Correlated Emission of Electrons

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We have studied the harmonic content of current generated by a single-point field emitter to determine if field emission electrons are correlated. We used a Si surface barrier particle detector to measure electron energy spectra at dramatically differing counting rates. Harmonic content was unusually high, with an average number of electrons per count of 1.6 for high (16,500 events/sec) and 1.7 for low (15 events/sec) count rates. This high harmonic content cannot be attributed to the counting system response, but must be considered as true events in which several electrons are emitted simultaneously and arrive within the resolution time of the detector and its electronics (~3 μsec). We also investigated possible spatial coherence by measuring the dependence of energy spectra on the area of the electron beam, whose size relative to that of the detector was varied using (1) a cylindrical magnet to increase beam diameter and (2) irises to reduce detector diameter. The harmonic content was larger than what one would expect if the spatial distribution of the electrons was entirely random, but not large enough to indicate that there is any attactive force between the simulateously emitted electrons that would overcome Coulomb repulsion.

Key Words: field emission, charge clustering, multiple electrons, anode spots.

1. Introduction

Electron field emission has been studied under a variety of experimental conditions. For the purposes of this discussion, we consider three levels of electron beam current: (a) low current where isolated emission events can be counted[1-19]; (b) moderate current where sporadic, noisy pulses are recorded with current measuring devices[20, 21]; (c) high current where plasma effects generally dominate[22-30] and plasma diagnostic techniques are employed. It has not been generally recognized that seemingly unrelated observations of electron clustering in the three current regimes may be governed by similar or related physics.

At low current, researchers were able to measure electron energy and hence spatial and temporal correlation between charges in isolated particle counting events. Herrmann and, later, Gazier first studied individual events using energy-dispersive detectors [1,2]. Gazier detected field-emitted multiple-electron events (2 to 5 electrons) originating in a region of less than 1 mm. Fursey has carried out extensive research in this area over the past two decades [3-14]. He and his colleagues have evaluated the effects of the field emitter temperature, emitter material composition and orientation, and pressure. They also investigated the influence of adsorption of residual gases on the harmonic content of the field emission, since this seemed important in the explanation of Gazier's experiments. Fursey's early results indicated field emission was of single electron character only (no harmonics). This lead to the conclusion that Gazier's results were artifacts connected with parasitic secondary emission from the intermediate electrodes [14]. Prompted by an unpublished low-current experiment that supported Gazier's results which was carried out by one of us at the Lawrence Livermore National Laboratory (LLNL) [15], James and coworkers undertook similar experiments with a thin-window proportional counter [16-18]. Their results also supported Gazier's experiment, as do the results reported herein and in [19]. A summary of low-current experimental results is tabulated in [19].

In the moderate current regime, emission current from field emitters (Spindt cathodes) is sporadic[20]. Single molybdenum tips exhibit burst (popcorn or telegraph) noise that consists of sequences of bi-stable current pulses of specific amplitude, but with random lengths and random intervals between pulses. These current pulses are separated by quiescent periods, which may be of the order of tens to hundreds of seconds. Current measurements of single Spindt cathodes are in the 10^{-6} to 10^{-8} A range. The burst noise sequences themselves may last from milliseconds to hours. As the resolving time is made shorter, burst current pulses are seen to consist of pulses of similar character, with a limiting pulse length on the order of milliseconds according to Kirton and Urens [21].

In the high current regime, experiments by Shoulders have indicated that high-density spherical charge clusters are possible [22-24]. His work in this area was limited to techniques that are more heuristic than would be desirable for proof of their existence. Shoulders' evidence that field emitted electrons were clustered is both passive (the form of craters on anode surfaces) and active (photographs with a high speed camera). Experiments and modeling which used more conventional plasma physics to describe the presence of spherical impact craters were reported by Schwirzke et al. [29] and Wright [30]. They observed circular cratering of both anode and cathode, and their explanation for this emission is quite different from Shoulders' [22]. Theoretical discussions of electron clustering were published by Beckmann, Aspden [25,26] and by Ziolkowski and Tippett[27,28]. Given the nature of Coulomb repulsion, it is difficult at first glance to understand spatial clustering of high current electrons without charge neutralization by trapped ions or image charges. However, as shown by these researchers [25-28] and by two of us [31] other mechanisms for clustering are possible.

A survey of the literature suggests that researchers in these three different current regimes were not generally aware of each other's work. To clarify some of these issues, experiments in the low current regime reported here and in [19] were undertaken with an energy dispersive Si surface barrier detector to determine both the temporal and spatial characteristics of thermal and field emission from single, isolated W tips.

2. Experiment

2.1. Apparatus

We utilized a modified transmission electron microscope to observe the energy spectra from a point tungsten filament. The experimental apparatus is shown schematically in Fig. 1. The electron source was standard, a commercially available W point filament that could be heated to 2800°K. Thus, the filament could be either a thermal emission (TE) or field emission (FE) source. The tip was positioned in the high field acceleration region of the microscope, through the cathode's aperture. There were no intermediate electrodes between the tip and the anode which was held at ground potential. All beam optical components such as apertures and magnetic lenses were downstream of the anode. To center the beam on the axis of the microscope, the tip could be shifted in relation to the anode in two normal directions without breaking vacuum. The microscope was operated at 50 kV, and was evacuated with an oil-diffusion pump. Operating pressure was 5×10^{-5} Torr or below. The microscope column had to be extended to accommodate a 25 mm² Si surface barrier detector that could be translated 100 mm along a horizontal axis. The detector was 595 mm from the tip, and was collimated with a 3-mm diameter iris to reduce the active detection area and to improve spatial resolution. The dimensions of the electron beam were controlled with the magnetic lens, and could be viewed with a retractable phosphorescent screen located 25 cm upstream of the detector. Charge pulses from the detector were processed in a counting system (see Fig. 2) consisting of a preamplifier, a main amplifier, a multichannel analyzer and a count rate meter. Amplified pulses (~ 3×10^{-6} sec) were also monitored with an oscilloscope.

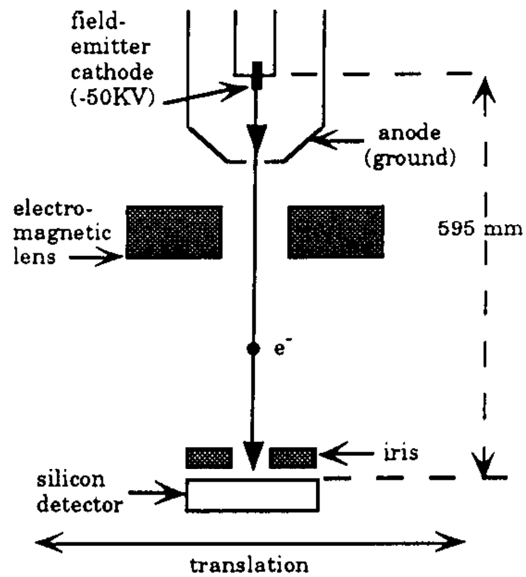

Figure 1. The apparatus used to study charge correlation.

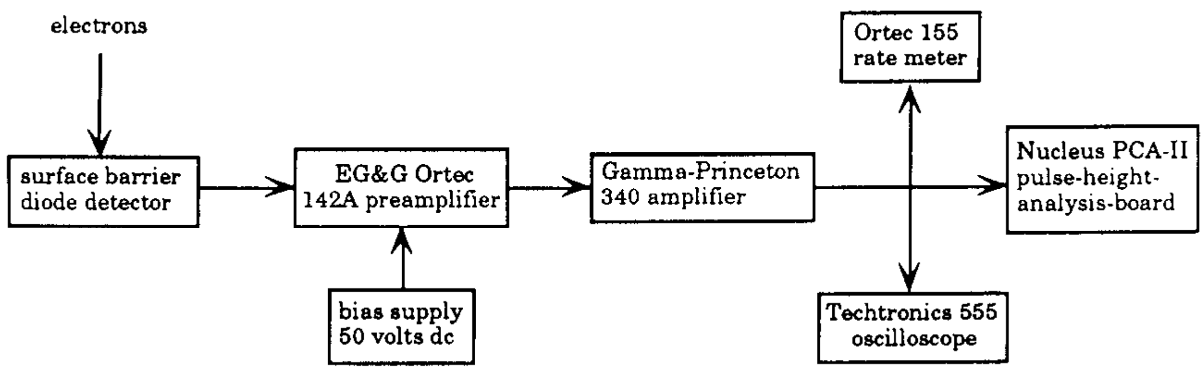

Figure 2. Block diagram of the electronics for pulse height analysis of the electron energy spectrum [29].

2.2 Counting System Behavior

Because the spectra reported herein have unusual characteristics (up to 11 electrons arriving simultaneously), it is important to briefly consider the characteristics of our counting system[32]. A count is a pulse that is registered in response to the deposition of energy in the detector. The detector is energy dispersive and linear, that is, the amplitude of the charge pulse generated in it is directly proportional to the energy deposited by the electron(s). Also, there is a fixed minimum time interval that separates two events such that they are recorded as separate pulses. During this interval, the system is "dead." Two electrons arriving during the "dead" time are recorded as a sum pulse, a single pulse with twice the energy. We were concerned that the counting system might have been overwhelmed by the high rates at which data were accumulated, thereby giving rise to an inordinately large number of sum pulses. Let the system resolving time be t, and the count rate for random emission of single electrons be r, then the probability of detecting n electrons within t is given by[32]

$$P_n(t) = (2rt)^n / n! \quad (1)$$

and $R_e(n)$, the expected ratio of counts of n electrons to single electron counts is

$$R_e(n) = (2rt)^{n-1} / n! \quad (2)$$

Values of $R_e(n)$ are given in Table 1 for count rates of 15 and 16,500 counts/sec, and system resolving time of 3×10^{-6} sec.

3. Experimental Results

3.1. Pulse Height Spectra

Electron-energy spectra were accumulated under several experimental conditions. The count rates were erratic and not controllable over the long term; however, count rate was monitored for stability during data collection. Fig. 3 shows spectra acquired at two vastly different count rates with the cathode at room temperature. The spectrum in 3(a) was taken over a 15 minute period at a count rate of 16,560 counts/sec, while spectrum 3(b) was taken over a 4.75 hour period at a count rate of 15 counts/sec. The lowest energy peak is at 50 keV, and higher energy peaks are at integral multiples of the acceleration voltage. Peaks are observable out to 550 keV, but the acceleration voltage was only 50 keV.

The two spectra are similar, and are very much like those obtained by Gazier,[2] Ebert[15] and James, et al.[16-18] Note that in the high count rate spectrum, the gain is shifted to slightly lower energy and peak energy resolution is poorer, suggesting that the counting system was well behaved and was operating properly. Also note that if the multiple energy peaks resulted from counting random single electron emission events in coincidence, then R(n), the ratio of counts of n elections to counts of a single electron would also be given by equation (2).

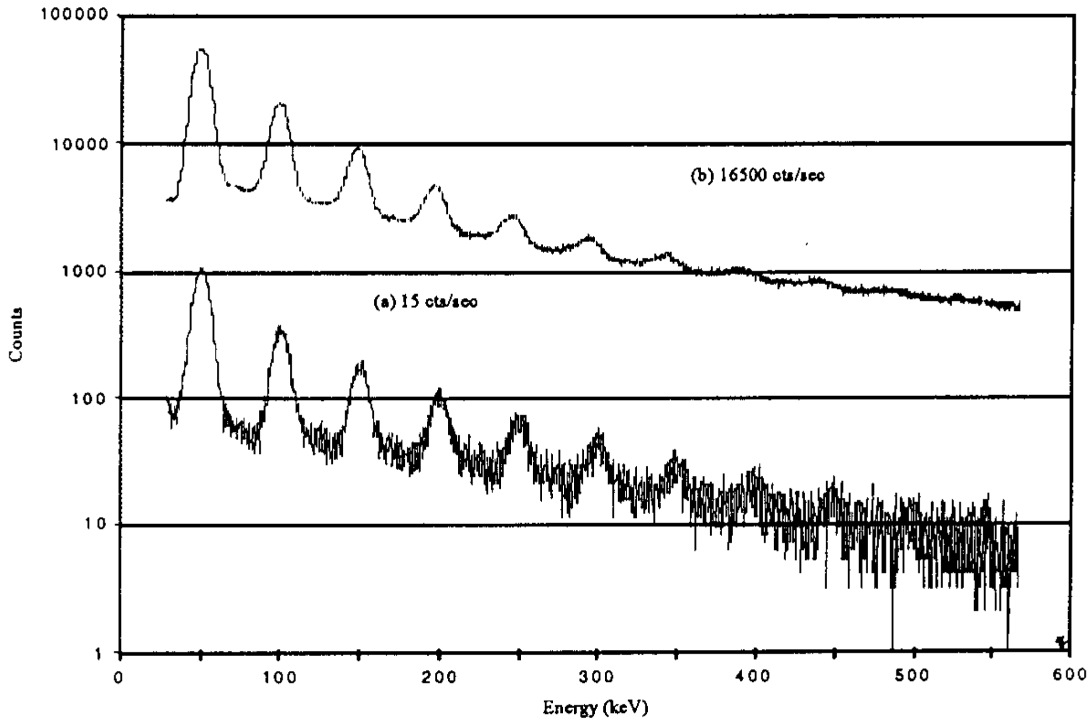

Figure 3. Pulse height spectra taken from the same field emitter but at different rates: 16,500 counts/sec and 15 counts/sec (from [19]).

Measured values $R_m(n)$ are compared with expected values $R_e(n)$ in Table 1. These were obtained by adding counts in each peak and subtracting the monotonically decreasing background. The measured values are orders of magnitude greater than those expected. The value $R_m(2)$ at 16500 counts/sec is higher than the corresponding value for 15 counts/sec. This is consistent with a higher number of random coincidences at the higher count rate. The differences for the other harmonics are smaller and are within the experimental errors for these ratios. Also, the average number of electrons detected per event was 1.7 ± 0.1 at 15 counts/sec and 1.6 ± 0.1 at 16500 counts/sec. Therefore the multiple energy peaks must be from simultaneous emission of more than a single electron.

Table 1. Expected and Measured Peak Ratios

peak	energy	15 counts/sec.		16500 counts / sec.	
no., n	keV	$R_e(n)$	$R_m(n)$	$R_e(n)$	$R_m(n)$
1	50	1	1	1	1
2	100	5.0×10^{-5}	3.0×10^{-1}	5.0×10^{-2}	3.5×10^{-1}
3	150	1.4×10^{-9}	1.4×10^{-1}	1.6×10^{-3}	1.2×10^{-1}
4	200	3.0×10^{-14}	7.2×10^{-2}	4.0×10^{-5}	5.3×10^{-2}
5	250	5.5×10^{-19}	4.0×10^{-2}	8.0×10^{-7}	2.0×10^{-2}
6	300	8.2×10^{-24}	2.2×10^{-2}	1.3×10^{-8}	8.1×10^{-3}

3.2. Electron Emission Source

The microscope's magnetic objective lens was used to demonstrate that the source of multiple electron emission (the FE source) was the tungsten tip. First, with the filament heated, the TE electron source was imaged on the phosphorescent screen, and its position and size checked. The detector was then translated through the beam and the beam profile measured. Next, the filament current was turned off, the count rate meter's discriminator was raised to count pulses that were double energy and higher, and the beam profile of double energy and higher pulses was measured. The two profiles were virtually identical[19]. To obtain higher spatial resolution, the iris sizes were reduced. The diameter of the iris for measuring TE was ~ 100 μm, while that for FE was 2 mm. The electromagnet was turned off to let the electron beam expand. With the filament off, the beam profile of double energy counts was measured (using counts from the pulse height analysis spectrum) and compared with that of the TE profile (using the count rate meter). As is evident in Fig. 4, the normalized profiles for the TE and FE distributions are nearly the same. The difference in resolution of the FE and TE distributions was due to the differing iris sizes. Thus the TE and FE sources were at the same location.

3.3. Effects of field emitter temperature

The emission rate also depended on the temperature of the field emitter. In this experiment, we utilized the fact that the tungsten field emitter could also be operated as a thermal emitter of electrons. We found that the rate of emission increases with increased temperature; however, the ratio of harmonics to the fundamental decreases as the emitter temperature increases. The FE rate could be overwhelmed by increasing the filament current, as can be seen in Fig. 5, which plots the ratio $R_m(2)$ as a function of filament voltage. The beam is nearly 100% thermal at 1.1 volts across the filament. The rate of emission over the 1.1 volt range varied from a few events/sec up to 10^5 events/sec (the limit of the detector electronics resolution). Thus although the relative harmonic content decreased, the overall rate of harmonic generation increased with increasing temperature.

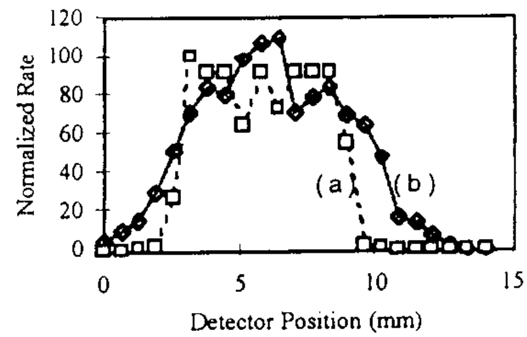

Figure 4. The normalized count rate of electrons for the cases of (a) thermal emission and (b) the field emission from harmonics above the fundamental both originating from a W point filament. A 2-mm iris was used to measure the FE rate (≥ 2nd harmonic) and a 100 μm iris was used to measure the TE rate.

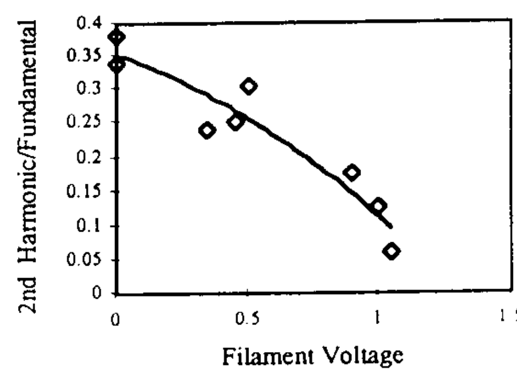

Figure 5. Harmonic content as a function of filament voltage (from [19]).

3.4. Effects of Detector Aperture Size

In our first experiment to explore the possibility that the electrons are spatially correlated, we increased the area of the electron beam so that it was much larger than the area of the Si detector aperture. The assumption was made that loss of higher harmonics would occur if the electrons were not spatially bound. If this was indeed the case, the electrons would have independent trajectories and would result in fewer counts in the harmonics relative to the fundamental. If the electrons are strongly correlated spatially, they will stay together with the same trajectory. Thus the energy spectrum of the increased area beam should still have a high harmonic content.

By simple calculation we can estimate the harmonic content of the beam. Assuming that the electrons stay completely correlated, the expanded electron beam would have the same harmonic content as in the case where the entire beam is focused on the detector. Measurements for the focused case showed that the ratio of the 2nd harmonic to the fundamental was 0.38. Thus, if the electrons remained totally spatially coherent, expanding the area of the beam at the detector would only reduce the rate of detection, not the harmonic content, and the ratio should remain 0.38. On the other hand, if the electrons were moving totally independently of one another, then the harmonic content would be reduced by the ratio of the area of the detector to that of the expanded area.

The pulse height spectra for the cases where the beam is focused onto the detector and where the beam's spot size is increased to 5 cm and 12 cm diameter are shown in Fig. 6. Both the rate and the harmonic content are seen to drop with increasing beam area. The measured ratio of the second harmonic to fundamental was 0.38 for the case where the electron beam was focused into the detector. Since the active area of the detector was 25 mm² (5.6 mm diameter), while the expanded electron beam at the detector was 1962 mm² (5 cm diameter), we should expect the 2nd harmonic/fundamental to be (25/1962) x 0.38 = 0.005 for the case of spatially uncorrelated electrons. For the 5 cm beam, the measured ratio of the 2nd harmonic to the fundamental was 0.08, a factor of 4.7 less than that of the focused case, but a factor of 16 higher than the incoherent case. Thus, the electrons show partial spatial coherence even after traveling a distance of 59.5 cm from the field emitter to the detector. The measured ratios of the 2nd harmonic/fundamental for the 5 cm and a 12 cm diameter spots are given in Table 2.

Table 2. Harmonic Ratios for Different Focus Settings

beam size at the detector	measured ratio of second harmonic to fundamental	expected ratio assuming no spatial coherence
focused	0.38	0.38
5 cm	0.08	0.005
12 cm	0.008	0.0008

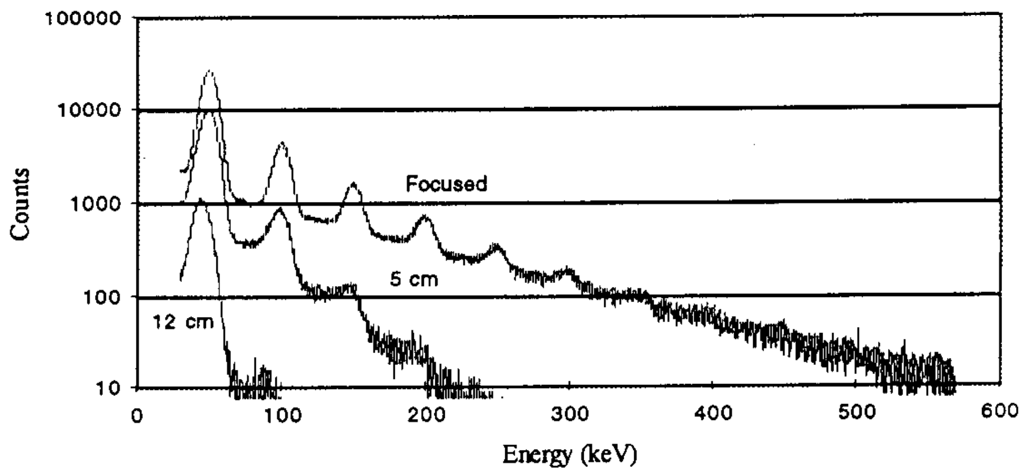

Figure 6. Pulse height spectrum from a tungsten field emitter for the cases of focused, 5 cm and 12 cm spot sizes at the detector. Detector active area is 25 mm^2.

3.5. Electron beam size reduction

To see if the magnetic focusing contributed to the increased randomization of the electron beam, we utilized the apertures (1.3 mm and 0.65 mm diameter irises) of the cylindrical magnet (with magnet off) to define the size of the electron beam. The electron beam was allowed to naturally expand as it traveled to the detector. The measured size of the electron beam at the detector was 1 cm. The irises could be placed 27.8 cm from the field emitters and 48.4 cm from the detector. In this experiment the detector was 762 mm from the source. We estimate the spot size of the beam to be 5 mm at the iris. As discussed above, limiting the size of the electron beam should not reduce the harmonic content if the electrons are highly spatially correlated. The results are shown in Fig. 7, where we compare three spectra, one with no aperture, one with 1.3 mm and one with 0.65 mm. The expected and the measured 2nd harmonic/fundamental ratios are given in Table 3. The expected values for no spatial coherence are calculated by assuming that the harmonic content is reduced by the ratio area of the irises to that of the area of the electron beam. Again the measured values show a degree of spatial correlation. For both irises, the measured ratio was a factor of 10 or more higher than the expected value if the electrons were uncorrelated.

Table 3. Harmonic Ratios for Different Iris Sizes

iris size	measured ratio of second harmonic to fundamental	expected ratio assuming no spatial coherence
focused	0.38	0.38
1.3 mm	0.26	0.025
0.65 mm	0.09	0.006

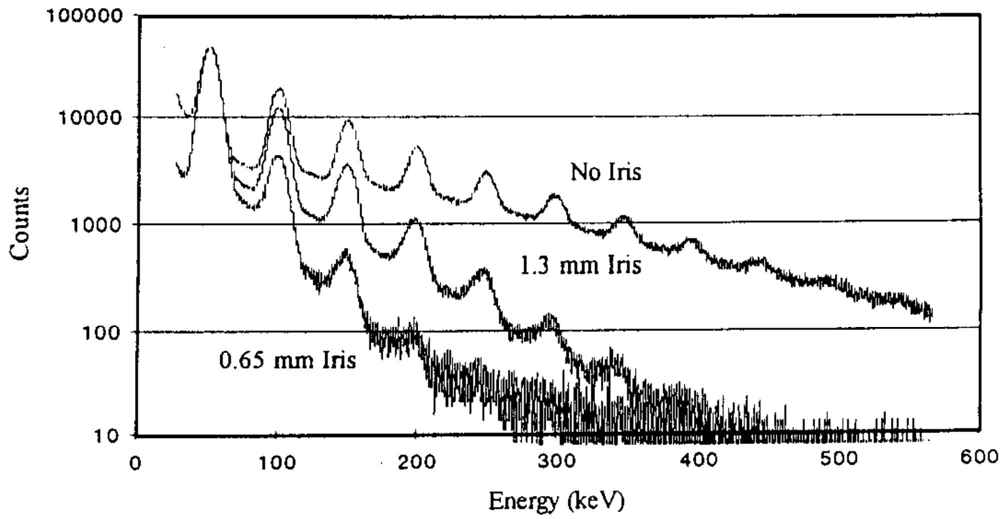

Figure 7. Pulse height spectrum from a tungsten field emitter for the cases of no iris and 1.3 mm, and 0.65 mm irises.

4. Discussion

We have observed the pulse height spectrum out to 600 keV (>10 electrons/bunch). Harmonic content does not vary appreciably with different tungsten field emitters. Each group or bunch of electrons is emitted simultaneously (within the resolving time of the detection system) from a highly localized point on the field emitter.

The rate of generation of the second harmonic can be used to map the spatial distribution of the cluster spectrum. Heating the field emitter results in an increase in total emission rate, but a decrease in the relative harmonic content of the energy spectrum. This indirectly shows that the multiple emission is coming directly from the field emitter and not from parasitic secondary emission from electrons striking the anode aperture.

In addition, our measurements have shown that there is harmonic content to electron beams whose diameters are larger than that of the detector aperture, thus showing that the electrons remained correlated over a large distance from the field emitter. However, this effect is not strong and cannot be said to show that there is an attractive force between the field emitted electrons.

Since there is no attractive force to keep the electrons together, the use of a cylindrical magnet to collect and focus electrons onto the detector was important to demonstrating temporal correlation. The magnet functions to keep all the simultaneously emitted electrons together so that they will be count ed as a multiple electron pulse. Indeed, the experiments of Fursey et al. [3-14] do not appear to use focusing and this may be the reason their results have fewer (and in some cases, no) multiple counts. It should be noted that another distinguishing feature of experiments that routinely detected multiple emission was that the vacuums were much poorer than in many of Fursei's experiments.

In summary, laboratory observation of high-density filamentation or clustering of electronic charge has motivated an investigation into potential cohesive mechanisms whereby repulsive Coulomb forces can be overcome by some form of compensatory attractive force. A class of models which invoke the possibility of charge confinement by van der Waals-type forces was suggested by Casimir. The resulting analysis [31] and the experimental results presented here indicate that confinement of small numbers of electrons by the van der Waals mechanism cannot be achieved under experimental conditions considered herein. However, as shown in [31], large numbers can be clustered by the van der Waals force.

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Atomic Electron Configuration

The nature of matter has plagued scientists and philosophers since the beginning of history. Early twentieth century theoretical physicists were coming to grips with the atom. Below, I suggest that they simply did not have enough facts or experimental data to formulate a consistent atomic model then. As a result, the concept of the atom needs to be revised. There are now available some first principles of Nature that can describe the structure of the atom and conform with experimental evidence. The new atomic is easy to understand and visualize, and provides a significant theoretical advance.

First, some history. A good starting point for the development of atomic theory is 1894, when Sir Joseph J. Thomson showed beyond doubt that cathode rays in a discharge tube actually do consist of negatively charged particles. Thomson constructed a fairly high-vacuum discharge tube with an auxiliary electrode that was connected to an electroscope. He used a magnet to deflect the rays to strike the auxiliary electrode of the electroscope which registered the presence of negatively charged particles.

In 1902 English physicist Lord Kelvin proposed an atomic model that was so strongly supported by Thomson that it became known as the Thomson atom. In this model the electrons were embedded in a positive sphere in various equilibrium positions, much like raisins in a pudding.

Another major event in the development occurred in 1910 when two researchers, under the supervision or direction of Er-