

[0025] FIG. 2 is a cross-sectional view of a “hooked” DMS apparatus, according to another embodiment of the invention.

[0026] FIG. 3 is a cross-sectional view of a “hooked” DMS apparatus, according to yet another embodiment of the invention.

[0027] FIG. 4 shows a perspective view of an outer casing for enclosing an embodiment of a “hooked” DMS apparatus of the invention.

[0028] FIG. 5 presents an exploded view of the outer casing of FIG. 4 for enclosing a preferred embodiment of a “hooked” DMS apparatus of the invention.

[0029] FIG. 6 is a cross-sectional view of a preferred embodiment of a “hooked” DMS apparatus integrated within an outer casing of FIG. 4.

[0030] FIG. 7 illustrates an exemplary instrument configuration employing a preferred embodiment of a “hooked” DMS apparatus of the invention.

[0031] FIGS. 8a-8c present resolution-sensitivity diagrams for reserpine and bradykinin solutions analyzed using a planar DMS/time-of-flight mass spectrometry system with and without the DMS/MS interface of the invention.

DETAILED DESCRIPTION

[0032] Described herein is a DMS apparatus of a new “hooked” design, comprising shaped segments including, but not limited to, planar and cylindrical, where ions separated in the first DMS region are subsequently focused in the second DMS region using inhomogeneous electric field. A voltage applied to a pair of curved electrodes creates a spatially inhomogeneous electric field in the gap therebetween. As known in the art, when the voltage is periodic and asymmetric, the electric field forces ions of the type set by $U_D(t)$ polarity to bunch near the gap median. That effect is used to focus ions in cylindrical DMS and its hemispherical terminus, but DMS resolution is impaired and planar DMS provides the highest resolution (see, e.g., *Anal. Chem.* 2006, 78, 3706). In the method and apparatus of the invention, focusing occurs after DMS separation and hence does not affect resolution. Compression of the ion beam to the gap median improves transmission through the slit-shaped inlet of subsequent ion stages, e.g., MS, IMS, or IMS/MS. The resulting sensitivity gain has been benchmarked by measurements for representative analytes vs. an otherwise identical planar DMS system. The evaluation is extended to several aperture sizes reflecting a range of possible MS inlet conditions. Applications envisioned here include, e.g., enabling practical high-resolution DMS analyses via coupling of planar DMS devices to MS or IMS/MS stages, particularly, but not exclusively, in conjunction with slit aperture and/or ion funnel interfaces described herein.

[0033] FIG. 1 illustrates a cross-section of a DMS apparatus 100 of a “hooked” design, according to one embodiment of the invention. Apparatus 100 is a planar DMS analyzer with improved interface to subsequent stages, including, but not limited to, MS, IMS, and IMS/MS stages of various types. In the figure, apparatus 100 includes a substantially planar DMS analyzer 10, integrated with a “hooked” DMS element 12 comprising two curved electrodes, 14 and 16, with a gap 18 therebetween that receives an ion beam 20 from DMS analyzer 10, to which ions are injected from an ion source or preceding instrument stage 22 via ion aperture 24. Width of gap 18 is selected in the range of from about 0.2 mm to about 10 mm, and, more particularly, from about 0.4 mm to about 5 mm. The radius of annular gap median is selected in the range from about 1 mm to about 100 mm, and more particularly

from about 3 mm to about 30 mm. Gap 18 is filled with a suitable gas as will be practiced by those of skill in the art.

[0034] As usual, DMS separation is provided by a uniform electric field 26 in planar analyzer 10. Electrode 14 carries the $U_D(t)$ and electrode 16 carries the CV that jointly establish inhomogeneous electric field 28 over gap 18, which focuses ion beam 20 received from DMS analyzer 10 toward the gap median. Beam 20 is thus compressed, becoming thinner compared to diffuse beam 20 received from analyzer 10. Thus, ion beam 20 exiting apparatus 100 is more effectively transmitted via aperture 30 to subsequent stage 32, e.g., an MS or IMS. In the instant embodiment, curved electrodes 14 and 16 are cylindrical segments produced by resection of an angular arc from two coaxial cylinders and positioned such that the cylindrical axis is parallel to the plane of analyzer 10. The median of gap 18 is substantially coincident with the median of the gap between planar electrodes of analyzer 10 at the point of closest proximity between curved electrodes 14 and 16 and electrodes of analyzer 10. In the instant embodiment, apparatus 100 focuses ion beam 20 over the angular span of 90 degrees as measured from the drift vector in DMS analyzer 10, but is not limited. In other embodiments, curved electrodes 14 and 16 may provide an angular span of from about 0 degrees to about 270 degrees and more particularly from about 30 degrees to about 180 degrees. No limitations are thus intended.

[0035] Ionization sources suitable for use in conjunction with the invention include, but are not limited to, electrospray (ESI), thermospray, sonic spray, desorption ESI (DESI), matrix-assisted laser desorption ionization (MALDI) and atmospheric pressure MALDI (AP-MALDI), surface-enhanced laser desorption ionization (SELDI), chemical ionization (CI) and atmospheric pressure CI (APCI), photoionization and atmospheric pressure photoionization (APPI), laser vaporization or desorption, secondary ion ionization, arc discharge, inductively coupled plasma (ICP), coronary or cathode discharge, electron impact (EI), liquid evaporation, liquid clustering, “pick-up”, and combinations thereof.

[0036] The invention may also be used to interface DMS analyzers operating on principles other than FAIMS, including, but not limited to, ion mobility spectrometers with alignment of the dipole direction (IMS-ADD) and higher-order differential ion mobility spectrometers (HODIMS). The invention may be used with MS systems including, e.g., quadrupole, quadrupole ion trap, Orbitrap, Fourier transform ion cyclotron resonance (FTICR), time-of-flight (TOF), magnetic sector, and combinations thereof without limitation.

[0037] Asymmetric waveforms for focusing ions include, e.g., clipped-sinusoidal, bisinusoidal, square, and their derivatives and superpositions. The exemplary embodiment employs a bisinusoidal $U_D(t)$ described by Shvartsburg et al. (*Anal. Chem.* 2006, 78, 3706) incorporated herein, but is not limited thereto. In the exemplary embodiment, the $U_D(t)$ with frequency of $w_e = 750$ kHz is produced by a power supply that adds 750 kHz and 1500 kHz harmonics (with 2:1 amplitude ratio) output by a standard resonating LC circuit known in the art.

[0038] FIG. 2 illustrates a cross-section of a “hooked” DMS apparatus 200, according to another embodiment of the invention. In the instant embodiment, apparatus 200 includes a planar DMS analyzer 10 integrated with two “hooked” elements 12, each comprising two curved electrodes 14 and 16 with gap 18 therebetween. The first “hooked” element 12 receives ion beam 20 from an ion source or preceding stage 22 through aperture 24. As shown in FIG. 2, position of ion source or preceding stage 22 is not limited and, in particular,