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FINAL REPORT

High-flux, extended-pulse ion accelerators

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1. Summary of program

This report summarizes work accomplished at the University of New Mexico under DOE Contract DE AC0383 ER13138. Work was performed between March, 1983 and February, 1986 with total funding of $267,924. The contract was supplemented by a $20,000 equipment contribution from UNM and $70,000 in personnel support from the State of New Mexico through the Rio Grande Resarch Initiative. The purpose of the program was to investigate physical phenomena associated with high flux ion beam generation and to develop technology for intense ion beam accelerators with pulselengths in the ms range. At the time the work was initiated, the chief area of application for the technology was ion implantation and materials modification.

Many of the original goals of the proposal have been accomplished. For example, the novel radial field plasma source described in the proposal has been successfully tested and reported in the literature. As work proceeded, we followed a number of promising new paths that lead to successful technology, such as metal vapor vacuum arc arrays and grid-controlled

extractors. At the same time, difficulties were encountered that prevented us from accomplishing some of the original goals. For example, despite considerable effort, we have not been able to prevent shorting of large-area magnetically-insulated extraction gaps.

All significant work related to the contract has been comprehensively documented in the literature. A collection of reprints is included with this report. An outline of accomplishments is given in Section 2. Section 3 summarizes on-going work on high flux ion generation and neutralized beam transport that evolved from the DOE contract. This work is currently supported by the Heavy Ion Fusion Program at Los Alamos National Laboratory. A bibliography of publications generated under DOE support is contained in Section 4. Section 5 lists conference presentations and Section 6 lists graduate degrees obtained under the contract. A list of included reprints is given in Section 7.

2. Status of work accomplished

A. An ion source test stand was completed and used for a number of experiments. The test stand consists of a custom fabricated stainless steel vacuum chamber, a cryopump, a floating equipment rack with anode power supplies and controllers, pulsed power equipment for extraction tests to 50 kV, three digital oscilloscopes, and a variety of diagnostics. The equipment is installed in a dedicated laboratory in Farris Engineering Center at UNM.

B. Parallel arrays of metal vapor vacuum arcs have been reliably operated on the test stand. The rationale for multiple arcs is to provide high flux over a large area and to achieve constant flux output by statistical smoothing. Current density of C^+ ions in the range 0.5 A/cm^2 has been achieved with total extractable ion flux up to 50 A for 600 microsecond pulses. The problem of parallel arc operation proved to be quite difficult, since plasma from one arc could effect initiation of other arcs and cause breakdowns along insulating feedthroughs. A number of geometries were tried before arriving at the successful configuration described in Reprints 2 and 8.

C. A magnetically insulated extraction gap for use on the test stand was constructed and tested for vacuum operation. The gap was mated to the vacuum arc array for high flux ion extraction experiments. Despite extensive testing and modifications, we could not prevent early shorting of the gap; this approach was abandoned.

D. We did achieve successful extraction of over 1 A of carbon ions using a high gradient conventional accel-decel extractor. Pulselengths of 600 microseconds were achieved with 15 kV extraction voltage (Reprint 8). This work demonstrated that vacuum arc arrays could be used successfully for long-pulse, high current ion extraction.

E. A variety of fundamental experiments were carried out to investigate the range of species that could be generated by metal vapor vacuum arcs, to determine flux limits for single arcs, and to determine the effects of arc current and gap spacing on extractable flux. These results are reported in Reprints 5 and 6.

G. A dedicated test stand with diffusion pump and Pyrex vacuum chamber was built to test the radial magnetic field plasma source described in the proposal. Three separate versions of the plasma source were built before achieving successful operation. Problems resulted from non-uniformities in the field produced by permanent magnets and breakdowns along field lines. Successful operation with a self-sustained discharge is described in Reprint 7.

H. One of the most interesting and successful results of our work was the demonstration of grid-controlled ion extractors for the generation of high brightness beams. This work was performed on a third high voltage test stand described in Reprints 4. Electrostatic control grids made it possible to extract low-divergence, constant current beams from plasma sources that had large temporal and spatial variations of flux. Furthermore, it was possible to generate single or multiply pulsed beams with no problem of plasma leakage into the extraction gap or downstream electrodes. Charge state filtering occurred in the extractor, so that we were able to achieve C^{+} with no detectable C^{++} contamination. Grid controlled extraction has potential application to a wide variety of ion extractors. We have published extensively in this area (Reprints 3 and 4) and have recently contributed a chapter on the subject to the book **Physics and Technology of Ion Sources**. A preprint of the book chapter will be forwarded in 1-2 months.

3. Continuing work

Continuing work on ion sources at UNM is supported by Los Alamos National Laboratory. The original purpose of the UNM program was to develop backup high-brightness ion sources for the LANL Accelerator Inertial Fusion Injector. The LANL project, in turn, supported the Lawrence Berkeley Laboratory program in Heavy Ion Fusion with linear induction accelerators. The UNM source has become the baseline approach for the HIF program. The thermionic ion sources originally considered for the applications cannot provide high flux and present imposing technological difficulties for incorporation into a high voltage, multi-beam system.

Experiments at UNM this year are centered on grid-controlled extraction of high flux (30-40 mA/cm^2) carbon ion beams. The species and flux levels were chosen to meet the requirements for near-term HIF accelerator experiments to be performed at Lawrence Berkeley Laboratory. In addition, we are using a 0.2 A, 35 kV carbon ion beam injector to perform basic studies of ion beam neutralization by cold electrons and to develop methods to guide high flux ion beam by magnetic control of neutralizing electrons. We have built a 1 meter transport tube with a precision 2 kG solenoidal field. Electrostatic bias fields can be applied at the periphery of the extracted beam to investigate electron confinement and ion guiding.

4. Publications

S. Humphries, Jr. and C.S. Hwang, "Miniature Penning Gauge for Pulsed Gas Measurements," Rev. Sci. Instrum. 55, 1663 (1984).

C. Burkhart, S. Coffey, G. Cooper, S. Humphries, Jr. L.K. Len, A.D. Logan, M. Savage and D.M. Woodall, "Vacuum Arc Arrays for Intense Metal Ion Injectors," Nucl. Instrum and Methods B10-11, 792 (1985).

H.L. Rutkowski, H. Oona, E.A. Meyer, R.P. Shurter, L.S. Englehardt and S. Humphries, Jr., "Ion Source Development for the Los Alamos Heavy Ion Fusion Injector," IEEE Trans. Nucl. Sci. NS-32, 1742 (1985).

S. Humphries, Jr., C. Burkhart, S. Coffey, G. Cooper, L.K. Len, M. Savage and D.M. Woodall, "Grid-controlled Extraction of Pulsed Ion Beams," J. Appl. Phys. 59, 1790 (1986),

S. Humphries, Jr., C. Burkhart and L.K. Len, "Pulsed Ion Sources for Accelerator Inertial Fusion", to be published, Particle Accelerators.

L.K. Len, C. Burkhart, G.W. Cooper, S. Humphries, Jr., M. Savage and D.M. Woodall, "Generation and measurements of ion species from metal vapor vacuum arc sources ", IEEE Trans. Plasma Science PS-14, 256 (1986).

L.K. Len, S. Humphries,Jr., and C. Burkhart, "Grid-controlled metal ion sources for heavy ion fusion accelerators," AIP Conference Proceedings, International Symposium on Heavy Ion Fusion, 1986.

S. Humphries, Jr. and L.K. Len, "Radial field Penning discharge for high flux ion extraction," to be published, Rev. Sci. Instrum.

S. Humphries, Jr. and C. Burkhart "Ion Sources for Heavy Ion Fusion Accelerators," **Proc. 2nd Int'l. Topical Symposium on ICF by Charged Particle Beams**, (Nagaoka, Japan, 1986), to be published, Laser and Particle Beams.

C. Burkhart and S. Humphries, Jr., "Vacuum Arc Array Ion Injector," to be published, **Proc. NATO Workshop on High Brightness Accelerators**, Pitlochry, Scotland, 1986.

S. Humphries, Jr., C. Burkhart and L.K. Len, "Generation of Pulsed High-Brightness Ion Beams," in **Physics and Technology of Ion Sources**, edited by I. Brown (J. Wiley and Sons, New York, 1987).

5. Presentations

"Vacuum Arc Arrays for Intense Metal Ion Beams," 8th International Conf. of the Application of Accelerators in Research and Industry, Denton, Texas, Nov. 1984 (C. Burkhart).

"Multiple vacuum arc source for neutralized beam transport experiment," Workshop on Metal Vapor Vacuum Arc Ion Sources, Berkeley, California, Sep. 1985 (C. Burkhart).

"Grid-controlled ion extraction," Workshop on Metal Vapor Vacuum Arc Ion Sources, Berkeley, California, Sep. 1985 (S. Humphries, Jr.)

"Vacuum arc array ion injector," NATO ASI on High Brightness Accelerators, Pitlochry, Scotland, Jul. 1986. (C. Burkhart)

"Metal ion source development for the multi-beam experiment," APS Div. Plasma Physics 26th Annual Meeting, Boston, Mass., Oct 1984. (D. Woodall).

"Extended-pulse pulselac injector for ion implantation," IEEE Plasma Science Conf., St. Louis, May, 1984. (L.K. Len).

"High-flux accelerators for Ion Implantation and Surface Modification," 8th International Conf. of the Application of Accelerators in Research and Industry, Denton, Texas, Nov. 1984 (S. Humphries, Jr.)

"Generation and measurements of ion species from metal vacuum arcs," Workshop on Metal Vapor Vacuum Arc Ion Sources, Berkeley, California, Sep. 1985 (L.K. Len).

6. Educational reports

"Extraction and propagation of high-intensity ion beams, " Ph.D. thesis, Craig P. Burkhart, expected, May, 1987

"Theta pinch high density plasma source," M.S. Thesis, Mark E. Savage, May, 1985.

7. Reprints included *

1. S. Humphries, Jr. and C.S. Hwang, "Miniature Penning Gauge for Pulsed Gas Measurements"

2. C. Burkhart, S. Coffey, G. Cooper, S. Humphries, Jr. L.K. Len, A.D. Logan, M. Savage and D.M. Woodall, "Vacuum Arc Arrays for Intense Metal Ion Injectors,"

3. S. Humphries, Jr., C. Burkhart, S. Coffey, G. Cooper, L.K. Len, M. Savage and D.M. Woodall, "Grid-controlled Extraction of Pulsed Ion Beams,"

4. S. Humphries, Jr., C. Burkhart and L.K. Len, "Pulsed Ion Sources for Accelerator Inertial Fusion", to be published, Particle Accelerators.

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5. L.K. Len, C. Burkhart, G.W. Cooper, S. Humphries, Jr., M. Savage and D.M. Woodall, "Generation and measurements of ion species from metal vapor vacuum arc sources "

6. L.K. Len, S. Humphries,Jr., and C. Burkhart, "Grid-controlled metal ion sources for heavy ion fusion accelerators,"

7. S. Humphries, Jr. and L.K. Len, "Radial field Penning discharge for high flux ion extraction,"

8. C. Burkhart and S. Humphries, Jr., "Vacuum Arc Array Ion Injector," to be published, **Proc. NATO Workshop on High Brightness Accelerators**, Pitlochry, Scotland, 1986.