A Molcular Beam Mass Spectrometer for Hall Thruster Plume Studies: Preliminary Data

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ABSTRACT

The motivation behind the construction of a Molecular Beam Mass Spectrometer (MBMS) for transport property measurements in Hall thruster plumes is presented. This system utilizes a set of orifice plates to skim off a small beam of plasma from the plume of a Hall thruster. This beam is collimated and energy filtered using a 45 degree parallel plate electrostatic energy analyzer. Data of a preliminary nature is presented including high-resolution ion energy distribution curves of Xe^+ propellant in the plume of an SPT-100. These data show a higher than expected most probable energy that is very near the thruster discharge voltage. In addition, the distributions indicate the presence of a high energy "tail" of ions with energies greater than the thruster discharge voltage.

I. Nomenclature

y= Spatial coordinate (m)
x= Spatial coordinate (m)
d= Analyzer plate separation (mm)
l= Inerslit distance (mm)
w= Entrance and exit slit width (mm)
θ= Ion launch angle (rad)
V_p= Repelling plate voltage (V)
E_i= Ion energy (eV)
k= Analyzer spectrometer constant
I_i= Ion current (A)
A_{coll}= Ion current collector area
e= Elementary charge (coul)
n_i= Ion number density (m^{-3})
u_i= Ion velocity (m/s)
q= Ionic charge state
m= Mass of ion (kg)
$I_{i,E}$= Current of ions with energy E (A)
$n_{i,E}$= Density of ions with energy E (m^{-3})
$F(E)$= Ion energy distribution function
V_d= Thruster discharge voltage (V)
I_d= Thruster discharge current (A)
c_r= Relative interparticle speed (m/s)
σ_{CEX}= Charge exchange cross section (m^2)

II. Introduction

1. Motivation. With the promise of high performance and economic benefits in the near future, there is currently a widespread effort to fully flight qualify Closed Drift Hall Thrusters (CDT's) and proceed to routine application of these devices.[1-5] The study reported in this paper represents an ongoing program at the University of Michigan to characterize the interaction between the plume of a CDT and the supporting spacecraft. Two basic interaction modes are being studied: the effect of the plasma environment on transmitted and received electromagnetic communication signals,[6] and the potential structural impact caused by high energy plume ions.[7]

To assess the interaction due to the direct impingement of the ions on spacecraft surfaces it is necessary to accurately quantify the ionic transport properties as a function of spatial coordinates around the thruster. These data can be combined with surface interaction models to predict surface erosion, contamination, and heating rates. Previous studies have used probe-based techniques to obtain the transport of mass, energy, and charge on a global (species-independent) scale within an extensive volume of the plume. This paper presents preliminary data from an effort to further improve the probe-based quantities by extending the data to species-dependent measurements of transport properties.

The construction of the Molecular Beam Mass Spectrometer (MBMS) reported herein was motivated by the shortcomings discovered in the previous probe-based techniques. The probe data has proven very useful, however, like any diagnostic technqiue they are subject to limitations. Although the MBMS system is subject to its own inherent imperfections, these limitations are different from and complimentary to the probe-based techniques.

Of great interest in calculating both plume transport properties and thruster performance is an accurate measurement of the ion energy distribution. This has previously been measured using a gridded Retarding Potential Analyzer (RPA) as an in-situ probe.[7] Recent experience has shown that the elevated density within the RPA due to the "ram" build-up inside the probe can cause both collisional broadening and attenuation of the incoming ion energy stream. Furthermore, the RPA technique has no dependence upon charge carrier mass or charge state, i.e. it cannot descriminate between multiply charged ions of the same mass nor ions of different masses. As another measure, ion energy data has also been obtained through Laser Induced Flourescence (LIF);[8] these data show a much narrower energy distribution than the probe-based RPA technique. A means of reconciling the discrepancy between these two techniques has not yet been proven.

Another desireable quantity for both thruster and spacecraft designers is the thruster erosion rate. Erosion limits the life of the thruster itself in addition to potentially depositing erosion material on sensitive spacraft surfaces. Previous methods to quantify this erosion include pre- and post-test weighing of the thruster itself to determine mass loss, and the examination of deposition material on witness plates and quartz crystal microbalances (QCM's) immersed in the plume. Although these methods provide accurate, useful data, a limitation to both is their sensitivity only to net deposition/erosion rate. The thruster simultaneously erodes the sample materials through plume ion sputtering while depositing thruster-body erosion products; the witness plate/QCM technique does not descriminate between these two processes. In addition, much of the deposited material may be due to facility effects (i.e. pump oil, sputtered material from vacuum chamber surfaces).

2. MBMS Diagnostic Goals. In order to complement the extensive data sets as described above, the construction of an MBMS system for CDT research was initiated.

A primary goal of this study is to measure the ion energy distribution of the primary plume mass species, Xe, to a greater accuracy than obtained through the RPA technique. In addition, this energy distribution will be measured as a function of the Xe charge state, i.e. separate energy distributions will be measured for Xe^{+}, Xe^{++}, and Xe^{3+}. Limitations inherent to the RPA such as collisional energy broadening, attenuation, and space charge shielding effects of the repelling grids are eliminated through the use of differential pumping and a small diameter ion beam. From a spacecraft interaction standpoint this will facilitate comparison between the previous RPA and LIF measured values for a more accurate evaluation of plume transport. In terms of thruster performance, these data are especially insightful. The ion energy distribution is intrinsically linked to the spatial distribution of ion production rate and the topography of the electric field within the thruster discharge chamber: knowledge of any two quantities uniquely specifies the third. By analyzing the charge state dependent distributions, it is possible to derive information regarding internal temperatures and ion production within the thruster.

Another main focus of this research is to measure the species fractions and transport rate of minority plume constituents such as

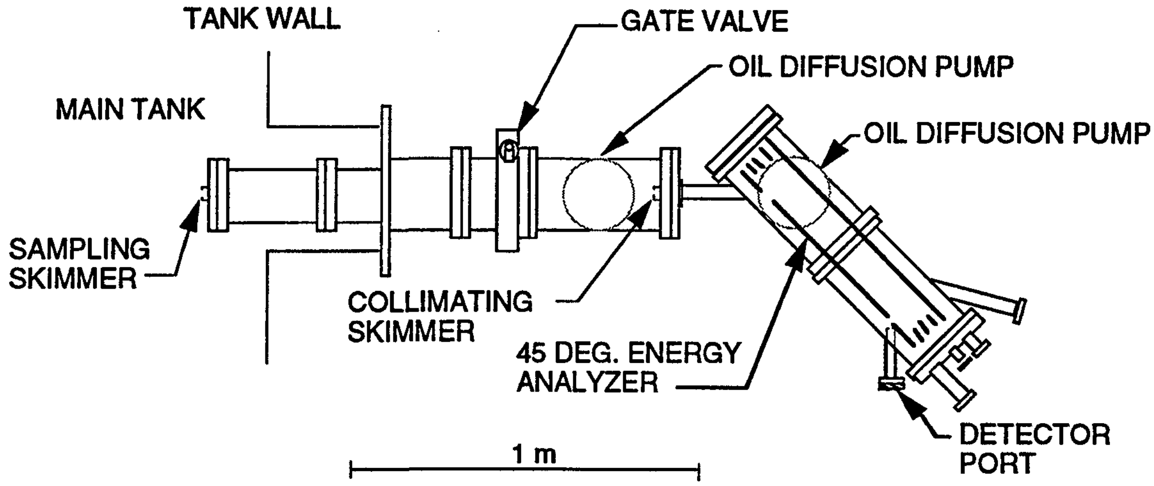

Fig. 1. Schematic showing overall layout of MBMS system in relation to main vacuum chamber.

heavy metals and ceramic components to more fully understand thruster erosion processes. By limiting the analysis of minority carriers to those particles with energies on the order of the thruster discharge voltage, this diagnostic will be insensitive to low energy minority species formed by ion sputtering of facility surfaces and will indicate only those particles which originated within the thruster. If signal strength permits, energy distributions of these minority constituents will also be performed. This will indicate the physical location within the thruster of possible thruster life-limiting erosion phenomena.

III. Description of Apparatus

1. Overall Configuration. The MBMS system uses a set of orifice skimmers to admit a beam of plume ions from the main vacuum chamber into an array of differentially pumped sub-chambers. The overall layout of the system is shown in Fig. 1. The skimmers are fashioned from 304 SS plates drilled and countersunk. This creates a very thin edge on the inlet orifice and minimizes skimmer wall effects. For this preliminary study relatively large diameter skimmers were used to maximize signal strength: 10-mm-dia. inlet and 4-mm-dia. collimator. The low densities within the plume and relatively large mean free paths permit the use of flat plates as opposed to cone or trumpet-shaped skimmers while introducing negligible upstream scattering.

An ion beam from a CDT plume is admitted through the sampling skimmer into the first sub-chamber. A second collimating skimmer geometrically confines the ions to a beam with half angle less than 60 mrad. This collimated beam passes through the entrance slit of a 45 degree parallel plate electrostatic energy analyzer. This system will be discussed in detail in Sec. III.2. A selected beam energy is allowed to exit the analyzer through an exit slit; the ions with a pre-selected energy then proceed to a detector, where the ion current is recorded as a function of repelling voltage.

The MBMS inlet chamber and skimmer are maintained at facility ground. Although this imposes a slight perturbation to the plume, previous research with such a system has shown that this small effect can easily be corrected and has no effect on the resulting data.[9] Prior to the inlet of the analyzer the beam consists of a quasi-neutral plasma of electrons and ions. This beam neutrality eliminates spatial space-charge spreading inherent to pure ion beams. The electric field within the energy analyzer then separates the ions and electrons.

The beam chambers are constructed of standard conflat-style vacuum hardware with tube I.D. of six inches for the portion of the MBMS within the main vacuum chamber and eight inch I.D. for the differential pumping and energy analysis chambers. The beam inlet chamber is pumped by a 10" oil diffusion pump, and the energy analysis chamber by a 6" oil diffusion pump. The system is capable of base pressures of 3×10^{-7} torr within 2 hrs of pumpdown with no system bakeout. A large 8" diameter gate valve is used to isolate the energy analysis section from the main tank to facilitate rapid re-configuration and pump cycles without the need to vent the main tank.

The MBMS is configured such that the ion beam detector is interchangeable. Initial tests were performed with a simple 304 SS current collecting plate whose output was monitored with a pico-ammeter. This, most simple arrangement, was used to verify operation of the skimmers and electrostatic deflection system. Additional detectors that will be implemented include a ceramic Channel Electron Multiplier (CEM) to greatly improve beam signal resolution as well as a Quadrupole Mass Analyzer (QMA).

To date, the MBMS system is not capable of mass species analysis, and thus operates only as a high-fidelity ion energy analyzer. Preliminary check-out tests have been performed only to verify operation of the electrostatic energy analyzer. In the near future (summer '97) a time-of-flight technique will be integrated to provide species mass analysis in addition to energy analysis.

2. Electrostatic Energy Analyzer. The 45 degree electrostatic energy analyzer is a flexible, robust method for particle energy filtering that has been utilized in a variety of research.[9-12] A schematic of this system is shown in Fig. 2.

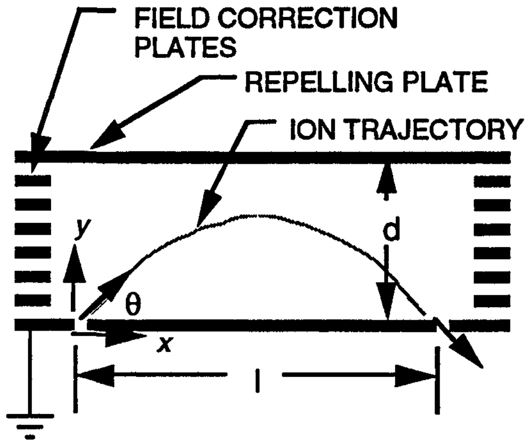

Fig. 2. Schematic of 45 degree electrostatic energy analyzer.

The plasma beam is admitted through the entrance slit and immediately enters a region of constant electric field of magnitude V_p/d with a launch angle of 45 deg. The much lower energy electrons are sharply deflected in a direction opposite to the ions and effectively removed from the beam. The ions experience a region of constant acceleration in the y-direction such that the spatial equation of their trajectory is

$$y = x - \frac{1}{2d}\frac{V_p}{E_i}x^2 .$$

In order for an ion to pass thru the exit slit and be detected it must intersect the point y=0, x=l; this pass constraint is defined as the spectrometer constant, k, and is given by

$$k \equiv \frac{V_p}{E_i} = \frac{2d}{l} .$$

The energy resolution, or resolving power, of the analyzer is dictated by instrument geometric parameters and is given by

$$\frac{\Delta E_i}{E_i} = \frac{w \sin\theta}{l} .$$

Table 1 outlines the pertinent parameters for the energy analyzer and MBMS system constructed for this study. The energy analyzer was constructed of 1.5-mm-thick aluminum plates. In order to eliminate field distortion due to the surrounding grounded vacuum chamber, a set of seven centrally slotted shim plates were biased using a voltage divider; this ensured a constant homogeneous electric field between the inlet plate and repeller.

Parameter	Value
l	571 mm
d	160 mm
w	2 mm
$\Delta E_i/E_i$	2.5×10^{-3}
k	0.56

Table 1. Defining parameters of 45 degree electrostatic energy analyzer.

The equation relating the collected current to the energy distribution function is

$$I_i = A_{coll} e n_i \langle u_i \rangle .$$

For a single value of pass energy,

$$\langle u_i \rangle = u_i = \sqrt{\frac{2qE_i}{m}}$$

so that now, the collected current for a given energy can be expressed as

$$I_{i,E} = A_{coll} e n_{i,E} \sqrt{\frac{2qE_i}{m}}$$

where $n_{i,E}$ is now the density of ions with energy E_i, which is precisely the ion energy distribution function:

$$F(E) \equiv n_{i,E} = \frac{1}{eA_{coll}} \sqrt{\frac{m}{2q}} \frac{I_{i,E}}{\sqrt{E_i}} .$$

The ion energy distribution function for a consant m/q is thus proportional to the collected current at a given pass energy divided by the square root of the pass energy.

IV. Preliminary Data

1. Experimental Set-up. Preliminary tests were done in the plume of an SPT-100 thruster operating from a brassboard power processing unit (PPU). Operating conditions were V_d=290V, I_d=4.5A, mass flow of 56 sccm Xe. The thruster was mounted to a rotary table such that the centerline of the thruster exit plane coincided with the axis of rotation of the table; this allowed remote rotation of the SPT-100 relative to the fixed MBMS skimmer inlet enabling data acquisition as a function of angle off plume centerline. The thruser/table assembly was mounted in the main vacuum chamber with the exit plane 0.5 m from the skimmer inlet.

In order to verify operation of the energy analyzer and skimmer system the MBMS was operated in two different modes. In the first, the 45 degree energy analyzer was configured with a simple ion current detector fashioned from 304 SS. This plate was mounted to the detector port as shown in Figure 1. The output of this detector was monitored using a pico-ammeter (Keithley 486) and recorded as a function of repelling plate voltage. The repelling voltage power supply had a maximum ripple of 50 mV peak-to-peak at a repelling voltage of 350 V. In the second mode, the system was basically set up to operate as a large, differentially pumped RPA. The collimating skimmer was covered with 80 line-per-inch nickel mesh and biased -40 V with respect to thruster cathode in order to remove the electrons from the plasma beam. Downstream of the collimating skimmer the 45 deg. plate system was completely removed and replaced with a simple stainless steel ion beam collector; this set-up is shown schematically in Fig. 3. The collector was then biased through a range of 0-450 V repelling voltage and the corresponding ion current was recorded. In this common diagnostic the ion energy distribution is directly proportional to the derivative of the I(V) vs. V curve.[7] This proven RPA method enabled verification of the somewhat more intricate 45 degree analyzer system.

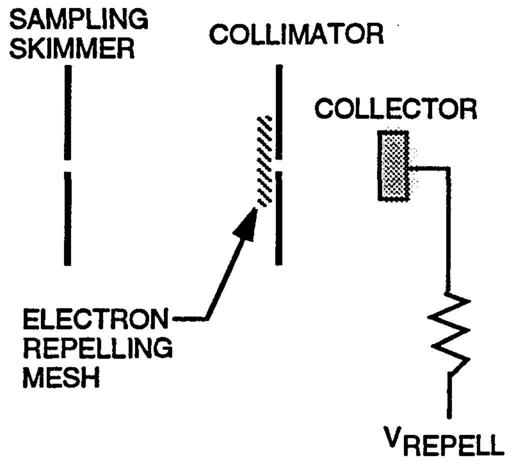

Fig. 3. Schematic showing set-up for MBMS operation in RPA-mode.

In order to correct for the plume perturbation imposed by the grounded MBMS inlet an emissive probe was used to measure the local plasma potential.[13] A single-loope probe was mounted 10 cm upstream of the skimmer. By subtracting the value of the local plasma potential from the measured ion energy, the data is corrected for the energy imparted to the ions as they "fall" from plasma potential through the sheath on the inlet skimmer to ground potential.

2. Results. During normal operation of the SPT-100 the cathode and anode are allowed to float. This fact occasionally introduces some ambiguity to the discussion of ion energies in the sense that the reference voltage is often assumed to be ground. However, it is more appropriate to speak of the ion energy as referenced to the potential of the cathode, as that is the fixed value of the discharge circuit. For these tests the cathode voltage was measured to be -19 V with respect to tank ground. All ion energies reported herein are referenced to this cathode potential.

The plasma potential was measured using the emissive probe to be 9 V ±1 V wrt tank ground 10 cm upstream of the MBMS skimmer for all plume angles studied in this paper. This value was subtracted from the measured ion energy and all plots reflect this correction.

The resulting ion energy distributions are shown in Fig. 4 for thruster centerline and 10 deg off centerline, respectively. Shown also for comparison is the measurement obtained in an earlier investigation with an in-situ RPA probe technique.[7] During MBMS and thruster operation the pressure in the inlet portion of the MBMS was maintained at less than 7×10^{-6} Torr and the pressure within the energy analyzer sub-chamber less than 5×10^{-6} Torr.

3. Discussion. The disagreement between the MBMS-obtained energy distributions and the in-situ RPA probe data highlight a shortcoming in the probe technique as applied to this plasma. Physically, the RPA probe resembles a cylinder closed on one end by a current collector, with the open end exposed to the flowing plasma. Gate grids are located along the axis of the cylinder to selectively repell and filter out charged particles of both signs, while admitting a select energy range of ion current to the collector. The problem with this technique arises when the plasma flow velocity and density increase sufficiently to "choke" the internal volume of the probe. It was shown using a neutral particle flux probe in a previous study[7] that the internal pressure due to neutral Xe within the probe can exceed 10 or 20 mTorr in the SPT-100 plume near centerline at 0.5 m. This stagnation pressure rise is due to the ram effect of the flowing high density plasma entering the probe and being neutralized by collisions with the probe walls or current collector. This relatively dense target gas scatters the incoming plume ions through both charge exchange (CEX) and momentum transfer collisions. The net effect is an attenuation and broadening of the measured ion energy as well as the appearance of a population of very low energy products ot CEX collisions.

The Xe-Xe^+ CEX cross section is reported by Rapp and Francis[14] as

$$\sigma_{CEX}=(-0.8821 \ln c_r + 15.1262)^2 \bullet 10^{-20}\ m^2.$$

Assuming that the internal probe pressure is 20 mTorr with a temperature near that of the probe walls (300 K), an incoming 300 V Xe^+ ion experiences a CEX mean free path

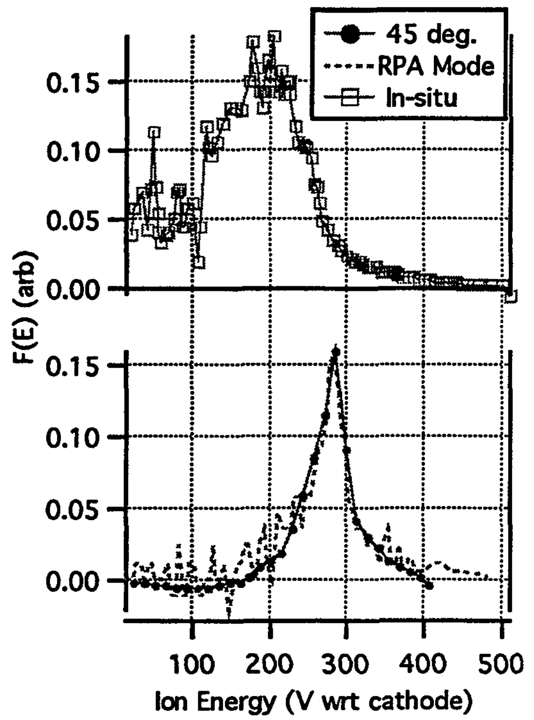

Fig. 4a

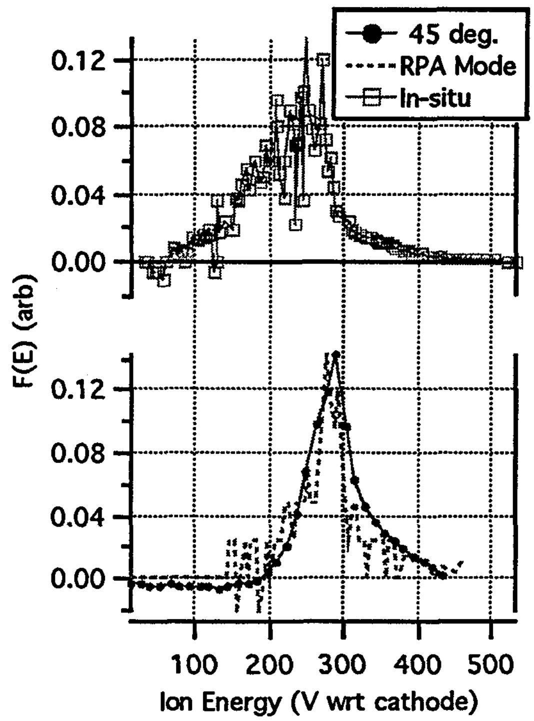

Fig. 4b

Fig. 4. Ion energy distribution function at 0.5 m radius from thruster: part a shows centerline values, part b shows data 10 degrees off plume centerline. Top curve in each plot shows data obtained with an in-situ RPA probe, while bottom curves were obtained using two modes of MBMS operation.

on the order of 3 mm. The RPA probe used to obtain this data had physical dimensions roughly 2.5 cm dia. and 2 cm long.[7,15] This would cause over 90% of the plume ions to suffer a CEX collision prior to detection. On the other hand, the low pressure in the MBMS admits a mean free path of roughly 10 m over a 1 m path length, equating to a 10% collision probability. An experimental study and detailed discussion of this phenomenon will be the subject of a future paper to be presented at the International Electric Propulsion Conference in Cleveland, Ohio.

This collisional broadening and attenuation effect is greatest on centerline; for the 10 degree case shown in Fig. 4b the RPA probe data shows much greater agreement with the MBMS data. Although the RPA is quite choked on centerline, the ion beam flux decreases to less than 30% of its peak value at 10 deg. as determined from independent studies.[7] This causes less attenuation and broadening within the probe at 10 deg and hence the data more closely resembles the non-broadened distributions of the MBMS.

As can be seen in Fig. 4, the measured ion energy distributions obtained in both modes of MBMS operation agree very well. The agreement between the new 45 degree analyzer method and the proven RPA-mode technique confirms the accuracy of the electrostatic analyzer. Furthermore, the 45 degree method produces a smoother, higher resolution curve owing to the numeric differentiation necessary with RPA techniques.

A result of this investigation was the discovery of higher than expected values of ion energy. For a 300 V discharge, previous studies of Hall thrusters imply a most probable energy near 200-250 V. In this study the most probable ion energy was found to be near 285 V for both data sets. In addition, there appears to be a significant fraction of ions with energies greater than the discharge voltage. This high energy "tail" is present in both modes of the MBMS as well as in the RPA probe data. These three independent confirmations tend to affirm the physical reality of the phenomenon, however a mechanism accounting for its appearance has yet to be justified. The presence of high energy ions has also been documented in previous research.[15] Possibilities may include plasma instability-driven resonance wave heating of the ions within the discharge chamber.[16]

V. Conclusions

Preliminary ion energy distribution measurements with the MBMS have highlighted the problems inherent to in-situ RPA probe techniques in high density flowing plasmas. The ram gas stagnation pressure buildup within the probe volume causes collisional broadening and energy attenuation of the incoming plume ion stream. The differential pumping of the MBMS increases the mean free path to a value large enough to render collisions negligible. The resulting energy distributions show a full-width at half-max of roughly 50 V.

The energy distributions obtained with the MBMS operating in two modes of measurement indicate unexpectedly high values of ion energy. This is manifested both in a most probable ion energy very near the discharge voltage as well as a "tail" of ions with energies up to 100 V greater than the discharge voltage. Currently an explanation for this phenomenon has not been proven.

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