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Measurement of hydrogen and lithium ion energy densities on PBFA II using direct nuclear activation diagnostics

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ABSTRACT

In the light-ion-beam fusion program at Sandia National Laboratories an intense lithium beam is being developed to drive inertial confinement fusion targets. An important issue is the purity of the beam. To assess this concern, direct nuclear activation diagnostics based on the reactions $^{7}Li(p,n)^{7}Be$, $^{10}B(p,\alpha)^{7}Be$, and $^{19}F(^{7}Li,d)^{24}Na$ were fielded to measure the energy densities of hydrogen and lithium in the beam. The hydrogen beam energy density was measured to be less than 2% of the lithium beam energy density on a majority (10) of the 19 LiF anode shots taken and was always less than 10%. The total hydrogen energy in the beam ranged from only 0.5 to 10 kilojoules. Over this shot series increasing efforts were made to clean the anode prior to each shot. In general, there was a modest reduction in the hydrogen energy fraction with improved cleaning, but no corresponding

increase in the lithium energy density was seen. The lithium energy density as a function of location was also measured and found to typically vary by factors of 1.5 to 4 over the diode.

I. INTRODUCTION

Intense lithium beams are being developed at Sandia National Laboratories (SNL) on the Particle Beam Fusion Accelerator II (PBFA II) as a driver for light-ion, inertial-confinement-fusion experiments. An important issue is the purity of the lithium beam. It has been conjectured that impurities in the beam create a "parasitic load" that significantly degrades the diode performance. The most likely beam impurities are hydrogen and carbon ions which could arise from hydrocarbons that might be contaminating the anode surface and/or remaining as residual gases in the diode. In addition, fluorine ions may be present since the most common anode material is lithium fluoride (LiF).

In an effort to reduce any hydrocarbon impurities in the beam, a series of experiments were performed on PBFA II in which the vacuum was improved and the anode surface was cleaned by heating and RF discharge.[1] To help quantify the effectiveness of these improvements, we developed and fielded a set of direct nuclear activation diagnostics that could measure the energy densities of the lithium and hydrogen ions in the beam. We also developed diagnostics for carbon and fluorine, but these two diagnostics are insensitive to ions having kinetic energies less than about 12 MeV which was the case in these experiments. The calibration of these diagnostics is discussed in a companion paper.[2]

II. EXPERIMENTAL APPROACH

A direct nuclear activation diagnostic is based on the fact that ions of sufficient kinetic energy can induce radioactivity in a material. This process can yield information about the beam[3-5] since the type and amount of activity induced in a particular material depends on the type, fluence, and kinetic energy distribution of the ions incident on the sample. In this work, we wish to measure the beam energy carried by each type of ion. To field such a diagnostic, a target material is exposed to the beam, recovered, and the induced activities, if any, measured. The beam energies are then inferred from the measured activities, the reaction thick target yields, and the time dependent diode voltage and current waveforms.

For this technique to be accurate, all the induced activity must be collected and counted. On PBFA II this requirement becomes an issue because the beam is sufficiently intense to ablate the sample. To address this potential problem, we field the samples in tantalum clad stainless steel containers which we call "pepper shakers". These pepper shakers are 1.5 cm long, 1 cm in diameter, and on one end have a 0.28 cm diameter hole through which a fraction of the beam can enter and strike the target. This approach minimizes ablation and its consequences by reducing the energy density incident on the samples and providing a reservoir to retain any ablation products. With this geometry, however, pin hole closure becomes a concern, but because the holes are large, closure is unlikely. We have evidence, discussed below, that neither ablation nor pin hole closure was a problem in these experiments.

The diagnostics used in this work are based on the reactions $^{7}Li(p,n)^{7}Be$, $^{10}B(p,n)^{7}Be$, $^{19}F(^{7}Li,d)^{24}Na$, $^{14}N(^{12}C,2p)^{24}Na$, and $^{11}B(^{19}F,2p)^{28}Mg$. LiF targets are used to measure hydrogen and lithium and boran nitride (BN) targets are used to measure hydrogen, carbon, and fluorine. Because the diagnostics were insensitive to carbon and fluorine at the typical ion kinetic energies encountered in these diode experiments, the majority of the data were taken with LiF targets which yielded the most information.

We fielded these diagnostics on a total of 25 barrel diode[1] shots. The barrel diode is fully described in reference 1 but basically consists of a cylindrical anode that is 15 cm in radius and has an active height of about 9 cm. A magnetic field suppresses electron flow, allowing ions to propagate radially inward through a virtual cathode and focus at the center of the diode. To provide ion beam current and charge neutralization, the central region of the diode is usually filled with a low-pressure argon gas which is contained by a 1.5 μm-thick, mylar window located at a radius of about 12 cm. On the experiments reported here, all shots used gas transport except for four vacuum transport shots. Two different ion sources were also used on these experiments. Nineteen of the shots employed a LiF anode source. The remaining six shots employed the Laser EVaporation Ion Source[6] (LEVIS) which is an active source that employs a LiAg anode and laser assisted ionization. On the last LEVIS shot, however, the long-pulsed laser was not employed.

We fielded vertical rows of 2 to 5 pepper shakers each in each of the three available quadrants of the diode. The pepper shakers were placed just inside the gas cell (when present) at a nominal radius of 12 cm. On the LiF anode shots the pepper shakers were centered about the diode midplane, while on the LEVIS shots they had to be located above the diode midplane so as not to obstruct the LEVIS laser beam. On five shots pepper shakers were also fielded immediately adjacent to the ErD_2 indirect activation diagnostic[3] which is located at a radius of 4 cm to provide a direct comparison between these two diagnostics.

The raw data consist of the measured activities of ^{7}Be and ^{24}Na induced in the LiF and/or BN samples. From these measurements, the thick target yield curves, and the voltage and current waveforms, we can infer the energy of hydrogen and lithium that was incident on each sample. From this energy and the pin hole size, we can obtain the energy density. In calculating each energy, we assume that the lithium is singly charged and that the hydrogen is atomic (H^+), although it is possible that the hydrogen is actually molecular (H_2^+). If the hydrogen were molecular, the values for the hydrogen beam energy reported here would increase by about a factor of two.

On each shot we obtain 8 to 20 "point" measurements of the lithium and hydrogen energy densities. To estimate the total hydrogen and lithium beam energy from their respective, measured energy densities, we first calculate the mean values of the energy densities and then scale them by an effective beam area. Because our measurements indicate that the beam is nonuniform and randomly distributed and because the pepper shakers only sample about one half of the predicted beam height, the total energy we calculate can only be approximate. We feel a reasonable, lower estimate for the total beam energy is obtained by assuming that the beam has a constant energy density equal to the mean value over the region sampled by the pepper shakers and decreases linearly to zero from the top and bottom pepper shakers to the top and bottom of the diode, respectively.

III. EXPERIMENTAL RESULTS

The quality of our results depends on adequately integrating the reaction yields over the voltage and current time histories and on avoiding ablation and pin hole closure. On five shots we addressed these issues by placing pepper shakers immediately adjacent to the ErD_2 indirect nuclear activation diagnostic[3] which is located at a diode radius of 4 cm. These two diagnostics employ different nuclear reactions and have different energy dependencies, so good agreement between the two would give us confidence that the energy measurements are accurate. In addition, the ErD_2 diagnostic is subject to neither ablation effects nor pin hole closure, so good agreement would also imply that the pepper shakers were not suffering significantly from these effects. Table I lists the lithium beam energy as determined by each of these diagnostics and the magnetic spectrometer when those results were available. Within error bars these diagnostics agree. Thus, we conclude that ablation and pin closure are not significant on these experiments and that our results are accurate within error bars.

Unfortunately, although our results are accurate, the uncertainties in the measurements are relatively large. The principal contributor to the uncertainty in our measurements was the spatial nonuniformity in the beam. To help quantify the spread in beam energy density that we observed, we calculated a mean and standard deviation on each shot for both lithium and hydrogen energy densities. We also calculated the ratio of the highest measured energy density to the lowest on each shot. For lithium, the standard deviations ranged from 9% to 108%. The average of the standard deviations was 30%. The ratios of the highest to lowest energy densities on each shot ranged typically from 1.2 to 4, although on two, atypical shots, the ratios were 95 and 300. The average ratio was three. In addition to the uncertainties due to these spatial variations, the total uncertainties include uncertainties associated with counting statistics, the thick target yield curves, and the voltage and current measurements. The total uncertainty in the lithium beam energy is typically +/- 50%.

The hydrogen energy density exhibited far more variability. Often one or two pepper shakers registered strong hydrogen signals while the rest would have small or zero signals (by "zero" we mean that the activity, if any, was below detectable limits). Calculating a mean value clearly has less validity in this case, but if one goes through the exercise, the average standard deviation would be 100% for the spatial variation observed. Although the total uncertainty then becomes +/- 150%, we did conclusively observe hydrogen on every shot so that the lower bound on the hydrogen energy density must always be greater than zero.

Fortunately, even with these large uncertainties, we can conclude that only a small fraction of the total beam energy is carried by hydrogen and that the lithium beam energy does not appear to depend strongly on how much beam energy carried by hydrogen. The LiF anode and LEVIS shots, however, exhibited quite different behavior with respect to the hydrogen content of the beam. In general, both the total energy carried by hydrogen and the hydrogen energy fraction were significantly lower on the LiF anode shots than on the LEVIS shots. Here the hydrogen energy fraction is defined as the hydrogen beam energy divided by the sum of the hydrogen and lithium beam energies; a definition that ignores any beam energy carried by other ions such as carbon.

On the LiF anode shots, the hydrogen beam energies and fractions ranged from 0.5 to 12 kJ(+/-150%) and 1% to 9%, respectively. These hydrogen levels are significantly lower than seen on an earlier diode series.[6] On the five shots on which the LEVIS source was fully implemented (those on which the long pulse-laser was fired), however, the total hydrogen beam energy ranged from 11 to 74 (+/- 150%) kJ and the hydrogen fractions ranged from 13% to 95%. These values are much higher than the LiF anode shots and also much higher than the sixth "LEVIS" shot on which no long-pulse laser was used and the hydrogen energy was only 3 kJ and the hydrogen fraction was only 4%. These values are nearly identical parameters to those observed on the LiF anode shots. These results strongly suggest that the significant differences observed between the two types of sources result from the use of the laser. It is possibly that the laser ionizes residual gases in the diode and/or liberates and ionizes contaminants on the surface of the anode which results in more energy being carried by hydrogen.

Despite the fact that the hydrogen fraction was reduced in the case of the LiF anode shots, there appeared to be no corresponding increase in the lithium beam energy beyond a certain level. Figure 1 shows lithium beam energy as a function of hydrogen beam fraction. The LEVIS data appear to show a gross trend in which the lithium beam energy increases as the hydrogen beam fraction decreases. For hydrogen beam fractions less than about 10%, which includes all LiF anode shots, however, there appears to be no correlation between the hydrogen beam fraction and lithium beam energy. It is possible that a correlation does exist but that the uncertainties in the measurements obscure it. Nor does there appear to be a correlation between hydrogen and lithium beam energies for hydrogen beam energies less than about 12 kJ. These results suggest that amount of lithium beam energy generated does not depend strongly on the absolute magnitude of the hydrogen energy in the beam. More subtle factors such as the timing of the hydrogen beam relative to the voltage pulse or the location of the hydrogen source within the diode may be more important than the magnitude of hydrogen energy in the beam. Unfortunately, the time-integrated, direct-nuclear-activation diagnostics cannot address the timing issue and in these experiments they were not fielded in a manner that might have allowed the source location issue to be addressed.

IV. CONCLUSIONS

We have successfully fielded direct nuclear activation diagnostics to measure the energy carried by lithium and hydrogen in the ion beams generated by the PBFA II barrel diode. In general, the hydrogen beam energy was only a small fraction of the lithium beam energy. The new diode system did result in a purer lithium beam, but there did not seem to be a corresponding increase in the total lithium beam energy.

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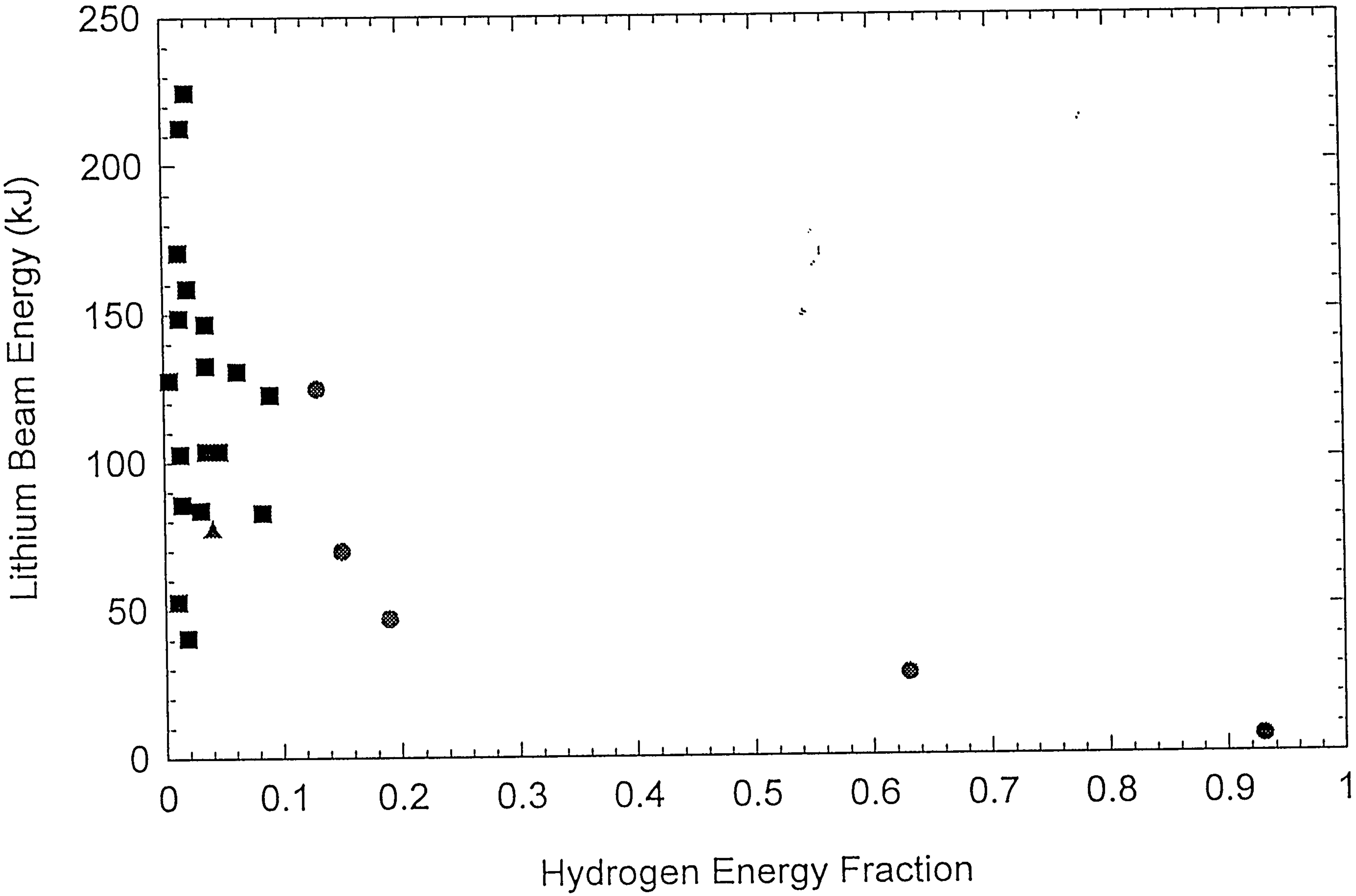
Table I

Total Lithium Beam Energy

Shot	Pepper Shakers at 4 cm	ErD_2	Magnetic Spectrometer
6711	98 kJ	96 kJ	89 kJ
6717	61 kJ	85 kJ	91 kJ
6725	64 kJ	44 kJ	---
6737	121 kJ	122 kJ	---
6740	34 kJ	58 kJ	---

FIGURE CAPTIONS

Figure 1. Plot of total lithium beam energy at a diode radius of 12 cm versus hydrogen beam fraction. The squares are LiF anode shots; the circles are LEVIS shots: and the triangle is the LEVIS shot on which the long-pulse laser was not employed.



250
200
150
100
50
0
Lithium Beam Energy (kJ)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Hydrogen Energy Fraction

Figure 1

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