AEOSR-TR- 91 0 0 . 9

Final Report • January 1991

IONIC SOLID HYDROGEN FUEL: EXPERIMENTAL INVESTIGATION OF CLUSTER-IMPACT FUSION

Young K. Bae, D. C. Lorents, S. Young, and K. Stalder
Molecular Physics Laboratory

SRI Project PYU 1317
Contract No. F49620-90-C-0048
MP 91-005

Prepared for:

Air Force Office of Scientific Research
Directorate of Chemical and Atmospheric Sciences
Building 410
Bolling Air Force Base, DC 20332-6448

Attn: Lt. Col. Larry W. Burggraf

Final Report • January 1991

IONIC SOLID HYDROGEN FUEL: EXPERIMENTAL INVESTIGATION OF CLUSTER-IMPACT FUSION

Young K. Bae, D. C. Lorents, S. Young, and K. Stalder
Molecular Physics Laboratory

SRI Project PYU 1317
Contract No. F49620-90-C-0048
MP 91-005

Prepared for:

Air Force Office of Scientific Research
Directorate of Chemical and Atmospheric Sciences
Building 410
Bolling Air Force Base, DC 20332-6448

Attn: Lt. Col. Larry W. Burggraf

Approved:

D. J. Eckstrom, Laboratory Director
Molecular Physics Laboratory

G. R. Abrahamson
Senior Vice President
Physical Sciences Division

SRI International 333 Ravenswood Avenue • Menlo Park, CA 94025-3493 • (415) 326-6200 • FAX (415) 326-5512 • Telex 334486

REPORT DOCUMENTATION PAGE	Form Approved OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	910124	Final 7/1/90 - 9/30/90

4. TITLE AND SUBTITLE
Ionic Solid Hydrogen Fuel: Experimental Investigation of Cluster Impact Fusion

5. FUNDING NUMBERS
61102F 5730 00

6. AUTHOR(S)
Y. K., Bae, D. C. Lorents, S. Young, K. Stalder,

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
SRI INTERNATIONAL
333 Ravenswood Avenue
Menlo Park, CA 94025

8. PERFORMING ORGANIZATION REPORT NUMBER
MP 91-005

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
AFOSR/NA
Building 410
Bolling AFB, DC 20332-6448
Attn: Lt. Col. Larry W. Birggraf

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
F49620-90-C-0048

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution is unlimited

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

We have investigated a new novel fusion method: the use of deuterium-containing clusters for igniting fusion (cluster-impact fusion, CIF). If CIF becomes practical, the energy density that can be achieved with the DT fuel is 3.4×10^{14} J/kg, which is eight orders of magnitude larger than the energy density of LOX/H_2 (1.6×10^6 J/kg). For missions with I_{sp} less than 100,000 s, the CIF rocket performance will be essentially identical to that of antimatter. Under the current project, we have successfully built and demonstrated a new cluster-impact fusion facility by extending the existing hydrogen cluster facility sponsored by the previous Air Force Contract (No. F04611-87-C-0025). With the new facility, we now have successfully reproduced and extended the results by Brookhaven scientists. As a result, we are confident that the new fusion method discovered at Brookhaven is very promising; thus, we are ready to investigate means of increasing the fusion yield to a practical level for rocket propulsion applications.

14. SUBJECT TERMS
Hydrogen fuel, cluster-impact, fusion

15. NUMBER OF PAGES
20

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	UL

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. 239-18
298-102

CONTENTS

INTRODUCTION

SRI International (SRI) is pleased to present this final report to the Air Force Office of Scientific Research (AFOSR) under Contract F49620-90-C-0048. The aim of the project was to investigate the recently discovered cluster-impact fusion,[1,2] which has an excellent potential to be used for new rocket propulsion concepts for near future Air Force missions. Although several evolutionary ($I_{sp} < 1000$ s) concepts are promising, including the use of ions, free radicals, and metastables trapped in a matrix, until now, no revolutionary ($I_{sp} > 1000$ s) concept has been proved promising. For instance, the proposition to utilize an energetic state of H_4 with predicted $I_{sp} \sim 1500$ s was thwarted because the state is now known to have a very short lifetime. Another concept utilizing antimatter was proposed, but it is limited by the technological difficulties in producing, bunching, and storing antimatter. Because future Air Force missions will clearly require revolutionary rocket engines, the search for new concepts continues.

The potential of utilizing nuclear fusion for rocket propulsion has been recognized for many decades, since the discovery of nuclear fusion. Fusion rocket engines have the potential of high I_{sp} and thrust comparable with that of antimatter. Conventional fusion devices with magnetic or inertial confinement schemes, however, seem too bulky and heavy to be used for rocket engines. Thus, to realize fusion powered rocket engines, new, innovative fusion schemes that are efficient and simple enough to allow compact fusion reactors must be sought.

We believe that the cluster-impact fusion (CIF) is an ideal candidate for a revolutionary rocket propulsion scheme.[1,2] Available results of experimental and theoretical studies on CIF suggest that it may be an extremely efficient and simple fusion power source. Thus, CIF will allow much more compact fusion devices than conventional fusion driven by lasers or heavy ions. Rapid development of practical rocket engines with CIF seems possible, because requisite technologies, such as accelerators and ion source technologies, are readily available. Furthermore, CIF can also be used for evolutionary rocket propulsion with the use of the existing thermal heat exchanger concept for a nuclear fission thermal rocket with an I_{sp} of 900 s. Therefore, if it becomes practical, CIF could serve both revolutionary and evolutionary rocket propulsion needs. The details of the discovery and the current status of CIF are described in our new proposal entitled "Cluster-Impact Fusion Propulsion" SRI International Proposal No. PYU 90-157R, submitted under separate cover.

Almost at the end of our previous Air Force contract (Contract F04611-87-C-0025), scientists from Brookhaven National Laboratory (BNL)[1] announced the discovery of CIF, and we concluded that CIF is the best candidate for the revolutionary rocket concepts that the Air Force has been seeking. Thus, we changed our research direction to study CIF in the previous contract and proposed a new three-month contract, which became the current contract. Under the previous contract, we began to modify our cluster source system for adapting the new cluster source and acquired and transported a 300-keV accelerator from the Lawrence Berkeley Laboratory (LBL). Under the current contract. we proposed to build and demonstrate a new water cluster ion source and its associated vacuum system and to adapt the 300-keV accelerator. We also proposed using the new facility to confirm the results of the BNL scientists.

We now have successfully accomplished these tasks and found that CIF is scientifically sound. Therefore, we are ready to attack the next tasks, described in the new proposal, to enhance the fusion yield to a practical level. The remainder of this report discusses our developments and findings in some detail. A brief summary of our accomplishments and an indication of our next efforts comprise the conclusion of this report.

RESULTS

The primary prerequisite tasks for investigating cluster-impact fusion have been to develop and demonstrate cluster ion source systems and to adapt the 300-kV accelerator to the pre-existing cluster facility. The following sections summarize our efforts and results on these tasks and the subsequent cluster impact fusion measurements.

CONSTRUCTION OF THE ION SOURCE VACUUM SYSTEM AND ION OPTICS

Figure 1 shows the schematic diagram of the completed cluster impact fusion facility. We have constructed a vacuum system composed of two sections and adapted it to the existing ion beam facility. The ion source vacuum chamber consists of two sections vacuum-isolated by a skimmer. The first vacuum section contains the ion source and is made of a Lucite tube for electrical insulation. This section is pumped by a 300 L/s Roots Blower pump backed by a 40 cfm mechanical pump. The pressure of the first section is typically 0.1 Torr when the source is operating. The skimmer has a 1.6-mm-ID entrance aperature and is located 1 cm away from the exit of the nozzle. The cluster ions are focused by a potential difference applied between the skimmer and the nozzle. The requisite potential difference varies as a function of the mean cluster size. For example, focusing of cluster ions with a mean size of 100 molecules/cluster requires a skimmer potential of +30 V relative to the nozzle, whereas focusing of monomer ions requires -100 V.

After passing the first skimmer, the ions are accelerated through the second skimmer, which has a 6-mm-ID entrance aperture to ground potential. The vacuum section defined between the first and second skimmers is pumped by a 10-inch diffusion pump backed by a 60-cfm mechanical pump. The pressure of the first section is typically 10^{-4} Torr when the source is operating. After being accelerated to 500 eV, the cluster ions are focused by two sets of symmetric einzel lenses through 3-mm image apertures. Both lenses are operated at an electrical potential on their central elements equal to roughly two-thirds of the ion beam energy. Vertical and horizontal deflection plates follow each einzel lens to allow small corrections to the ion beam direction. Voltages applied to the deflection plates are usually less than one-tenth of the beam acceleration voltage.

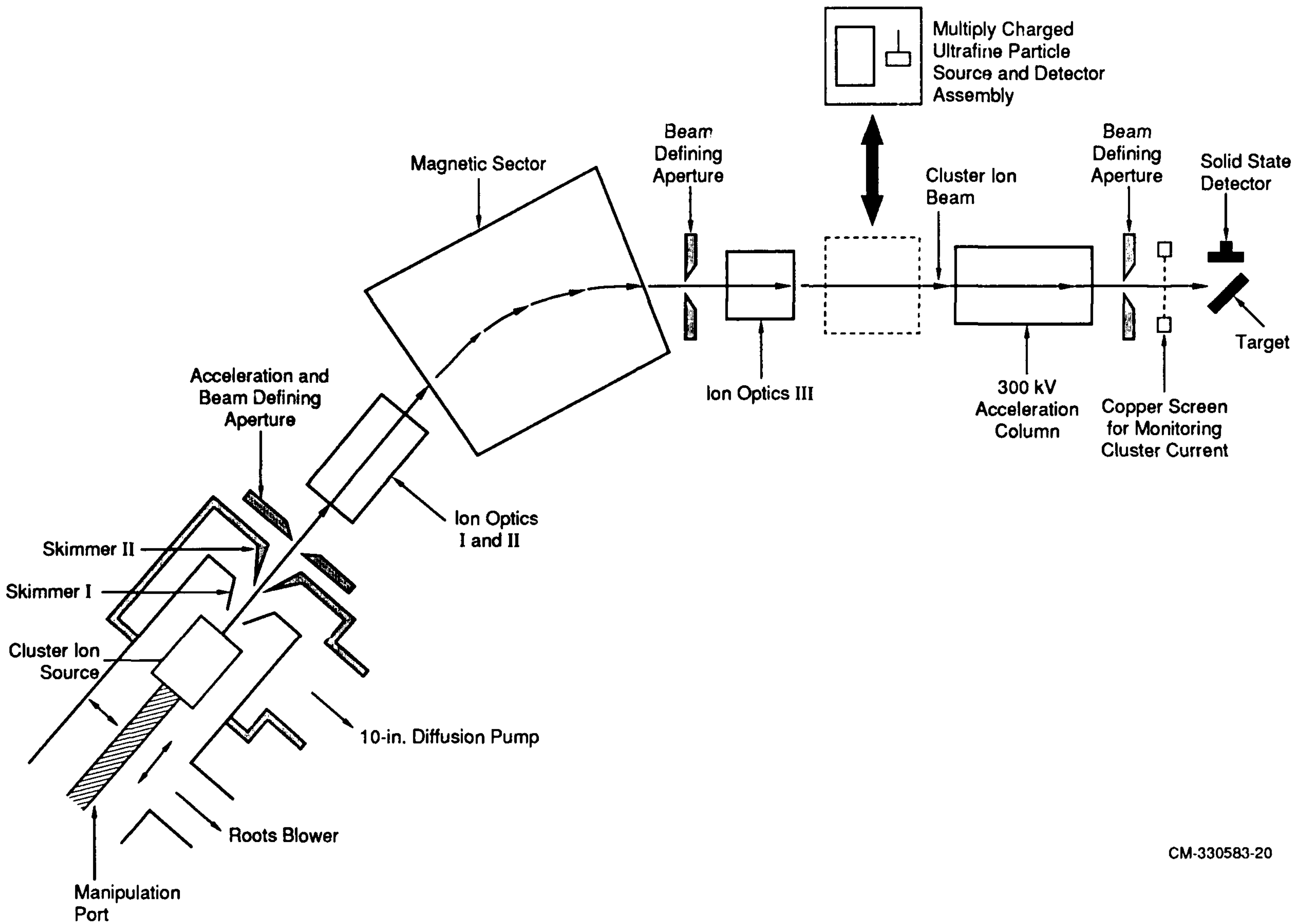


Figure 1. SRI Cluster Impact Facility.

The vacuum chamber that contains the ion optics is pumped by a 6-inch diffusion pump; with the source in operation, its pressure rose from 4×10^{-7} Torr to 2×10^{-6} Torr. The accelerated and collimated cluster ion beam is mass selected by a 40-cm-radius, 60° electromagnetic sector capable of bending 5500-keV-amu ions, passed through a 2-cm-diameter aperture, and further focused and collimated by the third set of einzel lenses and deflection plates. The beam is then sent to a movable Faraday cup located 65 cm away from the exit of the magnetic sector. The 2-cm aperture yields an effective mass resolution $\Delta M/M$ of ~0.05, which was measured with small cluster ions on the Faraday cup. Moving the Faraday cup out of the beam path allows the beam to pass through another 2-cm-diameter aperture and enter the acceleration column of the 300-keV accelerator. The effective mass resolution of the beam measured in front of the target after acceleration was also 0.05.

DEVELOPMENT OF A NEW HIGH INTENSITY WATER CLUSTER ION SOURCE

We have successfully developed and demonstrated a new high intensity H_2O cluster ion source. The detailed cross sectional drawing of the ion source together with skimmers is shown in Figure 2. The ion source was built by modifying the body of the commercial pulsed valve (Lasertechnics). The source assembly is mounted on a manipulation port that allows tilt adjustments on two axes orthogonal to the ion beam plus translation of the assembly along the ion beam direction. The purpose of these adjustments is to allow precise positioning of the assembly relative to the skimmer and ion optics, which are fixed to the apparatus. The optimum distance from the nozzle to the skimmer depends on the mean size of the clusters produced. The typical distance for generating clusters with a mean size of 100 molecules/cluster is 1 cm. The generation of larger clusters requires a larger distance, and shorter ones require a smaller distance. The source assembly and the first skimmer are maintained at 500 V to establish the final kinetic energy of the cluster ions after they are accelerated to ground potential on the second skimmer.

The principle of the new cluster ion source is very similar to that described by Beuhler et al.[1,2] The ion source produces high intensity cluster ion beams by generating abundant seed ions in the cluster source and expanding the ions that nucleate the condensation of neutrals for the growth of the cluster ion in a He and water vapor mixture. The seed ions are produced in a discharge of He and water vapor mixture between a stainless steel tip and the wall of the source near the nozzle. The mixture is produced by bubbling He through water in a gas washing bottle at room temperature. Production of water clusters of 100 molecules requires a He pressure of ~700 Torr. The nozzle-discharge-tip assembly is made of a commercial Lasertechnics nozzle. The tip is held to the nozzle by an adapter made of Macor. The tip holder has holes that allow conductance of

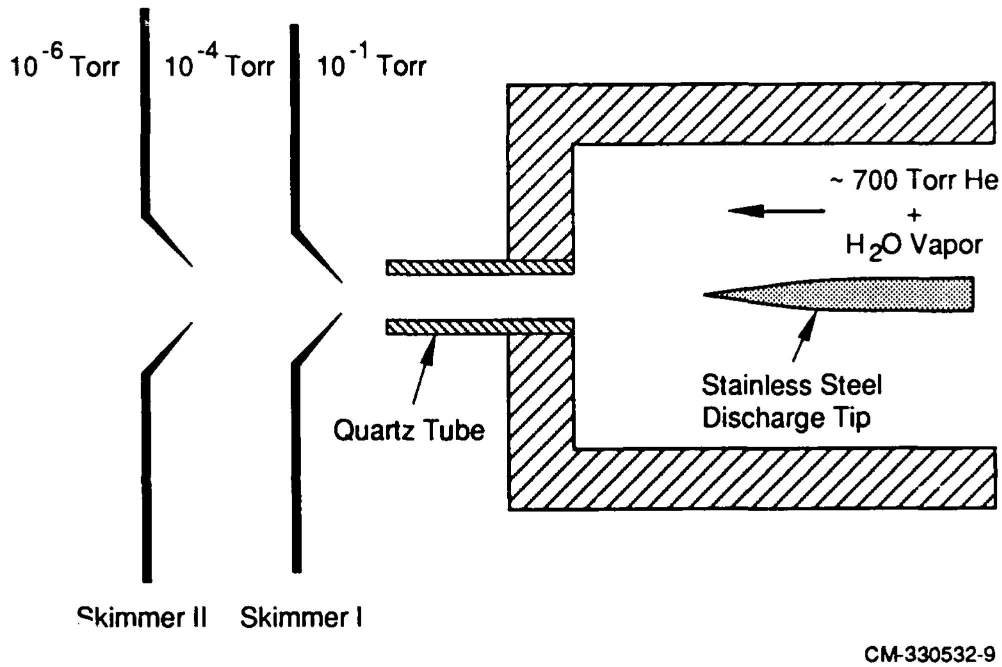


Figure 2. Schematic of the water cluster ion source.

the He water vapor mixture. The typical distance between the tip and the nozzle is 4 mm, and the typical current and impedance of the discharge are 2-3 mA and 100-200 kΩ, respectively.

Initially we had tried a Lasertechnics nozzle with a 0.5-mm-diameter hole and observed cluster ions with a mean size only up to 30 molecules/cluster. Increasing the source pressure to generate clusters with a mean size larger than 30 molecules/cluster triggered an arc between the ion source assembly and the vacuum chamber. We concluded that generating larger cluster ions with the nozzle requires a much higher pumping capacity to maintain the chamber pressure below the threshold of arcing. Thus, we investigated various ways of reducing the conductance of the nozzle and found that nozzles made of 8-mm-long, 0.5-mm-ID quartz tubes (which have much less conductance than a hole) worked best. The tubes were glued to the nozzle with epoxy. We found that covering the end of the quartz tube facing the discharge tip with metal prevents generation of an intense cluster ion beam. The reason for this finding is not well understood now. We also tried tubes made of other materials, such as stainless steel, alumina, and glass. The stainless steel tubes did not produce any cluster ions. Both alumina and glass tubes worked as well as quartz tubes, but the glass tubes cracked in only a few hours of operation.

A mass spectrum of the produced $(D_2O)_n^+$ cluster ions measured with the movable Faraday cup is shown in Figure 3. The spectrum has a full width at half maximum (FWHM) of 30% and should represent the mass distribution of the ion source convoluted with the resolution of the magnetic sector. The mean size of the clusters can be readily controlled by tuning the pressure of the source and the discharge current. Lower discharge currents and the higher pressures result in larger cluster ions. For generating monomer ions, no He pressure is necessary. With the source systems tuned for clusters of 100 molecules, the maximum observed current of cluster ions on the Faraday cup is 7 nA. Higher currents are generated with the source tuned for smaller clusters, and vice versa.

INSTALLATION OF A 300-keV ACCELERATOR AND CONSTRUCTION OF FUSION DIAGNOSTICS SYSTEMS

We have modified and adapted a 300-keV accelerator obtained from Lawrence Berkeley Laboratory (LBL). The new accelerator was connected with the flight chamber after the magnetic sector chamber, as shown in Figure 1. The target and fusion diagnostics systems constructed under this contract are described next.

The mass selected and collimated cluster ions are accelerated through a 45-cm-long acceleration column of the 300-keV accelerator and, then enter a chamber that contains the target and the detector which is maintained at the full terminal voltage. The target is a 2-cm-diameter disk made of perdeuteropolyethylene $[(C_2D_4)_n]$ and tilted 45 degrees with respect to the beam axis. The

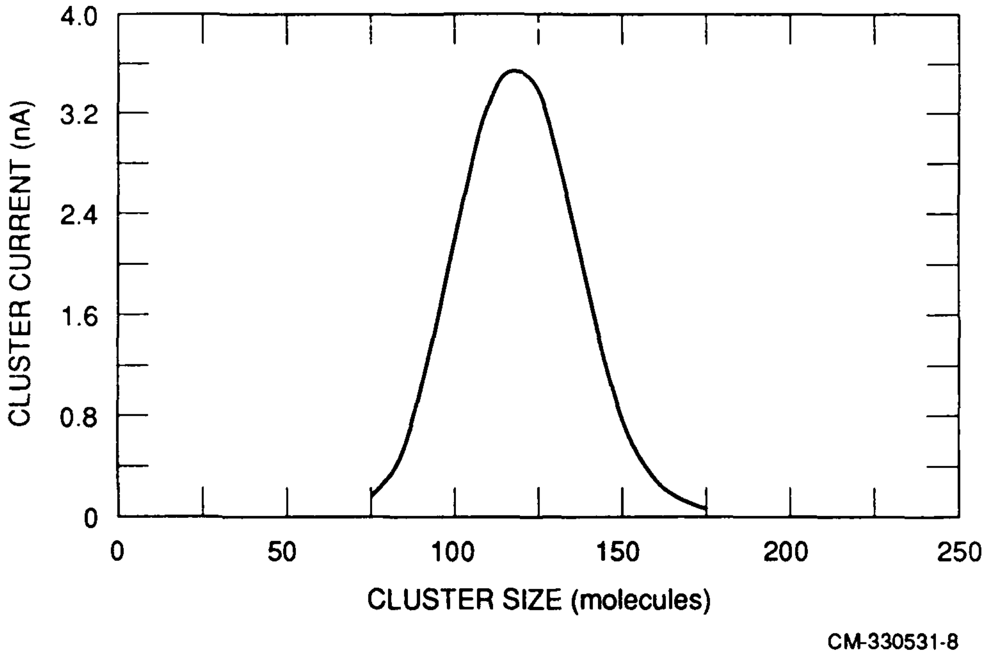


Figure 3. Size distribution of the generated $(D_2O)_n^+$ clusters from the ion source.

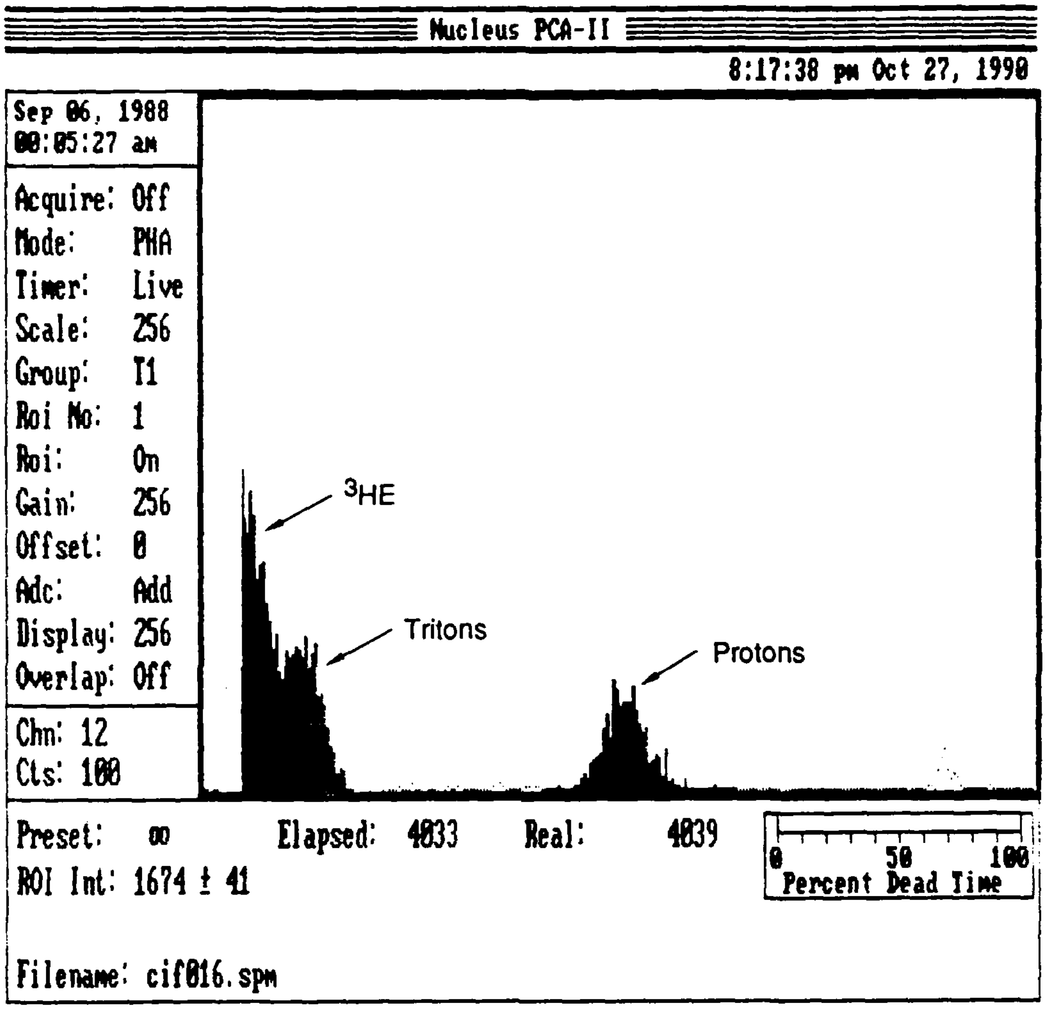
current of the accelerated cluster ions is measured by monitoring secondary electrons from a copper grid upstream of the target. The grid is maintained at 50 V relative to the high voltage terminal, and the loss of the electrons from it is monitored with a DC current amplifier connected through a fiber optic link and monitored by an ADC in a CAMAC crate interfaced with a computer. Fusion product particles are detected by a particle detector, which is a 300-mm^2 Ortec "ruggedized" silicon solid-state detector. The active surface of the detector is covered with a 50 $\mu g/cm^2$ layer of aluminum. The detector is located 2.5 cm from the center of the target. The amplified detector pulses are sent through a fiber optic link to a pulse height analyzer interfaced with a computer. The detector system, including the fiber optic link, is calibrated with 5.48-MeV α particles from ^{241}Am and with DD fusion particles, protons, tritons, and ^{3}He produced by D^+ impact on the $(C_2D_4)_n$ target. Typical fusion signals observed in the collisions of $(D_2O)_n^+$ clusters with a $(C_2D_4)_n$ target in this facility are shown in Figure 4.

MEASUREMENT OF FUSION YIELDS

We measured DD fusion yields with $(C_2D_4)_n$ targets. The targets were made by compacting $(C_2D_4)_n$ powder mixed with 1 wt% colloidal carbon under ~1 kbar. Figure 5 shows the energy dependence of the 3-MeV fusion proton yields measured when D_2O clusters impacted on the targets. The incident clusters had a mass distribution with a peak at 115 molecules/cluster and 5% FWHM. In Figure 5, our data are shown as open squares and those of Beuhler et al. are shown as filled-in circles.[2] Both the magnitude and energy dependence of our data are in excellent agreement with those of Beuhler et al. The agreement is striking considering that our experimental arrangement is very different from theirs.

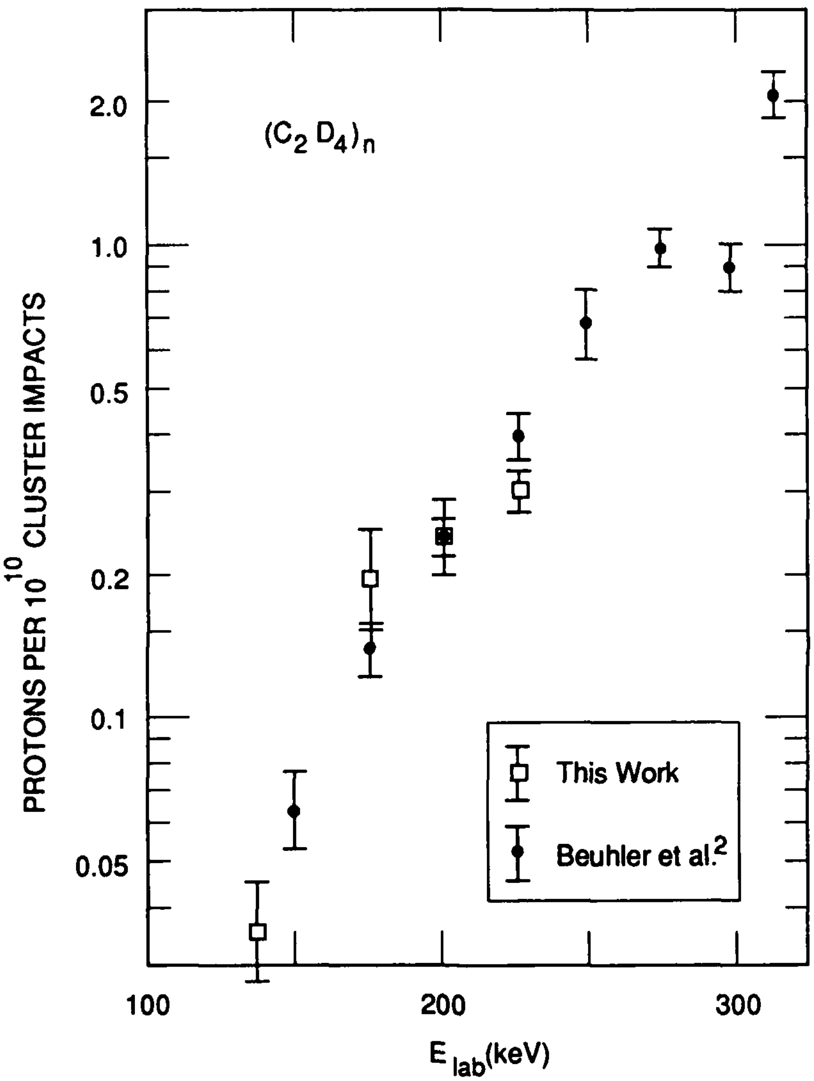
The first successful explanation of the experimental results was reported by Echenique et al.[3] Using a model based on the large energy and density fluctuations in swift-cluster impact, they calculated orders of magnitude and energy dependence of the fusion yield qualitatively similar to those of the experimental data. In their model, the major contribution to the enhanced fusion yield resulted from the small number of D atoms in the high energy tail of the Maxwell-Boltzmann velocity distribution function. They also suggested that the temperature of the collision region is very high because the highly correlated, coherent collisions confine atoms in the clusters to regions of the target with dimensions comparable to the cluster size.

Figure 6 shows the cluster size dependence of the total DD fusion yield measured at a cluster beam energy of 225 keV. A log-log scale is used for this plot. Beuhler et al.[2] obtained the cluster size dependence at 300 keV using clusters with a mass distribution of 38% FWHM. Their yield has a peak at n = 200 and decreases by a factor of three at n = 100 and 350. Our measured yield at 225 keV has a less pronounced size dependence and seems to have a peak near n = 100.



CA-330583-16

Figure 4. Typical DD fusion signals observed with the impact of $(D_2O)_n^+$ clusters on a $(C_2D_4)_n$ target.



CM-330532-10A

Figure 5. Energy dependence of the observed 3-MeV protons from DD reactions with the impact of $(D_2O)^+_{115}$ clusters on a $(C_2D_4)_n$ target.

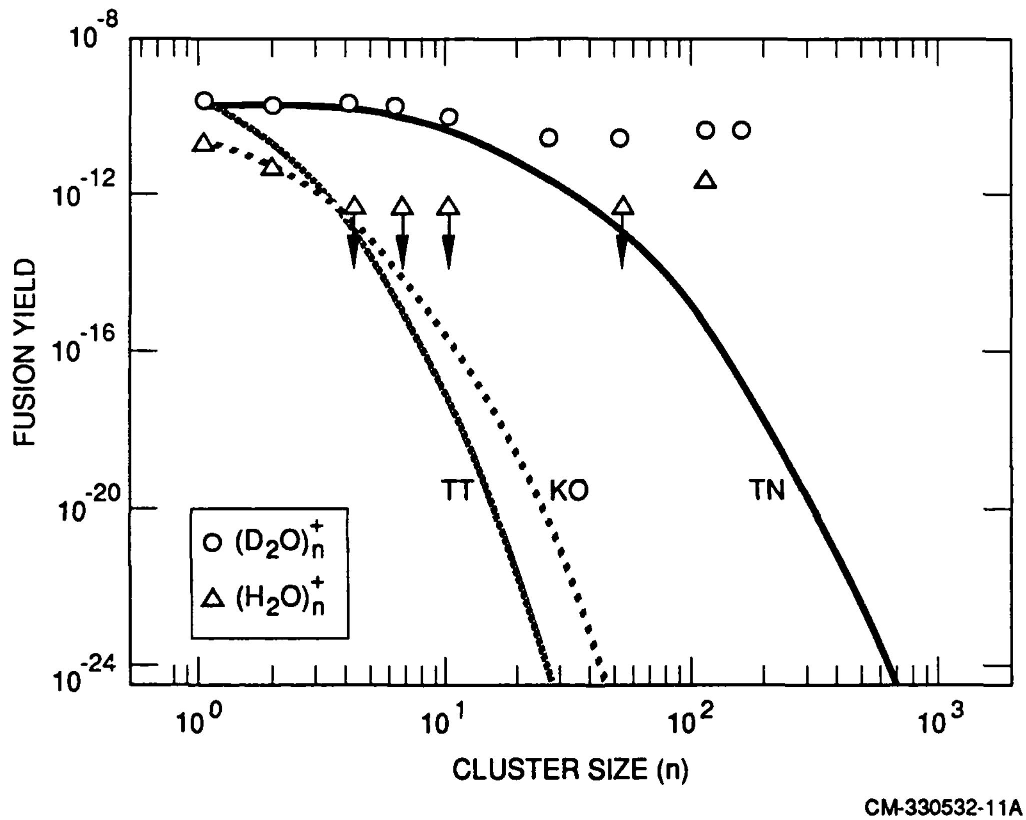


Figure 6. The total DD fusion yield at the impact energy of 225 keV as a function of the cluster size n.

Carraro et al.[4] have obtained analytical formulas for fusion yields using several different models. So that general trends and orders of magnitude can be compared, Figure 6 also shows the results of theoretical calculations by various models of the fusion yield of D_2O clusters impacting on a TiD target. In Figure 6, the TT curve represents the thick-target model, which assumes that deuterons in the projectile clusters undergo fusion reactions with the target deuterons while slowing down in the target as a function of the stopping power. The KO curve represents the knock-on model, which considers substrate deuterons knocked on by oxygen atoms in incident clusters. This curve was obtained by dividing Eq. (8) in Reference 4 by a factor of 10 to compensate for the deficiencies of the parameterization in the universal cross section, Eq. (7) of this reference, used in their modeling. The TN curve represents a thermonuclear model that assumes thermalization of the atomic degrees of freedom upon impact of clusters.

It is interesting that our measured data on D_2O clusters follow the TN model curve for clusters up to 10 molecules in size. However, for $n > 10$, our data deviate rapidly from the TN curve as n increases; this deviation indicates the existence of some unknown cluster size effects. The difference between thermonuclear model of Carraro et al.[4] and the model of Echenique et al.[3] is the existence in the latter of a temperature enhancing mechanism caused by the correlated, coherent collisions. Echenique et al.[3] qualitatively explain that the observed size dependence of the yield results from two effects: The decrease observed in the larger clusters is due to the same amount of translational energy being distributed over a larger region of the target, which results in a lower effective temperature of the localized impact spot. However, if the cluster becomes substantially smaller than 100 molecules, the impact region has dimensions comparable with the mean free path between collisions; here too, the energy is dispersed, resulting in a lower temperature of the localized impact spot. Thus, one might wonder if the deviation appearing above $n = 10$ results from the triggering of correlated collisions.

The possibly related cluster size effect had also been observed in an earlier study of cluster impact by Beuhler.[5] In his experiment, he observed the the secondary electron coefficients of water cluster ion impact on copper at velocities near 100 km/s. He found that the secondary electron coefficients at velocities less than 100 km/s obey an additive relationship: the electron yield from a cluster at a particular velocity is equal to the sum of the contribution from each of the component molecules in the cluster.[5] The secondary electron yield at those velocities agrees well with the theoretical yield estimated from the conventional stopping power model. However, the yield at velocities greater than 100 km/s was found to deviate from yield calculated using the conventional model. Beuhler[5] proposed that the deviation results from the formation of a partial plasma in the top layers of the target. He also proposed that the deviation might occur because the nuclear stopping power of the correlated cluster collision, similar to the one proposed by

Echenique et al.,[3] may be significantly higher than that of a single particle impact. The increase in the nuclear stopping power decreases the projected range and, thus results in a decrease in the secondary electron yield, which is a function of the electronic stopping power only. The deviation of the secondary electron yield also seems to be related with the highly correlated multiple collisions induced by cluster impact. Therefore, measurement of the secondary electron yield should be a good diagnostic for studying cluster impact process.

Fusion reactions were also observed for H_2O clusters impacting on the $(C_2D_4)_n$ targets. Both the magnitude and cluster size dependence of the fusion yield of H_2O clusters are much different from those of D_2O clusters. The fusion yields of $(H_2O)_n^+$ clusters with n = 1 and 2 seem to agree with the value based on the knock-on (KO) model. No fusion event was observed for $(H_2O)_n^+$ clusters with n between 4 and 50 during the integration times of 3 hours for each datum. For comparison, the upper bounds (which were obtained by setting the observed counts at 0.5) are shown in Figure 6 as arrows. However, n = 115 clusters produced an observable fusion yield, i.e., 5 ± 2% of the yield of D_2O clusters. This observed ratio is in excellent agreement with the ratio of ~5% observed by Beuhler et al. The difference between the fusion yields of D_2O and H_2O clusters is very intriguing. One might wonder whether the difference indicates that thermalization of projectile D atoms is different from thermalization of target D atoms.

CONCLUSIONS AND IMPLICATIONS FOR FUTURE WORK

We proposed that cluster-impact fusion (CIF), the use of cluster ions for igniting nuclear fusion, is a promising way of achieving an extremely high energy density for rocket propulsion. The energy density that can be achieved by CIF with DT fuel is 3.4×10^{14} J/kg, which is eight orders of magnitude larger than the energy density of LOX/H_2 (1.6×10^6 J/kg). We predicted, that for missions with $I_{sp} < 10^5$ s, CIF rocket performance will be essentially identical to that of antimatter. However, production and storage of CIF fuels will be straightforward, because it uses regular matter instead of antimatter.

Under the current project, we have constructed and demonstrated a cluster-impact fusion facility that includes a new high intensity water cluster ion source and a 300-kV electrostatic accelerator. With the facility, we have successfully reproduced and extended the results obtained by BNL scientists. We are now confident that the extreme fusion enhancement observed in cluster-impact fusion is real, and we are ready to investigate means of increasing the fusion yield to a practical level. Our ideas are explained in detail in our new proposal entitled "Cluster Impact Fusion Propulsion," which is submitted under separate cover.

REFERENCES

1. R. J. Beuhler, G. Friedlander, and L. Friedman, Phys. Rev. Lett. **63**, 1292 (1989).
2. R. J. Beuhler, Y. Y. Chu, G. Friedlander, L. Friedman, and W. Kunnmann, J. Phys. Chem. **94**, 7665 (1990).
3. P. M. Echenique, J. R. Manson, and R. H. Ritchie, Phys. Rev. Lett. **64**, 1413 (1990).
4. C. Carraro, B. Q. Chen, S. Schramm, and S. E. Koonin, Phys. Rev. A **42**, 1379 (1990).
5. R. J. Beuhler, J. Appl. Phys. **54**, 4118 (1983).