Introduction
Vacuum-based processes exhibit decreased performance in the presence of adventitious hydrocarbons that are volatile from various sources, such as oils and solvents, as well as chamber and sample surfaces [1]. For example, in electron microscopy the presence of hydrocarbons (HC) gives rise to unwanted effects such as image blur, "black square," and "black frame" formation during lengthy beam exposure times (2). These and related issues have directed the need for RF-driven plasmas to decontaminate vacuum chambers via generation of metastable state species (typically oxygen radicals) that gently remove contamination via gentile chemical reaction.

The oxygen radicals created in the plasma oxidize carbon compounds, producing CO, CO₂, and H₂O, which are evaporated from the instrument. Quantum chemistry rules regarding energy loss state that these oxygen radicals do not react with diatomic molecules in two body collisions but require a third body to kinetically carry away excess energy. Oxygen radicals also react on solid surfaces such as metals where they can react or recombine with hydrocarbons. Numerous studies performed at XEI Scientific using pre-contaminated quartz crystal microbalances (QCM) to measure cleaning rates have shown that the Evactron is very effective at removing hydrocarbons [3,4]. Faster decontamination rates were documented in SEMs and FIBs equipped with turbo molecular pumps.

The current generation of Evactron plasma cleaners includes models such as the EP (Fig. 1) and the new Evactron E50 (Fig. 2). The EP model is designed for high efficiency cleaning with reduced cost by simplification of both hardware and software. The compact design of the EP model in the Evactron product line makes it a versatile solution for either SEM/FIB chambers, load locks, or sample handling chambers.

The new Evactron E50 model uses new external hollow cathode technology. The electrode is wrapped around the outside of a Marcor Ceramic plasma chamber (Patent pending) helping maintain high electron density of the plasma by secondary electron emission. It gives faster cleaning efficiency at higher operation power.

Materials and Methods
To demonstrate the effect of Evactron Turbo Plasma Cleaning on pump down time and HC contamination removal, a study was done using two models of Evactron plasma cleaners:

1. An EP model Evactron Plasma De-Contaminator was placed on a large, highly oil-contaminated 50 L vacuum chamber equipped with a 450 L/sec turbo molecular pump, 14 CFM scroll pump. The chamber was equipped with a QCM at 25 cm from mounting nipple.

2. An E50 model of Evactron De-Contaminator was mounted on a 22 L vacuum chamber to measure cleaning rates as a function of distance from the plasma source for the data in Figure 12. For both systems, cleaning rates were measured by means of QCMs placed 25cm and 70 cm from the mounting nipple with the plasma radical source operating at 20-50 Watts.

Results and Discussion

With Evactron plasma cleaning technology, short cleaning times of 5 minutes or less are often sufficient to remove all hydrocarbon contaminants as shown in this before and after image pair (Fig. 5 and 6).

The length of pump down time varies depending on HC contamination levels in SEMs and FIBs. Therefore the pump down time could be used as an indicator of the cleanliness of the vacuum system. The data in Figures 10 and 11 shows that Evactron plasma cleaning can significantly reduce both the pump down time of pump pressures to 1.00E-03 Torr and HC peaks as well as HC contamination, thus increasing sample processing throughput without compromising the quality of analysis. Figure 12 demonstrates that efficient HC decontamination rates of hundreds of Angstroms/minute are achieved at normal SEM/FIB working distances.

Conclusions
As the need for higher quality data and higher throughput of samples in Scanning Electron Microscopes (SEMs) and Focused Ion Beam (FIB) systems continues, so does the necessity for fast pump down times between samples. Industry demands SEM/FIB systems to be operational 24/7 and ideally maintained in pristine condition with uncompromised image quality. Frequent venting and cleaning of the vacuum chamber is required to remove and contaminate into the vacuum chamber, leading to much longer pump down times and decreased efficiency. Evactron plasma cleaning removes this contamination easily. Samples can be imaged more quickly in a clean environment, and if contamination is found, it can be quickly removed, the SEM pumped back to operating pressure quickly and, with only minutes of cleaning delay, imaging and analysis resumed. This results in higher productivity.

The new Evactron® Turbo Plasma™ De-Contaminators remove hydrocarbon (HC) contamination from SEMs, FIBs and other analytical tools using a gentle, low pressure plasma afterflow process. At turbo pump pressures, Evactron plasma cleaning becomes faster and more efficient than previously used methods. This does not happen without a desire to move to lower mean-free-paths that cause less recombination of oxygen radicals in the required three body collisions and decreased scattering to chamber walls. Most cases, short plasma cleaning cycles are sufficient to remove contamination and significantly shorten pump down time, allowing for high throughput for sample processing and analysis.

The Evactron® Turbo Plasma™ De-Contaminators family of plasma cleaners offer fast, effective, and powerful cleaning over a wide range of pressures enabling high quality, artifact-free images and increased efficiency of sample analysis. The Fastest Way to Plasma is a slogan that translates into the fastest productivity for your laboratory.

Summary
Vacuum chambers can be cleaned to maintain pristine conditions with the Evactron® Turbo Plasma™ De-Contaminators at 10⁻² to 10⁻⁴ Torr. Typical cleaning times are 2 - 10 minutes. SEM/FIBs return to normal operating pressures in less than 20 minutes. Current users of Evactron Turbo Plasma Cleaner™ report significant reduction in pump down times for SEMs/FIBs, which are also easier when the pristine state of their SEMs and FIBs. RGA scans show complete removal of hydrocarbons with less than 30 minutes of cleaning. The new Evactron E50 model delivers fast cleaning of larger SEM and FIB chambers, superior image quality with less waiting time for high vacuum and more efficient microscopy and microanalysis results.

Technology
The Evactron plasma cleaner is based on the RF hollow cathode excitation (RHCE) plasma technology uniquely available from XEI Scientific, Inc. Other plasma cleaner use excitation methods such as ICP (inductively coupled plasma) that use more power and create more heat for similar cleaning rates. RF creates more neutral radicals for chemical etching, and higher energetic ions that can cause spatter damage to the surfaces being cleaned.

The original Evactron plasma source used an internal plasma electrode that was designed to be used on chambers at pressures between 1 Torr and 200 mTorr obtained by roughing pumps. Lower pressures were avoided because of the then common oil diffusion pumps used to obtain high vacuum (down to 10⁻¹0 Torr). The conversion to turbo molecular pumps on new SEMs has made it possible to decrease plasma cleaning pressures to very high vacuum levels in the 10⁻² Torr range. At these low pressures there is a balance between input gas pressure and pump speed that yields plasma operating pressures in the 10⁻² to 10⁻¹ Torr range. In the new Evactron E50 model gas input down to 7 cm³/s creates a plasma with a chamber pressure in the 10⁻¹ Torr range, but with a loss of cleaning rate due to lower radical production (Fig. 3). In this pressure range there is a trade-off between low pressures from low flow and higher cleaning rates from more input gas flow.

The Evactron® Turbo Plasma™ Cleaning Reduction Time with Evactron® Turbo Plasma™ Cleaning.

The EP combination of higher power and lower pressures offers good cleaning rates throughout large vacuum chambers. Remote plasma cleaning can be performed on SEMs and FIBs at pressures below 25 mTorr (50 Pa) during direct pumping with a turbo molecular pump. Previous studies [5] showed that low chamber pressures increased the rate of cleaning and the distance at which cleaning was observed. Low pressure increase cleaning efficiency by increasing the mean free paths and reducing the recombination rates of the oxygen radicals by these body collisions. This result plus the new hollow cathode design allows more effective cleaning strategies for large instrument vacuum chambers at low operating pressures.

Ignition at low pressure also allows the plasma to be turned off after cleaning a short time (1-5 minutes), resulting in a quick return to base pressure with the turbo pump to remove reaction products, then restarted to repeat the cleaning cycle. While at base pressure any remaining hydrocarbons can degas and redissolve within the chamber due to long free path molecular flow. The redistributed products can be removed in the next plasma cycle. Cyclical plasma cleaning is shown to be a very effective way to achieve a pristine chamber using this new plasma cleaning technology. At high vacuum, typical turbo molecular pump input flows of 20 csc give good cleaning and do not over heat the pump.

References