Distribution of Ions in Laser Driven Fusion Reactions

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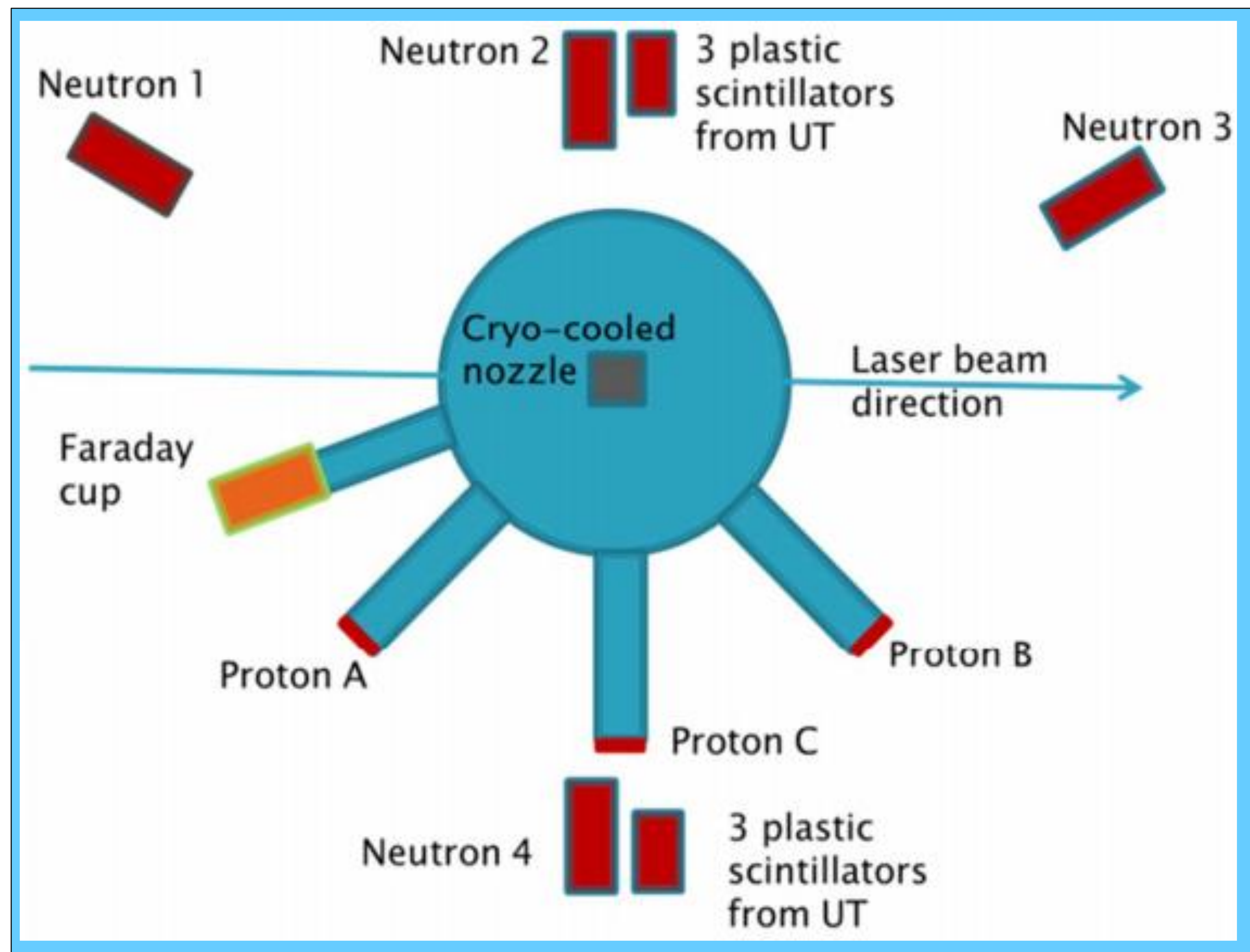
Introduction

Experiments of fusion reactions driven by lasers are important for many aspects, such as measuring the cross section and reaction rates of plasma. In experiments using the Texas Pettawatt Laser at University of Texas, D_2 clusters of various sizes mixed with ^{3}He gas absorb laser's energy and are ionized. The D_2+^{3}He clusters undergo a Coulomb explosion, creating a hot plasma which causes the reactions. [1-3] This analysis studies two possible fusions: D(d, ^{3}He)n and ^{3}He(d,p)^{4}He. The energy distribution of the ions within the clusters can be described by a Maxwell-Boltzmann distribution, a shifted Maxwell-Boltzmann distribution, or a log-normal distribution. [4] This work analyzes the log-normal distribution by using the S-factor and the fits to estimate the number of fusions. These yields are compared with experimental data to determine if the log-normal distribution is an accurate description.

The Experiment



A faraday cup with a diameter of 16mm was placed 1.07m from the plasma. A cryo-cooled gas mixture of D_2+^{3}He was released from gas jet. A 90-180J pulse from the Texas Pettawatt Laser removed the electrons from the D_2 clusters. The clusters form a hot plasma due to the Coulomb explosion. [1-4]

Figure 1: A diagram of the experimental set up [1-3]

The hot deuterium ions in the plasma can undergo three possible fusion reactions: D(d,t)p, D(d, ^{3}He)n, and D(^{3}He,p) ^{4}He. The last two reactions, which produce 2.45 MeV protons and 14.7 MeV neutrons, are analyzed. Only the D_2 clusters in the laser field are irradiated, so some D_2 clusters are cold. The hot deuterium ions can fuse with other hot deuterium ions or cold deuterium ions to form ^{3}He. Thus there are two contributions to the number of neutrons produced. Since the ^{3}He is cold, there is only one contribution to the number of protons produced. [1-3]

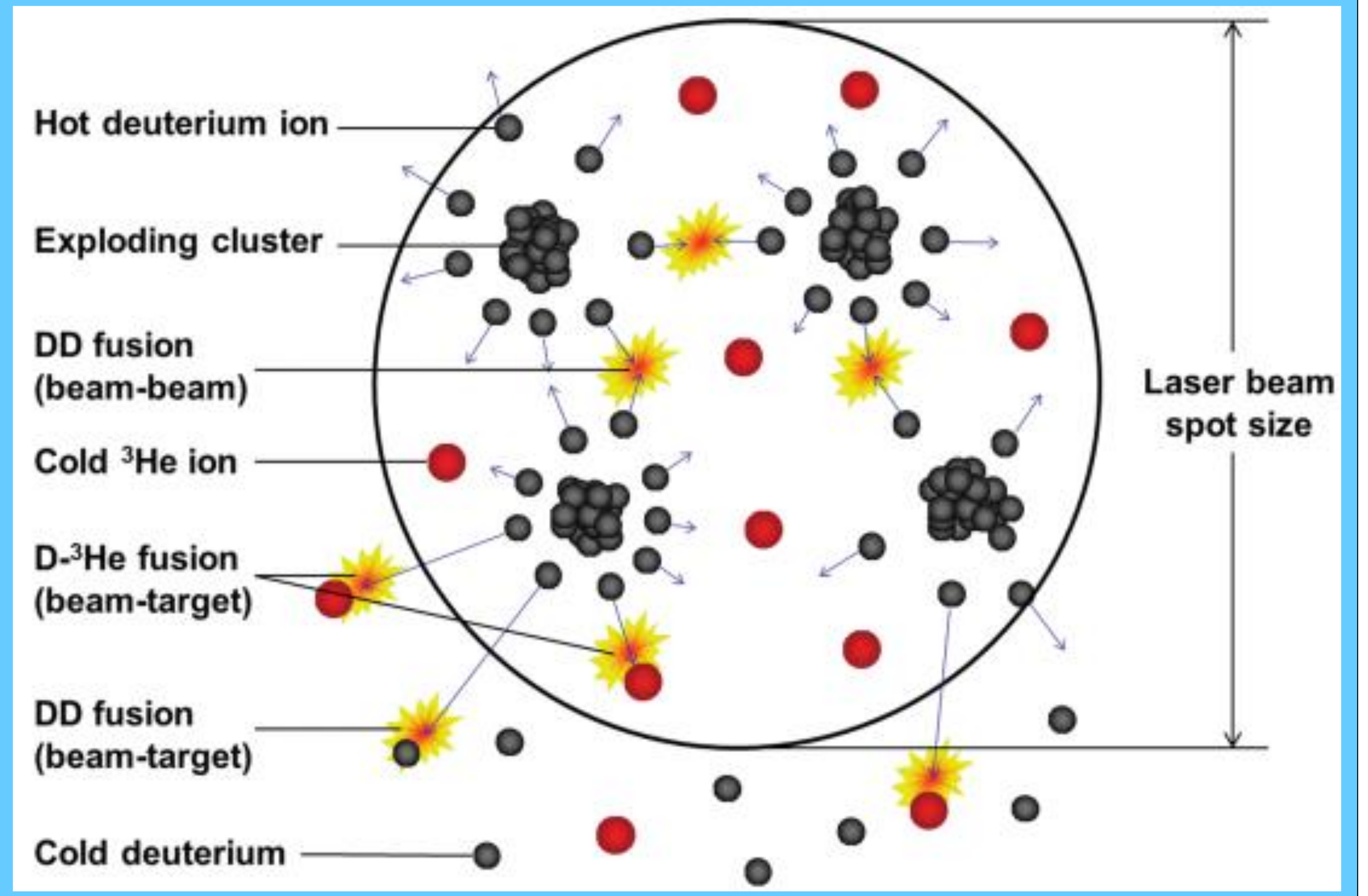


Figure 2: A diagram of the different reactions [1-3]

The Signal

The Faraday cup records the current. The initial spike is caused by intense x-ray emission due to the electromagnetic field. [1] The x-rays affect the response time of the Faraday cup.

The data is transformed into energy space for analysis using the equation:

$$\frac{dN}{dE} = \frac{s}{mv^3}\frac{dV}{qeR}$$

Where s is the distance of the Faraday cup, m is the mass of deuterium, v is the velocity of the ions, dV is the voltage, q is the charge state, e is the elementary electron charge, and R is the resistance. [1-3]

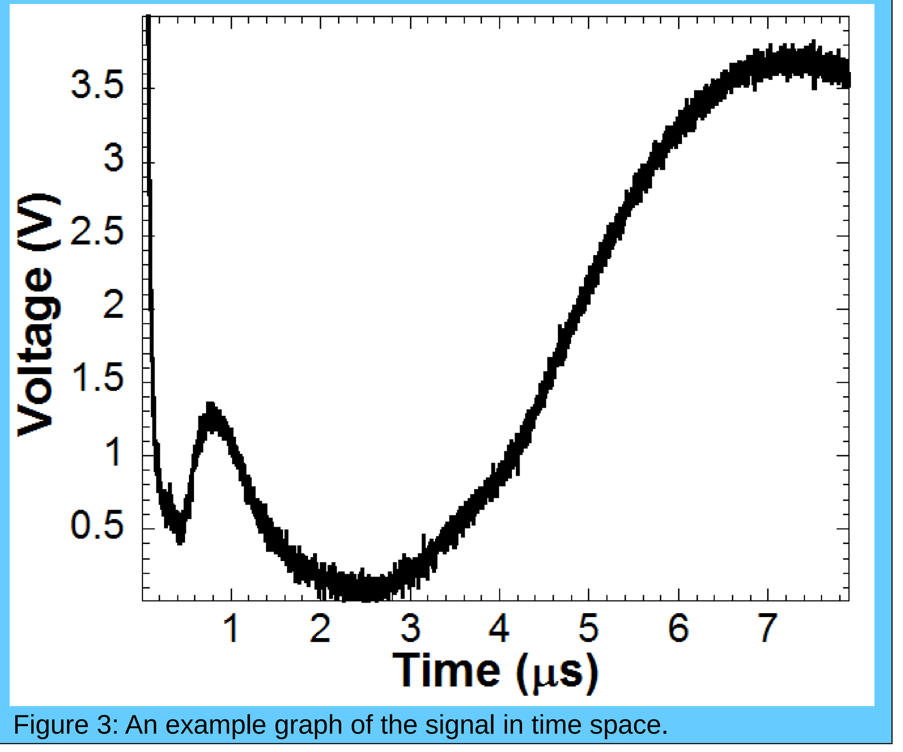


Figure 3: An example graph of the signal in time space.

Log-normal Distribution

The log-normal distribution of the density of cluster size M takes the form:

$$n_C(M) = \frac{M_0}{M\sqrt{2\pi\sigma^2}} e^{-\frac{(\ln M-\mu)^2}{2\sigma^2}}$$

Where M_0 is the normalization constant, μ and σ are the mean and standard deviation of the distribution of the natural logarithm of the cluster size. [1-2,4-8] The Coulomb energy E is related to M through the equation:

$$\frac{V_C}{M} = 5.1 * 10^{-3} M^{\frac{2}{3}} = E_d \text{ [9]}$$

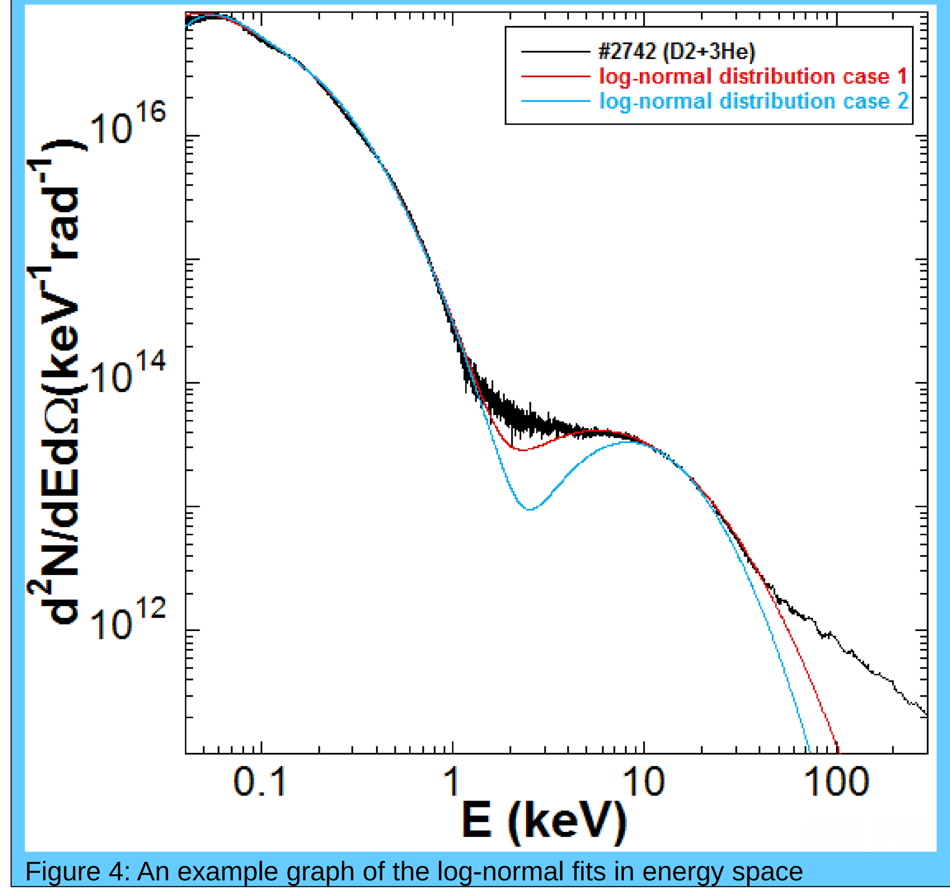


Figure 4: An example graph of the log-normal fits in energy space

The signal is analyzed and fit in M space then transformed to energy space. The log-normal distribution describes the distribution of the cluster size, but by using the transformation, also describes the energy distribution of the deuterium ions. [1-2,4-8] If the log-normal distribution is the best description, the energy distribution of the hot deuterium ions is so chaotic that it appears thermalized. The chaos is caused by many-body interactions over long distances as well as different charges and different masses of the particles involved. [10]

Fusions

From the fit in energy space and using the measured cross section for the appropriate reaction, the number of fusions is estimated. For d+d hot-hot fusions, the following equation is used:

$$< NoF > = \rho_D l N_D < \sigma_{D+D} >$$

where ρ_D is the density of deuterium ions, l is the "radius of a sphere with volume equal to a cylindrical plasma of radius r and height R" [9] (.25 cm), and $< \sigma_{D+D} > = \int \frac{dN}{dE}\sigma(E)dE$ is the average cross section between hot deuterium ions. For d+d hot-cold fusions, R-l is used instead of l and the cross section for hot-cold deuterium ions is used, i.e., $E_{CM\,hc} = \frac{1}{2}E_{CM\,hh}$. For d+3He fusions, the following equation is used:

$$< NoF > = \rho_{3He} R N_D < \sigma_{D+3He} >$$

where the cross section for d+3He is used, i.e., $E_{CM\,D+3He} = \frac{3}{5}E_{CM\,hh}$ [1-3]

Results

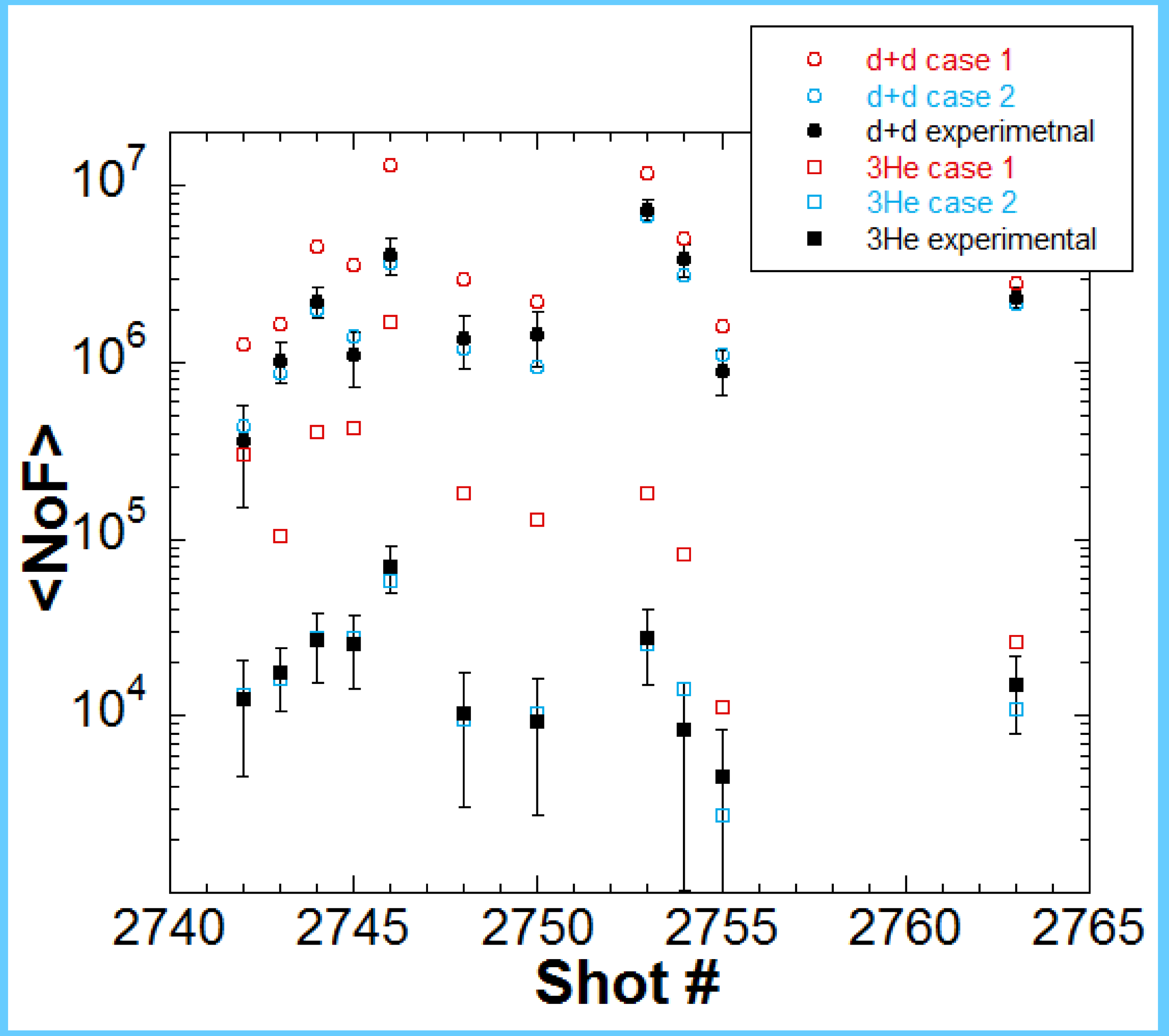


Figure 5: The graph of number of fusions by each shot

Conclusions

We were able to fit the signal well using the log-normal distribution. However, using the good fit, the number of fusions is an overestimation in all cases, as seen with case one (red) in Figure 5. Then we adjusted the fit until we were able to match the experimental yield i.e., log-normal distribution case two (blue). However, the fit does not actually fit the data, as seen in Figure 4. We were unable to both fit the data and match the experimental yield with the same curve, indicating that the log-normal distribution does not accurately describe the energy distribution of the ions.

References

[1] E. W. Gaul *et al.*, Appl. Opt. 49, 1676 (2010).
[2] W. Bang, M. Barbui, A. Bonasera, G. Dyer, H. J. Quevedo, K. Hagel, K. Schmidt, F. Consoli, R. De Angelis, P. Andreoli, E. Gaul, A. C. Bernstein, M. Donovan, M. Barbarino, S. Kimura, M. Mazzocco, J. Sura, J. B. Natowitz, and T. Ditmire, Phys. Rev. Lett. 111, 055002 (2013).
[3] M. Barbui, W. Bang, A. Bonasera, K. Hagel, K. Schmidt, J. B. Natowitz, R. Burch, G. Giuliani, M. Barbarino, H. Zheng, G. Dyer, H. J. Quevedo, E. Gaul, A. C. Bernstein, M. Donovan, S. Kimura, M. Mazzocco, F. Consoli, R. DeAngelis, P. Andreoli and T. Ditmire, Phys. Rev. Lett.
[4] J. Zweiback, R. A. Smith, T. E. Cowan, G. Hays, K. B. Wharton, V. P. Yanovsky, and T. Ditmire, Phys. Rev. Lett. 84, 2634 (2000).
[5] W. Bang, H. J. Quevedo, G. Dyer, J. Rougk, I. Kim, M. McCormick, A. C. Bernstein, and T. Ditmire, Rev. Sci. Instrum. 83, 063504 (2012).
[6] M. Lewerenz, B. Schilling, and J. P. Toennies, Chem. Phys. Lett. 206, 381 (1993).
[7] K. W. Madison, P. K. Patel, D. Price, A. Edens, M. Allen, T. E. Cowan, J. Zweiback, and T. Ditmire, Phys. Plasmas 11, 270 (2004).
[8] W. Bang, G. Dyer, H. J. Quevedo, A. C. Bernstein, E. Gaul, M. Donovan, and T. Ditmire, Phys. Rev. E 87, 023106 (2013).
[9]] M. Barbarino, M. Warrens, D. Lattuada, W. Bang, A. Bonasera *et al.*, Is the process of laser driven fusion so chaotic to resemble thermalization? To be published
[10]A. Bonasera, Fusion 2003, Progr.Theor.Phys.154,261 (2004).

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