INSTRUCTIONS
Mass spectrometry is an analytical method widely used by chemists and biologists to determine the presence or the abundance of specific molecules and proteins in a sample. Capability to detect very low concentrations of a molecule is often critical in applications such as finding cancer biomarkers in blood samples. To identify molecules in a mass spectrometer, they must be ionized and put into a gas phase. Electrospray ionization [1] has gained prominence over the last decade and is the method of choice to produce multiply charged analyte ions. Although the electrohydrodynamic process responsible for producing individual gas phase ionized molecule from a charged droplet is not fully understood, it is estimated that less than 1% of the gas phase ions that have been created will be successfully captured by the mass spectrometer.

This inefficiency is due to the coulombic repulsive force scattering the ions of same polarity away from each other. The air amplifier shown on Figure 1 can refocus the scattered ions and increase the abundance of the captured ions [3-6]. However, very little is known about the effect of the geometry of the amplifier on its performance. A multidisciplinary effort to design, fabricate and test a precision engineered, diamond turned air amplifier with a piezo-actuator to control the annular gap.

DESIGN
Proof of concept showing signal improvement using an air amplifier has been made using a crude commercial device. It was found that imprecise gap control and misalignment were impacting the performance and repeatability of the results. With the collaboration of NCSU's Aerospace Engineering CFD Laboratory, a suitable aerodynamic profile has been established. The air amplifier relies on the Venturi and the Coanda effects to focus the scattering ions. The Coanda effect describes the formation of a thin boundary layer of fluid along a curved surface. The Venturi effect is based on Bernoulli's Principle where a reduced pressure region is created from the conversion of a high pressure gas (in this case) to a high velocity jet. The velocity profile plot presented in Figure 2 illustrates this phenomenon and provides more details on the geometry of the proposed device. According to the CFD model, the ideal annular gap was in the range of 50-70 µm and to ensure a uniform and radially symmetrical flow, the annular gap faces had to be parallel to < 1 µm. The finish of the Coanda surfaces had to be smooth and radially symmetric. Because the optimal annular gap was to be set experimentally, the gap is controlled with three D1CM20 piezoelectric actuators.
actuators from Kinetic Ceramics. Preload of the actuators is done using Belleville washers. Preload is sufficient to keep the piezo-stacks in compression plenum is pressurized at 45 psi (max operating pressure).

FIGURE 2. Enlarged section view of the Coanda profile and the annular gap region of the air amplifier. Coanda effect is the tendency of a fluid to stay attached to a smooth surface. Velocity profile plot from CFD models shows the pressurized (N₂) from the plenum accelerate as it decompresses and remains attached to the Coanda profile.

The top and bottom inserts were designed to be interchangeable items so that other profiles can be tested without fabricating an completely new device. The air amplifier was fabricated in aluminum 6061-T6, selected for its machinability and resistance to chemical corrosion (ESI involves organic solvent solutions). A section view of the device is presented on figure 3.

FABRICATION
The components for the air amplifier were rough machined at a local CNC shop. The geometric and dimensional tolerances for the rough part machining were designed to ensure that enough material would remain to perform final diamond turning for dimensional accuracy and surface finish. This final machining was performed at the PEC using a precision lathe (ASG 2500 from Rank Pneumo) and a single crystal diamond tool. The in-house controller of the diamond turning machine has a resolution of the tool position on the order of 0.01µm.

To create uniform flow around the air amplifier, the mating surfaces have to be parallel and concentric and the variation in the assembled gap has to be small compared to the desired 50-70 µm value. To machine a specific diameter, the location of the tool edge must be known with respect to the rotational center of the spindle. To get a specific length, the tool edge must be known with respect to some fiducial surface. Efforts were made to determine the tool location using tool centering techniques developed at the PEC [2] and in conjunction with the slide encoder, the OD and ID of parts could be produced to high fidelity. To ensure the desired gap, the OD was machined first and 1 µm steps were removed on the ID until parts could be assembled, guaranteeing a maximum misalignment of 1 µm for both the top and bottom insert.

The annular gap between the top and bottom of the plenum cannot be measured directly because it is not accessible once the parts are assembled. Indirect measurements were performed to set the nominal gap to 50 µm. For the axial machining, all parts were machined to their nominal dimension except for the top insert mating face. Parallelism between faces and flatness of each part were measured with a Gage 2000 Coordinate Measurement Machine (CMM) from Brown & Sharpe and maintained below 3 µm.

FIGURE 3. Section view of the air amplifier. Annular gap can be changed from 50 µm to 70 µm using three piezo-actuators.

FIGURE 4. Indirect measurements performed with CMM to adjust parallelism. Left : distance between plane and point above pzt (see Table 1). Right : Plane-Plane parallelism and distance.
TABLE 1. Perpendicular distance between plane and point above PZT as shown on Figure 4.

<table>
<thead>
<tr>
<th>PZT</th>
<th>Before Correction</th>
<th>Shim Used</th>
<th>After Correction</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>26.333</td>
<td>1</td>
<td>26.352</td>
</tr>
<tr>
<td>B</td>
<td>26.332</td>
<td>2</td>
<td>26.350</td>
</tr>
<tr>
<td>C</td>
<td>26.348</td>
<td>0</td>
<td>26.351</td>
</tr>
</tbody>
</table>

All parts were assembled except for the top insert. Parallelism between mating face of the top insert and the annular gap bottom face was then adjusted. Because height of the PZT stacks are part of the measurement chain defining the annular width and that this dimension can vary by more than 10 µm, 13 µm (0.0005 in) SS shims are used on top of PZT to correct the resulting parallelism error between the two faces. These critical measurements are presented in Figure 4 and results before and after shimming are presented in Table 1. In Figure 5 is presented the relation between the voltage applied to the PZT stacks and the plane-plane distance. After level correction, an out of parallelism of 2 µm at top insert bolting radius will result in an out of parallelism of 0.5 µm between the two annular gap faces, which satisfies the design criteria of 1 µm established earlier.

RESULTS

When pressurized, the air amplifier successfully created a Venturi effect and static pressure has been measured along the flow axis for different pressure and annular gap position using a pitot tube. From Bernoulli’s relation for an adiabatic gas, the the pressure drops as the velocity of the fluid is increased. The maximum vacuum pressure was measured 1 mm downstream of the annular gap, revealing the existence and location of a focal point. Moreover, increasing the annular gap width had the same effect on the flow profile as increasing the plenum pressure.

Stagnation pressure measured at the outlet of the air amplifier using an open ended pitot tube was used to compare the flow profile along the radial line and evaluate its symmetry. A clear improvement in the symmetry of the radial has been obtained with the precision engineered air amplifier when compared to the commercial device in Figure 6.

A second iteration of the air amplifier has been designed and fabricated. Although the outlet cone of the device is shorter to allow a more compact design, the Coanda geometry and the aerodynamic profiles are exactly the same. This iteration does not have piezoelectric actuators and has a fixed gap of 50 µm. Analysis of static pressure profiles demonstrated that reproducible results could be obtained and therefore fabrication procedure allow the production of identical devices (result not included).

Several mass spectrometry experiments were performed to evaluate the effect of the air amplifier on the signal abundance. The mass spectrometer signal obtained without any air amplifier was compared to the signal obtained with the air amplifier. To systematically explore the experimental space defined by the many variables that can affect the performance of the air amplifier (position, plenum pressure, annular gap width, solvent composition, ESI voltage, etc), fractional factorial design was used to find the significance of each. The results showed that signal improvement could not be obtained under all condition but were significant at higher solvent flow rates and larger ESI capillary tips (up to 34 folds of improvement in this case [7]). Mass spectrometry tests to be performed with 2nd iteration of the device will serve to better explore this specific zone of the experimental space.
CONCLUSION
Tests performed on the air amplifiers showed that the design and fabrication of a high precision air amplifier with adjustable annular gap has been successfully achieved. Air flow measurements correlated with the CFD model and it was demonstrated that radial symmetry had been improved significantly leading to more precise focusing capability. Although experiments on mass spectrometry instrument have shown improvements under specific operating conditions, a better understanding of the effect of air amplifier on the mass spectrometer is now possible since a improved control on the device quality has been achieved.

REFERENCES