the incoming ions. A 1-in. diameter has sufficed for ions expanding from as al inlet at the front end of MS or IMS stages. The funnels at DTIMS termini may need a larger opening, depending on the tube length, drift voltage, and gas temperature that control the ion expansion in the tube, and a 2-in. diameter has been used with longer tubes.

The base funnel implementation transmits incoming ions without significant delay, which is suitable for coupling to MS and has been broadly adopted to interface ESI, conventional IMS, and FAIMS units to various MS systems. However, DTIMS accepts ions in pulses and thus strongly benefits from ion accumulation before the starting gate. This need has been addressed using "hourglass" ion funnel traps (IFT) that comprise sections where apertures broaden along the direction of ion travel (FIG. **2***b*), providing the ion storage volume at a reduced pressure equal, or close, to that in the following chamber. on packets injected into the tube may be refocused (e.g., for better IMS resolving power) employing a "double hourglass" IFT that comprises another section of narrowing apertures (FIG. **2***c*). Such funnels are equally appropriate with DTIMS in the multiplexed mode and can work with any stage requiring pulsed ion introduction.

Non-accumulating funnels can transmit close to 100% of ions, at least at not-too-high flux where Coulomb repulsion is limited. "Hourglass" IFTs also have high ion utilization efficiency until the charge capacity is reached. For API/MS interfaces, the transmission through the inlet is roughly determined by the ratio of its cross-section (c) at the conductance limit to the area of incoming plum. However, at a given pumping capacity on the funnel, the pressure inside (P) is determined by the gas load that is proportional to c. Thus, the maximum feasible c depends on the highest usable P value. The performance and practicality of DTIMS also improves at higher pressure: in particular, the tube can be shortened without resolution loss. Again, the maximum pressure in DTIMS with front and/or back funnel interfaces is set by their limitations. The FAIMS resolving power also benefits from higher gas pressure (other factors being equal). Hence maximizing the operating pressure of ion funnels, ideally to 1 atm, is a key technological goal in the MS and IMS/MS field.

Physics of the ion focusing in Dehmelt potential requires a certain ratio of w to the ion-molecule collision frequency that depends on the ion species but is always proportional to pressure, hence w should be scaled with P. At a given gas temperature, effective focusing further requires a minimum potential depth that, by theory, scales as A^2/w^2. Therefore, raising the operating pressure also necessitates a proportional increase of A. An ion funnel is a capacitive bad and the power needed to drive it is proportional to electrical capacitance (c). Hence the realizable w and A values are limited by c, which thus should be minimized. First-generation funnels (with g=0.5 mm) developed in 1997-2002 had large capacitances that, with practical power supplies, limited w to ~400 kHz and U to ~40 V. These parameters allowed P up to ~5 Torr depending on the species, which was close to the values in first stages of MS instruments with skimmer interfaces. Thus API/MS inlets were restricted to c~0.3 mm^2, resulting in large ion losses at the inlet faces and materially constraining the capabilities and utility of IMS/MS platforms. These devices still transmit ions an order of magnitude better than prior skimmer interfaces, and are now adopted in research and commercial MS systems as well as IMS/MS and FAIMS/MS platforms.

In 2^{nd}-generation funnels developed since 2004, the capacitance was reduced 4-fold via a change of geometry and machining/assembly methods that minimized electrode surfaces and replaced the insulation between electrodes by air gaps with the lowest possible dielectric constant of 1. That has enabled a proportionally greater w~2 MHz and U~200 V, permitting similar increases of P to ~30 Torr and c to ~2 mm^2 and higher, depending on the vacuum pumps and inlet capillary length. A single capillary with that large c would not desolvate ions completely and uniformly enough, but multiple (e.g., six) capillaries of regular diameter summing to c may be parallelized to reach high total flow while keeping the established desolvation regime. Large ion capture area and current capacity of such multicapillary inlets are of particular value with ESI emitter arrays. A higher pressure in the funnel similarly elevates that in the following MS chamber, increasing which by 5 times is generally untenable. Hence a high-pressure funnel was coupled to MS using an original (low-pressure) funnel. Such multicapillary inlet/tandem ion funnel interfaces (FIG. **2***d*) have improved the sensitivity of API/MS by ~5 times compared to "standard" funnels, in proportion to the increase of P and gas intake via the inlet. However, losses are still large and further increase of the operating pressure and gas intake is desired. However, w and A could not be raised further within the existing paradigm of funnel assembly from individually machined macroscopic electrodes.

The field intensity in a gas is limited by the electrical breakdown threshold, which depends on the gas identity and pressure. While the rf voltages and thus A values in existing funnels can be raised using more powerful power supplies, a breakdown near the waveform peak would occur. Hence an approach to increase the funnel pressure by raising w and A must include the means to avoid breakdown.

An approach alternative to raising the funnel pressure is ESI in a sealed chamber at sub-ambient pressure. Such "SPIN" sources have been shown to work at a pressure as low as ~30 Torr, allowing operation inside high-pressure funnels. While this virtually eliminates ion losses, the lower efficiency of ESI at 30 Torr offsets that, and the final ion yield is close to that using atmospheric-pressure ESI with multicapillary inlet/tandem ion funnel interface. Even if future ESI sources could hypothetically overcome that problem, the need for better ion focusing in IMS/MS and FAIMS/MS interlaces would remain and so would the need to increase the operating pressure of ion funnels, ideally to 1 atm.

The force of mutual Coulomb repulsion scales as the ion density squared and thus rapidly grows for stronger ion currents. The resulting space-charge expansions limit the resolving power of MS [in particular, orthogonal time-of-flight (o-ToF) MS] or IMS systems and their sensitivity, as ions exceeding the analyzer charge capacity are eliminated. Large ion flux gains provided by funnel interlaces known in the art already cause notable peak broadening in DTIMS, which would worsen as funnels at higher pressures deliver even greater ion currents. Hence reducing the space-charge effects is important for MS and IMS technology development and becomes increasingly topical as improvements of ion sources and front interfaces produce more intense ion beams.

SUMMARY OF THE INVENTION

The invention includes electrodynamic ion funnels (the devices that focus ions in gases using RF electric fields) operating at much higher pressures than previous ion funnels, and planar ion beam analyzers involving same. To enable the high-pressure operation, these devices are built with much smaller features using the MEMS platform and technology and, in a particular implementation, having the "wedge" geometry. The device includes a plurality of electrodes with gaps therebetween, which carry an oscillatory electric field created by alternating voltages to produce a Dehmelt potential. The field intensity required for effective focusing at high