large magnetic fields required to focus ions often require bulky, heavy and yet precisely machined magnets. As research moves toward larger