

Cold-Cathode Magnetron Gauge Characteristics*

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A description of cold cathode magnetrons operating as gauges has been developed in terms of the conditions for establishing a discharge and the effects of space-charge buildup. Pressure response curves for NRC type 552 (Redhead) and GCA model 1410 (Kreisman) gauges were determined by a conductance-regulated, pressure-ratio method using Bayard-Alpert type gauges for upstream pressure reference. Four characteristics of normal magnetrons operated below cutoff are predicted from the discharge mechanism and correlated with test data: (1) an out-of-strike state characterized by a steady pressure-independent gauge reading (about 5×10^{-14} Torr) due to leakage current; (2) a minimum pressure threshold for operation, 2.7×10^{-12} Torr for the NRC 552, 1.7×10^{-10} Torr for the GCA 1410; (3) a range (below 10^{-9} Torr) of nonlinear pressure-dependent response moderated by space charge buildup; and (4) a range of near linear response corresponding to the region of nearly saturated space charge.

Introduction

A magnetron may be defined as an assembly of two concentric cylindrical electrodes operated in an axial magnetic field. When used as a pressure gauge, the electric and magnetic fields are chosen such that the bulk of the cavity is beyond magnetron cutoff. That is, in the absence of some space-charge oscillation or instability electrons are not able to travel from cathode to anode unless they lose energy by colliding with gas molecules (see Fig. 1). The gauge, therefore, remains in an out-of-strike state, unless the gas pressure is high enough to support a discharge. The present article investigates this phenomenon as well as the basic operation of magnetron gauges. Two commercial gauges which may be described as magnetrons, the NRC type 552 (Redhead) gauge and the GCA model 1410 (Kreisman) gauge, were available for this investigation.

In 1952, Beck and Brisbane¹ reported a series of experiments using both normal and inverted magnetron arrangements. A central wire and a cylinder with several bulkhead disks were employed as electrodes. The sensitivity was higher when used as an inverted magnetron; however, it had two disadvantages: a background current, due to field emission, which was equivalent to about 10^{-8} Torr; and a power law rather than a linear relation between cathode current and gas pressure. However, a useful gauge circuit was designed for pressure above 10^{-8} Torr by using a nonlinear meter scale.

Haefer² developed a magnetron for an investigation of striking characteristics of a gaseous discharge in

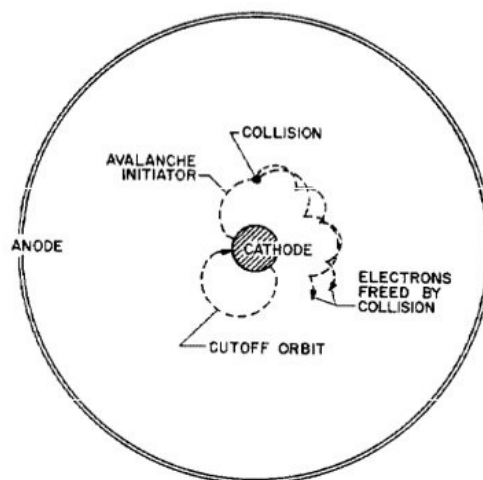


FIGURE 1. Electron orbits in a coaxial magnetron structure. Electrons either return to the cathode or collide with gas molecules to change their momentum and in event of ionizing collisions to release secondary electrons.

transverse electric and magnetic fields. The magnetron was found to strike at pressures below the sustaining discharge level for Penning cells designed up to that time. Much of the existing theory of magnetron gauge operation has been adapted from Haefer's work with the assumptions of negligible space charge and uniform electric field. The first assumption holds only prior to striking, and the second does not hold for the electrode arrangements used in pressure gauges.

The next advance in magnetron pressure gauges was made by Redhead and Hobson,^{3,4} who installed auxiliary cathodes as shield electrodes to eliminate the recording of erroneous field-emission current from the main cathode in an inverted magnetron structure. However, the linear response which Beck and Bris-

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¹ A. H. Beck and A. D. Brisbane, *Vacuum* 2, 137 (1952).

² R. Haefer, *Acta Phys. Austriaca* 7, 52 and 251 (1953); 8, 213 (1954).

³ P. A. Redhead, *Can. J. Phys.* 36, 255 (1958).

⁴ J. P. Hobson and P. A. Redhead, *Can. J. Phys.* 36, 271 (1958).

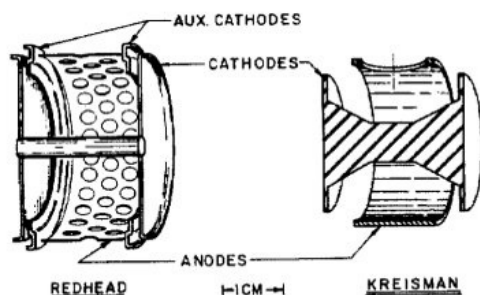


FIGURE 2. Electrode configurations of commercial magnetron gauges, shown to scale in cutaway; anode diameters: Redhead 3.0 cm, Kreisman 2.5 cm.

bane¹ had predicted for operation near 2500 G was not obtained.

Redhead⁵ also designed a modification of the normal magnetron structure with cathode endplates in contact with the central cathode bar and with large rings as auxiliary cathodes (Fig. 2). Thus, field emission was again removed from the ion current measuring circuit. A response near linearity (46° slope on a log current-log pressure plot) from about 5×10^{-10} Torr to 10^{-3} Torr, and a departure from linearity (59° slope) below 5×10^{-10} Torr, was found. At extremely low pressures, additional photoelectric action was necessary to ensure starting. Using this modified design, Hobson⁶ reported a limiting pressure measurement of 1.5×10^{-12} Torr in a liquid-helium-cooled system. The limit was assumed to be due to helium permeation through the walls of the glass system. The data actually appear to be the first published⁶ indication of the threshold phenomenon as described in this paper.

Kreisman has devised several versions of cold cathode normal magnetrons⁷⁻⁹ placed in metal envelopes to avoid a breakage problem. One of these models⁹ (GCA 1410), which does not employ auxiliary cathodes (see Fig. 2), is available commercially. Also, the NRC magnetron gauge design was modified for flight tests¹⁰ by removing the auxiliary cathodes; a significant alteration of response occurred, as described later.

Rutherford's results¹¹ on the behavior of Penning cells at low pressures show a large change of sensitivity as evidenced by a change of operating mode. These data for Penning cells are similar to the behavior of magnetron gauges at low pressures as reported here. However, the description¹² of a triggered Penning cell does not report a similar response.

⁵ P. A. Redhead, *Can. J. Phys.* **37**, 1260 (1959).

⁶ J. P. Hobson, *Can. J. Phys.* **37**, 300 (1959).

⁷ W. S. Kreisman and R. Herzog, GCA Tech. Rept. 61-18-N (1961).

⁸ Wallace Kreisman, GCA Tech. Rept. No. 64-8-N (1964).

⁹ W. Kreisman, GCA Tech. Rept. No. 64-17-N (1964).

¹⁰ G. P. Newton, D. T. Pelz, G. E. Miller, and R. Horowitz in *Transactions of the Tenth National Vacuum Symposium* (The Macmillan Co., Inc., New York, New York, 1963), p. 208.

¹¹ S. L. Rutherford in *Transactions of the Ninth National Vacuum Symposium* (The Macmillan Co., Inc., New York, New York, 1962), p. 185.

¹² J. R. Young and F. P. Hession, Ref. 11, p. 234.

In this paper, the expected characteristics of a magnetron gauge, with the space charge necessary to operate as an ionization gauge are discussed. Then a pressure-ratio technique used to test commercial magnetron gauges is described. The quantitative results of these tests are correlated with the qualitative features expected for space-charge-limited operation. The pressure response curves are then compared with the design features of the regular Redhead gauge, incorporating auxiliary cathodes, as well as with a special flight gauge and Kreisman design, both without auxiliary cathodes.

Theory

Jepsen¹³ has developed a theory which gives extensive consideration to the existence of a fully developed space charge of uniform density in both normal and inverted magnetron arrangements. The present consideration of space-charge buildup with increasing pressure is treated qualitatively since the electron loss mechanisms are not well known. The basic electron loss mechanism has been assumed to be their arrival at the anode after several collisions. In the extremely high vacuum range, orbital lifetimes of electrons traveling from cathode to anode may extend to hours,^{2,4} if electronic oscillations do not interfere. When the cycloidal behavior of the electrons is considered, these long lifetimes and the velocity differences of the electrons could lead, for example, to slipping stream instabilities which could return some electrons to the cathode and send others to the anode without the electron-molecule interactions postulated in the Townsend discharge theory.

Redhead has further investigated¹⁴ the "region of instability" reported earlier.⁵ Two operating states are reported for magnetic fields above and below a critical value. Radio frequency oscillations were found in the higher field state and sporadic noise in the lower or normal state. The maintenance of a maximum value of space charge was found in the linear response region. These important discoveries¹⁴ emphasize the role of space-charge effects upon magnetron operation.

The qualitative picture of space-charge moderated operation of a magnetron gauge is now given. At sufficiently low pressure, electron loss mechanisms exceed the pressure dependent source of electrons to preclude the maintenance of a discharge. However, a background current (due to insulator leakage) gives an indicated pressure reading. These low-pressure indications are not affected by removal of the magnet, a fact which confirms the lack of ion current in this cutoff state.

Electrons emitted from the cathode describe short

¹³ R. L. Jepsen, *J. Appl. Phys.* **32**, 2619 (1961).

¹⁴ P. A. Redhead, *Can. J. Phys.* **43**, 1001 (1965).

cutoff orbits starting from and ending on the cathode. (As Redhead⁵ indicates, these paths can cover a significant part of the cathode-anode distance.) However, the electron density in the gauge volume is negligible until the number of electron-molecule interactions becomes significant.

For pressure values above a lower operating threshold, there are enough gas phase collisions to release electrons to cathode-independent paths at a rate which exceeds the total loss rate. A space charge then begins to build up (see Fig. 1). The ions produced are detected at the cathode and the electrometer reading changes rather suddenly from a steady background value to a threshold ion current plus background reading when the discharge strikes.

As the space charge increases, the secondary electrons caused by ion bombardment of the cathode cylinder see a lower electric field; and, although the number should increase with increasing ion current, the maximum kinetic energy in a complete cycloidal arc and the arc length is reduced. The increase of space charge may eventually lead to a complete inactivation of the central portion of the cathode as an electron source. Thus, the cathode endplates or cones (Fig. 2) become increasingly important in defining the gamma coefficient for the discharge as pressure increases.

Finally, the electron space charge saturates and becomes nearly pressure independent so that a near-constant gas ionization probability is maintained for further pressure rise. Thus the basically pressure-dependent discharge is constrained by saturation to be constant and produce a linear ion current to pressure response. The onset of this desirable feature near 10^{-9} Torr defines the transition from nonlinear to linear response.

In summary, we would expect magnetron gauge operation to exhibit the following characteristics as pressure rises: (1) absence of a discharge below some low pressure level; (2) a threshold ion current at a pressure dependent on gauge geometry, voltage and magnetic field; (3) a greater-than-linear rise of ion current with pressure due to the pressure dependent rise of the electron density itself; and (4) a saturated electron space charge (above about 10^{-9} Torr) giving a linear ion current to pressure response.

Equipment

The characteristic response of ion current to pressure for cold cathode magnetron gauges was determined by a conductance-regulated, pressure-ratio method.¹⁵ This technique provided continuous opera-

tion of a reference Bayard-Alpert type hot-filament ionization gauge (BAG) located at a pressure two orders of magnitude above the pressure at the test magnetron gauge position (see Fig. 3). Thus the linear response of a BAG with constant emission current was used to obtain a continuous plot of the response curve for the magnetron gauges without the necessity of lowering the BAG to the level of residual collector current. The constancy of the pressure ratio was confirmed by using two BAG tubes on either side of the known conductance. Of course, the downstream BAG was then required to operate to a pressure below the x-ray photocurrent value. When corrections for total residual current were made (using the modulation technique¹⁶), changes of the downstream gauge were found to remain linear with changes of the upstream gauge within gauge reading error.

The characteristic ion current-to-pressure response curves for both NRC type 552 (Redhead) and GCA model 1410 (Kreisman) gauges were determined to their lowest operating pressures. The pressure-ratio method was employed for both gauge types. In addition, the GCA 1410 gauges were studied by direct comparisons to a BAG, since the commercial BAG type employed (Varian model UHV-12) covers the full operating range of the GCA 1410 gauge. The response curve determined by direct comparison, with corrections for residual current in the BAG readings, agreed with the response curve obtained by the pressure-ratio method. No correction for residual current in the upstream BAG was required for this set of pressure-ratio data, since the two order-of-magnitude ratio permitted operation to the low pressure limit of the Kreisman gauge without operating the BAG below 10^{-8} Torr.

Output currents from the upstream BAG, used as the reference gauge, and the magnetron test gauge were simultaneously plotted on a uniform time base, as indicated in Fig. 3, by means of a two-channel, strip-chart recorder. NRC type 752, and GCA model

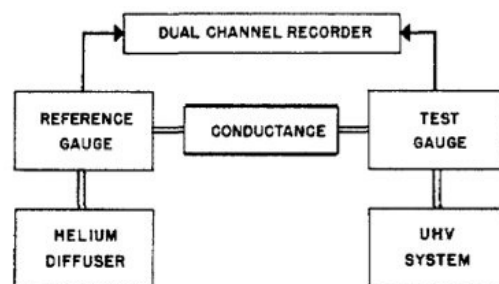


FIGURE 3. Vacuum gauge comparison system employing the pressure-ratio technique. The flow of helium through a fixed conductance establishes a pressure ratio. The ultimate vacuum attainable by the ultrahigh vacuum system exceeded the operating range of each magnetron gauge.

¹⁵ J. R. Roehrig and J. C. Simons, Jr., in *Transactions of the Eighth National Vacuum Symposium* (Pergamon Press, Inc., New York, New York 1962), p. 511.

¹⁶ P. A. Redhead, *Rev. Sci. Instr.* 31, 343 (1960).

1400 control units were used with the Redhead and Kreisman gauges, respectively. Ion currents and background currents for the magnetron gauges were checked with a Cary model 35 vibrating reed electrometer. High voltages for the magnetron gauges were set at the specified values of 4800 V for the Redhead type and 4000 V for the Kreisman type and regularly monitored with a sensitive electrostatic voltmeter. Magnetic field strengths of the permanent magnets were also checked periodically with a gauss meter and found to remain near 1040 G.

The BAG tubes (Varian model UHV-12) were operated with a grid potential of 130 V, and an emission current of 4 mA, so that the sensitivity was 25/Torr. Therefore, all operating parameters were carefully maintained at the values specified by the manufacturers of each type of gauge.

Response Curves

The characteristic response curves, determined from a large amount of data using the methods described above, are plotted in Figs. 4, 5, and 6. Actual pressure values in dry air equivalent are plotted on the abscissas, and indicated pressures from the magnetron control units are plotted on the ordinates. Ordinate values may be converted to ion current values by multiplication with the dry air sensitivity factors (4.5 A/Torr for the NRC 552 gauge tube and 2.0 A/Torr for the GCA 1410 gauge tube), since the control unit circuits (NRC 752 and GCA 1400) are designed on the assumption of linear response, i.e., constant sensitivity.

The ultrahigh vacuum portion of the response curve for NRC type 552 glass envelope (Redhead) gauges (Fig. 5) shows the following characteristics: (1) a

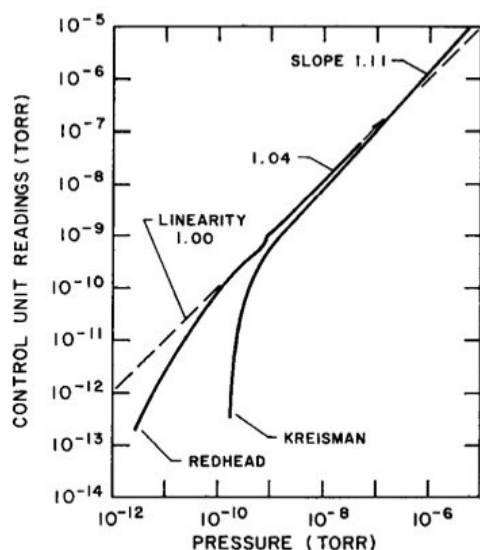


FIGURE 4. Characteristic response curves for two magnetron gauge models (upper portion of Redhead curve omitted) showing differences which result from variations in the designs.

background leakage current corresponding to an indicated pressure reading of 5×10^{-14} Torr when the real pressure is below the threshold for operation; (2) a total current value of 9×10^{-13} A for initiation of a sustaining discharge; this threshold level corresponds to an indicated pressure of 2×10^{-13} Torr and a real pressure of about 2.7×10^{-12} Torr; (3) a nonlinear response curve for values above threshold with a continuously changing slope approaching linearity near 10^{-9} Torr; this is presumably due to the continuous buildup of space charge toward a saturated value, i.e., the sensitivity of the gauge increases as space charge increases until a nearly saturated state is reached at 10^{-9} Torr; (4) a region of instability or resonance around 7×10^{-10} Torr characterized by oscillations in the output current; and (5) a response curve above 10^{-9} Torr which has a nearly linear slope of 1.04 with a slow rise in sensitivity, due to additional buildup of the essentially saturated space charge. The 46° slope reported by Redhead⁵ for the response curve above 10^{-10} Torr is essentially identical to the value given here. The data below 10^{-10} Torr agree closely with the data points given by Feakes and Torney,¹⁷ except for two differences of interpretation: (1) a theory invoking space-charge buildup and saturation is proposed to explain the continuously moderated response, rather than fitting straight line segments to the data; and (2) the pressure independent readings below 10^{-12} Torr are ascribed to leakage current in an out-of-strike state rather than to ion current. The data presented in Fig. 5 represent the response of clean Redhead gauges operated with the recommended potential of 4800 V and a magnetic field of 1040 G.

The ultrahigh vacuum portion of the response curve for clean GCA model 1410 (Kreisman) gauges (Fig. 6) shows the following characteristics: (1) a background leakage current corresponding to an indicated pressure reading of about 4.5×10^{-14} Torr for any real gas pressure value below 1.7×10^{-10} Torr, i.e., for

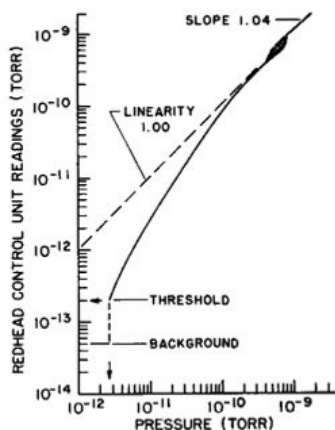


FIGURE 5. Characteristic response of clean Redhead (NRC 552 glass envelope) gauges. Ultrahigh vacuum range shows: background reading below operating threshold, sensitivity rise with pressure, an unstable region around 7×10^{-10} Torr, and near linear response above that region.

¹⁷ F. Feakes and F. L. Torney, Jr., Ref. 10, p. 257.

pressures below operating threshold, the gauge remains in the out-of-strike state; (2) a total current value of 7×10^{-13} A for initiation of a discharge; this threshold level corresponds to an indicated pressure reading of 3.5×10^{-13} Torr and a real pressure of 1.7×10^{-10} Torr; (3) a nonlinear response curve for values above threshold with a continuously moderated slope, due to the self-moderation of space-charge buildup; (4) a region of instability around 10^{-8} Torr; and (5) a sensitivity above 10^{-8} Torr which continues to increase with pressure along a response curve of slope 1.11; thus a linear response is not achieved over any portion of the pressure range. This latter feature is also found¹⁰ for a Redhead flight gauge from which auxiliary cathodes have been removed.

Kreisman reported⁹ the current-pressure characteristics of two standard GCA model 1410 gauges. The first gauge exhibited linear response over one decade of pressure from 5×10^{-8} to 5×10^{-7} Torr. The second gauge gave a nonlinear response curve (of slope 1.10) for the pressure range from 6×10^{-9} to 1×10^{-6} Torr; no data were given for pressures below the 10^{-9} Torr range. Thus, the data in the range reported⁹ for the second gauge agree with the response curve, Fig. 6, given here.

The threshold phenomenon may be repeatedly observed by raising and lowering the real pressure around the value necessary to sustain a discharge, i.e., 2.7×10^{-12} Torr for NRC 552 and 1.7×10^{-10} Torr for GCA 1410 gauges. To accomplish small pressure changes around the threshold values, the helium flow rate was slightly increased and decreased by varying the Vycor-helium diffuser temperature. Although the small pressure changes are recorded by the reference ion gauge, large stepwise changes from the background to the threshold value are indicated by the magnetron gauges. In addition, the magnetron gauges do not respond to pressure changes below their threshold pressure levels; i.e., the steady background leakage current values are indicated without an ion

current component for all pressures below the threshold level.

Discussion and Conclusions

Qualitatively, at least, the threshold phenomenon may be thought of in terms of the minimum number of avalanche initiating electrons required for a sustaining discharge. Figure 1 illustrates the process by which electrons may escape from the cathode and enter the trapping region as avalanche initiators. An avalanche initiating electron may make an ionizing collision, for example, with a gas molecule, and lose sufficient energy so that it travels in an approximately hypercycloidal path which does not intersect the cathode. The secondary electron produced by the ionization normally is also trapped in the discharge. However, for magnetron devices operated below cutoff, as is the case for both gauges discussed herein, electrons emitted from the cathode execute approximately hypercycloidal paths which intersect the cathode on the first orbit (see Fig. 1) unless a collision occurs, leading to a high probability of recapture. For the electric and magnetic field values employed in these gauges, an avalanche does not develop unless a sufficient number of gas molecules exists inside the anode cage to provide the threshold number of avalanche initiating collisions.

The total cathode current corresponding to threshold for the magnetron gauges is between 7 and 9×10^{-13} A, including currents from avalanche initiating electrons, ions, and background. Since this total value is four to seven times greater than the background alone, there is a clearly distinguishable difference between operation of the gauges above and below threshold. Even the cleanest tubes exhibit this threshold phenomenon.

The real pressure corresponding to threshold is about 60 times different for the two magnetron designs, which suggests a possible difference in the number of electrons available for avalanche initiation. Differences between at least two parameters of these gauges lead to a prediction of different electric field values at the cathode surfaces: (1) the recommended operating potential is 800 V lower for the GCA 1410 gauge; and (2) the central cathode radius is about double that used in the NRC 552 gauge (see Fig. 2). Whether or not these differences alone are sufficient to account for the difference in threshold pressures is an open question.

The continuously modified, nonlinear-response curve above threshold and the approach to linear response due to space-charge saturation are two additional qualitative characteristics observed experimentally for both magnetron gauges. However, we

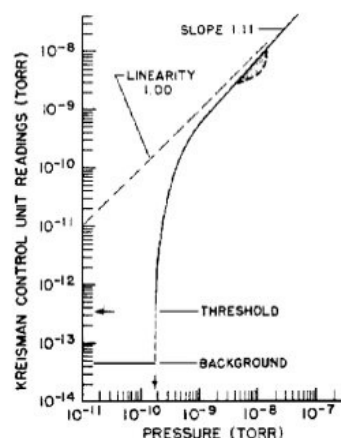


FIGURE 6. Characteristic response of clean Kreisman (GCA 1410) gauges. Notice the following: background indicating $10^{-13.5}$ Torr range when real pressure is below operating threshold of 1.7×10^{-10} Torr, rapid buildup of space charge, a possible unstable region around 10^{-8} Torr, and a slow sensitivity rise with pressure along a 1.11 slope.

again note that quantitative values are different for the two commercial designs. The nonlinear response above threshold is steeper for the Kreisman tube, beginning with a slope of about 14 and reaching 1.11, whereas the Redhead response curve begins with 2.2 and reaches a nearly linear slope of 1.04. These differences may be viewed alternatively in terms of an increase with pressure of the ionization probability or the number of ionizing electrons in the contained discharge.

The containment of space charge appears to be relevant to the attainment of linear response. The unique feature of auxiliary cathodes in the Redhead design permits a much closer spacing between cathode and anode electrodes; thus, the anode cage is tightly enclosed electrostatically and the space charge is ap-

parently contained within this fixed volume at a more closely saturated value. It is interesting to note, in closing, that calibration of the flight model NRC magnetron design,¹⁰ in which no auxiliary cathodes are used gave a response curve with a slope of 1.15. That is, the flight-model magnetron response was similar to the 1.11 slope of the Kreisman design for normal operation above 10^{-10} Torr. Thus the data for flight gauges¹⁰ and Kreisman gauges both without auxiliary cathodes show only an approach to saturation and linearity. On the other hand, the response (1.04 slope) of regular Redhead gauges with auxiliary cathodes and the electrostatically tight anode cage which results, exhibits almost complete fulfillment of the space-charge saturation hypothesis for linear response, which is described in this article.