Low jitter metal vapor vacuum arc ion source for electron beam ion trap injections

Glenn E. Holland
SFA Inc., 2200 Defense Highway, Suite 405, Crofton, Maryland 21114

Craig N. Boyer
Praxis Inc., 2200 Mill Road, Alexandria, Virginia 22314

John F. Seely[a]
Naval Research Laboratory, Washington, DC 20375

J. N. Tan, J. M. Pomeroy, and J. D. Gillaspy
National Institute of Standards and Technology, Gaithersburg, Maryland 20899

(Received 22 February 2005; accepted 18 May 2005; published online 27 June 2005)

We describe a metal vapor vacuum arc (MeVVA) ion source containing eight different cathodes that are individually selectable via the control electronics which does not require moving components in vacuum. Inside the vacuum assembly, the arc plasma is produced by means of a 30 μs pulse (26 kV, 125 A) delivering 2.4 mC of charge to the cathode sample material. The trigger jitter is minimized (<200 ns) to improve the capture efficiency of the ions which are injected into an ion trap. During a single discharge, the over-damped pulse produces an ion flux of 8.4×10^9 ions/cm^2, measured by an unbiased Faraday cup positioned 20 cm from the extractor grid, at discharge rates up to 5 Hz. The electronic triggering of the discharge is via a fiber optic interface. We present the design, fabrication details, and performance of this MeVVA, recently installed on the National Institute of Standards and Technology electron beam ion trap (EBIT). [DOI: 10.1063/1.1948396]

I. INTRODUCTION

For many years, metal vapor vacuum arc (MeVVA) ion source systems have been used to produce beams of metal ions for injection into electron beam ion traps (EBIT),[1–3] particle accelerators, and for ion implantation applications. The previous MeVVA designs were based on the construction of a three wire system having one cathode, one anode, and one trigger wire all in close proximity in the vacuum arc head.[4] Some of these systems employed a low voltage (about 12 μF) capacitor which was charged to 200 VDC–500 VDC in permanent contact with the anode and cathode.[5] Triggering the discharge was accomplished via a third wire, which supplied a low current pulse of high voltage (10 kV to 30 kV), placed in vacuum near the anode and cathode of the MeVVA ion source head. There are two known limitations to this design in our experience: First, the arc jitter is large, 3 μs–6 μs. Second, the number of shots which can be obtained before a rebuild is relatively small, about 100 000 shots. The failure mode of the three wire design occurs when the cathode sample material sputters sufficiently to coat the insulator of the trigger pin causing an electrical short that renders the system to a nontriggerable state. Three wire, water cooled, multi-element (selected by moving parts within the vacuum enclosure) MeVVA systems have been previously built by other workers.[6–8]

[a]Author to whom correspondence should be addressed; electronic mail: john.seely@nrl.navy.mil

In this article, we describe the design and initial operation of a two wire MeVVA that has eight different cathodes which can be individually selected from the control panel without internal vacuum motion. The benefits of the two wire system are a compact multi-element MeVVA vacuum head having no moving parts in vacuum and no gas or fluid cooling. Bench tests demonstrated that greater than 7×10^5 shots per cathode sample are possible. These benefits are accomplished by storing the energy needed to form the arc in one high voltage capacitor. This high voltage capacitor is isolated from the cathode wire via a pressurized high voltage spark gap switch[9] making it possible for the sample cathode wire to also become the trigger wire inside the MeVVA vacuum head allowing low jitter (<200 ns) on the discharge of the arc. After the arc is formed inside the MeVVA head, the voltage drops to a few tens of volts across the cathode-anode gap. Thus the ions can be extracted from the meniscus of the arc plasma at the desired potential for injection into the EBIT.

II. MeVVA SYSTEM OVERVIEW

Figure 1 is an overview of the MeVVA system. The sequence for ion production is as follows: an optical pulse is received by the trigger generator which then triggers the pressurized spark gap switch. This switch rapidly conducts the charge through a damping resistor and 10 m of RG-8 coaxial cable, used as a high voltage cable, forming a high voltage pulse that arrives at the radio frequency (rf) tight enclosure at the MeVVA head assembly. This assembly has

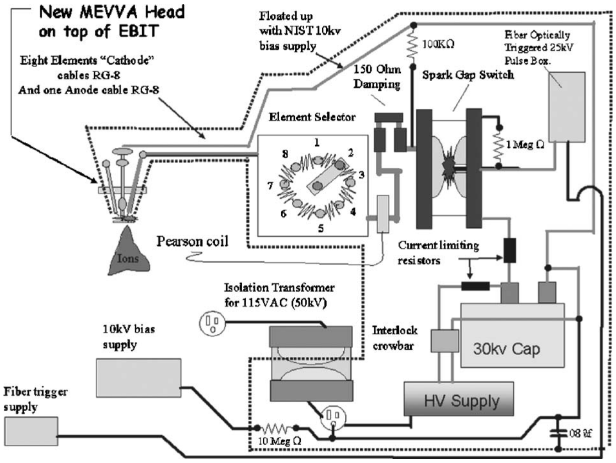

FIG. 1. MeVVA system overview.

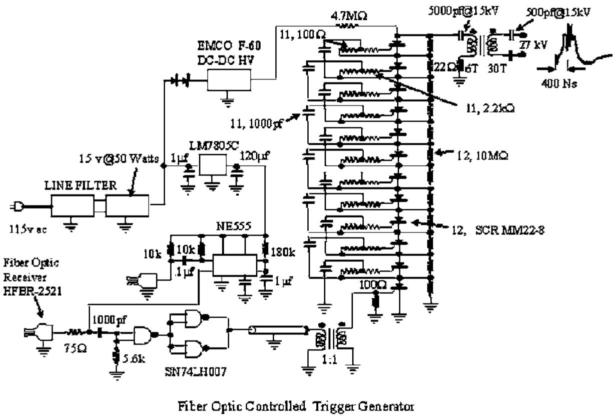

FIG. 3. Optically controlled trigger generator circuit.

two sections, an upper stage which is the rf-tight RG-8 cable interface and a lower section which houses the high voltage vacuum feedthrough flange. When the high voltage pulse reaches the tip of the cathode sample material in vacuum, it jumps a small gap to the anode which allows the arc discharge to occur. Both the cathode and anode grids are floated up to an applied bias voltage relative to the extractor grid which remains at chamber ground. Hence ions are extracted from the arc plasma and accelerated toward the EBIT system with a kinetic energy established by the bias voltage. We found that electrons were stopped at the extractor grid and that the extracted ions could be efficiently transported along an axial magnetic field downstream of the arc plasma.

III. MeVVA ELECTRONICS DESIGN

The electronics enclosure is built into a standard rack mounted system. Weighing approximately 45 kg, it supports all functions for the ion production except the extractor bias. Figure 2 is a photograph of the enclosure taken with the rf covers removed. The bias voltage was supplied from a pre-existing control station at the EBIT and was positive 10 kV. There are three sections inside the electronics control enclosure: (1) The power management and interlocks, (2) The fiber optic trigger command, and (3) The pulsed power, high voltage switch and damping section. The electronics enclosure is powered by 120 VAC, 20 A mains input. The enclosures for both the MeVVA rf head assembly and the control electronics have interlocks which will shut down the pulsed power section and command a high voltage relay[10] to crowbar the energy stored in the capacitor, as a safety precaution, if the rf covers are removed. A 1 kW isolation transformer[11] rated at 50 kV was used inside the enclosure to allow the pulsed power section to float at the supplied bias level. The pulsed power section contains a negative 40 kV, 15 mA dc high voltage supply[12] which is used to charge a 0.09 μF high voltage capacitor[13] rated at 40 kV. A fiber optically controlled trigger generator was constructed to reliably trigger the spark gap switch with very low jitter. The generator circuit is shown in Fig. 3. This trigger generator delivers a 27 kV pulse with 400 ns duration to the spark gap switch trigger electrode. The spark gap switch triggers within a few tens of ns after receiving the pulse and rapidly conducts the energy from the high voltage capacitor. The energy pulse is over damped with six 1 kW, 100 Ω wire-wound resistors which form a series resistor of 150 Ω. This allows 2.4 mC of charge to be delivered to the cathode sample in the MeVVA head.

FIG. 2. Photograph of the rack mounted control electronics with the side rf covers removed.

A Pearson coil[14] was used to monitor the discharge current, typically 125 A, which decayed exponentially over a period of 50 μs as shown in Fig. 4(a). A rotary selector switch was constructed to allow one of the eight cathodes to be selected for arc discharge. All the cathodes were biased simultaneously via a ladder of 10 MΩ resistors connected to the output of the rotary switch system. Nine separate RG-8 coaxial cables are used to carry the energy pulse from the electronics enclosure directly to the MeVVA head. The outside braid of the coaxial cable is sufficient for good rf shielding, and the internal polyethylene insulation for the center conductor functions well below 50 kV. One coaxial cable is the common anode and the other eight connect to the different cathode sample materials. The rotary selector switch is manually actuated from the outside of the control electronics via a knob which is connected to the switch by means of a

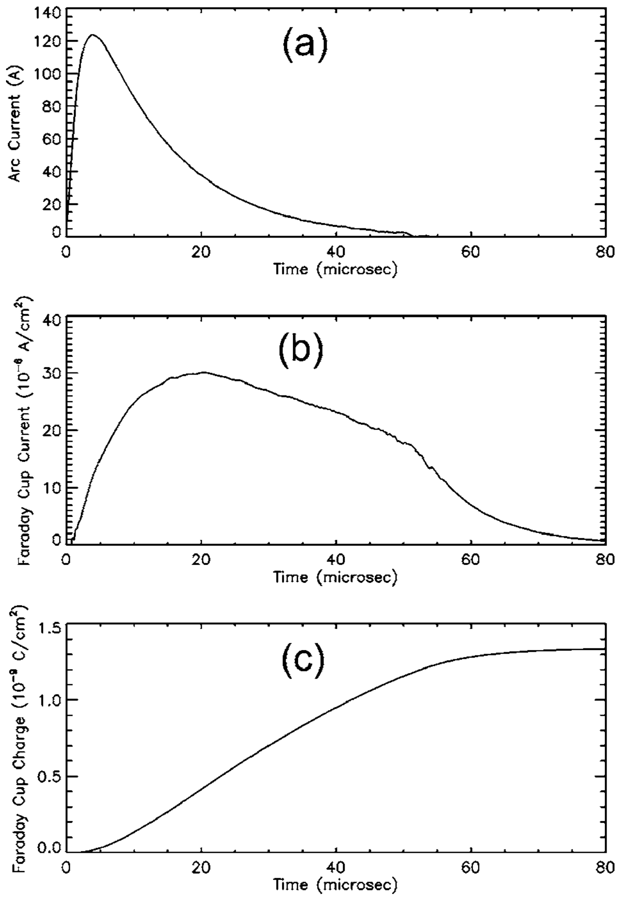

FIG. 4. Oscilloscope traces obtained during the bench tests of the MeVVA system. (a) The arc current recorded by the Pearson coil. (b) The current recorded by the unbiased Faraday cup. (c) The integral of the unbiased Faraday cup current representing the accumulated charge detected. The total charge is equivalent to 8.4×10^{9} ions/cm^{2} assuming singly charged ions.

high voltage insulated rod. The high voltage pulse then travels 10 m down the selected cathode sample's RG-8 coaxial cable to the rf-tight enclosure of the MeVVA head assembly.

The MeVVA system was tested at the Naval Research Laboratory (NRL), prior to installation on the EBIT at the National Institute of Standards and Technology (NIST), for more than a million discharges at various voltages and trigger rates. The standard conditions were 26 kV at 1 Hz. Discharge rates as high as 5 Hz were attained, and charging voltages up to 32 kV were tested. The electronics enclosure was designed to allow the bias of 10 kV to be achieved, and it was tested up to 12 kV. The system design has no inherent limit on the desired bias level. The present system can be biased up to 15 kV before changes in the bias supply connector on the rear of the control electronics would be needed. It should be noted that the damping circuit requires sufficient air flow to prevent heat damage to the resistors.

Since the control electronics reside inside a preexisting screen room near the EBIT facility, a discharge indicator was built onto the top of the MeVVA head rf enclosure. The triggering of the discharge indictor was accomplished by teeing the output of the Pearson coil which was then connected to a high impedance input of a pulse-forming circuit. This circuit also triggered two digital counters on the front panel of the control electronics used to record total system shots

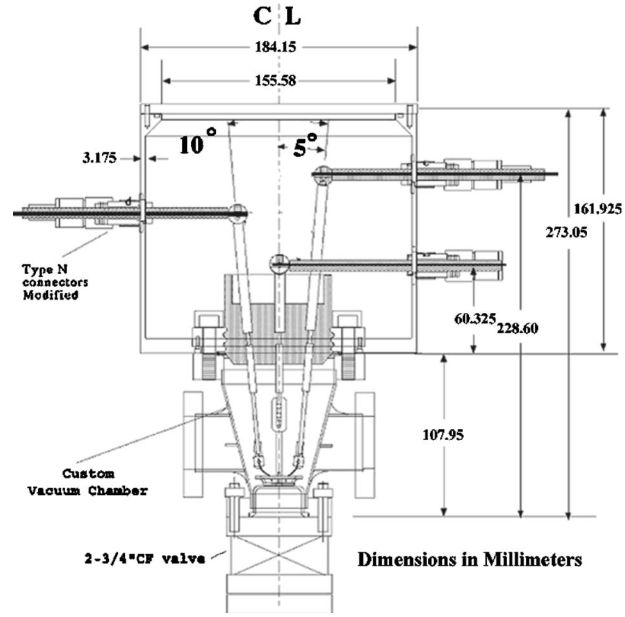

FIG. 5. Overview of the MeVVA head and rf enclosure. Dimensions in millimeters.

and shots on selected cathode materials. The other side of the Pearson coil output was attenuated by a 20× inline coaxial module so that the signal could be monitored by an oscilloscope which was on scale at 1 V=100 A with a 1 MΩ input.

IV. MeVVA HEAD DESIGN

Details of the custom designed and fabricated MeVVA head assembly are shown in Figs. 5–7. The high voltage vacuum feedthrough is a modified 4.5 in. Conflat flange in which nine type 316 stainless steel 2.387-mm-diam cathode support rods, with integrated alumina tube support insulators, are potted with a low outgassing epoxy rated at 600 V per 0.025 mm. The conductors are arranged with the center one as the common anode and the surrounding eight as the individually selectable cathodes. This high voltage flange assembly supports the eight cathode samples, anode insulator, anode grid, and the rf-tight coaxial cable enclosure which resides above the vacuum interface. The completed high voltage MeVVA head flange was helium leak tested at $<5\times10^{-8}$cm^{3}/s and was pumped to 4×10^{-8} Torr via a 20 l/s ion pump. This system was not baked because the pressure was sufficiently low and to avoid needless risk to the epoxy potting.

The cathode sample wires can be pure or alloy conductive metals 1–2 mm in diameter. The following pure elements have been tested as cathodes: Ti, V, Fe, Ni, Cu, Y, Mo, Sn, Ag and W. In principle, any desired metal can be used as a cathode in this system. The gap between the anode and cathode is 0.5 mm. The discharge is aided by a quartz insulator which is held in good physical contact with the cathode sample material and the anode grid. The anode insulator was fabricated from GE214 fused silica (quartz) rod, as shown in Fig. 7, to allow a sliding spark discharge between the cathode and anode and also to act as a shield to mitigate cross contamination of the cathode samples. A support rod is used to affix the anode grid to the center conductor on the potted

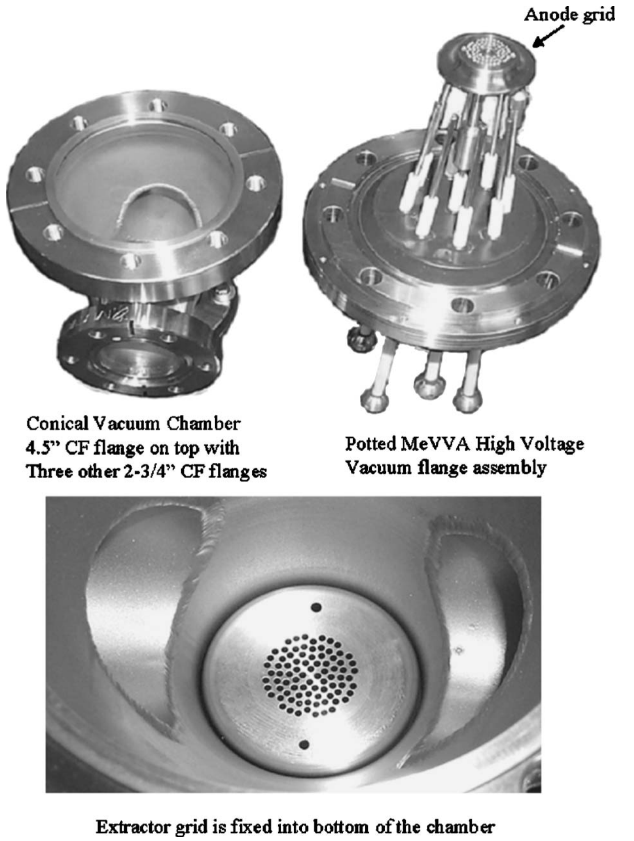

FIG. 6. Photographs of the MeVVA head (top) and the extractor grid (bottom).

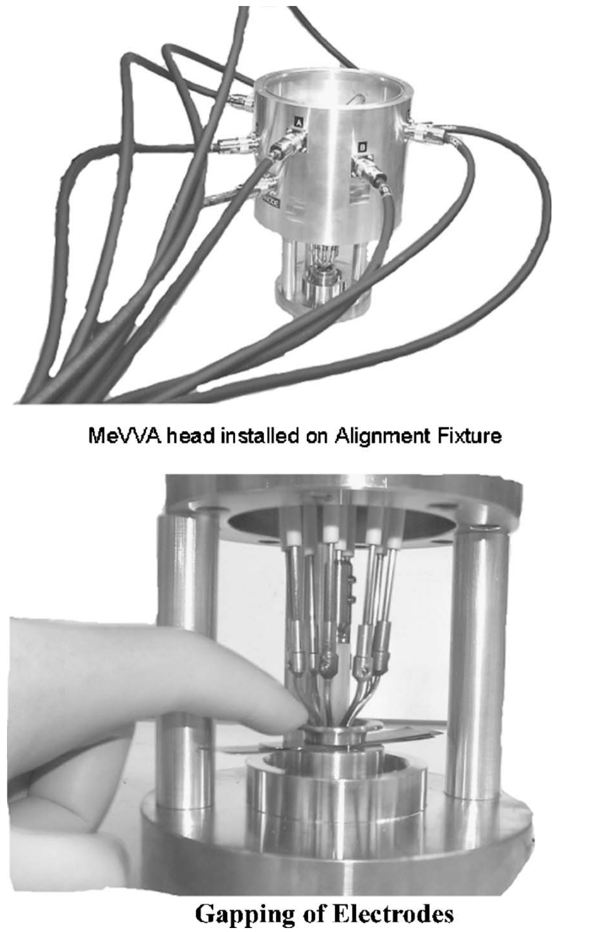

FIG. 8. Photographs of the MeVVA head attached to the alignment fixture.

vacuum flange. This support rod allows adjustment so the correct anode-cathode gap can be achieved. The outside diameter of the anode grid plate is 31.75 mm and is dished in the center where the cathode sample wires reside. A total of 72 holes, each 1 mm in diameter, are arranged in concentric patterns with the smallest being a 6.35-mm-diam circle having eight holes. This design allows the entire anode-cathode assembly to be field graded by the anode grid plate. The opposing surfaces of the anode and extractor grid plates are polished to a mirror finish. The extractor grid plate has the same hole size and pattern as the anode grid and is positioned with the holes co-aligned during operation. The extractor grid, anode support rod, and grid plate were all fabricated from 303 stainless steel. Alignment and proper gapping of the MeVVA head's electrodes were accomplished by means of a fixture shown in Fig. 8. This fixture was adjusted to exactly match the vacuum chamber dimensions, including the correct depth and rotation of the extractor grid. The extractor grid was clamped in electrical contact with the base of the vacuum chamber. This allowed the MeVVA head alignment of the cathode samples and the anode grid to be accomplished outside the vacuum chamber in a straightforward manner. The assembled MeVVA head, weighing about 5.5 kg, was then easily installed directly into the vacuum chamber as one unit with no blind connections. The assembled electrode spacing is shown in Fig. 9.

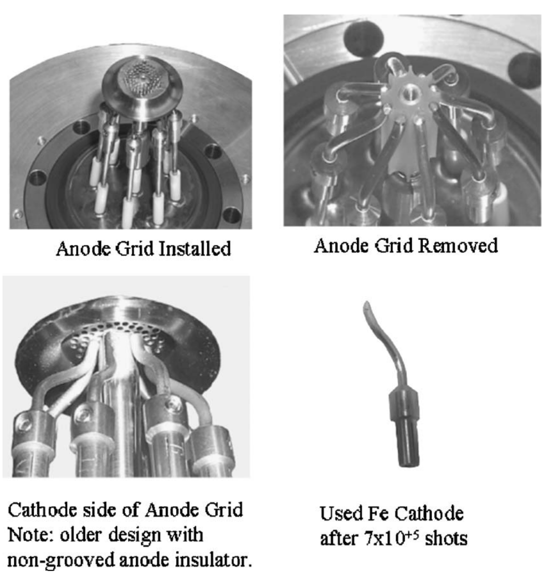

FIG. 7. Photographs of the MeVVA anode grid, anode insulator, and cathode samples.

V. ION PRODUCTION

A bench test setup, shown in Fig. 9, was fabricated to allow vacuum tests and ion production measurements to be performed on the new MeVVA head. The system was constructed from standard Conflat vacuum hardware and contained an unbiased Faraday cup which could be moved via a linear feedthrough to vary the distance from the MeVVA arc plasma. The arc discharge could also be observed through

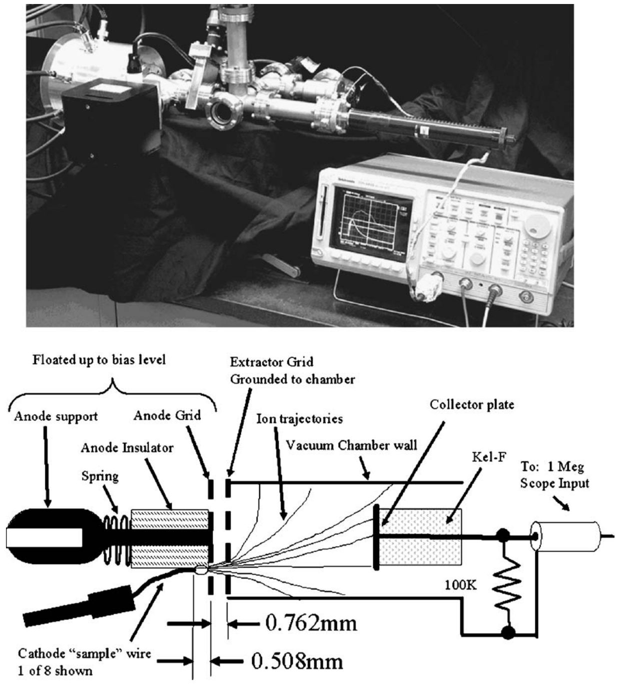

FIG. 9. The bench test setup (top) and the electrode spacing diagram (bottom).

viewing ports using a mirror. The system was pumped to 1×10^{-7} Torr during the bench testing phase. After the extractor and anode grid were degassed and conditioned, the shot-to-shot variation in discharge current was typically <2%. The bias supplied to the control electronics was +12 kV for the bench testing.

Shown in Fig. 4 are the oscilloscope traces obtained during the bench tests of the MeVVA system. On average, a single discharge from an iron cathode produced an ion flux of 8.4×10^9 ions/cm^2 detected by the unbiased Faraday cup which was 1.9 cm in diameter and positioned 20 cm from the extractor grid. This flux was stable for the first 500 000 shots, and the signal was recorded by an oscilloscope running a five shot average and assumes singly charged ion species. The number of ions detected decreases after 700 000 shots to 4.2×10^9 ions/cm^2 collected per pulse. This decrease is thought to be caused by the sample material coating the quartz insulator which effectively moves the anode closer to the cathode sample wire, thus further from the extractor grid, which limits ion extraction. It should be noted that at no time was the sample material shorted or rendered to a non-triggerable state during the bench testing. The metals which are ductile and readily sputter are presumed to have shorter lifetimes, but tests conducted on a pure tin sample produced 35 000 shots without failure. Details of the cathode samples and anode insulator are shown in Fig. 7.

VI. DATA OBTAINED AT NIST EBIT

Great care was taken in the design of the new MeVVA system to mitigate rf noise into the NIST EBIT laboratory. Once installed, the new MeVVA system operated without any rf disturbance affecting other equipment used in the NIST EBIT laboratory. This equipment included an x-ray microcalorimeter[15] and an atomic force microscope.[16]

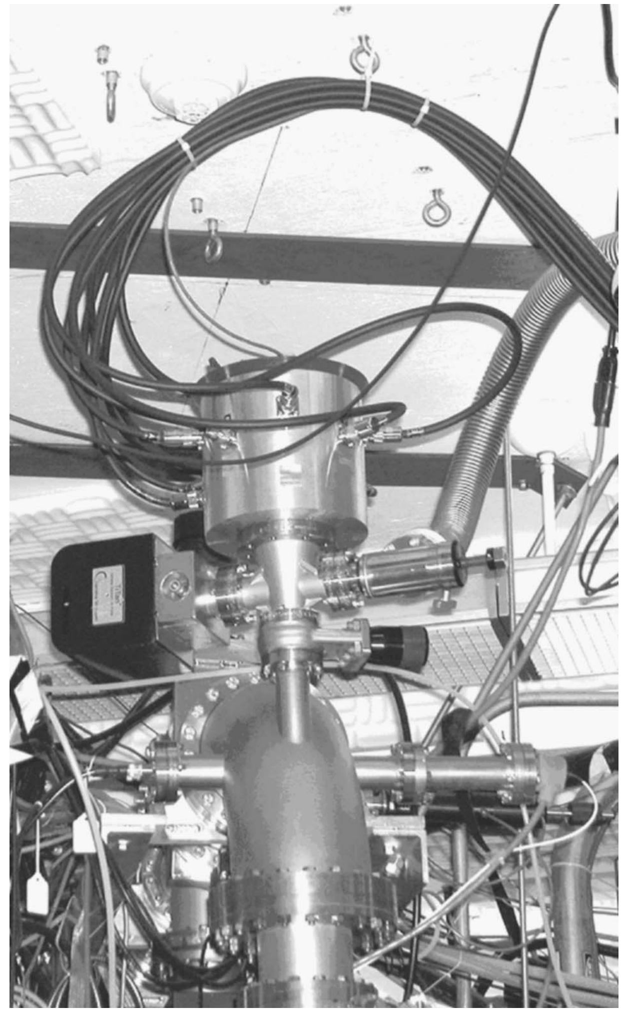

FIG. 10. Photograph of the MeVVA installed on the NIST EBIT.

The entire system was installed and put into operation on the NIST EBIT (as shown in Fig. 10) in less than five days. The new MeVVA head was loaded with samples of Ti, Fe, Mo, and W. Subsequent sample changes required only a few days before ion production could resume, mainly due to the degas time of the electrodes. The cathode samples functioned well, and when desired a different sample element could be selected via the selector switch on the control electronics thus producing new sample ions within a few minutes.

During the commissioning tests of the new MeVVA on the NIST EBIT, x-ray spectra were collected under 1 Hz operation with 10 kV bias as shown in Fig. 11. It should be noted that these x-ray spectra indicate no cross contamination between adjacent cathode samples in the MeVVA head.

VII. DISCUSSION

A new MeVVA system was designed and built by NRL and was installed on the NIST EBIT. The MeVVA incorporates a two wire design which allows for a compact multi-element, individually selectable cathode head. During laboratory testing, the arc jitter was low (<200 ns), and lifetimes of the cathode sample were demonstrated at 7×10^5 shots or

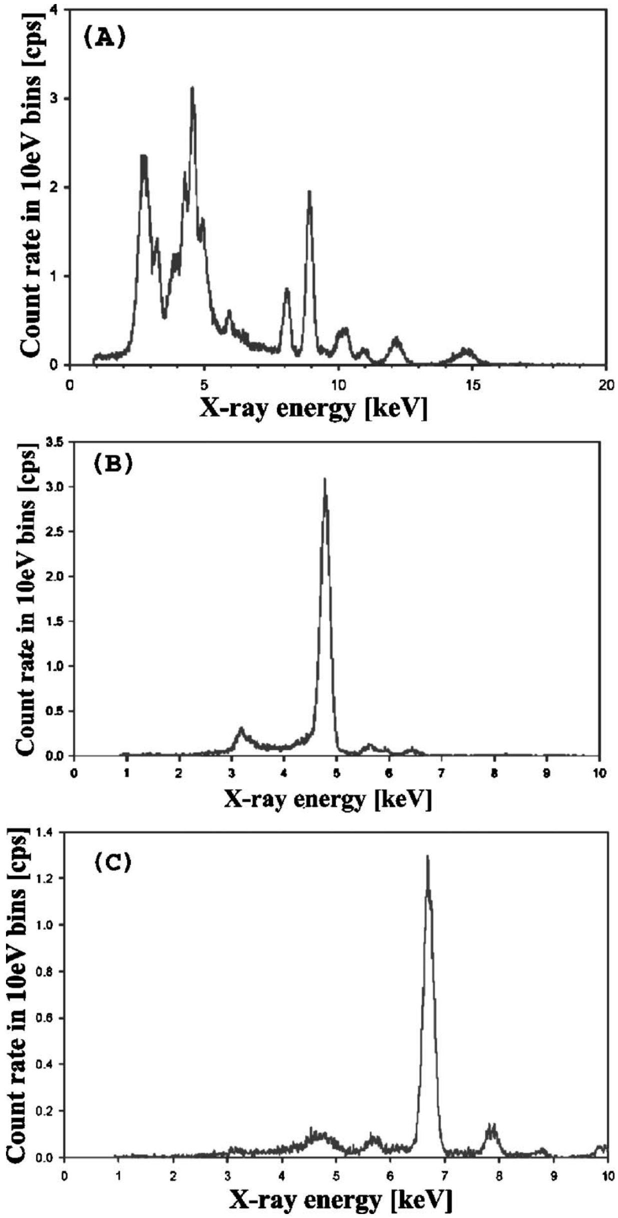

FIG. 11. X-ray spectra, recorded by a silicon lithium (SiLi) detector in units of counts per second (cps), from the drift tube region of the NIST EBIT while operating the MeVVA at 1 Hz and with 10 kV bias. The cathodes and total count rates were (A) tungsten and 655 cps, (B) titanium and 99 cps, and (C) iron and 51 cps.

more with the system mounted horizontally as shown in Fig. 9. During the commissioning tests while attached to the NIST EBIT in the vertical orientation as shown in Fig. 10, we found that the material sputtered from the cathode, and extracted through the anode cup holes, could accumulate and cause the anode cup to be shorted to the extractor cup. The gap between the cathode and anode was subsequently increased from 0.508 to 3.175 mm, and this greatly improved the lifetime of the cathode sample. In a recent data run on the NIST EBIT, an iron cathode was operated in this configuration, the arc jitter remained low (<200 ns), and high ion injection rates were demonstrated. The cathodes continued to operate without failure while running at 1 Hz and with $>60\,000$ shots on one cathode.

ACKNOWLEDGMENTS

The implementation of the MeVVA system would not have been possible without the help of the following: Greg, Aaron, and Monica Edmunds, Scott Lambert, John Albritton, Steve and Dwight Cumberland, Tim Witten, Chris Rempel, Debbie Mcintire, Sue Curtis, Karen Saul, Paul Jacob, Bill Bassett, Albert Henins, Larry Hudson, Csilla Szabo, Endre Takacs, Doug Alderson, and Lorie Holland. The authors greatly appreciate the help of the following vendors who constructed the prototype design into hardware required for this system to function: High voltage potted vacuum feedthrough;[17] rotary high voltage switch, electronics enclosure, anode and extractor grids, alignment fixture;[18] and anode insulator.[19] The identification of equipment and vendors does not imply endorsement or recommendation.

[1] F. G. Serpa, E. S. Meyer, C. A. Morgan, J. D. Gillaspy, J. Suger, J. R. Roberts, C. M. Brown, and U. Feldman, Phys. Rev. A **53**, 2220 (1996).
[2] H. Watanabe, F. J. Currell, H. Kuramoto, S. Ohtani, B. E. O'Rourke, and X. M. Tong, J. Phys. B **35**, 5095 (2002).
[3] N. Nakamura, T. Kinugawa, H. Shimizu, H. Watanabe, S. Ito, S. Ohtani, C. Yamada, K. Okazaki, M. Sakurai, M. R. Tarbutt, and J. D. Silver, Rev. Sci. Instrum. **71**, 684 (2000).
[4] I. G. Brown, IEEE Trans. Nucl. Sci. **NS-32**, 1723 (1985).
[5] I. G. Brown, J. E. Galvin, R. A. MacGill, and R. T. Wright, Appl. Phys. Lett. **49**, 1019 (1986).
[6] I. G. Brown, Rev. Sci. Instrum. **65**, 3061 (1994).
[7] R. Hollinger, M. Galonska, and P. Spadtke, Rev. Sci. Instrum. **75**, 1595 (2004).
[8] R. A. MacGill, I. G. Brown, and J. E. Galvin, Rev. Sci. Instrum. **61**, 580 (1990).
[9] Perkin-Elmer Optoelectronics, 44370 Christy Street, Fremont CA 94538. Specialty Products Division, Model GP-70-40 spark gap switch.
[10] Ross Engineering Corporation, 540 Westchester Drive, Campbell CA 95008. Part No.: E40-nc-40-1-0-bd.
[11] Stangenes Industries Inc., 1052 East Meadow Circle, Palo Alto, CA 94303. Model SIT-50-1000.
[12] Glassman High Voltage Inc., PO Box 317, 124 West Main Street, High Bridge, NJ 08829. EK Series negative 40 kV at 15 mA.
[13] General Atomics, 4949 Greencraig Lane, San Diego, CA 92123. Catalog No. 31662.
[14] Pearson Electronics Inc., 4009 Transport Street, Palo Alto, CA 94303. Pearson Coil model 6600.
[15] E. Silver, H. Schnopper, S. Bandler, N. Brickhouse, S. Murray, M. Barbera, E. Takacs, J. D. Gillaspy, J. V. Porto, I. Kink, J. M. Laming, N. Madden, D. Landis, J. Beeman, and E. Haller, Astrophys. J. **541**, 495 (2000).
[16] J. E. Sanabia, S. N. Goldie, L. P. Ratliff, L. S. Goldner, and J. D. Gillaspy, AIP Conf. Proc. **680**, 568 (2003).
[17] Douglas Electrical Components Inc., Rockaway, NJ.
[18] Edmunds Engineering, Marlow Heights, MD.
[19] J. R. Cumberland, Optics, Marlow Heights, MD.