

IEEE Guide for the Measurement of DC Electric-Field Strength and Ion Related Quantities

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Abstract: IEEE Std 1227-1990, IEEE Guide for the Measurement of DC Electric-Field Strength and Ion Related Quantities (ANSI), provides guidance for measuring the electric-field strength, ion-current density, conductivity, monopolar space-charge density, and net space-charge density in the vicinity of HVDC power lines, in converter substations, and in apparatus designed to simulate the HVDC power-line environment.

Keywords: conductivity, electric-field strength, ion-current density, monopolar space-charge density, net space-charge density, power lines.

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Foreword

(This Foreword is not a part of IEEE Std 1227-1990, IEEE Guide for the Measurement of DC Electric-Field Strength and Ion Related Quantities.)

Because of interest in the electrical environment near high-voltage dc transmissions lines, the DC Fields and Ions Working Group felt that there was a need to prepare a document that would provide some guidance for the measurement of several relevant electrical parameters. The electrical parameters that are considered in this standard include the electric-field strength, the ion-current density, the monopolar charge density, and the net space-charge density.

The working group expresses its appreciation to Martin Misakian for his work in preparing the draft of this document in collaboration with members of the working group. The text of the standard includes the results of many studies by researchers at the Bonneville Power Administration, the Electric Power Research Institute's High-Voltage Transmission Research Center, Institut de Recherche d'Hydro-Québec, the Jet Propulsion Laboratory, and the National Institute of Standards and Technology. These studies were supported by internal funding, as well as by funding from the U.S. Department of Energy and the Electric Power Research Institute. Constructive suggestions from those committees that had requested coordination have also been incorporated into the text.

At the time this standard was completed, the DC Field and Ions Working Group had the following membership:

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IEEE Guide for the Measurement of DC Electric-Field Strength and Ion Related Quantities

1. Purpose

The purpose of this document is to provide guidance for the measurement of the electric-field strength, ion-current density, conductivity, monopolar space-charge density, and net space-charge density in the vicinity of high-voltage dc (HVDC) power lines, in converter substations, and in apparatus designed to simulate the HVDC power-line environment. The document

- Defines the terms that are used
- Describes the interrelationship between electrical parameters
- Describes operating principles of measuring instruments
- Suggests methods of calibration where applicable
- Describes measurement procedures
- Identifies significant sources of measurement error

2. Definitions

For additional definitions, see IEEE Std 100-1988 [1] and IEEE Std 539 [3].

charged aerosol: Ion comprised of charged particles, liquid or solid, suspended in air. Typical radius is in the range of 2×10^{-8} m to 2×10^{-7} m. Mobility is in the range of 10^{-9} m to 10^{-7} m²/Vs.

NOTE—Historically, these have been referred to as large or Langevin ions. The use of the term “charged aerosols” is encouraged.

corona: A luminous discharge due to ionization of the air surrounding an electrode caused by a voltage gradient exceeding a certain critical value.

current density: A vector-point function describing the magnitude and direction of charge flow per unit area. The preferred unit is amperes per square meter (A/m²).

dc electric-field strength (dc electric field): The time-invariant electric field, produced by dc power systems and space charge, defined by its space components along three orthogonal axes. The magnitudes of the components are expressed in volts per meter (V/m).

NOTES:

1—The convention in the discussion of electric fields near HVDC transmission lines has been to designate the electric field into the ground as positive; i.e., the electric field under a positive conductor is denoted as positive.

2—The “time-invariant” electric field in this definition is an idealization of actual conditions. Typically, climatic effects will perturb the space charge, which will then perturb the electric-field strength.

electric conductivity: The property of a material or medium permitting flow of electricity through its volume, expressed as the ratio of the electric-current density to electric-field strength in a material or medium. For isotropic homogeneous media, the conductivity is a scalar quantity with the preferred unit, siemens per meter (S/m); 1 S/m = 1 mho/m.

Faraday cage: A conducting enclosure that is used to measure the net space charge per unit volume. *Syn:* **space charge cage, space charge density meter.**

field mill: A device in which a conductor is alternately exposed to the electric field to be measured and then shielded from it. *Syn:* **generating voltmeter, generating electric-field meter.**

NOTE—The resulting induced current to the conductor is a measure of the electric-field strength at the conductor surface.

form factor: An empirical parameter representing the increased electric field at the surface of a dc field meter that is mounted above the ground plane. The increased field is due to field perturbation by the instrument. In a uniform field, the unperturbed electric field is given by the measured field divided by the form factor for the instrument.

ion: The isolated atom, molecule, molecular cluster, or aerosol that by loss or gain of one or more electrons has acquired a net electric charge.

NOTE—The inclusion of aerosols (particles) under this definition is consistent with historical usage. The use of the terms “small ion” and “charged aerosol” is encouraged.

ion counter: An instrument that determines monopolar space-charge density by measuring the charge collected from a known volume of air.

ion mobility: The drift speed of an ion in a liquid or gas per unit electric-field strength. The preferred unit is m^2/Vs ; another commonly used unit is cm^2/Vs .

large ion: See **charged aerosol**.

medium ion: Ion comprised of several molecules or molecular clusters bound together by charge that is larger and less mobile than a small ion due to more mass or a greater number of molecular clusters. Typical radius is in the range of 10^{-9} m to 2×10^{-8} m. Mobility is in the range of 10^{-7} m^2/Vs to 10^{-5} m^2/Vs .

monopolar ion density: The number of ions of a given polarity per unit volume. The preferred unit is m^{-3} ; another commonly used unit is cm^{-3} .

monopolar space-charge density: The density of space charge of one polarity. The preferred unit is C/m^3 .

net space charge: The free unbalanced charge in a given region, taking no account of the charges of both signs that balance each other. The preferred unit is the coulomb (C).

NOTE—The term “space charge” is often used to refer to net space charge.

net space-charge density: Net space charge (space charge) per unit volume. The preferred unit is C/m^3 . This

quantity provides no information about the monopolar space-charge density.

small ion: An ion comprised of molecules or molecular clusters bound together by charge. Mobilities are in the range of $10^{-5} \text{ m}^2/\text{Vs}$ to $2 \times 10^{-4} \text{ m}^2/\text{Vs}$. Typical radius is less than $1 \times 10^{-9} \text{ m}$.

NOTE—To avoid confusion with the more general term “ion,” the use of the term “small ion” is encouraged.

space-charge filter: A device used to measure net space-charge density in which a filter medium is used to remove the charge from an air stream.

vibrating probe: A device in which a plate is modulated below an aperture of a face plate in the electric field to be measured. *Syn:* **vibrating plate electric-field meter.**

NOTE—The meter responds to the oscillating displacement current from the induced charge on the vibrating plate by generating a negative feedback voltage on the face plate to null the signal from the vibrating plate. The electric-field strength is proportional to the feedback voltage.

Wilson plate: A conducting plate that is grounded through an ammeter; it is used to collect the ion current, which is measured as it flows through the ammeter. The plate is sensitive to both ion-current density and changes in electric field (displacement current). *Syn:* **current plate; ion-current plate.**

NOTE—Long integration times are used to minimize the effects of the changes in the electric field (displacement current). If the power-line voltage and geometry are constant with time, the average displacement current is zero.

3. Formula Symbols

This section provides a list of symbols used in the formulas that appear in this guide. While the same symbol is sometimes used to designate more than one physical parameter, there should be little confusion because of the very different contexts in which they are used. The use of SI units for all the physical parameters is encouraged.

E	Electric-field strength
J	Ion-current density
K	Average ion mobility
ρ	Monopolar charge density
v_a	Wind velocity
q_s	Induced charge—shutter-type field mill
ϵ_0	Permittivity of free space
$a(t)$	Sensing electrode area—shutter-type field mill
$i(t)$	Induced current—shutter-type field mill
q_c	Induced charge—cylindrical field mill
L	Cylinder length—cylindrical field mill; side dimension of plate of parallel-plate system; distance ion travels in duct; side dimension of cubical Faraday cage
r^0	Cylinder radius—cylindrical field mill
i_c	Induced current—cylindrical field mill
d	Spacing of parallel plates
V	Voltage
v	Volume of electric-field meter probe
D	Distance between center of electric-field meter probe and either plate of a parallel-plate system

$E(z)$	Electric-field strength as function of height above bottom plate of parallel-plate system with space charge
$\phi(z)$	Electric space potential as function of height above bottom plate of parallel-plate system with space charge
V_t	Voltage of top plate of parallel-plate system
E_t	Electric field at top plate of parallel-plate system with space charge
A	Area of Wilson plate
I	Ion current
R	Resistance value; radius of duct
λ	Electrical conductivity of air
M_0	Volumetric flow rate
C	Interelectrode capacitance of Gerdien table
k	Ion mobility; Boltzmann constant
k_c	Critical ion mobility
$f(k)$	Mobility distribution function
$f(k)dk$	Number of ions with mobility between k and $k+dk$
e	Charge of electron; charge of ion
N	Number of ions
$\rho(L)$	Charge density after charge traverses distance L in cylindrical duct
ρ_0	Charge density at entrance of duct; monopolar charge density outside hemispherical Faraday cage
u	Air velocity in duct
τ	Ion time-of-flight
s	Radially outward displacement of ions due to Coulomb repulsion
s'	Radially outward displacement of ions due to diffusion
T	Temperature in degrees K
$\phi(x,y,z)$	Space potential in Faraday cage
ρ_s	Net space-charge density
a,b,c	Dimensions of Faraday cage
i,j,k	Odd integers in summation
ϕ	Space potential at center of cubical Faraday cage
ϕ'	Space potential at center of cylindrical Faraday cage
ρ_i	Monopolar charge density inside hemispheric Faraday cage
E_0	Uniform electric-field strength in vicinity of hemispheric Faraday cage

4. References

This guide shall be used in conjunction with the following publications:

- [1] IEEE Std 100-1988, IEEE Standard Dictionary of Electrical and Electronics Terms.¹
- [2] IEEE Std 510-1983, IEEE Recommended Practices for Safety in High-Voltage and High-Power Testing.

¹IEEE publications are available from the Institute of Electrical and Electronics Engineers, Service Center, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331, USA.

- [3] IEEE Std 539, IEEE Standard Definitions of Terms Relating to Corona and Field Effects of Overhead Power Lines.²
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²This standard will be available from the Institute of Electrical and Electronics Engineers, Service Center, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331, USA, in early 1991.

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5. Electrical Parameters Near HVDC Transmission Lines

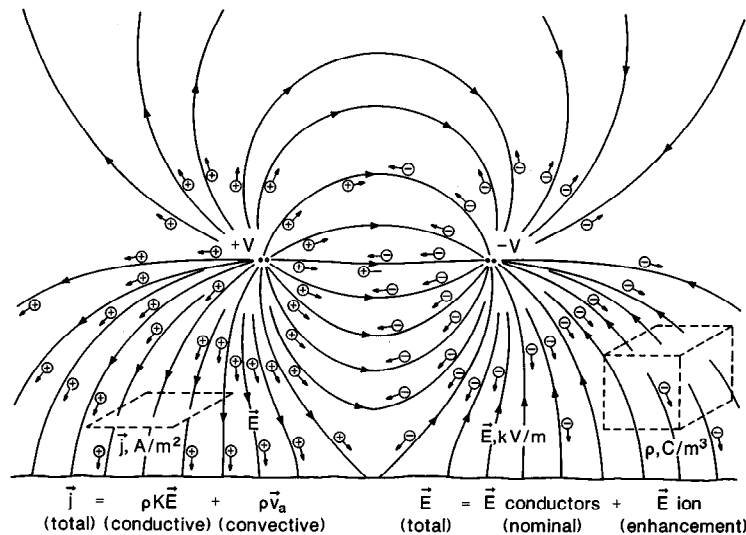
The electrical environment in the vicinity of HVDC transmission lines is characterized by several electrical parameters including the electric-field strength ($\vec{E}$), the ion-current density ($\vec{J}$), and the monopolar space-charge density (ρ) [8], [9], [30]. HVDC transmission lines are normally designed to operate in a bipolar configuration with a conductor bundle for each polarity. The electric field is due in part to the high voltages applied to the conductors. Copious amounts of ions are produced by corona at each conductor bundle, and the presence of the ions contributes significantly to the electric-field strength at ground level [9]. In the absence of wind, the ions travel along electric-field lines to the conductors of opposite polarity, to the ground wires, and to the ground plane. Depending on the air composition, a number of resultant ion species, each with its characteristic mobility, are formed following ion-molecule reactions by the primary ions that are initially produced by the corona. The drift velocity of each ion is equal to the product of its mobility and the electric-field strength. In the presence of wind, the ion velocity is given by the sum of the drift velocity and wind velocity (v_a). The monopolar ion current density in this case is given by

$$\vec{J} = \rho K \vec{E} + \rho \vec{v}_i \quad (1)$$

where

K = the average ion mobility

The wind can be thought of as a perturbing influence because it causes temporal fluctuations in the values of ρ , and therefore $\vec{E}$ and $\vec{J}$, at a given point. In addition, when the wind velocity is comparable to or greater than the ion drift velocity, significant numbers of ions can leave the vicinity of the right-of-way and travel downwind from the transmission line. A schematic view of the electrical environment in the vicinity of an HVDC transmission line is shown in Fig 1, which is taken from [8]. For clarity, the influence of the air motion has been taken to be negligible. It is common practice to assume that the ions are singly charged and to calculate the monopolar ion number density from ρ [12]. A more complete description of the electrical environment near HVDC transmission lines is given in references [8], [9], [30]. It should be noted that, in general, dc electric fields with ions cannot realistically be modeled using 60 Hz electric fields because of the significant and often unpredictable influence of the ions that can vary the electric-field strength at a point because of wind action or by charging nearby insulator surfaces.



NOTE—Ions produced by corona at each conductor bundle travel along electric-field lines to the conductors of opposite polarity and to ground in the absence of wind.

Figure 1 — Schematic View of a Bipolar High-Voltage DC Transmission Line

6. Electric-Field-Strength Measurements

6.1 Instrumentation and Principle of Operation.

Two types of dc electric-field-strength meters are considered in this guide: field mills or generating voltmeters and vibrating plate electric-field meters (i.e., field meters employing probes that contain vibrating plates). Both devices determine the electric-field strength by measuring modulated, capacitively induced charges or currents sensed by metal electrodes. Other instrumentation for measuring dc electric fields in the presence of space charge have been reported in the technical literature,³ but they are not considered here because of their specialized nature and/or their lack of availability.

6.1.1 Field Mill (Generating Voltmeter).

Two types of field mills are described in the technical literature, the shutter type and the cylindrical type. The more common is the shutter-type field mill, which has a sensing electrode that is periodically exposed and shielded from the electric field by a grounded rotating shutter. Shutter-type field mills are usually operated with the shutter nearly flush with the ground plane. The induced charge at any instant, q_s , as well as the induced current (i_s) between ground and the sensing electrode as the sensing electrode is alternately exposed and shielded, are proportional to the electric-field strength (E). That is,

$$i_s(t) = \epsilon_0 E a(t) \quad (2)$$

³See, for example, Tassicker, O. J. "Boundary Probe for Measurement of Current Density and Electric Field Strength—With Special Reference to Ionized Gases." *Proceedings of the IEEE*. vol. 121, 1974, pp. 213–220; Cooperman, P. "A New Technique for the Measurement of Corona Field Strength and Current Density in Electrical Precipitation." *Transactions of the American Institute of Electrical Engineers*. vol. 75, 1956, pp. 64–67; Hidaka, K. "A New Method of Electric Field Measurements in Corona Discharge Using Pockels Device." *Journal of Applied Physics*. vol. 53, 1982, pp. 5999–6003.

where

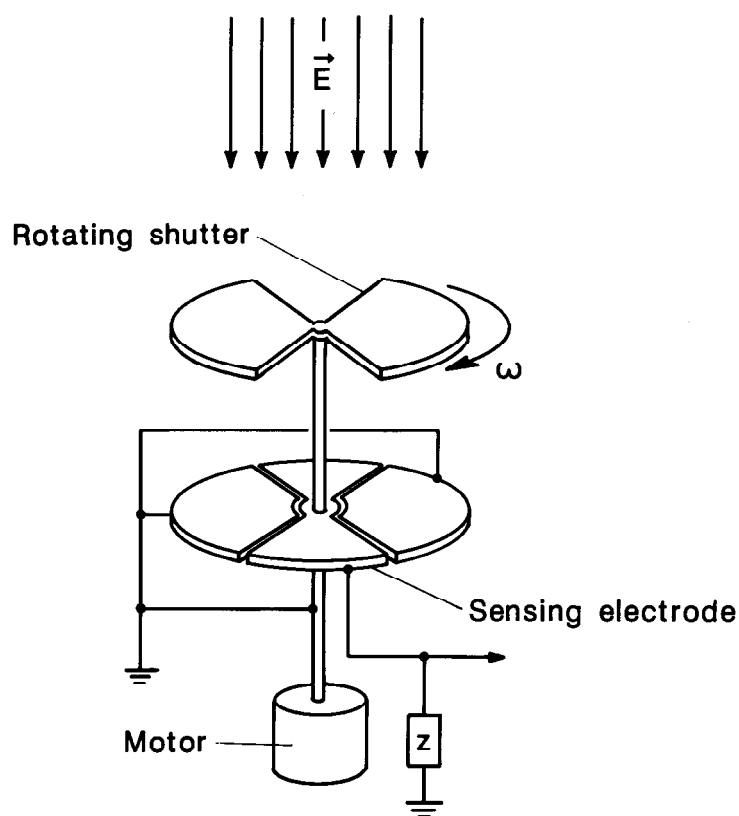
ϵ_0 = the permittivity of free space
 $a(t)$ = the exposed area of the sensing electrode at time t

The induced current is found by taking the derivative of Eq 2:

$$i_s(t) = \frac{dq_s(t)}{dt} = \frac{\epsilon_0 E da(t)}{dt} \quad (3)$$

Thus, the field strength can be determined by measurement of the induced charge, current, or voltage across an impedance that is located between the sensing electrode and ground. A simplified schematic view of a shutter-type field mill is shown in Fig 2.

If the induced-current signal is rectified by a phase-sensitive detector operating with a suitable phase angle relation to the motion of the shutter, the dc signal output will indicate the polarity and magnitude of the electric-field strength [61].



NOTE—The grounded rotating shutter periodically shields the sensing electrode, which leads to a time-varying current between ground and the sensing electrode.

Figure 2 — Simplified Schematic View of a Shutter-Type Electric Field Mill

Because of the presence of space charge in the vicinity of dc power lines, it is possible to have, in addition to the induced current, conduction current (of ions) to the sensing electrodes of the field meter. This additional current, which is chopped by the rotating shutter, represents an error signal and shall be corrected for in the instrumentation. One approach is to use phase-sensitive signal processing that discriminates against the conduction current, which is in quadrature with the induced-current signal [61].

While shutter-type field mills are normally operated in the ground plane in order to measure the field at ground level, measurements of the field at ground level can also be made with a field mill that is mounted on a stand, provided the measurements are corrected for the associated field enhancement through some calibration procedure (see *form factor* in Section 2). It should be noted that the geometry that exists during the calibration process shall be maintained during the measurements. For example, if grass or weeds are allowed to grow near the stand, the effective ground plane could rise. Similarly, the ground plane would be affected by the accumulation of snow on the ground. A method for establishing a well-defined ground plane for most weather conditions during measurements at ground level is described in 6.3.1.1.

During the measurements, the observer should be well removed from the measurement location to avoid perturbing the electric field. Some signal processing occurs in the housing that contains the sensing electrode and shutter. The remainder of the signal-processing circuit and field-strength display are contained in a shielded enclosure that is connected to the sensing electrode housing with a shielded cable.

Because the electric field in the vicinity of a dc power line is not uniform, it may be of interest to measure the electric-field strength at points above the ground plane. This can be done with the second type of field mill, the cylindrical field mill. Typically, the charges are induced by the electric field on two exposed half-cylinder sensing electrodes. The induced charges on the sensing electrodes are varied periodically by rotating the sensing electrodes about the cylinder axis at a constant angular frequency, as shown schematically in Fig 3. Expressions for the induced charge (q_c) and current (i_c) between the half-cylinders for a cylinder of length L , ignoring end effects, are [39]

$$i_c = 4\epsilon_0 r_0 L E \sin \omega t \quad (4)$$

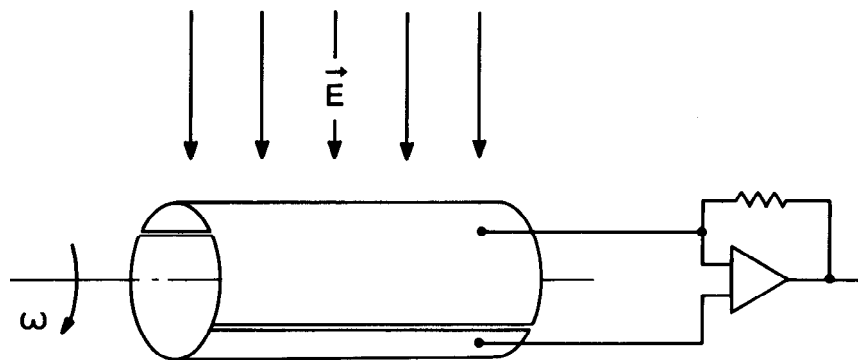
and

$$q_c = 4\epsilon_0 r_0 L E \cos \omega t \quad (5)$$

where

r_0 = the cylinder radius

Eq 4 and Eq 5 show again that measurement of the induced charge or current permits a determination of the electric-field strength.



NOTE—The charge induced on each half-cylinder by the electric field is made to vary periodically by rotating the cylinder at a constant angular velocity.

Figure 3 — Schematic View of a Cylindrical Field Mill

Cylindrical field mills that operate at near space potential [37], [38], [43] and at ground potential [50] have been developed for measurements above the ground plane near dc power lines. For both cases, the field at the surface of the cylinder will be a superposition of two components, one due to the field from the dc power line (distorted by the cylindrical probe) and the other due to a constant, symmetrically distributed charge on the cylinder. Fig 4 schematically shows these two field components and the field resulting from their superposition for the case of a ground-referenced cylindrical field mill. Because no electrical signal is generated by the symmetrically distributed self-charge [Fig 4(b)] as the cylinder rotates [38], the signal that is produced is due to the time-varying induced charge or current approximately described by Eqs 4 and 5 and, as for the case of the shutter-type field mill, a time-varying ion current due to the space charge in the field. In order to determine the electric-field strength with both currents present, ground-referenced cylindrical field mills require two sets of rotating cylinders with different frequencies of rotation [50].

The picture corresponding to Fig 4 for an electrically isolated cylindrical field mill is similar, except that the self-charge uniformly distributed on the cylinder is of opposite polarity and results from a charging process due to ions in the field impinging on the cylinder. The cylinder becomes fully charged in a negligible time and prevents the further flow of ions to the sensing electrodes. Thus, the need for a second set of sensing electrodes rotating at a different frequency, as required for the ground-referenced cylindrical field mill, is eliminated.

The abbreviated account of field mills presented here is intended as a brief introduction. Since the first report of the shutter-type field mill by Harnwell and Van Voorhis in 1933 [27] and the cylindrical field mill by Kirkpatrick and Miyake in 1932 [44], numerous articles have been published⁴ describing variations of the basic designs as well as methods for signal detection.⁵

⁴See, for example, Mapleson, W. W. and Whitlock, W. S. "Apparatus for the accurate and continuous measurement of the earth's electric field." *Journal of Atmospheric and Terrestrial Physics*. vol. 7, 1955, pp. 61–72 and the references therein; Malan, D. J. and Schonland, F. J. "An Electrostatic Fluxmeter of Short Response-time for use in Studies of Transient Field-changes." *Proceedings of the Physical Society*. vol. 63, pt. 6-B, 1950, pp. 402–408; Smiddy, M. and Chalmers, J. A. "The double field-mill." *Journal of Atmospheric and Terrestrial Physics* vol. 12, 1958, pp. 206–210; Gathman, S. G. and Anderson, R. V. "Improved Field Meter for Electrostatic Measurements." *Review of Scientific Instruments*. vol. 36, 1965, pp. 1490–1493; Collocot, S. J. "A Novel Method for Deriving the Reference Signal in Electric Field Mills." *Journal of Electrostatics*. vol. 9, 1981, pp. 389–391.

⁵Use of a vibrating shutter rather than one that rotates is described in Horenstein, M. N. "Peak sampled vibrating-reed for the measurement of electric fields in the presence of space charge." *Review of Scientific Instruments*. vol. 54, 1983, pp. 591–593.