High current ion source

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We describe a new kind of ion source using a metal vapor vacuum arc as the plasma formation mechanism. The source is simple and reliable and can produce long pulse intense ion beams from any solid electrically conducting material. Using a range of materials from lithium to uranium we have extracted low divergence beams with ion current up to 1 A.

The production of intense ion beams is a field of great interest to a diverse and growing community. Impressive advances have been made in the technology of production of high current beams of hydrogen and deuterium, in neutralized form as required for the controlled fusion program,[1-3] and of other gaseous ions.[1,4] High current, magnetically insulated diode sources have been used to produce very high current ion beams for the inertial confinement fusion research program[5-9]; these beams have been limited to pulse times of submicrosecond duration, however. The production of long pulse or dc ion beams from solids has not witnessed similar progress. Conventionally these sources make use of surface ionization,[10,11] evaporation,[10,12-14] or sputtering [10,15,16] of the solid material into the gaseous/plasma state, and the beam intensity is inherently limited. Currents as high as several tens of milliamperes of metal ions have been produced.[10,15]

We have developed a source for the production of high current beams of ions from solid materials in which a metal vapor vacuum arc is used as the plasma medium from which ions are extracted. This constitutes a new kind of ion source, from which ion beams can be extracted with currents which are, in some cases, over two orders of magnitude greater than hitherto possible for long pulse or dc metal ion beams.

The vacuum arc discharge is a plasma phenomenon that has been well investigated for many years.[17,18] This field of research has largely been the domain of the high current switching community. We have drawn upon this work, and most especially from the work of Gilmour and Lockwood[19] who have described a metal vapor arc configuration which is particularly well suited to the requirements of an ion source. We have called our source the MEVVA ion source—metal vapor vacuum arc. In the MEVVA source an arc is established in vacuum between a cathode and an anode. Typically the arc current is a few hundred amperes and the arc drop is 15–100 V. A basic characteristic of this kind of discharge is the formation of "cathode spots"—minute regions of intense current concentration (thought to be well in excess of 10^6 A/cm^2)—on the cathode surface, at which cathode material is vaporized and ionized. The assemblage of cathode spots thus gives rise to the formation of a dense plasma of cathode material. This quasi-neutral plasma plumes away from the cathode toward the anode, thereby allowing the arc current to flow and the phenomenon to persist. A central hole located in the anode allows a portion of the metal vapor arc plasma to plume through the hole and into the field-free region beyond. A system of multiaperture extraction grids in the usual accel-decel configuration[20,21] is used to extract the ion component from the plasma plume, thus forming an intense ion beam of cathode material. The addition of a small magnetic field produced by a coil in the anode plane helps to duct a large fraction of the arc plasma through the anode hole, and provides additional control over the plasma density at the extractor; this is useful for optimizing the extraction for minimum beam emittance. It is also possible that the favorable field curvature in the arc region helps to suppress the growth of plasma macroturbulence[22,23] and so results in a quieter extracted beam. We have constructed several MEVVA ion sources, and one source with which we have conducted much of our research is outlined in Fig. 1.

For our developmental tests we have operated the source in a pulsed mode. A 5-section, 300-μs, 0.5-Ω pulse line is connected anode to cathode and the discharge is triggered by applying a 10-kV spark between a trigger electrode and the cathode; the trigger electrode is located coaxially within the cathode and insulated from it by an alumina sheath. The arc circuit and the first extractor grid are floated to the desired extractor voltage, typically about 20 kV for our work to date. The intermediate extractor grid is for electron suppression and is sold at about -1 kV. The outermost grid is at ground potential. Each grid is an array of around 100 small apertures, with the array diameter being 2 cm; thus the initial diameter of the extracted beam is also 2 cm. For the results reported here the beam was injected into a field-free vacuum vessel at a pressure in the mid 10^{-6} Torr range.

Using this MEVVA ion source configuration we have run tests with a variety of cathode materials. We have measured the beam current using both a Faraday cup and a ca-

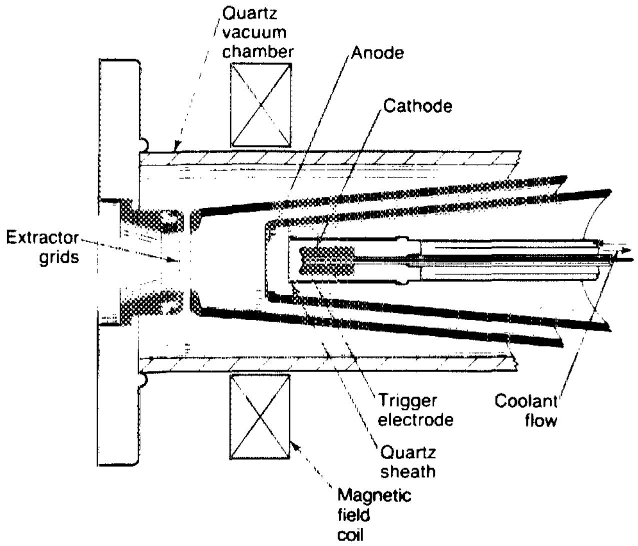

FIG. 1. Simplified, cutaway view of the MEVVA II ion source.

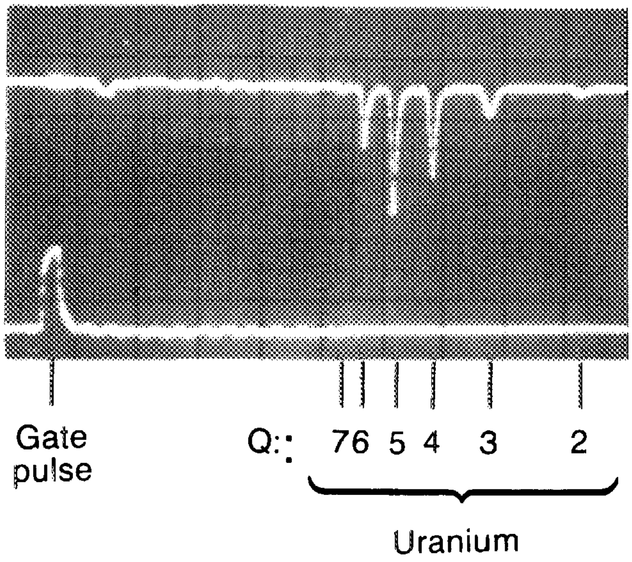

FIG. 2. Time-of-flight charge state spectrum for uranium. Upper trace, detector output; lower trace, gate pulse; sweep speed, 2 μs/cm.

lorimeter. The beam profile has been measured with a multicup detector array,[24] allowing a determination of beam divergence and emittance. The charge state spectrum of the extracted ion beam has been measured with a time-of-flight charge-to-mass analyzer and confirmed in some particular cases by a magnetic analysis. As well as these "routine" diagnostics, we have also made use of a wide range of other diagnostic techniques to confirm and provide cross checks on the MEVVA ion source performance. We have studied the arc growth using a framing camera with 1 μs exposure time; visible photography shows the cathode spots clearly. We have monitored arc voltage and arc current as a function of numerous source and performance parameters. Characteristics of the plasma plume have been measured by the deposition of mass onto a target plate, by ion energy analysis and ion density measurement using a gridded electrostatic energy analyzer, and photographically. The extracted ion beam has been monitored via Faraday cup measurements, calorimetric measurements, beam profile monitor measurements, extractor power supply current drain, approximate beam momentum, and incandescence of a thin carbon foil target.

Most of our work has been done using a tantalum cathode, but we have also extracted beams of lithium, boron, carbon, aluminum, silicon, titanium, iron, niobium, lanthanum, gold, lead, and uranium. We believe that the MEVVA ion source will work satisfactorily with a cathode of any solid electrically conducting material. It is interesting to note that a cathode of lanthanum hexaboride produced a beam containing a mixture of lanthanum (mostly La^{2+} and La^{3+}) and boron (mostly B^+ and B^{2+}) ions. That is, it is possible to create a beam from a nonconductor (boron) if it forms part of a conducting cathode (lanthanum hexaboride); this may well also hold for alloyed mixtures as well as for compounds. A typical charge state spectrum for uranium is shown in Fig. 2. In this case the arc voltage was about 100 V, which compares to the ionization potential of the most highly stripped state seen—105 V for U^{7+}.[25] The charge state distribution can be varied somewhat via the arc current, but the variation is not sensitive. Lower Z materials yielded lower charge states and, concomittantly, lower arc voltage drops. Thus a carbon cathode produces a beam of C^+, the singly ionized species only, and the arc drop is 15–20 V.

At an extraction voltage of 25 kV we have measured an ion beam current as high as 1.1 A (electrical) for tantalum. Approximately half of this current, 550 electrical milliamperes, is contained within the half-width of the beam radial profile, corresponding to a beam divergence half-angle of about 2.5° and a normalized emittance of 0.07 π cm mrad. For good beam emittance the plasma density must be matched to the geometry of the multiaperture extraction grids.[20,21,26,27] Thus the beam quality is not independent of the grids, and the grids (spacing and aperture size) should be optimized for each specific cathode and beam voltage and current. Total beam currents up to $\sim$ 1 A have been measured for lithium and uranium.

There is a vast amount of further work to be done to fully characterize the MEVVA ion source. Detailed studies need to be carried out on features of the source operation that so far we have only been able to quickly skim over. The geometry of cathode, anode, and extractor is clearly vital to efficient operation and need to be optimized. The details of the trigger electrode and the trigger pulse are critical to long-source lifetime. Cathode and anode cooling should be increased to allow high duty cycle or dc operation. Efficient transport of the intense beam in neutralization-unfriendly environments is important. These and other things are on our agenda. Our work to date has demonstrated that the MEVVA ion source is an exciting addition to the gamut of ion sources available. We expect that the source will find wide application in research and industry.

This letter will be followed by a more detailed publication. We are indebted to Dr. Jack Gavin and Dr. Wulf Kunkel for valuable discussions and elucidation of ion source idiosyncrasies. This work was supported by the Director, Office of Energy Research, Office of High Energy and Nuclear Physics, Nuclear Science Division, U. S. Department of Energy, under contract No. DE-AC03-76SF00098.

[1] Proceedings of the Second Symposium on Ion Sources and Formation of Ion Beams, Lawrence Berkeley Laboratory, Berkeley, California 22–25 Oct. 1974 (LBL-3399).

[2] R. Keller, Proceedings of the 1984 Linear Accelerator Conference, GSI, Darmstadt, W. Germany, 7–11 May 1984, p. 19.

[3] P. J. M. van Bommel, P. Massmann, E. H. A. Granneman, H. J. Hopman, and J. Los, Vacuum **34**, 25 (1984).

[4] R. Keller, F. Noehmayer, P. Spaedtke, and M.-H. Schoenenberg, Vacuum **34**, 31 (1984).

[5] J. M. Neri, D. A. Hammer, G. Ginet, and R. N. Sudan, Appl. Phys. Lett. **37**, 101 (1980).

[6] J. M. Neri and D. A. Hammer, IEEE Trans. Nucl. Sci. **NS-28**, 3378 (1981).

[7] S. Humphries, Jr., Nucl. Fusion **20**, 1549 (1980).

[8] S. Humphries, Jr., R. N. Sudan, and L. Wiley, J. Appl. Phys. **47**, 2382 (1976).

[9] S. Humphries, Jr., C. Eichenberger, and R. N. Sudan, J. Appl. Phys. **48**, 2738 (1977).

[10] L. Valyi, *Atom and Ion Sources* (Wiley, New York, 1977).

[11] R. K. Feeney, W. E. Sayle, II, and J. W. Hooper, Rev. Sci. Instrum. **47**, 964 (1976).

[12] J. Ishikawa and T. Takagi, Jpn. J. Appl. Phys. **22**, 534 (1983).

[13] J. Ishikawa, Y. Takeiri, and T. Takagi, Rev. Sci. Instrum. **55**, 449 (1984).

[14] A. Rockett, S. A. Barnett, and J. E. Greene, J. Vac. Sci. Technol. B **2**, 306 (1984).

[15] B. Gavin, S. Abbott, R. MacGill, R. Sorensen, J. Staples, and R. Thatcher, IEEE Trans. Nucl. Sci. **NS-28**, 2684 (1981).

[16] Y. Saito, Y. Mitsuoka, and S. Suganomata, Rev. Sci. Instrum. **55**, 1760 (1984).

[17] *Vacuum Arcs—Theory and Application*, edited by J. M. Lafferty (Wiley, New York, 1980).

[18] IEEE Trans. Plasma Sci., Special Issue on Vacuum Discharge Plasmas, IEEE **PS-11**, Sept. (1983).

[19] A. S. Gilmour, Jr. and D. L. Lockwood, Proc. IEEE **60**, 977 (1972).

[20] J. R. Coupland, T. S. Green, D. P. Hammond, and A. C. Riviere, Rev. Sci. Instrum. **44**, 1258 (1973).

[21] T. S. Green, IEEE Trans. Nucl. Sci. **NS-23**, 918 (1976).

[22] J. D. Jukes, Rep. Prog. Phys. **31**, 333 (1968).

[23] W. M. Manheimer and C. Lashmore-Davies, Naval Research Laboratory, Washington, D. C., 1984.

[24] J. E. Galvin and I. G. Brown, Rev. Sci. Instrum. **55**, 1866 (1984).

[25] T. A. Carlson, C. W. Nestor, Jr., N. Wasserman, and J. D. McDonell, At. Data **2**, 63 (1970).

[26] M. Dembinski and P. K. John, J. Appl. Phys. **50**, 6113 (1979).

[27] M. G. Rosing and J. R. Conrad, J. Appl. Phys. **57**, 816 (1958).