

A light-weight optics-free EUV spectrometer with substantially improved efficiency and spectral resolution

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ABSTRACT

We present a simple EUV spectrometer based on chemically inert rare gas photon ionization and energy analysis of the resulting electrons. Precise photoelectron focusing and high electron transmission efficiency from the gas ionization area to the detector are combined with an optimum luminosity angle of 90 deg in an axi-symmetric design. All together, these features will allow us to achieve higher efficiency and spectral resolution than other spectrometers of this type reported to date. The modeled (neon) spectral resolution in the spectral range of 5 – 40 nm is 0.1 – 0.035 nm, respectively. A model of the proposed photoelectron focusing system is analyzed.

Keywords: EUV spectrometer, electron beam focusing system, gas ionization chamber

1. INTRODUCTION

A gas ionization chamber for detecting UV radiation with sufficient photon energy for rare gas ionization was first described for *laboratory* measurements by Samson.¹ In contrast to ionization chambers developed to measure the total photo-ionization current produced in the gas volume by the radiation, gas ionization spectrometers can measure the photoelectron energy distribution, which corresponds to the energy (spectrum) of incoming photons reduced by the gas ionization potential. The gas ionization potentials for the rare gases are well known from the photo-ionization cross-section.²

Satellite measurements of solar Extreme Ultraviolet (EUV) fluxes for the last four decades of the 20th century (overviews may be found in Schmidtke,³ and Woods⁴) were performed with EUV spectrometers that used both filters and other optical components such as reflecting gratings. Using such instruments for long term satellite measurements of solar EUV radiation requires periodic in flight calibrations and sounding rocket under-flights using on orbit instrument “clones”. All of these space based EUV spectrometers develop some time dependent degradation of their optical surfaces related to mirror and/or grating reflectivity, or to deposition of carbon or other material on their thin film filters. The rocket based instruments used in sounding rocket underflight calibrations require periodic radiometric calibrations of their own. Radiometric calibration errors, e.g. misalignment of the instrument to the calibration beam and beam non-uniformities, combined with rocket measurement uncertainties increase the total error in degradation estimates, and thus, decrease the accuracy of space measurements. These sources of error in EUV measurements may be avoided if the space spectrometer is a degradation free instrument.

The first successful *rocket-based* experiments using gas ionization chambers were reported by Carlson et al.,⁵ and Ogawa and Judge.⁶ These brief rocket experiments confirmed that a gas ionization chamber may be used as an absolute EUV photometric detector, but because the flights last only a short time, these measurements did not demonstrate the major important advantage of the gas ionization cell EUV instruments, namely, the absence of degradable optical components. Because of this advantage, electron energy analysis capability was added to the ionization cell spectrally integrating EUV detectors. These spectrally instruments are referred to as Optics-Free Spectrometers (OFS).^{7,10} An OFS using a degradation free detector such as a photoelectron counter, does not have **any** components that require a degradation correction, and may thus be used for highly accurate absolute EUV flux measurements during long space missions. OFS spectrometers do not require any metal filters such as thin film aluminum filters, to reject unwanted visible light. Photons with energies below the gas ionization potential (about 22 eV for Ne, for example,) cannot produce any photoelectrons, so the spectrometer is blind to

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visible light as well as a portion of UV light with photon energy lower than the gas ionization potential. To realize these advantages for a long space mission an OFS spectrometer should be designed with a spectral resolution comparable to those reported for diffraction grating spectrometers. This is possible when the photoelectron energy discrimination system provides a narrow and properly focused electron beam on the detector aperture. Additionally, good focusing should be combined with a high electron beam throughput efficiency to increase the number of output electrons, i.e., those reaching the detector, and thus achieve a high Signal to Noise Ratio (SNR). The high beam efficiency increases the ratio between the number of output photoelectrons and number of incoming gas molecules. This efficiency is important to minimize the size and weight of the gas supply system and sensibly avoid the influence of ejected gas on space platform stability. Finally, the OFS design should be light-weight and compact.

To develop an advanced OFS, all known laboratory and flight prototypes were analyzed to determine how existing instruments might be refined to improve their spectral resolution and efficiency, and to lower their sensitivity to changes of the gas ionization area (both size and position), and to the photoelectron beam injection angle. Models of photoelectron focusing systems with simple dual-electrode designs are discussed in Section 2. Section 3 reviews the recent OFS instrument advances resulting from research at USC's Space Science Center. An analysis of gas ionization chamber efficiency is shown in Section 4. Section 5 presents a model of the photoelectron focusing system with substantially improved efficiency. The most important characteristics of the proposed OFS, focusing and spectral resolution, are evaluated in Section 6. A linear relation between the photoelectron energy and control potentials of the focusing system required to scan through the spectral range is shown in Section 7. Dimensions of the proposed OFS are compared to the known prototypes in Section 8. Concluding remarks are given in the Summary.

2. MODELING OF SIMPLE DUAL-ELECTRODE PHOTOELECTRON FOCUSING SYSTEMS

Gas ionization chambers for solar EUV spectral measurements proposed a few decades ago^{1,5,8} were realized based on a couple of designs with dual-electrode photoelectron focusing systems. The design of the Gas Ionization Solar Spectral MONitor (GISSMO) proposed by Vickers et al.⁹ used two concentric toroids – a toroidal electrostatic analyzer. A wide beam of electrons with different energies was directed into the toroidal electrostatic analyzer instrumented with a microchannel plate detector. Practically simultaneously with the development of GISSMO, an improved OFS design was proposed and successfully used by Judge et al.,⁷ and Daybell and Judge¹⁰. In addition to its spectroscopic capability the OFS design can work as a monochromator in a narrow spectral window of interest using two electron beam concentrators on the optical axis of the instrument. A number of limiting circular apertures provided the required discrimination of electron energies at the channeltron detector. These two (GISSMO and OFS) instruments were designed and built with simple dual-electrode photoelectron focusing systems. The photoelectron focusing systems for these two instruments were modeled¹¹ using the ray tracing software SIMION.¹²

A model of the GISSMO design¹¹ showed that some improvements in the photoelectron beam efficiency related to the use of the microchannel detector were accompanied by decreased focusing and spectral resolution. The GISSMO efficiency was not affected by limiting apertures as in the OFS design. The GISSMO beam was actually limited by the microchannel plate detector size in contrast to the OFS design which has a small detector aperture defined by a circular diaphragm. Nevertheless, the GISSMO dual-electrode focusing system was not designed to create a large flat focal plane to fit the microchannel plate detector, which resulted in a decreased spectral resolution across the detector.

Analysis of the OFS data observations¹¹ showed that the OFS design, with its two concentrators of the electron beam and its limiting apertures allowed the USC team to achieve a maximum spectral resolution of about 0.1 nm, at approximately 20 nm, in both laboratory tests and sounding rocket measurements. The relative amplitudes for the strongest spectral lines in the spectral range of 16 – 31 nm for the measured OFS spectrum in the 2003/12/05 sounding rocket flight were compared¹³ with the modeled spectrum for the quiet sun¹⁴. A comparison of these two spectra showed that the OFS was capable of resolving the two-peak structure of the Fe XII spectral line (peak numbers 7 and 8) with a difference in wavelength of 0.16 nm. Nevertheless, the model of the OFS focusing system¹¹ showed that in terms of both spectral resolution and efficiency, it was more sensitive

to variations in photoelectron ionization area and injection elevation angle than would a multi-electrode focusing system.

These analyses showed that the formation of a narrow beam by a multi-electrode focusing system leads to improved SNR (nearly all emitted electrons in the selected acceptance angle reach the detector), and improved spectral resolution.

3. MODELING OF MULTI-ELECTRODE PHOTOELECTRON FOCUSING SYSTEMS

Analysis of the simplest dual-electrode electron focusing systems for gas ionization chambers has stimulated development of multi-electrode systems with improved spectral resolution and high SNR^{11, 13}. An eight-electrode system¹¹ was modeled to work with Ne as a target gas in a spectral range of 20.0 – 40.6 nm with a high SNR and a mean spectral resolution of about 0.25 nm (0.1 nm at the short wavelengths). The focusing of the photoelectron beam in the eight-electrode design was less affected by deviations of the ionization area (from 6 to 12 mm in diameter), and by deviations of the injection elevation angle (within ± 0.7 deg) than in the dual-electrode systems. A convenient feature of that design was the option to scan through the spectral range of interest by changing potential on just one of the eight electrodes. The modeling of this eight-electrode electron focusing system provided the experience which led to an improved version of the OFS with better spectral resolution and higher SNR.¹³ This model of the OFS focusing system¹³ used six electrodes, and operated over a wider spectral range (5.0 – 50.0 nm) than the previous system. An improved spectral resolution of 0.1 nm after optimization of the electrode potentials in the spectral window of interest was also achieved with this model. Another advantage of the six electrode design was a system with all low-voltage potentials (less than 300 V compared to 5000 V in the previous eight electrode design). The disadvantage of this design (as well as the previous one) was their large physical dimensions, D=180 mm; L=380 mm.

The new OFS design with a diameter D of 8.8 cm and a length, L, of 8.8 cm, presented in this paper has substantially smaller dimensions for the focused photoelectron beam in a spectral range of 5 – 40 nm. Additionally, a means for substantially (by up to an order of magnitude) increasing the photoelectron beam intensity (OFS efficiency) was found based on an analysis of efficiency of gas ionization chambers.

4. PHOTOELECTRON EFFICIENCY OF A GAS IONIZATION CHAMBER

The efficiency of any photoelectron analyzer is determined by the ratio of the photoelectrons that reach the detector to the total number of ejected photoelectrons. To be detected, electrons must be focused on the detector by the focusing system, which creates a configuration of electric fields inside the analyzer corresponding to each resolved range of photoelectron energies. The spectral resolution of the analyzer depends on the analyzer's positional sensitivity to photoelectrons with different energies, the size of the focused beam at the detector, and the detector's aperture. The size of the focused beam depends on a number of parameters, e.g., the gas ionization area, the range of injection elevation angles of the photoelectrons in the beam, the focusing potentials (focusing system's geometry and any possible "stray" potentials related to the charging of the insulators between the electrodes), presence and configuration of magnetic fields inside the focusing system, stability and optimal values of control potentials on electrodes during a scan through the spectral region, etc. With the optimal elevation angle (see below) and optimized focusing system, a larger deviation of electron trajectories leads to worse focusing (larger aberrations). Some limitation on the collection of dispersed electrons is achieved by incorporating the number of limiting diaphragms in the OFS (as in the dual-electrode OFS design). However, these diaphragms decrease the transmission of the photoelectrons, resulting in a lower efficiency of the analyzer. From this point of view, it is very important to know and to optimize all the parameters mentioned above. For the simplest, cylindrical focusing system, the optimal solution is to combine the best focusing (injection elevation) angle with the best luminosity of the beam. The best luminosity of the beam may be inferred from the angular distribution of photoelectrons.

A number of authors (e.g. Grimm, 1972 and references therein) have studied the angular distribution of photoelectrons of gas phase atoms and molecules. Their theoretical work for low-energy (e.g. UV and EUV compared to X-ray and Gamma-ray) ionizing radiation was based on the electric dipole approximation.

Experimental measurements of the intensity $I(\Theta)$ of the ejected electrons as a function of the angle between a beam of un-polarized radiation and the photoelectron detector have confirmed the calculations and shown that the expression in the case of both gaseous atoms and molecules is

$$I(\Theta) = 1 + \frac{\beta}{2}(1.5\sin^2(\Theta) - 1) \quad (1)$$

where β is the asymmetry parameter ($\beta \leq 2$). Thus, the photoelectron beam is of maximum intensity in a direction perpendicular to the propagation of the radiation, i.e., the elevation angle to the optical axis is 90 deg. This knowledge, however, was not widely used in the subsequent development of photoelectron analyzers since this optimum elevation angle did not allow for acceptable focusing of the electron beam in the *dual-electrode* designs. The best focusing of the electron beam and, consequently, the best transmission in a *cylindrical* analyzer with a number of limiting diaphragms is achieved when the elevation angle is about 42.3 deg (second-order focusing), quite far from the best luminosity angle of 90 deg. This compromise inherent to the two electrode analyzers, raises the question whether it is possible, with a different electrode design, to meet both objectives (luminosity and focusing) and thus optimize efficiency and Signal to Noise Ratio, SNR. The work presented in this paper indicates that it is.

To date, we know of just one design which achieved both objectives,¹⁹ but the analyzer used two off-axis laboratory sources of radiation located at about 47.7 deg with respect to the optical axis of the analyzer. The off-axis position of the source of radiation breaks the symmetry in azimuth distribution (0 – 360) deg of the photoelectrons, allowing only a small angular portion of the beam, about 1/300 of the whole distribution, to reach the detector. The electron energy analyzer¹⁹ was built with a second-order focusing system using two coaxial cylinders with approximate dimensions of 350(L) \times 210(D) mm. The angle between the incident beam, and the beam of emitted photoelectrons was set to 90 deg, while the photoelectron beams were formed with the elevation angles equal to the second-order focusing angles. That design, utilizing both the best luminosity angle and the second-order focusing for the electron beam, required non-axial fields of view of the laboratory X-Ray or UV sources. For solar observations, axial symmetry is an obvious advantage for any optics-free design.

Other photoelectron spectroscopic analyzers have been either built or modeled with electron beam elevation angles between 50 and 60 deg, e.g. with 55 – 60 deg,²⁰ 60.0 deg,²¹ 54.7 deg (Ogawa and Judge, 1986, Vickers et al., 1992, Daybell and Judge, 1996, Didkovsky, Judge, and Jones, 2005a,b). These elevation angles between the best focusing at 42.3 deg and the best luminosity at 90 deg were chosen as a compromise between maximum efficiency and best focusing. As an example of such compromise, Sar-El (1967) measured both transmission and luminosity of the photoelectron beam for angles 42.3 and 60 deg. It was shown that for cylindrical analyzers with required limiting electron beam diaphragms the transmission of the beam at $\Theta = 60$ deg is about 0.01 whereas at the 42.3 deg (second order focusing) it is approximately 0.1 (due to better focusing). The luminosity at 60 deg was, however, **more than 10 times** the luminosity at 42.3 deg. The design proposed here, is suitable for solar observations and/or for studying the EUV spectral distribution in planetary atmospheres through occultation measurements. It combines **for the first time** the best focusing and transmission in a multi-electrode focusing system with the best luminosity at the photoelectron ejection angle of 90 deg in the on-axis instrument.

5. A MODEL OF AN OFS EUV SPECTROMETER WITH AN ADVANCED ELECTRON FOCUSING SYSTEM

The model of the new OFS spectrometer is based on a multi-electrode focusing system defined such that it can focus a photoelectron beam ejected at 90 deg to the incoming EUV radiation, the direction of maximum efficiency according to (1). An axi-symmetrical 7-electrode focusing system is shown in Figure 1 as a 2-D cut through the optical axis. The electrodes are marked with numbers 1 through 7. The incoming EUV radiation is marked with an arrow to the electrode 1. The electronically controlled gas pulses come to the ionization area from the gas supplying system. The direction of the ejected beam of photoelectrons is controlled by one or two circular apertures with required openings.

The first advantage of this proposed focusing system is an optimized electrode design (not realized in the previous multi-electrode systems^{11,13}). The size and shape of each electrode was determined and optimized

according to two criteria; tight focusing and minimum scattered photoelectron charging of the insulators (not shown in Figure 1) located between the electrodes. The scattered photoelectrons have no direct path to the insulators in the proposed design, and it was tested for the whole energy (spectral) range of 5 – 40 nm. The system of electrodes includes an input electrode (1) (the gas ionization area), three circular concentric electrodes numbered 2, 4, and 7, and three axial electrodes 3, 5, and 6.

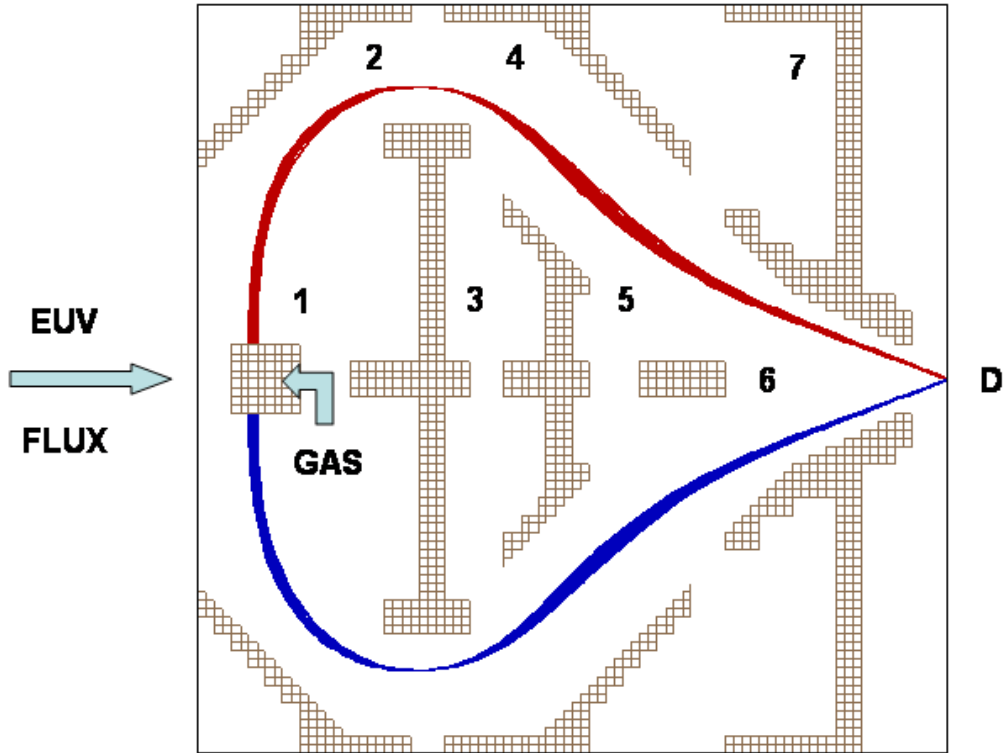


Figure 1. A 2D cut through the proposed OFS focusing system. The dimensions of the system are: $D = L = 88$ mm. A system of electrodes (1–7) allows one to focus, align and control the photoelectrons in the required energy range (determined by input EUV photon energy reduced by the gas ionization potential). The beam originates in the photo-ionization area (1) and proceeds to the detector D. The top half (red color) shows the beam produced by photoelectrons with energies 19.157 eV in the photon-gas ionization area with diameter 8 mm and the beam’s elevation angle of 90 deg. The target gas is Ne. The bottom half (blue color) shows the beam with energies 19.025 eV. The difference between these two energies can be measured and resolved by the OFS (see chapter 6). The electrons with energies 19.157 eV (top beam) correspond to the He II spectral line (30.4 nm).

The photoelectron beam goes through a limiting beam aperture (not shown in Figure 1) close to the ionization area. For short missions, e.g., sounding rocket flights, a diode may be used as a detector. For long term missions, when the stability of the instrument is a key factor, a sensibly degradation-free channeltron detector is the best choice.

The potentials on the electrodes for the configuration shown in Figure 1 (top beam) are presented in Table 1.

Table 1. Potentials on the electrodes (see Figure 1) optimized for the spectral band centered at the 30.4 nm He II spectral line. It corresponds to an electron energy of 19.157 eV using Ne gas as the target.

Electrode number	Potential, V
1	0.0
2	-7.5
3	47.5
4	-5.2
5	-1.6
6	64.0
7	90.0

6. FOCUSING AND SPECTRAL RESOLUTION

A gas ionization spectrometer with an electron focusing system uses spatial selection of the photoelectrons based on the potentials inside the focusing system and on photoelectron energy, which is a function of the photon energy, the gas ionization potential, and the portion of the external magnetic field that penetrates inside the spectrometer

$$E_{el.} = h\nu - E_{ioniz.pot.} + E_{magn.} \quad (2)$$

The focusing potentials inside the spectrometer can be changed to scan through the photoelectron energies and to bring electrons to the detector with as small a $\Delta E_{el.}$ as possible. In the other words, the spectral resolution $\Delta\lambda$ is a function of three parameters: a focusing parameter $F_{ion.chamb.}$, a coefficient of spatial sensitivity to the different electron energies K_{θ} , and a detector aperture $D_{det.}$

The focusing parameter $F_{ion.chamb.}$ may be determined as the ratio of the output size of the beam (in the detector plane) divided by the input size of the beam at the limiting aperture (not an ionization area)

$$F_{ion.chamb.} = \frac{D_{out}}{D_{lim.aper}} \quad (3)$$

The coefficient of positional sensitivity K_{θ} ranges from 0.0 when the positions ($P(E_{el.1})$ and $P(E_{el.2})$) of the output beams for two $E_{el.}$ are overlapping to 1.0 when the positions are shifted by a distance equal to the output beam size.

$$K_{\theta} = \frac{P(E_{el.2}) - P(E_{el.1})}{D_{out}} = \frac{P(E_{el.2}) - P(E_{el.1})}{F_{ion.chamb.} D_{lim.aper}} \quad (4)$$

With the assumptions that the detector aperture is equal to the D_{out} , and there is no magnetic field inside the spectrometer, the spectral resolution is

$$\Delta\nu = \frac{E_{el.2} - E_{el.1}}{h}, \quad (5)$$

where $E_{el.1}$ and $E_{el.2}$ correspond to the beam spatial positions for which

$$P(E_{el.2}) - P(E_{el.1}) = K_{\theta} D_{out} \quad (6)$$

To estimate the spectral resolution of the proposed OFS, the output portion of the electron beam was zoomed. Figure 2 shows focusing for two beams shown in Figure 1 with energies 19.157 and 19.025 eV, $\Delta E_{el.} = 0.132$ eV. The focusing parameter $F_{ion.chamb.}$ is 4.0 with the diameter of the output beam 0.25 mm. The spectral resolution for the example shown is about 0.1 nm if the detector aperture is 0.25 nm or better for smaller detector apertures. The spectral resolution for the high energy part of the spectral region is about 0.04 nm.

Better focusing of the beams at the detector plane is possible but there is a natural limitation on the focusing (not applied to the model used) related to the Coulomb force between electrons. We did not attempt to optimize beam focusing beyond a beam diameter $D = 0.25$ mm assuming that Coulomb effects would not prohibit this degree of focusing, since it has been achieved in other devices, e.g., oscilloscopes.

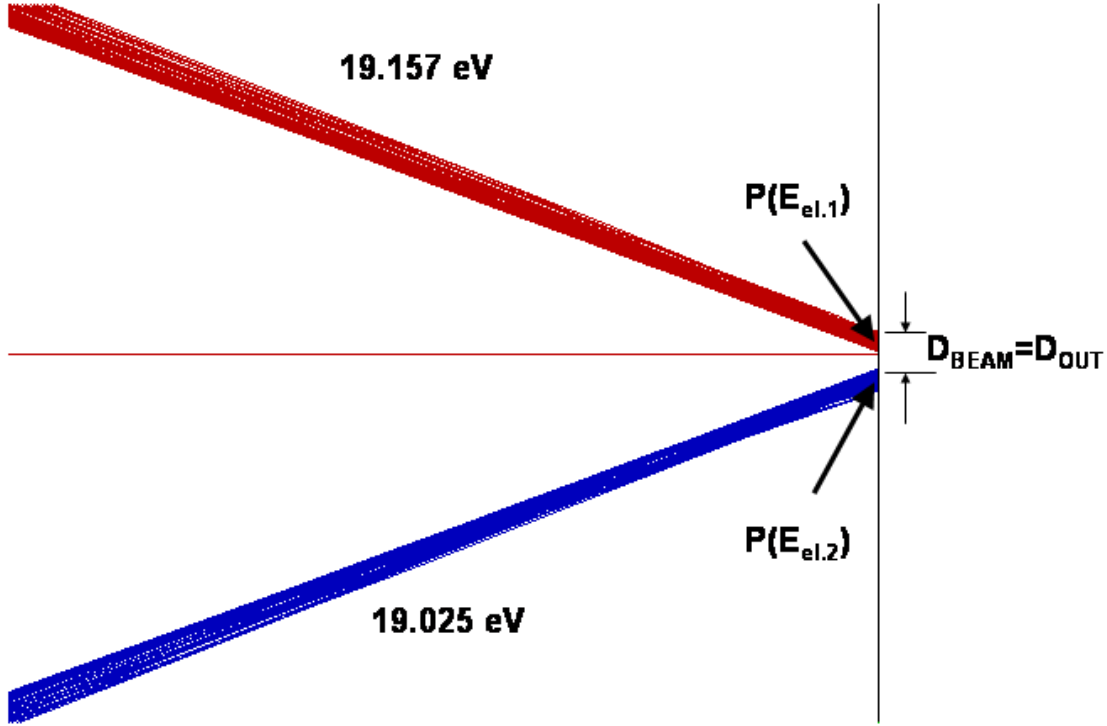


Figure 2. A zoomed view of a portion of the two beams shown in Figure 1. The spectral resolution near the spectral line He II 30.4 nm is about 0.1 nm. The top (red color) beam corresponds to electron energy 19.157 eV, and the bottom (blue color) beam is for electrons with energy 19.025 eV. The diameter of the top beam is 0.25 mm. Spatial positions of the two beams are shown.

7. THE CONTROL POTENTIALS

The second advantage of the proposed OFS is a simple way to control a scan through the spectral region. The proposed focusing system was designed to develop a linear relation between the applied voltages (electrode potentials) and the photoelectron energy:

$$V_i = V_{i,0} \frac{E_{el.,j}}{E_{el.,0}} \quad (7)$$

where i is the electrode index, and j is a discrete level of photoelectron energy range. $V_{i,0}$ and $E_{el.,0}$ are the potentials on electrodes that correspond to the best focusing for the photoelectron energy $E_{el.,0}$

For example, to focus the electron beam with the electron energy of 191.57 eV (ten times larger than shown in Figure 1, and Figure 2 (red color beams), control voltages should be ten times larger than those shown in Table 1. To demonstrate this feature of the proposed OFS, we show Figure 3 with a zoomed portion of the beam close to the detector plane.

8. A COMPARISON OF DIMENSIONS FOR DIFFERENT GAS IONIZATION CHAMBERS

The third advantage of the proposed OFS is its compact size. The dimensions of the focusing system are $D = L = 88$ mm. A comparison of dimensions for different gas ionization chambers is shown in Table 2.

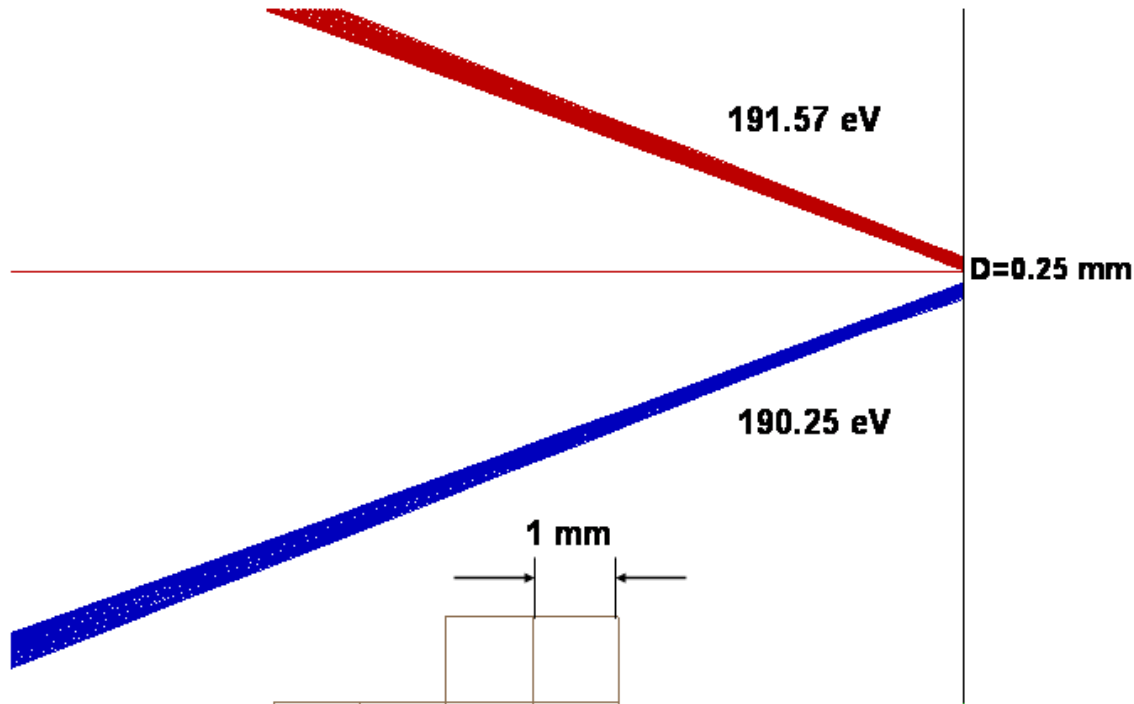


Figure 3. The same as in Figure 2 but for the electron beams with ten times larger energy (191.57 and 190.25 eV) for the top and bottom beams, correspondingly. The control potentials were set ten times larger than shown in Table 1. Two squares (one mm on a side) at the bottom portion of the Figure 3 are portions of electrode 7. They are shown to compare the sizes of the focused beams at the detector plane.

Table 2. Approximate dimensions of focusing systems ($D \times L$) in mm.

Type of focusing system	Dimensions, mm
New OFS (This paper)	88 × 88
OFS ⁷ (1994)	200 × 800
OFS ¹¹ (2005)	140 × 200
OFS ¹³ (2005)	180 × 380
GISSMO ⁹ (1992)	(approx)250 × 230
Gas Ion. Chamb. ¹⁹	210 × 350

The dimensions of the proposed OFS are small compared to the all previous known gas ionization spectrometers. Nevertheless, the word “small” is of course relative. The fourth advantage of the proposed design is its scalability. The dimensions of the proposed focusing system can be simply scaled up or down, the design retained good efficiency and resolution when modeled at 2:1 and 1:2 scale. A 1:2 scaled version of the OFS, e.g., $D = L = 44$ mm may be a major advantage if assembled with a compact suite of instruments, although smaller OFS dimensions require larger potentials to work in the same spectral range. In contrast, 2:1 scaled version (which is still smaller than the other reported gas ionization chambers) with dimensions $D = L = 176$ mm allows even

better spectral resolution than shown here for the basic design with smaller potentials. Any scaling factor may be applied to the design (not just integers) and may be tailored to some specific requirements or configured for precise measurements and calibration of solar radiation using rocket under-flights or long term satellite or probe missions.

9. SUMMARY

The seven-electrode focusing system developed for a new OFS spectrometer offers substantially better focusing than previous designs, with a focusing parameter $F_{ion.chamb.} = 4$, and output beam diameter about 0.25 mm. This degree of focusing together with a high spatial (positional) sensitivity to photoelectrons with different energies results in improved spectral resolution of 0.1 to 0.035 nm. The new design for the focusing system allows substantially higher efficiency with the use of the theoretically maximal efficiency angle of 90 deg to the incoming EUV radiation. The spectral range of the new OFS is 5 – 40 nm using Ne as the working (target) gas.

The currently proposed OFS focusing system realizes four important advantages compared to the other spectrometers of this type reported to date. The first is the minimized amount of photoelectrons that could go to insulators inside the focusing system and thereby change the potential distribution (change the modeled electron trajectories). The second is a linear relation to control a scan through the spectral region. The third is the compact size of the OFS focusing system, substantially smaller than all previous designs. Finally, the focusing system dimensions are scalable to fit the requirements of either a small (e.g. less than 2") size or higher (than reported here) spectral resolution and lower potentials.

The presented model was developed to serve as a prototype of a new generation of OFS EUV spectrometers for degradation-free, stable, and accurate measurements of solar EUV radiation, and to support calibration of existing instruments.

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REFERENCES

1. J. A. R. Samson, "Absolute Intensity Measurements in the Vacuum Ultraviolet", *J. Opt. Soc. Am.*, **34**, p. 6 - 15, 1964.
2. G. V. Marr, and J. B. West, "Absolute Photoionization Cross-Section Tables for Helium, Neon, Argon, and Krypton in the VUV Spectral Regions", *At. Data Nucl. Data Tables*, **18**, p. 497-508, 1976.
3. G. Schmidtke, "Observations of the solar EUV spectral irradiance", in *Proc. of the Workshop on the Solar Electromagnetic Radiation Study for Solar Cycle 22*, ed. R. Donnelly, p. 303, 1992.
4. T. N. Woods, F. G. Eparvier, S. M. Bailey, S. C. Solomon, G. J. Rottman, G. M. Lawrence, R. G. Roble, O. R. White, J. Lean, and W. K. Tobiska, "TIMED Solar EUV Experiment", *SPIE Proceedings*, **3442**, p. 180-191, 1998.
5. R. W. Carlson, H. S. Ogawa, E. Phillips and D. L. Judge, "Absolute measurements of the extreme UV solar flux", *Applied Optics*, **23**, p. 2327, 1984.
6. H. S. Ogawa, and D. L. Judge, "Absolute solar flux measurements shortward of 575 Å", *J. Geophys. Res.*, **91**, p. 7089, 1986.
7. D. L. Judge, M. D. Daybell, J. R. Hoffman, M. A. Gruntman, H. S. Ogawa, J.A. R. Samson "An optics free spectrometer for the extreme ultraviolet", in *Nuclear Instruments and Methods in Physics Research*, **A347**, p. 472-474, 1994.
8. T. Sasaki, T. Oda, and H. Sugawara, "Measurement of Absolute Intensity of Radiation in XUV by a Rare-Gas Photoelectron Counter", *Appl. Optics*, **16**, p. 3115-3121, 1977.
9. J. S. Vickers, D. M. Cotton, T. A. Cook and S. Chakrabarti, "Gas ionization solar spectral monitor (GISSMO)", <http://www.bu.edu/csp/wv/terriers/gissmo.html>, 1992.
10. M. D. Daybell and D. L. Judge, "The solar EUV spectrum obtained with an optics free spectrometer on September 12, 1995", in *AGU Meeting Proc.*, 1996.

11. L. V. Didkovsky, D. L. Judge, and A. R. Jones, "Extreme Ultraviolet Spectrometer", *SPIE Proceedings*, **5677**, p. 141-152, 2005.
12. D. A. Dahl, "SIMION 3D Version 7.0 User's Manual", *Idaho Nat. Engin. and Envir. Lab*, 2000.
13. L. V. Didkovsky, D. L. Judge, and A. R. Jones, "An Extreme Ultraviolet Optics-Free Spectrometer With Improved Spectral Resolution and High Signal-to-Noise Ratio", *SPIE Proceedings*, **5898**, p. 1I1-1I8, 2005.
14. H. P. Warren, J. T. Mariska, and J. Lean, "A new reference spectrum for the EUV irradiance of the quiet Sun: 1. Emission measure formulation", *J. Geophys. Res.*, **103**, p. 12077, 1998.
15. D. Hovestadt, M. Hilchenbach, A. Burgi, et al. "CELIAS - Charge, Element and Isotope Analysis System for SOHO", *Solar Phys.*, **162**, p. 441-481, 1995.
16. D. L. Judge, D. R. McMullin, H. S. Ogawa, et al. "First Solar EUV Irradiances From SOHO by the CELIAS/SEM", *Solar Phys.*, **177**, p. 161-173, 1998.
17. D. L. Judge and H. Ogawa, "Solar EUV Sounding Rocket Measurements", in Proc. of the Workshop on the Solar Electromagnetic Radiation Study for Solar Cycle 22, R. F. Donnelly ed., *NOAA Environmental Res. Labs*, p. 327, 1992.
18. F. A. Grimm. "Photoelectron Angular Distribution", in *Electron Spectroscopy*, D. A. Shirley ed., p. 199-206, 1972.
19. K. Maeda. "A Small-Size X-Ray Photoelectron Spectrometer", in *Electron Spectroscopy*, D. A. Shirley ed., p. 177-185, 1972.
20. J. Berkowitz. "Photoelectron Spectroscopic Studie With a Cylindrical-Mirror Analyzer", in *Electron Spectroscopy*, D. A. Shirley ed., p. 391-399, 1972.
21. P. H. Citrin, R. W. Shaw, Jr., and T. D. Thomas. "Cylindrical Electrostatic Analyzer for Photoelecron Spectroscopy", in *Electron Spectroscopy*, D. A. Shirley ed., p. 105-120, 1972.
22. H. Z. Sar-El, *Rev. Sci. Instr.*, **38**, p. 1210, 1967.