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**ABSOLUTE SPECTRAL MEASUREMENTS
OF ELECTRONS FROM HIGH-INTENSITY,
NONREPETITIVELY PULSED SOURCES**

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MASTER

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MASTER

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Abstract

We discuss the design and calibration of electron spectrometers applicable to spectral measurements of high-intensity, nonrepetitively pulsed sources. The main emphasis is on flat permanent-magnet spectrometers that enable one to measure several spectral points simul-

taneously. We discuss low-energy electron detectors suitable for use in these spectrometers as well as systems to record detector output current. Calibration procedures and results are presented for the silicon detectors we have found to be most effective.

Introduction

Most electron spectrum measurements are made on low-intensity sources for which conventional counting techniques are appropriate. Such methods are not applicable to spectral measurements of high-intensity, nonrepetitively pulsed sources. In this report we will discuss electron spectrometer designs and calibration techniques that have evolved during a series of diagnostics experiments for which the sources were nonrepetitively pulsed and required one or

two completely calibrated spectrometers for each submicrosecond radiation burst. These spectrometers are of great value in the measurement of electrons emanating from a laser-produced plasma. We are presently conducting a series of laser plasma electron measurements with a spectrometer of the latest design. We will also outline characteristics of associated high-current electron detectors and pulse recording systems.

Electron Spectrometer Design

Most of the electron spectrometers discussed in the literature have been designed to analyze magnetically electrons emitted from small radioactive sources.¹ For this application, the source must usually be located in the magnetic field, often surrounded by the

apparatus. One thereby obtains the necessary high transmission (where transmission refers to the fraction of emitted electrons incident on a detector) with good energy resolution. Transmission values as high as 20% with better than 2% energy resolution have been obtained

using large, iron-free, toroidal designs.¹

These designs are not appropriate for the case under consideration, however, in which the spectrometer is placed at a distance from the source, e.g., when intrusion into the source region interferes with an incident beam or other experiments, or when the spectrometer detectors must be well shielded from other radiations produced by the source. Some designs suitable in this case are described below. In choosing a design, one must take into account the defining electron-aperture dimensions, the source size, and the source-to-aperture distance to optimize the spectrometer transmission and resolution.

UNIFORM-FIELD DESIGNS

The simplest, and for many applications best, spectrometer design consists of an electron aperture, a flat uniform-field magnet, and an array of detectors situated on a focal plane. Spectrometers using this design have several important advantages over those requiring a nonuniform field. They are easily constructed and can be made relatively compact. The magnetic field can be accurately measured and, hence, the performance accurately predicted. Also, several spectral points can be obtained for a single source pulse, the spectrum being registered either with an array of detectors or photographically (though in the latter case, with diminished absolute-intensity accuracy).

Flat permanent-magnet spectrometers have been designed in both 90°- and 180°-focusing configurations. The design

choice is dependent on source-spectrometer geometry for the intended application. We have used both for single-pulse field measurements. As can be seen in Fig. 1, the base resolving power of a 180° spectrometer is strongly dependent on the electron aperture width, but is relatively insensitive to the source size. Hence, this design is particularly useful when observing a large source with adequate intensity to permit a small entrance aperture. The 180°-focusing spectrometer shown in Fig. 2 was constructed using ceramic pole pieces and used on an experiment to measure electron energies from 0.3 to 4 MeV.

Fig. 1. Focusing characteristics of flat electron spectrometers. The magnetic field is directed into the page in each case. (a) Relatively wide entrance aperture with no incident beam divergence. (b) Relatively narrow entrance aperture with a 4° incident beam divergence.

Fig. 2. Electron spectrometer (180° focusing) with ceramic magnet pole pieces and silicon detectors.

An example of a 90° assembly is shown in Fig. 3. Pole pieces of "plastiform" and iron were appropriately designed to obtain a field that rapidly increases near the entrance aperture from zero to the design value, thus minimizing the effects of fringing fields. Good field uniformity from the entrance to the detector plane is required to insure predictable spectrometer performance. As shown in Fig. 1, the base resolving power for 90° focusing is sensitive to the beam divergence at the aperture, but is insensitive to the aperture size. Thus, 90° focusing is superior when the source-to-aperture distance is large. An additional advantage of 90° over 180° focusing stems from the shorter electron path lengths, which

result in a smaller beam divergence across the magnet gap.

The main disadvantage of uniform-field spectrometers is, of course, that focusing occurs in only one dimension.

DOUBLE-FOCUSING SPECTROMETERS

A variety of double-focusing spectrometers have been designed to increase system transmission without loss of base resolving power¹ (or to decrease detector dimensions and thus improve the rise time of an output pulse). Such spectrometers have several disadvantages over uniform-field designs (a) they are more difficult to construct, (b) their performance is harder to calculate, and (c)

Fig. 3. Electron spectrometer (90° focusing). (a) Magnet. (b) Associated detector array.

generally only one spectrum point can be obtained per source pulse.

A natural extension of the uniform-field design would involve shaping the fringe field for second-order focusing in the median plane. A carefully shaped inhomogeneous field is required for higher-order double focusing. An exam-

ple of a double-focusing spectrometer suitable for electron energies below 1 MeV is a design with a field that varies as $(\rho)^{-1/2}$ in the vicinity of ρ_0 (ρ_0 being the radius of curvature of the central electron path). Such a field can be obtained using, for example, two concentric solenoids or properly shaped pole

pieces.¹ The base resolving power of this design in relation to that of a flat spectrometer is a factor of 2 less sensitive to source and detector dimensions

and is less sensitive to aperture dimensions; in fact, it may be made very insensitive to the aperture width in one dimension.

Spectrometer Response Functions

Energy-response functions for spectrometers of the designs shown in Figs. 2 and 3 have been measured using 150-keV to 4-MeV electron beams at the National Bureau of Standards and 30- to 100-keV electron beams at ULL. Results are in good agreement with response functions calculated using our ray-tracing design

code. The code is discussed in detail in Appendix A. The code will also fold in an input-electron spectrum, which is useful for predicting detector output values. Using calculated response functions and values of measured detector output charge, we can accurately generate a source-electron spectrum.

Electron Detectors

Several types of low-energy electron detectors suitable for use in magnetic spectrometers have been developed. They include silicon diodes, anthracene or plastic scintillators coupled to photomultipliers, plastic scintillators coupled to photodiodes, and Faraday cups. Some of their more significant characteristics are listed in Table 1.²

SILICON DETECTORS

Silicon semiconductor detectors are very useful for making electron measurements because of their small volume, insensitivity to magnetic fields, low electron reflectivity (about 10% from 50 to

400 keV),² and accurately measured electron-ionization energy.³ Also, their output charge is linearly related to the energy input over a wide dynamic range, and the absorbed electron energy can be accurately measured experimentally from pulse-height distributions obtained using monoenergetic incident electrons.

There are three silicon detectors that have been widely used for electron detection: lithium drifted, surface barrier, and double-diffused p-i-n. Lithium-drifted devices are commonly used to detect high-energy charged particles. They can be made relatively thick (as thick as several millimeters), giving them a low capacitance and high energy resolution (when cooled to reduce leakage currents). However, their dead layers are generally thicker than are those of other silicon detectors.

²Reference to a company or product name does not imply approval or recommendation of the product by the University of California or the U.S. Atomic Energy Commission to the exclusion of others that may be suitable.

Table 1. Detectors.

Detector system	Rise time (nsec)	FWHM (nsec)	Charge gain at 100 keV	Peak linear current (A)	Input electron range (sec ⁻¹)
Faraday Cup ^a	<30 psec	<60 psec	~1	Very high	~10 ^{2b} to 10 ¹⁹
Fluor (NE-111) ^c	0.35	1.3			
Photodiode (ITT FW114)	<0.3 } 0.46	<0.4 } 1.4	40	60	10 ^b to 10 ¹⁰
Fluor (NE-111)	0.35	1.3			
Photomultiplier ^d (RCA C31024)	1.6 } 1.64	3.6 } 3.8	<10 ³	100 mA to 1A	1 to 9 × 10 ⁵
Silicon 1000 V bias ^e (6 mm ²)	1	1.5	2.5 × 10 ⁴	10	1 to 6 × 10 ⁶
Silicon at 1000 V ^e (150 mm ²)	5	7	2.5 × 10 ⁴	10	1 to 3 × 10 ⁷

^aSee Ref. 10.^bIf used with a charge sensitive amplifier.^cSee Ref. 7.^dSee Ref. 8.^eSee Ref. 4.

Silicon surface-barrier detectors are now available in thicknesses as great as 5 mm (the range of a 2-MeV electron). They can be obtained with thin, front, dead layers (0.05 mg/cm² aluminum) and good signal-to-noise performance. A cooled detector should be especially useful at low electron energies. Disadvantages of surface-barrier detectors include high sensitivity to light and low breakdown bias voltage (hence, a lower linear output current than either lithium-drifted or double-diffused detectors). A further consideration is that the effect of a slow charge collection from weak field regions has not been well documented. If charge collection is slow compared to the detector output-charge integration time, accurate detector calibration becomes difficult. In the counting mode, a period of one to several microseconds is normally used to integrate the detector output current generated by an individual electron. With

such a time constant, measured pulse-height distributions are not greatly affected by slow charge collection.

Double-diffused silicon p-i-n detectors have been developed specifically for single-pulse field applications requiring high linear output currents (>10 A) and reasonably fast response times (2- to 10-nsec rise times).⁴ They can be produced with thin entrance windows (equivalent to 0.2 to 0.5 μ m of undepleted silicon), so that the fraction of input electron energy absorbed by the active volume will be large. We have measured the electron energy absorbed in p-i-n detectors at NBS and LLL (incident electron energies from 150 keV to 4 MeV and from 50 to 100 keV, respectively). These measurements are discussed in detail in Appendix B. Experimental results for detectors thicker than an electron range are in agreement with calculations of Berger and Seltzer⁵ and with those of Brown.²

Time-response characteristics of p-n detectors have been measured using the Edgerton, Germeshausen and Griev Linac (Santa Barbara).⁴ The rise time is roughly proportional to the square root of the detector area; therefore, time response can be improved in spectrometer applications at the expense of output pulse amplitude.

ANTHRACENE AND PLASTIC SCINTILLATORS COUPLED TO PHOTOMULTIPLIERS

Another high-gain detector that can be used in electron spectrometers consists of a low-Z scintillator coupled to a photomultiplier tube. The output of this detector is somewhat nonlinear at low energies. However, as in the case of silicon detectors, efficiencies can be measured experimentally with counting techniques.

Anthracene and plastic scintillators have similar properties. Compared to plastic, anthracene has a greater light output, but longer decay time. A bare anthracene crystal mounted directly on a photomultiplier tube can be used down to, and perhaps below, 5-keV electron energy, provided that the crystal is properly cleaved and the combination is cooled to reduce the noise level and prevent sublimation of the crystal in vacuo.⁶ (A bare scintillator is, of course, very light-sensitive and must be shielded to prevent background signals.) At present, the best

time response is obtained using an NE-111 plastic fluor⁷ coupled to an RCA C31024⁸ or an Amperex Pm2106 phototube (see Table I).

FLUOR-PHOTODIODES

A plastic scintillator has a relatively good time response that is degraded when it is coupled to a photomultiplier tube. If high gain is not needed, the scintillator can be coupled to a planar photodiode that will not greatly modify the scintillator response. As can be seen from the parameters listed in Table I, the time response of the combination is limited primarily by the scintillator.⁷ The peak, linear, output current of the fluor-photodiode is high, substantially greater than that of high-gain detectors.

FAST FARADAY CUPS

Coaxial Faraday cups designed to provide excellent time response have been used for some time.^{9,10} A Faraday cup essentially transfers the incident electron pulse to the recording system via a coaxial cable with no energy selection and no charge gain. A good time response can be achieved by giving careful attention to impedance matching. For such a design, the recording system rather than the detector is the limiting factor in timing measurements.

Recording Systems

Except for the tedious data reduction involved, the most satisfactory recording system for detector pulses in the nano-

second range is the oscilloscope. The oscilloscope trace is recorded on film, which can be read accurately and provides

both time information and a measure of detector charge output. Time-dependent backgrounds can be examined and appropriately subtracted.

If pulse amplification is required, the most satisfactory device from the standpoint of wide range, time response, and linearity is the scope plug-in amplifier. Two types of systems are characterized in Table 2, one with a good time response in which the detector signal is coupled directly to the scope deflection plates, and one with greater sensitivity but poorer time response, in which a plug-in

amplifier is used to permit coverage of a wide output-voltage range.

The time response of the scope is not a limiting factor for the detectors described above, except in the case of the well-designed Faraday cup. If time information is not needed and time-dependent backgrounds are not a problem, current integrators can be used to record pulse signals. A low-noise current integrating system has been developed at LLL¹¹ covering a wide dynamic range, thus overcoming the main disadvantage of commercial systems.

Table 2. Recording systems.

Oscilloscope	Rise time (psec)	Vertical deflection characteristics	Input impedance (Ω)
Tektronix 7904	800	10 mV/div.	50
	(1.5 nsec) ^a		
	350	Direct coupled	50
		4 V/div.	
Tektronix 519	350	10 V/div.	125
EG&G OS-40	200	200 V full scale	100
French Ferisol OZ100C	150	Direct coupled (in same range as OS-40)	

^aPractical operating limit.

Use of Flat Magnetic Spectrometers for Laser-Produced Plasmas

We are currently measuring spectra of electrons emitted from laser-generated plasmas. In the production of fusion energy by laser-driven implosion, super-thermal electron escape is one of the important energy-loss mechanisms. There is thus considerable interest in absolute energy measurements and angu-

lar distributions of the emitted electrons.¹² Three characteristics of this measurement prescribe the use of a flat uniform-field spectrometer: (1) the electron current is high; (2) the spectrometer must view the source through a collimator external to a target chamber; and (3) because of a low pulse-repetition rate (3

pulses per hour to 1 pulse per day) and variations in pulse characteristics, it is desirable to measure several energy channels simultaneously.

Expected spectrometer output signals for this experiment have been calculated based on the x-ray spectrum measurement of Slivinsky and Kornblum.^{13,14} (They measured the x-ray energy output from a plasma produced by a 50-J laser pulse and obtained a value of 5×10^7 keV for the integrated energy between 50 and 100 keV.) Finding that predicted electron-spectrometer signals

were in a detectable range, we began plasma diagnostic measurements at the Long Path laser facility. A 90°-focusing spectrometer was obtained that, with suitable detectors, covers a 6- to 180-keV energy range. It was necessary to use a rather sensitive recording system based on Tektronix 7904 oscilloscopes. With available plug-in preamplifiers, we were able to measure the amplitude of the detector signals down to a level of 10 mV before the noise became significant. These measurements will be described in more detail in a later report.

Conclusion

We conclude that flat, permanent-magnet, electron spectrometers are very suitable for spectral measurements of high-intensity, nonrepetitively pulsed sources. The channel resolution of a 180°-focusing spectrometer is sensitive to its entrance aperture dimensions, whereas that of a 90°-focusing spectrometer is sensitive to the divergence of the electrons from the source to aperture. Choice of the optimum design thus

requires detailed analysis of the source-spectrometer geometry. Of the available electron detectors, silicon semiconductor detectors are very satisfactory and have been accurately calibrated between 30 keV and several MeV. Anthracene or plastic scintillators coupled to photomultiplier tubes have been used at lower electron energies. Plastic scintillators coupled to photodiodes and Faraday cups may be considered for better time response.

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Appendix A

SPECTROMETER CHANNEL RESPONSE

Computer programs describing the performance of the 90°-focusing spectrometer were first developed at LLL by Delynn Clark and have been extensively refined by Lloyd Multhau. The spectrometer design-code input is a detailed description of the spectrometer geometry. The input parameters include aperture dimensions, the finite extension of the source, a detailed description of the spectrometer magnetic field, and detector location. The output is the response of the spectrometer channel as a function of incident energy. The detector output current is also computed for a given input electron flux.

Each of the detector locations can be optimized with this code to obtain the desired electron center energy and the best spatial electron-energy resolution. (The response function with the steepest sides corresponds roughly to optimum resolution.) The calculation involves a numerical integration in which both the

source and the entrance slit are divided into small area elements. The code chooses a weighted area element in the source and examines a ray of electrons originating from this element and passing through a selected area element in the entrance slit. The code traces the ray through a slit to the detector plane taking into account field nonuniformities (particularly those at the entrance) and determines whether it passes within the entrance aperture of the detector under investigation.

All the rays from the source through the entrance slit are similarly examined. The weights calculated for those rays incident on the detector are then summed to obtain the response of the spectrometer channel to electrons of energy E . An incremental change in the electron energy is made, and the calculation is repeated over the desired energy range.

Examples of the response vs energy determined for three different-sized detectors in a 90°-focusing spectrometer are shown in Fig. 4. The width of each

Fig. 4. Representative spectrometer channel-response functions with 90° focusing. (a) 0.3-MeV channel, (b) 1.0-MeV channel, (c) 3.0-MeV channel.

response curve is determined mainly by the width of the detector entrance aperture. The channel width ΔE is taken to be the full width at half maximum of the response curve. The flat top and steep sides of the 300-keV response function indicate that the spatial electron-energy resolution is very good relative to the dimensions of the detector aperture. Note the change in slope of the sides of the response function with increasing

energy. This is mainly due to the decrease of the spatial electron-energy resolution.

The determination of ΔE is considered to be good to within $\pm 3\%$ for each channel. Sources of error in the energy E include $\pm 0,5$ -mm uncertainties in detector positioning and 2% uncertainties in the spectrometer magnetic field. The uncertainties lead to an estimated error in E of 3% for each spectrometer channel.

Appendix B

SILICON DETECTOR CALIBRATION

Silicon detectors were calibrated from 30 keV to 4 MeV in counting experiments using electron accelerators at LLL and NBS. Three calibration techniques were considered: pulse, direct-current, and counting methods. The first technique was ruled out because pulsed operation of the accelerators was not readily available. The dc method involved the measurement of the detector output current for a known incident, monoenergetic, electron-beam current. When this technique was used with lithium-drifted silicon detectors, the observed detector output currents were found to be erroneously large because of a slow component contribution from the silicon dead layers. Therefore, dc measurements were made on the p-i-n detector only to check the counting method, which was considered more reliable.

What we seek to determine from a counting measurement is the average energy deposited in the active region of a detector per incident electron. Knowing Δe , we can then derive the electron-flux input to a detector from the observed output current, using the fact that 3.67 ± 0.02 charge pairs are produced per electron volt of energy deposited in silicon. The technique involves pulse-height analysis of the detector output charge.⁵ The amplitude of each output pulse is, of course, directly proportional to the amount of energy deposited in the detector by the incident electron.

Electron currents suitable for analyzing silicon-detector pulse heights have been developed at NBS to cover a wide

energy range.⁵ Since a small input-electron current is required to prevent piling up of pulses, the primary beam of the dc accelerator was scattered from a thin gold foil (20 to 30 $\mu\text{g}/\text{cm}^2$). The scattered electrons were collimated at an angle of 30° with respect to the incident beam. Upon emerging through a port in the scattering chamber into an evacuated collimator assembly designed at LLL, the electrons were perpendicularly incident upon the face of the silicon detector. The detector was located in a collimator assembly similar to that used in the spectrometer. This assembly included an entrance aperture and a low-Z backing to limit backscattering from transmitted electrons. A remote control arrangement was designed so that the absorber could be positioned to intercept the electron beam. The beam-interrupt mode was used to monitor background, the main source of which was bremsstrahlung produced in the primary electron-beam trap.

The counting method was limited to those field detectors available with energy resolution suitable for pulse-height analysis; in this case, there were three small ($7 \times 14 \text{ mm}^2$), two medium ($8 \times 18 \text{ mm}^2$), and two large ($20 \times 22 \text{ mm}^2$) detectors. For a given detector and incident electron energy, a pulse-height spectrum was obtained from which the observed background spectrum was subtracted. The analyzer energy calibration was made using internal conversion peaks of ^{113}Sn (366 keV), ^{137}Cs (624 keV), and ^{207}Bi (975 keV). Whenever possible, the full energy peak of the electron beam was

also used. Thus the distribution of absorbed electron energy was obtained, from which the average, deposited, electron energy $\Delta\epsilon$ could be readily derived. The observed dependence of $\Delta\epsilon$ on the incident electron energy is shown in Fig. 5. The theoretical results, which were derived from Monte Carlo calculations of Berger and Seltzer, are shown for comparison.

As can be seen, good agreement between experiment and theory was obtained for the 0.2-mm case at low energies. Here the principal cause for incomplete electron-energy deposition is backscattering of electrons from the front detector surface, a mechanism reasonably well understood. However, for the 0.5-mm detector, there is a gradual divergence of the observed $\Delta\epsilon$ from the

Fig. 5. Dependence of the average, deposited, electron energy $\Delta\epsilon$ on the incident electron energy.

theoretical curve with increasing electron energy. Thus, greater energy absorption is observed at higher energies than is calculated. Apparently there are difficulties in handling electron straggling in the random walk calculation, resulting in too much transmission through the detector and hence not enough absorption.

Estimated errors incurred in the measurement of $\Delta\epsilon$ included uncertainties in detector thickness, incident beam energy, and analyzer energy calibration. Errors that could be neglected included those due to background subtraction, analyzer spectrum statistics, and analyzer nonlinearities. Effects due to the 1- μm detector dead layers could also be neglected.

Detector thickness tolerance was $\pm 12.5 \mu\text{m}$, resulting in uncertainties of 5% in $\Delta\epsilon$. For 150-keV electrons, there was no error due to detector thickness variations, since the detector is totally absorbing (except for the reflected component). Because the electron full-energy peak could be used to help calibrate the analyzer, a substantial part of the error in $\Delta\epsilon$ at 150 keV was from the uncertainty of the incident beam energy itself.

The absolute energy of the beam was known to within 2% for the 150-, 400-, and 700-keV electron energies, yielding errors in $\Delta\epsilon$ of 2%, 2%, and 1.5%, respectively.

In the broad transmission region above 2 MeV, the value of $\Delta\epsilon$ and the corresponding uncertainty were rather insensitive to the beam energy. The chief source of error involved the analyzer calibration, since the electron full-energy peak could not be readily

observed. By comparison, the 400- and 700-keV points were more sensitive to beam energy, but the analyzer calibrations were subject to less uncertainty.

The main factors to be considered in extending the results of this calibration to detectors that could not be calibrated include possible variations in the detector thickness and quality of the silicon used. The final errors were increased to take into account possible thickness variations based on information from the manufacturer.

At energies between 30 and 150 keV, for detector efficiency values we used the Monte Carlo results of Brown, which included the effects of energy loss in the detector dead layer and backscattering losses caused by electron-atom interactions. Experimental verification was obtained for 60 and 100 keV. These measurements were made at LLL with the silicon detector assembly and using a low-energy (<100 keV) electron accelerator. Electrons were scattered from a thin gold foil to reduce the beam current adequately for a counting experiment. Monoenergetic electrons of energy determined by acceleration-tube voltage measurements were collimated into a 300- μm detector having a dead layer of 0.5 μm . The measured spectrum included a noise contribution that increased rapidly below 20 keV. In this region, the electron response was generated by linearly extrapolating from the higher energy regions.

Experimental results at 60 and 100 keV gave the same efficiency value of $91 \pm 3\%$, which compares well with Brown's calculations of 93% and 90%. The dominant contribution to the

experimental error is from the extrapolation procedure.

Lower-energy efficiency values have not been verified experimentally. Low-

energy measurements are more difficult to make because of detector noise and errors produced by the increased significance of losses in the detector dead layer.

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