A New End-Hall Ion Source with Improved Performance

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ABSTRACT

End-Hall ion sources have been used for almost 20 years in the optical coating industry for ion assisted deposition (IAD) and substrate pre-clean. In these applications, end-Hall ion sources have several desirable performance characteristics. They produce a large current of low energy ions, and they distribute the ions uniformly over a large coverage area. The sources can operate on either argon or oxygen, and maintenance requirements are typically lower than for gridded ion sources. The trends toward higher production volumes and reduced cost of ownership in the optical coatings industry require ion sources with higher output, modular integration, and more effective maintenance features. This paper presents a new end-Hall ion source that has improvements in performance, form factor, and required maintenance over the current industry-leading end-Hall ion source. Ion production rates, beam uniformity, and thermal characteristics are presented at discharge powers up to 3 kW.

INTRODUCTION

For the past few decades, end-Hall ion sources have been widely used in the industry for ion-assisted deposition, direct ion beam deposition and surface pre-cleaning operations [1]. The gridless ion source has been favored for many applications because of its relatively high ion flux density, wide spatial distribution, moderate beam energy levels (40-200 eV) and its ability to handle either inert or reactive gases when using a hollow-cathode electron source. However, as modern manufacturing processes scale to larger systems, higher rates, and larger substrate areas, it has become necessary to increase power capacity of the end-Hall ion sources, reduce form-factors and significantly improve their serviceability and maintenance requirements and, thereby, reduce cost of ownership.

Recently a new series of end-Hall ion sources has been developed (Veeco Instruments, Mark II+ Ion Source) that has a smaller form factor, enables a wider range of output ion beam capacity, and incorporates improved assembly features that greatly reduce maintenance time and cost of ownership. In this paper we review the operational and output performance of two types of the Mark II+ Ion Sources: (a) a low power series (1kW max.) that uses a hot-filament electron emitter that is either radiation or water-cooled, and (b) a high power version (3kW max.) that uses a hollow-cathode electron emitter and is water-cooled. The operating properties of these new end-Hall sources are presented alongside output properties of the Mark II predecessors to demonstrate increased output capacity and efficiency. Also, mechanical and performance features are presented to illustrate improved thermal management, reduced part count, ease of maintenance and increased mean-time-between-maintenance (MTBM).

End-Hall Ion Source Operation

Figure 1 illustrates the basic operation of an end-Hall source. These ion sources operate by providing a divergent DC magnetic field in front of an angular (e.g. conical or beveled) anode through which a working gas is introduced. An electron-emitting cathode, either a hot filament or hollow cathode electron source (HCES), is placed downstream of the ion source and a voltage is applied between anode and cathode to drive a plasma discharge. The cusp-shaped, divergent magnetic field impedes the mobility of electrons in the plasma as they drift to the anode, which in turn results in a spatially distributed plasma potential field that accelerates ions away from the source. The actual energy of any accelerated ion is predominantly dependent upon where the ion has been formed along the spatial potential field. Thus the collective energy distribution of the downstream ion beam is broadly spread with a mean energy that is typically about 60 to 70\% of the anode potential.

Figure 1: Principles of end-Hall ion source operation.
End-Hall ion sources require routine maintenance in surface cleaning and deposition assist processes. Specifically one must routinely replace electron emission components (filaments or cathode tips) and clean or recondition the anode and input gas distribution end-plate from wear or build-up of process deposition materials that diffuse back into the source’s anode assembly.

**IMPROVEMENTS IN THE MARK II+ END-HALL ION SOURCE ASSEMBLY**

The new Mark II+ series end-Hall sources have several features that enhance both serviceability and performance. As shown in Figure 2, a significant improvement has been made to the assembly of the source by consolidating all serviceable parts to one main removable subassembly. Specifically, the new design allows one to remove the front pole piece and anode assembly as a single composite assembly for both water-cooled and radiation-cooled options [2]. Because the anode sub-assembly is indirectly-cooled by a fixed water-cooled, input gas service partition plate, water cooling and gas feed lines need not be disrupted during scheduled preventative maintenance. This and other assembly changes have dramatically decreased the number of assembly parts related to routine service (from about 50 to about 10) and reduced the chance of hardware damage and galling. Given the new design, ion source parts and surfaces that need routine servicing can be swapped out during normal manufacturing preventative maintenance practice in about 3-5 min., a time that is considerably shorter than the typical 30-50 min. compared to the earlier Mark II source.

As shown in Figure 3, the new Mark II+ series ion source has a 30% height reduction over its predecessor. While making the source more compact, the critical magnetic field profile about the anode was optimized to improve source performance, and the thermal protection of the interior permanent magnet was enhanced to improve long term operating stability at high powers and temperatures.

**Table 1:** Mark II+ options that feature modular anode and gas distribution sub-assembly.

<table>
<thead>
<tr>
<th>New Mark II+ Option</th>
<th>Typical Operating Range</th>
<th>Veeco Source Controller</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low-Power, Radiation-Cooled w/ Wire-filament Electron Emitter</td>
<td>1-5A, 50-300V (900W Max)</td>
<td>Mark II+ Controller</td>
</tr>
<tr>
<td>Low-Power, Water-cooled, w/ Wire-filament Electron Emitter</td>
<td>1-5A, 100-300V (1.5kW Max)</td>
<td>Mark II+ Controller</td>
</tr>
<tr>
<td>High-Power, Water-cooled w/ Hollow Cathode Electron Source</td>
<td>1-15A, 50-300V (3kW Max)</td>
<td>Mark II+ HO or Mark III+ Controller</td>
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**ION SOURCE PERFORMANCE**

**Operating Current, Voltage and Flow Characteristics**

The preferred manner of operating end-Hall sources is to control the actual input power into the source through both voltage and current control. This is accomplished through the Mark II+ Controller when connected to the source’s input mass flow controller [3]. When the source is run in an automated mode, the mass flow controller is adjusted by the power supply to maintain the source’s plasma impedance and, thereby, maintain the user’s set points of anode voltage and current. As
an example, Figures 4 and 5 show typical operating trends for argon and oxygen for the water-cooled Mark II+ High Power option. Relatively high input gas flows are required for low voltage operation (<100V) while relatively low flows are required for high voltage (>100V) operation, the latter being desired for most ion beam assisted processes.

Figure 4: Source current, voltage and argon input flow characteristics for the Mark II+ (High Power option).

Figure 5: Source current, voltage and oxygen input flow characteristics for the Mark II+ (High Power Option).

The operating performance trend lines given in Figures 4-5 are typical for both the Mark II and Mark II+ sources. It should be noted that the Mark II+ sources operate at slightly higher flows (2-5 sccm) for a given operational power setting when compared to its Mark II predecessor. However, as will be discussed in later sections, these higher flows are more than offset by substantial increases in downstream ion beam current output.

**Ion Beam Current Measurements**

Detailed ion beam measurements were made to examine spatial ion beam current density, total ion beam current and ion energy to characterize and compare the old and new versions of the end-Hall source under reference conditions. Specifically, a Faraday cup was angularly rotated at a fixed radius of 30 cm from the front face of the source in a single plane to provide an angular ion beam current density profile, \( J_B(\theta) \). Since it was observed that \( J_B(\theta) \) was near zero for \( |\theta|>90^\circ \), \( J_B \) measurements were limited to an angle of +/-90° with respect to the source’s axis. Assuming azimuthal symmetry of the source’s output, total output ion beam currents (\( I_B \)) were approximated by numerically integrating \( J_B(\theta) \) over a hemisphere at R=30 cm.

Figure 6 shows ion beam current density profiles from a reference Mark II (MII) and the newly designed Mark II+ (MII+) source, both units having water cooling and rated for low power option with hot-filament electron emitter. The exemplary profiles were made in argon at 5 A for several anode voltage set points (100, 200 and 300V). Compared to the Mark II source, the Mark II+ has a significantly broader ion beam profile and higher output ion beam currents for a given input power setting. This is most noticeable at operating anode potentials above 100 V. [While not shown here, similar performance was obtained when operating with oxygen.]

Figure 6: Ion beam current density measurements, \( J_B(\theta) \), at various anode voltage set points for both Mark II (MII) and Mark II+ (MII+) sources at R = 30 cm in argon and with \( I_A = 5 \) A.

The typical increase in ion beam current output of the Mark II+ source is shown in Figure 7 for the case of argon with \( I_A = 5 \) A. In this case, the increase in total ion beam current ranges from about 20 to 70% over the working voltage range of the source. The dramatic increase could be explained in part by the fact that the Mark II+ source utilizes about 2-5 sccm more input gas than the Mark II for the same stable operating conditions. However, as also shown in Figure 7, the ratio of ion beam current to input gas indicates that the Mark II+ source is operating more efficiently in terms of input gas utilization. The improved ion current output is therefore more likely due to more efficient ionization resulting from optimization of the magnetic circuit assembly.
Examination of Ion Beam Flux Energy Distributions and Doubly Charged Ions

To make certain that the ions generated by the new source have similar characteristics, measurements of the source’s ion current energy distribution and production of doubly charged ions were also examined. Such properties may be important to practitioners looking to retrofit the new source into existing processes that are sensitive to changes in the spread in incident ion current energy. It should be noted that an excessive increase in doubly charged ions could account for the increase in total beam currents.

Ion beam current energy distributions were obtained in argon and oxygen with a commercial, multi-gridded ion energy analyzer (Baumville Ion Probe Set, Model 3m51.LPT) at an on-axis distance of 30 cm from the face of the source. The ion current energy distribution is typically defined as -dI_C/dV_R, where I_C is the collector current and V_R is the swept retarding potential of the collection probe. With this probe, normalized ion beam flux energy distributions were measured under reference conditions to determine if the output energy properties of the Mark II+ source ion beam have been significantly altered over the earlier Mark II version.

Figure 8 shows on-axis, normalized ion current energy distributions in argon at various power levels for three different water-cooled versions of the end-Hall source: one Mark II version and two Mark II+ versions using different electron emitters. In all cases the ion current energy distributions exhibit a “low energy” ion current (10-50 eV) and a “high energy” ion current that is centered about the anode set-point potential of 100 V. (The low energy ions mainly arise from ionization events that take place away from regions near the source anode and magnetic field where the accelerating space charge within the source’s plasma body is relatively low and from charge exchange processes in the ion beam.) Qualitatively, the high energy ion current features, which are most important to downstream processes, are very similar across old and new versions of the end-Hall source. There appear to be minor differences in the characteristics of low ion current energy features, however, the observed differences (particularly at about 20eV) are believed to be attributable to a electronic instrument error in the collector power supply or subtle changes in the positioning of the probe over the course of the experiments.

To further confirm that doubly-charged ions were not contributing to high current readings of the new source, an ExB-filtered ion collection probe [4] was used to filter ions with different charge-to-mass ratios under typical operating conditions. Measurements made with this diagnostic system on the new Mark II+ source indicated that the ratio of doubly-charged to singly-charged ions in argon was about 0.1 to 0.2 depending on power and operating conditions, a range that was very comparable with the original Mark II version when operated under the same conditions.

Taken together, the survey of ion current energy distribution and doubly-charged ions indicate that the design improvements incorporated into the Mark II+ end-Hall source have not shifted the intrinsic output properties of the ion beam. This is an important result for practitioners with established processes based on the Mark II source.
THERMAL PERFORMANCE

All plasma sources have limitations in converting electrical power into ionized species and accelerated ions. Typically 50 to 75% of the input power is lost as waste heat into heated gases and source components. As such, high material temperatures within the end-Hall source often limit high-power operation. Typically the anode and input gas distribution assembly see the largest power flux from the source’s plasma and must be actively cooled to enable high power (>900W) operation. Also, one of the most thermally sensitive components in the end-Hall ion source is the Alnico permanent magnet, which has a peak service temperature of about 500-550°C. While it is important to maintain a magnet temperature below about 500°C to avoid permanent damage, it is also beneficial to keep the magnet temperature as low as possible to avoid thermal drifts in the source’s performance since magnetic flux density reversibly decreases with magnet temperature (0.01-0.02 %/°C) [5].

Direct water-cooling of the anode had been included within an earlier version of the Mark II end-Hall source to enable high power operation. This particular approach can have several drawbacks when performing preventative maintenance, and it does not address thermal management of the input gas distribution assembly at the throat of the source. In contrast, the use of an indirect-cooled anode sub-assembly and input gas distribution components in the water-cooled Mark II+ end-Hall source moves the active cooling to a partition plate between the anode and magnet assemblies. As a result, the magnet and wearable input gas distribution components run at much lower overall temperatures. However, the convenience of an indirectly-cooled anode does lead to significantly higher anode temperatures when compared to direct cooling.

Thermal experiments were performed to explore the effectiveness of indirect anode cooling and determine peak, steady state ion source component temperatures of both low power and high power versions of the end-Hall sources. Temperatures of components at ground potential, the magnet and front pole plate, were surveyed with thermocouples while temperatures of electrically active or floating components, the anode and gas distributor plate, were surveyed with an infrared thermal imaging system (FLIR Systems P40 long-wave IR camera). Thermal camera images were obtained outside the vacuum chamber through an infrared-transparent view port and calibrated against the thermocouple readings of the front pole plate to account for the effects of view port transmissivity and material surface emissivity. [Note: Thermal camera images could not be obtained for source operating with the hot filament because of the filament’s strong radiative intensity.] Steady-state temperatures of surveyed components for radiation- and water-cooled version of the Mark II and Mark II+ source are compared in Figure 9 for reference operating conditions. Data for the radiation-cooled versions using a filament cathode (left) were made at 875 W (5 A, 175 V) in argon. Data for the water-cooled versions using a HCES (right) were made at 3000 W (15 A, 200 V) in oxygen.

The results indicate that the Mark II and Mark II+ reach similar temperatures although there is a noteworthy reduction in magnet temperature with the Mark II+ source. Note that the Mark II+ with indirect anode cooling has a cooler magnet, front plate, and gas distributor compared to the Mark II. Since Mark II+ magnet is 84°C cooler, it should provide more consistent operating characteristics and ion beam performance than the Mark II. Also the Mark II+ gas distributor runs 418 °C cooler than the Mark II, which is an important improvement since the material wear rate of the gas distributor plate from ion-bombardment is greatly accelerated at elevated temperatures. One compromise in the indirectly-cooled Mark II+ anode assembly is the fact that the anode operates 592 °C hotter than the Mark II anode, but since an end-Hall source anode does not experience significant erosion from ion bombardment, the elevated temperatures do not affect ion source maintenance.

CONCLUSION

A new series of end-Hall ion source has been developed with radiation and water-cooling features that allow for ease of assembly and a ten-fold reduction in assembly part count and maintenance time. The new source also has a 30% reduction in over-all height. Ion beam current and beam current energy of this new series of ion source were measured under a typical range of operating conditions. Total output beam currents were increased by as much as 20 to 70% (for only about a 10% increase in input gas flow) over its predecessor. The angular spread of the gridless ion beam and the source’s gas utilization were also significantly enhanced. These improvements were realized while maintaining fundamental output energy and charge-state properties of the ion beam. Thermal surveys
of the new source show very significant improvements in the water-cooled version of the instrument as required for high-power and high-rate applications. Specifically, steady state peak temperatures of magnet, front pole piece and input gas distribution components have been improved allowing for more stable operation and longer life-time of consumable components.

REFERENCES


