Title

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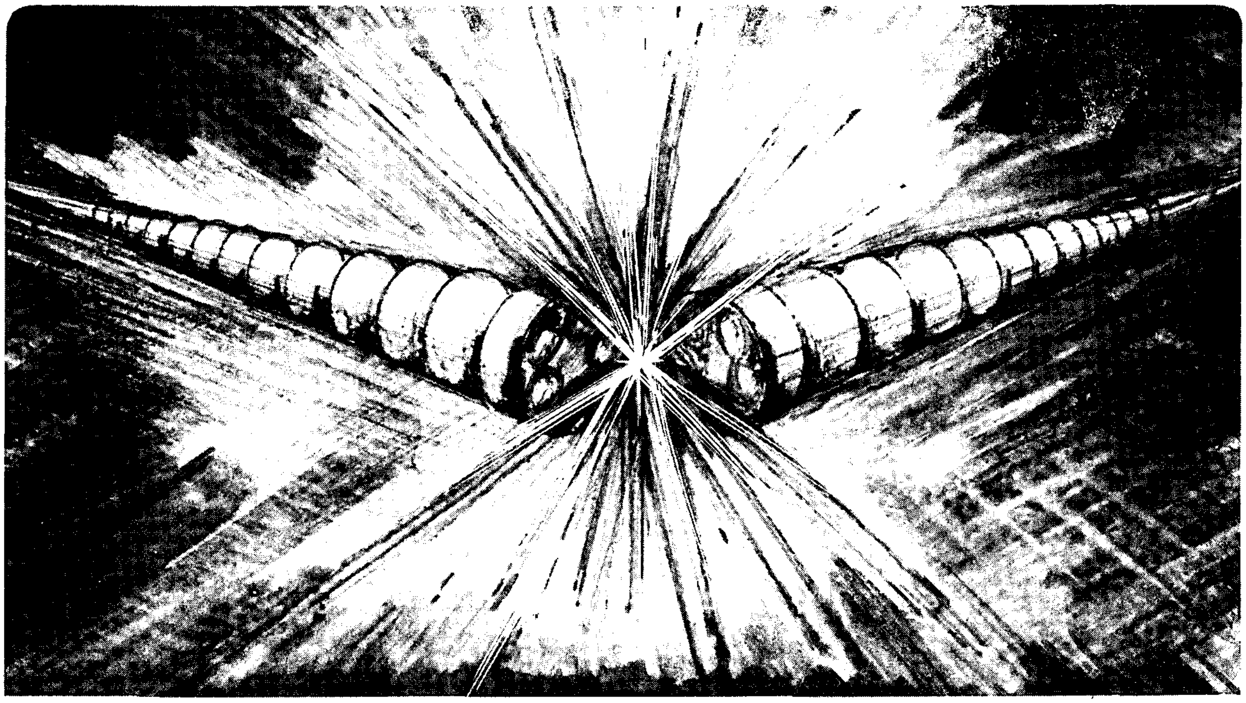

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A NEUTRAL-BEAM DIAGNOSTIC FOR FAST CONFINED ALPHA PARTICLES IN A BURNING PLASMA: APPLICATION ON CIT*

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Measurement of the slowing-down distribution for fast confined alpha particles is essential for a D-T burning-plasma experiment. Quantitative estimates of signal level for a fast neutral-beam probe using a two-electron-capture method of measuring the alpha-particle velocity distribution are presented as applied to the proposed tokamak CIT (Compact Ignition Tokamak). The best probe is found to be a fast ground-state helium-atom beam because of its relatively good penetration into a dense plasma and because of the large cross section for two-electron capture; fast He^0 can be produced in useful quantities from fast HeH^+, which is sufficient to allow time-resolved measurements of the alpha-particle velocity distribution in CIT.

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INTRODUCTION

A necessary condition for the achievement of ignition in a magnetically confined fusion-reactor plasma is that the energy produced by the fusion of the reactants be used to maintain the ignition conditions of the plasma . In a tokamak reactor, a large part of this energy feed-back will come from the thermalization of alpha particles produced in the reaction

$$T(d,n)\ {}^{4}He\ (17.6\ MeV). \qquad (1)$$

The alpha particles (${}^{4}He$ nuclei) are produced with a center-of-mass energy of 3.5 MeV (880 keV/u specific energy, which is equivalent to a velocity of 1.3×10^{9} cm/s) and are contained, for the most part, by the magnetic field of the tokamak. Thermalization is expected to occur through binary collisions with slower plasma constituants, thus heating the plasma to maintain reactor conditions. This "classical" slowing-down process results in a density distribution which has a $1/v^{3}$ dependence between the initial energy and thermalized energy of the alpha particles.[1]

The purpose of this paper is to present an analysis of one method (two-electron capture from a neutral-atom probe beam) for determining the alpha-particle distribution in the proposed Compact Ignition Tokamak (CIT) which is being planned to achieve ignition conditions.[2]

I. Experimental Considerations

A. The Compact Ignition Tokamak

The CIT is being designed as a high-density (> 10^{14} cm^{-3}), high-magnetic field (~ 10 T), relatively small toroidal reactor, with energy gain greater than 1. The CIT geometry[3], as it is presently planned, offers rather limited access to the plasma for diagnostic purposes. The diagnostic must utilize a pair of parallel vertical diagnostic ports, which are presently planned to be 5 m apart, with entrance and exit diameters of 5 and 10 cm, and offset radially from each other. At a mimimum, the plans will have to be modified to include two such ports of about 5-cm. diameter, which are coaxial or with axes that intersect near the center of the plasma.

B. Two-Electron Capture

Neutral atoms with two or more electrons, injected into the CIT plasma, could serve as a target for two-electron transfer with the fast alpha-particles to produce fast neutral He atoms (Eq. 2).

$$He^{++} + X^{o} \rightarrow He^{o} + X^{++} \qquad (2)$$

Some of the atoms thus produced will traverse the remaining plasma and can be reionized and energy analyzed, or otherwise detected. One of the early proposals for the use of this technique was made by D. E. Post et al[1] who suggested that a neutral He beam be used because of the large two-electron-capture cross section for this resonant process at low relative velocities. If the target beam had sufficient energy, it could selectively probe the alpha-particle distribution by matching velocities. The cross section for 2-electron transfer is appreciable only at small relative velocities. Later proposals included use of a neutral Li beam.[4] Since the initial distribution of the alpha particles at birth is around 880 keV/u, the target beam must have a specific energy of the same order (e.g., 500 - 900 keV/u).

C. Beam Penetration

The choice of a probing beam depends not only on the cross section for producing He^o by 2-electron capture, but also (especially in the hot, dense CIT plasma) upon its penetration into the plasma. To estimate the penetration length for various atom beams, the penetration of H^o atoms was studied first because of the existence of a computer code which includes multistep processes (HEXNB, written by C. D. Boley et al[5]). These results were compared with the measured cross section for ionization of H by proton impact to obtain an enhancement ratio for multistep processes and plasma impurities, and then that ratio was applied to the ionization cross sections for the various neutral beam candidates to obtain an approximate beam-stopping cross section including multistep processes and the effects of plasma impurities. Three candidate beams were selected for study (He, H_2 and Li): the penetration of these beams is shown in Fig. 1, along with that of H^o for comparison.

D. Beam Production

An intense energetic beam of neutral atoms or molecules can be produced by starting with a beam of ions from a suitable ion source. The beam is accelerated to a specific energy of the order of 880 keV/u, and then neutralized. Energetic beams of most species can be efficiently produced by neutralization of negative ions. Neutral beams can also be produced from positive molecular ions, e.g., a beam of H_2^o can be produced by breakup of H_3^+[6], and a beam of He^o can be produced by breakup of HeH^+[7]. A negative lithium ion beam can be produced with about 10 mA/cm^2 intensity and neutralized in a gas target with 40 - 50 % yield of Li^o at MeV energies.[8-10]. A beam of H_3^+ at 100 mA/cm^2 would yield about 4 mA/cm^2 (equivalent) fast H_2^o, and He^o from 30 mA/cm^2 HeH$^+$ could be made as intense as about 1 mA/cm^2. H_2^o and He^o yields are estimated from extrapolations of measured cross sections[6,7] and an expected 10 - 15% HeH$^+$ yield from a mixed He, H_2 ion source.[8]

E. Ion Source

The geometry of the CIT vertical ports and the emissivity of the beam determine the maximum useful size of the ion source. A good large-area ion source can produce a 100-keV beam with a divergence of 0.5^o. By scaling to 3 MeV (e.g., 750 keV/u ^{3}HeH$^+$) the emissivity is reduced such that the beam from a 600-cm^2 ion source focused at the center of the CIT could pass through both 5-cm-diam ports. Such a large-area source could produce about 15 A of HeH$^+$, which is much more current than is practical to accelerate to these energies. On the assumption that it is practical to accelerate 100 mA to these high energies, the neutral atom or molecule flux from HeH$^+$, H_3^+ and Li$^-$ would be 2 x 10^{16} He or H_2 particles/s or 2 x 10^{17} Li atoms/s respectively.

II. Calculation

A. Distribution Function

The calculation of the charge-transfer rate between injected fast atoms in the probe beam and alpha particles in CIT requires an estimate of the alpha-particle energy density distribution. The alpha particles are born at 880 keV/u in the center-of-mass of the d-t collision, with an energy spread that is determined by the center of mass velocity distribution of the reactants. The plasma temperature is 20 keV, while the $\overline{\sigma v}$ curve peaks at about 60 keV, hence the reaction will favor head-on collisions. The distribution of the center-of-mass motion of the fusing nuclei must peak at some lower equivalent energy so the expected quasi-thermal component of the alpha particles at birth will be small. The kinetic energy of the reactants is small compared to the reaction energy, therefore, the initial energy distribution of the alpha particles can be approximated as

$$F(E)_{init} = \exp\left(-\left(\sqrt{880} - \sqrt{E}\right)^2 /10 \qquad (3)$$

where E is in keV/u.

As the alpha particles slow down through binary collisions with the bulk of the plasma they will acquire a distribution which, in steady state, will have a constant form that terminates at some energy in the bulk thermal distribution of the plasma. For a simple $1/v^3$ velocity dependence this distribution becomes

$$F(E) = N_o /(1 + (E/E_o)^{1.5}) \int_{\infty}^{\sqrt{E}} f(u)_{init}\, du \qquad (4)$$

where N_o is the normalizing constant and E_o determines the low-energy point of merging with the bulk plasma distribution. N_o was chosen to give a total alpha-particle density of 3×10^{13} cm^{-3}, E_o chosen to be 100 keV/u. Figure 2 shows this distribution as a function of alpha-particle velocity. Also shown in Fig. 2 is a distribution function which assumes an anomalous loss of fast alpha particles. This distribution is similar to the ad-hoc non-classical distribution of Ref. 1. It is produced by taking the distribution of Eq. 4 and multiplying by the factor $(E/880)^2$.

B. Signal Calculation

Let v_r be the speed of the injected diagnostic beam relative to plasma alpha particles ($v_r = v^2 + v^2_b - 2vv_b\cos\theta)^{1/2}$ for alpha-particle velocity v, beam velocity v_b, and angle of encounter θ, and let L be the total length of the plasma probed by the beam. Then the interaction time $t = L/v_b$ and the effective reaction length is $v_r t = Lv_r/v_b$.

We have assumed that the input and output ports are 5-cm diameter, and the distance to the center of the plasma is 2.5 m, which implies an acceptance angle of $\sim \pm 0.01$ radian. Thus the volume of velocity space probed will be approximately $(0.01)^2/4\pi$ and the relative speed $v_r = (v^2 + v^2_b - 2\ vv_b \cos \theta)^{1/2}$ becomes just $v_r = |v - v_b|$ Hence for a velocity distribution f(v) with a total alpha-particle density n and isotropic velocity vectors, the total neutralized alpha-particle intensity produced in length L is

$$I_n = I_b \frac{L}{v_b} v_r \sigma(v_r) N \frac{0.0001}{4\pi} f(v) \tag{5}$$

for sufficiently small L (neglecting attenuation), where I_b is the probe-beam intensity.

The injected atom beam as well as the neutralized alpha particles will be highly attenuated by ionization in the plasma. Let $I_b(x) = I_0 e^{-\lambda_1 x}$, where λ_1 is the attenuation constant of the input beam, and let $I_\alpha(x) = I_n e^{-\lambda_2 (L-x)}$ be the observed intensity at the output, where λ_2 is the energy-dependent He^0 attenuation constant for the neutralized alpha particles. If we let $A_b = \lambda_1 L$ and $A_\alpha = \lambda_2 L$, and if we express all energy terms in units of keV/u, then we can define $v \equiv \sqrt{E}$ and, for discrete energy bins $E \pm \Delta E/2$, we get

$$\frac{I_\alpha}{I_b} = L \sqrt{\frac{E_r}{E_b}}\ \sigma(E_r)\ N\ \frac{0.0001}{4\pi}\ f(E)\ \sqrt{E}/2\ \ \mathrm{Atn}(E)\,\Delta E \tag{6}$$

where $\mathrm{Atn}(E) = \exp(-A_\alpha)/(A_\alpha - A_b) \times (\exp(A_\alpha - A_b) - 1)$ and where we have replaced the velocities by energies with the same subscript. The value E_r is related to E by the square root, i.e., $E_r = (\sqrt{E} - \sqrt{E_b})^2$. Thus for an E range of $\pm$ 100 keV/u, the corresponding range of E_r is $E_b - 430 < E < E_b + 630$ keV/u for E = 700 keV/u. In familiar terms,

$$V(10^7\ \mathrm{cm/s}) = 4.4\sqrt{E\ (\mathrm{keV/u})} \tag{7}$$

III. Results

Beams of $H^o{}_2$ and Li^o do not penetrate the plasma sufficiently well to probe the center of CIT; most charge transfer with a Li^o of $H^o{}_2$ probe will take place near the entrance to the CIT plasma. Calculation of the He^o (neutralized alpha particle) signal for a probe beam other than He^o shows that, for a beam which attenuates faster than He^o, e.g., Li^o, most of this signal comes from charge transfer which takes place near the entrance of the probe beam into the plasma (i.e., before the probe beam has significantly attenuated). This could provide crude information on the spatial distribution of alpha particles in the plasma.

Overlapping results for several probe-beam energies can be used to determine the alpha-particle velocity distribution function over a fairly large range. Results shown in Figs.3 and 4 are for $^3He^0$ probe-beams at 400 - 900 keV/u specific energy. Shown are the flux of neutralized alpha particles exiting the plasma in counts/s per 5-keV/u energy bin, relative to the incident beam energy ± 100 keV/u, for 100 mA of accelerated HeH^+. The figures include attenuation of the incident $^3He^0$ and exiting $^4He^0$ for vertical passage through a CIT plasma, and are calculated using the distribution functions shown in Fig. 2. The simulated data shown in Fig. 3 correspond to the classical distribution of Eq. 4, which varies as $1/v^3$ over most of its width; Fig. 4 shows data which would result from the anomalous losses assumed in the non-classical distribution. The two distribution functions are clearly distinguishable by comparison of the energy dependence of the data. A large portion of the actual distribution function could be determined by inverting data such as these, using measurements at several probe-beam energies.

IV. Detection

The use of $^3He^0$ for the probe beam would allow it to be distinguished from the neutralized alpha particles. The fast $^4He^0$ (neutralized alpha particles) atoms exiting the plasma can be reionized to $^4He^+$ in a gas target, or to $^4He^{++}$ in a thicker gas target or foil, with an efficiency of the order of 90% for producing He^{++}. These ions can be separated from reionized ^3He probe atoms by a momentum selector. With the detection region removed from the line of sight of the plasma, it can be well shielded and the ^4He ions detected with a surface-barrier or other single-particle detector. The ^3He ions will be detected by a Faraday cup or a surface-barrier detector, depending on the intensity. The energy distribution for the reionized ^4He ions can be obtained from the energy resolution inherent in the surface-barrier detector. Energy resolution may be improved, if necessary, by use of a position-sensitive detector. A gas cell will be essentially transparent to the intense neutron and gamma flux emitted by the plasma and be thus unaffected.

V. Conclusion

Two-electron capture from a He-atom probe beam by the fast alpha-particles in an ignited CIT plasma presents a feasible method for determining the energy distribution of the slowing-down alpha-particles integrated along a chord in the direction along the probe-beam path. The high count rate would allow a time resolution of the order of 1 ms. Limited information about the spatial distribution of alpha particles may be discernable through the use of a probe beam which attenuates faster than He^0. This determination might be better made with optical methods in concert with the two-electron-capture method. The same He^0 probe beam which serves as a target for two-electron capture will serve as a target for one-electron capture to form $He^+(nl)$. Emission measurements could be made through a horizontal port to determine the spatial distribution of the alpha particles at the same time as the two-electron-capture measurements are made using the vertical ports.

REFERENCES

1. D. E. Post, D. R. Mikkelsen, R. A. Hulse, L. D. Stewart, and J. C. Weisheit, "Techniques for Measuring the Alpha-Particle Distribution in Magnetically Confined Plasmas," J. Fusion Energy, 1 129 (1981).

2. Alpha-Particle Effects Workshop, Courant Institute of Mathematical Sciences, New York University, December 5-6, 1985; Presentations from the Workshop on Alpha-Particle Diagnostics on CIT, PPPL, 3-5 June 1987.

3. S.S. Medley, K.M. Young et al, "Plasma Diagnostics for the Compact Ignition Tokamak," this conference.

4. L. R. Grisham, D. E. Post, and D. R. Mikkelsen, "Mult-MeV Li^o Beam as a Diagnostic for Fast Confined Alpha Particles," Nucl. Technol./Fusion 3 121 (1983).

5. C. D. Boley, R. K. Janev, and D. E. Post, "Enhancement of the Neutral-Beam Stopping Cross Section in Fusion Plasmas Due to Multistep Collision Processes," Phys Rev Lett 52, 534, (1984).

6. K. H. Berkner, T. J. Morgan, R. V. Pyle, and J. W. Stearns, "Collision Cross Sections of 400- to 1800-keV H_3^+ Ions in Collisions with H_2 and N_2 Gases," Phys. Rev. A8, 2870 (73).

7. J. W. Stearns, K. H. Berkner, R. V. Pyle, B. P. Briegleb and M. L. Warren, "Dissociation Cross Sections for 0.5- to 1-MeV HeH^+ Ions in H_2, He, N_2, and Ne Gases," Phys. Rev. A4, 1960 (1971).

8. S. Walther, K. N. Leung, and W. B. Kunkel, "Volume Production of Li^- in a Small Multicusp Ion Source," LBL-23298 (1987); Appl. Phys. Lett. 51, 566 (1987).

9. L. R. Grisham, D. E. Post, B. M. Johnson, K. W. Jones, J. Barrette, T. H. Kruse, I. Tserruya, and W. Da-Hai, "Efficiencies for Gas Neutralizers for Multi-Beams of Light Negative Ions," Rev. Sci. Instrum 53, 281 (1982).

10. K. N. Leung, (private communication).

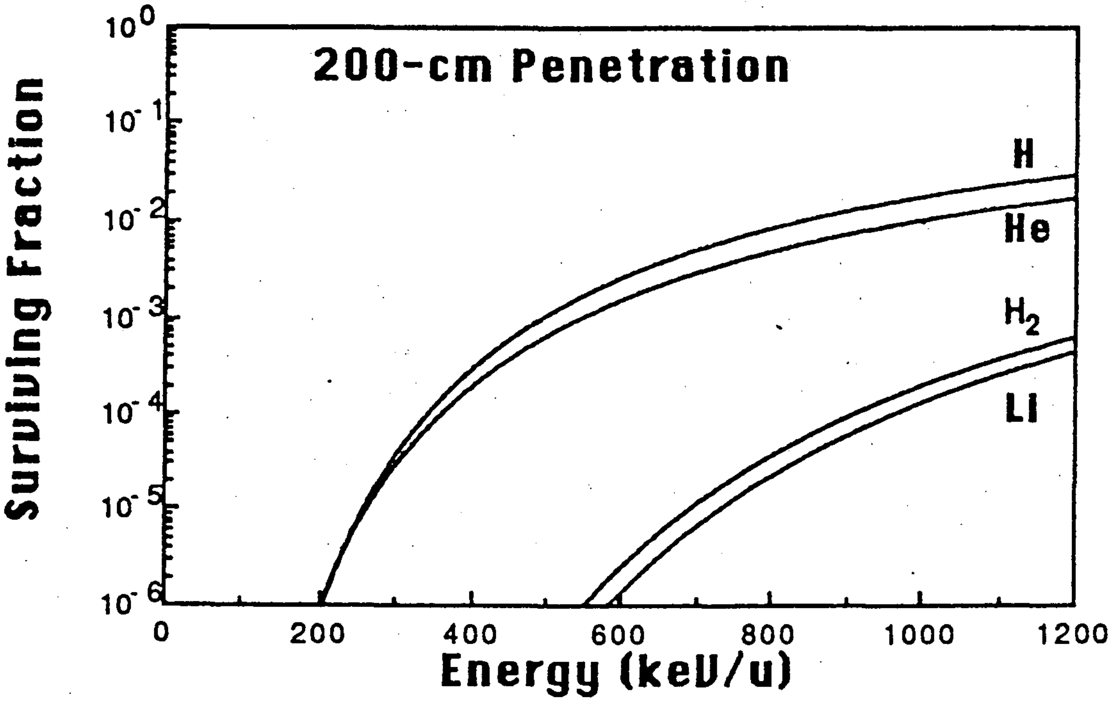
FIGURE CAPTIONS

Fig. 1. Calculation of surviving fraction of atoms or molecules after traversing a CIT plasma in a vertical plane (200 cm). Plasma parameters assumed are $n_e = 5 \times 10^{14}$ cm^{-3}, $Z_{eff} = 1.5$ with carbon as the impurity, $T_i = T_e = 10$ keV.

Fig. 2. Classical and non-classical alpha-particle velocity distribution assumed for calculations of charge transfer.

Fig. 3. $^4He^o$ signal (count/s) for a $^3H^o$ probe beam produced from 100 mA $^3HeH^+$ beam, shown as a function of $^4He^o$ (neutralized alpha particle) energy, for $^3H^o$ probe-beam energies of 400-900 keV/u and the classical distribution function of Eq. 8. The signal shown is count/s per 5-keV/u energy bin, relative to the incident beam energy ± 100 keV/u. Attenuation of beam and signal is included.

Fig. 4. Same as Fig. 3, for the non-classical velocity distribution.



XBL 8711-4662

Fig. 1

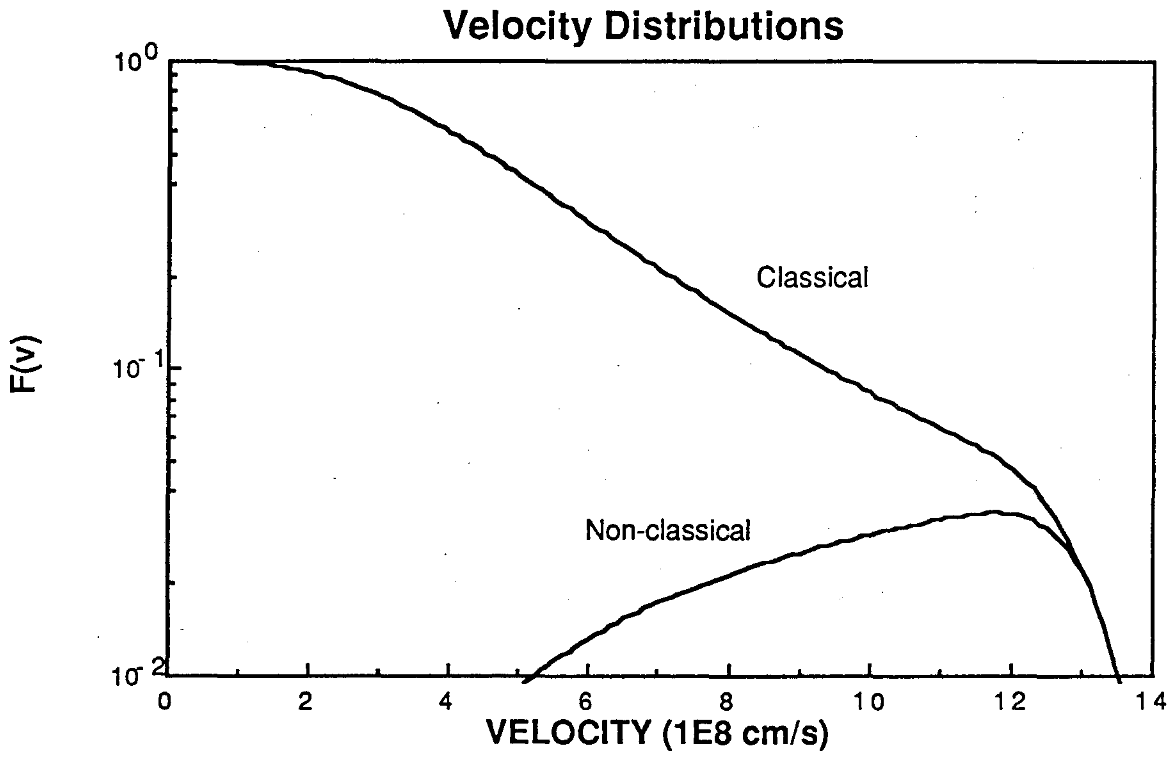

Velocity Distributions
F(v)
10^0
10^-1
10^-2
0
2
4
6
8
10
12
14
VELOCITY (1E8 cm/s)
Classical
Non-classical

Fig. 2

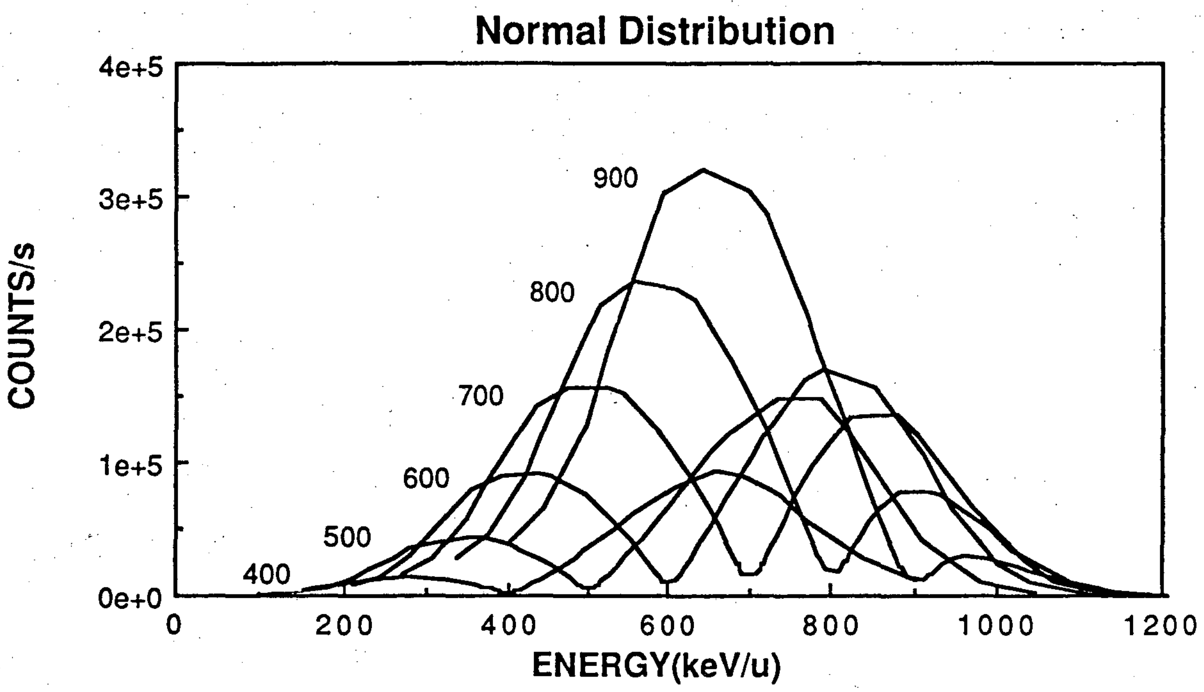

Normal Distribution
COUNTS/s
4e+5
3e+5
2e+5
1e+5
0e+0
0
200
400
600
800
1000
1200
ENERGY(keV/u)
900
800
700
600
500
400

Fig. 3

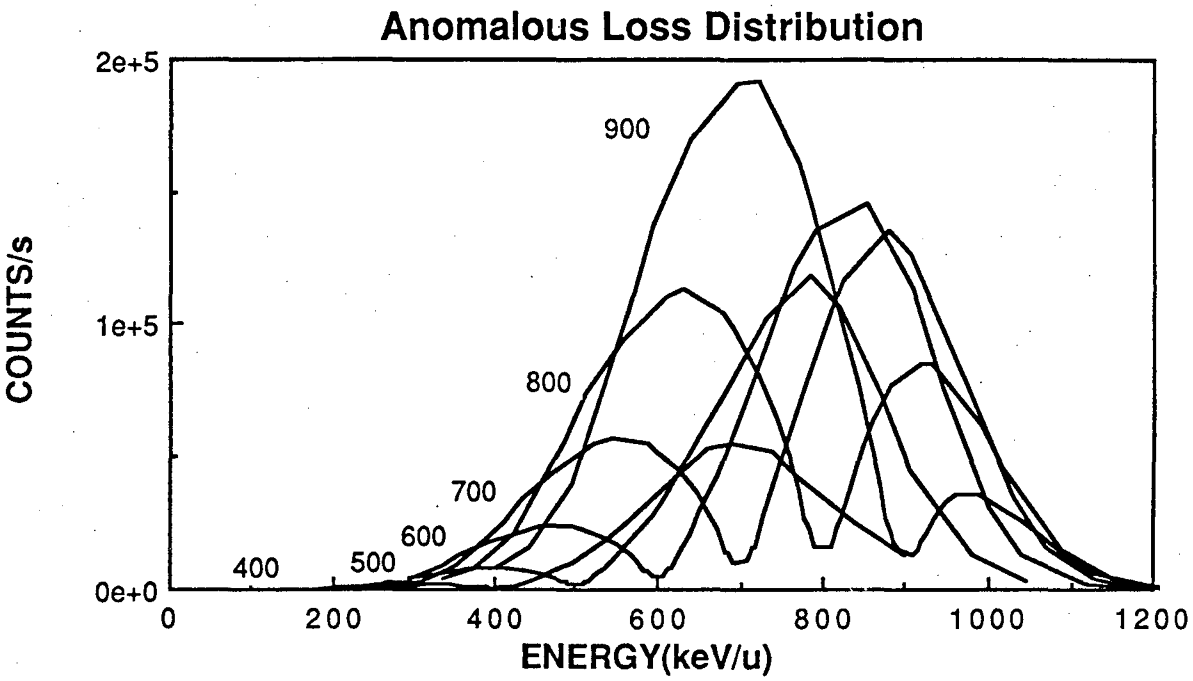

Anomalous Loss Distribution
2e+5
1e+5
0e+0
COUNTS/s
0
200
400
600
800
1000
1200
ENERGY(keV/u)
900
800
700
600
500
400

Fig. 4

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