An Extreme Ultraviolet Spectrometer
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ABSTRACT
A concept and preliminary design of an Extreme Ultraviolet (EUV) spectrometer is presented. The spectrometer is based on a gas ionization chamber and an advanced eight-electrode electron focusing system to form a narrow electron beam on a photodiode aperture. The design is modeled with the SIMulation of IONs (SIMION) tools and shows the ability to scan through the spectral range of 20.0 – 40.6 nm by changing the potential on a single control electrode between about 200 and 1100 V. The spectral resolution is about 0.25 nm in the middle of the band.

The set of the focusing potentials may be changed to allow detection of solar EUV radiation in a wider spectral band, e.g. 5.0–50.0 nm. The potentials may be also optimized to improve the spectral resolution in a required spectral window.

Keywords: EUV spectrometer, Electron beam focusing system, Gas Ionization chamber

1. INTRODUCTION
Systematic observations of the solar spectral irradiance below 100 nm began in the 1920s, first from mountain sites, balloons and rockets. The spectra were recorded using films as detectors. In 1952 Rense identified the solar hydrogen Lyman-α emission of 121.6 nm from a rocket spectrogram for the first time.

The ‘golden’ era for rocket and space-based solar radiation measurements using EUV instruments started in the 1960s after applying new detection methods based on the photo-electric effect.

The first successful rocket-based experiment with a gas ionization chamber described for laboratory use by Samson was reported by Ogawa and Judge in 1986. After the film-based and initial photo-ionization instruments, it opened the third generation of EUV instruments with ability to provide in flight calibrations. A detailed review of satellite measurements of solar EUV fluxes for the last four decades of the 20th century may be found in Schmidtke and Woods. A brief summary of EUV instruments and some of their advantages and disadvantages are shown in Table I.

An example of a filter based design may be found in the pioneering work of Ogawa and Judge or, more recent, in a description of the Thermosphere, Ionosphere, and Mesosphere Energetics and Dynamics (TIMED) Solar EUV Experiment (SEE). One of the SEE instruments - the XUV Photometer System (XPS) includes nine silicon XUV photodiodes with thin film filters deposited directly on the photodiodes. The silicon photodiodes with thin film filters were developed by R. Korde at the International Radiation Detectors. The XPS measures solar irradiance from 1 to 35 nm with each filter having a spectral window of about 5 nm.

The second SEE instrument - the EUV Grating Spectrometer (EGS) is a normal incidence Rowland circle spectrograph with a spectral range of 25 to 195 nm and 0.4 nm spectral resolution. To achieve the spectral resolution the EGS has a CODACON array detector with 64x 1024 anodes. The grating has a gold coating with sufficient reflectivity down to 25 nm.

A typical transmission grating spectrometer for EUV measurements from a sounding rocket was based on a combination of a transmitting grating and a number of coated photodiodes with thin film metal filters. The first photodiodes flown were coated with an aluminum layer, which passed the solar wavelengths centered at 30 nm and blocked radiation at wavelengths longer than approximately 80 nm.

Details of gas ionization chambers for EUV measurements are presented in the next section.

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Table 1. Major types of EUV instruments with some advantages and disadvantages

<table>
<thead>
<tr>
<th>Type of instrument</th>
<th>Advantages</th>
<th>Disadvantages</th>
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<tr>
<td>EUV filters</td>
<td>A simple design</td>
<td>Relatively low spectral resolution</td>
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<td>Hydrocarbon contamination</td>
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<td>Normal incidence reflecting grating</td>
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<td>Reduced reflectivity below 25 nm</td>
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<td></td>
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<tr>
<td>Grazing incidence reflecting grating</td>
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<tr>
<td>Transmission grating(s)</td>
<td>A simple and stable design</td>
<td>Spectral contamination</td>
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<td>Gas ionization chambers</td>
<td>An option to scan through the spectrum.</td>
<td>Sensitivity to gas concentration in optically thin</td>
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<td></td>
<td>Blind to radiation at λ longer than the photoionization threshold</td>
<td>gas cells, to external electrical and magnetic fields</td>
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<tr>
<td>Combined, e.g. a grating plus filters</td>
<td>Allows to improve spectral resolution, reduce spectral contamination</td>
<td>More complicated design</td>
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2. DESIGN PROTOTYPES

The idea to employ a gas ionization chamber for solar EUV spectral measurements and its realization have been successfully used by Daybell and Judge to design and build the Optics Free Spectrometer (OFS). EUV radiation is incident on a gas target. Electrons are released from the interaction by the photoelectric effect. As knowledge of the gas cross-sections with a reasonable accuracy became available it was possible to convert the energy spectrum of photo-electrons into the spectrum of solar EUV radiation. The OFS was tested in laboratory using argon as a target gas. The helium emission spectrum obtained with the OFS showed a good coincidence with the spectrum taken using a grating spectrometer. A flight instrument was launched for the first time on September 12, 1995 and provided two real solar scans in a range of about 10-50 nm. Further flights have continued to validate the instrument concept.

The OFS photo-electron focusing system contained two concentric cylinders with a number of slits for selecting appropriate trajectories and directing the electron beam to the channeltron detector. A voltage between the cylinders created the necessary electrical field corresponded range of electron energies. Slits were used to further constrain possible electron trajectories to the detector. If the voltage was constant, the OFS worked as a monochromator. A scan through the spectra of electron energies was made by changing the voltage between the cylinders. To improve the spectral resolution, the beam intersected the axis of the cylinders (the optical axis) twice, forming a sine trajectory in any azimuthal plane. The starting point on this trajectory was a gas ionization aperture and the ending point was the detector.

Some modifications of the OFS design were proposed by Vickers et al. in the Gas Ionization Solar Spectral Monitor (GISSMO). The GISSMO’s focusing system contained two electrodes, like in the OFS design but they were concentric toroids sized accordingly to the mean electron trajectory - the toroidal electrostatic analyzer. Another proposed difference was to use a microchannel plate (MCP) as the detector. The MCP allowed some wider deviation of photo-electron trajectories to be detected without any changes of potentials on toroids.

2.1. A model of the toroidal electrostatic analyzer prototype

Both the OFS and the GISSMO spectral monitors were designed with the dual-electrode focusing systems. A few important questions may arise from this fact. Is the obtained spectrometer’s performance in the desired range of EUV spectrum optimal? If it is not, may it be improved with an advanced electron focusing system?
Is there a way to optimize a spectrometer with one pixel detector, like in the OFS design, instead of using a multichannel detector, e.g. a MCP?

The optimization of the design may lead to increased sensitivity and spectral resolution so obtaining the required count rate with a smaller output gas pressure, an important parameter for a long duration project.

To answer these questions the simplest toroidal focusing system, similar to that used in the GISSMO design was modeled with the SIMION, analyzed and compared to a new (see the next section) design.

We have assumed for this simplified model that photo-electrons are produced in a thin cylindrical layer with diameter of either 6 mm (the OFS and GISSMO apertures were about 4.0 and 6.35 mm in diameter) or 12 mm and there are no further interactions between produced photo-electrons and neon atoms. This assumption is consistent with description of the GISSMO design, where the mean free path for electron-neon impact ionization in the toroidal space was found as about 0.4 m. The electron escape elevation angle was set to ±54.7 deg with a zero deviation for a reference beam. The influence of this parameter on the focusing characteristics was tested in the model for a tested beam by introducing some deviation to this angle. The escape angle models electron’s path through circular slits normally used in any gas ionization based EUV monitor. All emitted electrons in the modeled design may enter the space between toroids. We also assumed that there is no any other electrical or magnetic fields, except created by the focussing electrodes.

To model the photo-electron trajectories in a toroidal electrostatic analyzer a few toroidal focusing systems have been created in some range of dimensions, including the outer diameter, length and space between toroids. The working model has the outer diameter $D = 250$ mm, length $L = 230$ mm and the space between electrodes $d = 85$ mm. The dimensions were chosen from points of view of fitting the electron beam and allowing its deviation for different energies. The basic potentials on electrodes were the following. The photon-neon interaction aperture with diameter 6 or 12 mm had a zero potential. The outer and inner toroids were connected to -6 and +4.4 V accordingly and a MCP detector with diameter 60 mm had a +1 V potential.

A model of the toroidal focusing system for a fixed, small, and required ranges of electron energies is shown in Figure 1.

**Figure 1.** A 2D cut through a toroidal focusing system. A) The bottom half of the system shows electrons with the energy of 9.4 eV, equal to created by photons with $\lambda = 40.0$ nm in neon. The photon-gas ionization area’s diameter is 6 mm. The electron beam elevation angle is -54.7 deg. The top half shows electron trajectories for electrons with energies in a range of 9.4 to 10.6 eV, which corresponds to the spectral band of 40.0–38.5 nm. The outer and inner electrodes had potentials of -6 and +4.4 V accordingly. Electrons are collected by a MCP detector (D=60 mm) shown at the right side of the system. B) The same as in A) for the bottom half of the system, except the ionization area’s diameter is 12 mm and the elevation angles are in a range of -54.0 to -55.4 deg. The top half shows electron trajectories with the A) setup but with energies of electrons in a range of 9.4 to 143.4 eV, which corresponds to the required spectral band of 40.0–7.5 nm.
Figure 1 shows four different output beams as a function of the monitor input parameters. The first (ideal) situation (Figure 1 A, bottom half) is for the lowest and fixed electron energy of 9.4 eV, the moderate diameter (6 mm) of the ionization area and the fixed elevation angle of the electron beam equal to -54.7 deg. These conditions together with an appropriate potentials on toroidal system (-6 V on outer electrode and +4.4 V on the inner) create a good focusing system and the model may work as a monochromator for the 40.0 nm wavelength.

The second setup (Figure 1 A, top half) allows to collect and detect electrons in some range of their energies, 9.4–10.6 eV. The electron trajectories in this range of energies, which corresponds to the input radiation band of 40.0–38.5 nm fit the MCP aperture and the shown system may be used as a spectral EUV monitor in this small range of wavelengths. All other conditions for this setup are the same as for the bottom half of the Figure 1 A, except the elevation angle corresponds to 54.7 deg. This setup shows the model in a spectrometer (monitor) mode.

When some perturbation of input parameters is applied (Figure 1 B), the model shows changes in the monitor’s ability to work as either a monochromator (bottom half) or a spectrometer (top half). The changes of the diameter of the ionization area from 6 to 12 mm together with the elevation angles from -54.0 to -55.4 deg are shown in the bottom part of Figure 1 B, while changes of the input radiation range to the required in GISSMO are shown in the top half of the picture. Electrons with energies above about 10.6 eV are scattered in the area between toroids. Just a small portion of electrons fit the MCP entrance aperture with diameter 60 mm. Other electrons are lost for the analysis.

As the applied potentials cannot bend trajectories of the high-energy electrons (Figure 1 B, top half) to fit the space between toroids, someone may expect that some increasing of the negative potential at the outer toroid may solve the problem. The subsequent modeling of the electrical field in the space between toroids in a wide range of voltages showed that there was no any appropriate choice to direct electrons to the MCP in the model. The Figure 2 shows one of these examples with potentials of -100 V and 4.4 V on outer and inner electrodes correspondingly, when the high-energy electrons are still strongly scattered in the space between toroids but the low-energy electrons are totally refracted by the electrical field and do not leave the ionization area.

Figure 2. The same as in Figure 1 B but with outer toroid’s potential equal to -100 V. Only a small portion of electrons goes to the MCP detector. Others are collected mainly by the toroids. The low energy electrons visible in the Figure 1 (bottom halves) are totally refracted by created electrical field.

The modeling of a two-electrodes toroidal EUV monitor showed that the system may work as a monochromator or may detect photo-electrons in some range of their energies. However, in the required (wider) range of the EUV spectrum or having some wider variation of the input parameters, the toroidal system cannot work effectively. Some changes of both the system’s geometry and the focusing system are required.
3. A MODEL OF AN EUV SPECTROMETER WITH AN ADVANCED ELECTRON FOCUSING SYSTEM

A logical way to improve the performance of an EUV gas-ionization spectrometer is to make it more flexible to changes of the input parameters, such as photon-gas ionization area, gas temperature and pressure, electron beam elevation angles, and to a range of photo-electron energies, which corresponds to the measured range of EUV radiation. This flexibility is directly connected to the number of 'degrees of freedom', which is related to a number of electrodes for focusing of the electron beam.

A design of the focusing system and a number of electrodes depends of the output electron beam profile requirement. Solving the task of adjustment to a wider range of input parameters (flexibility), the system may be designed with a better focussing characteristic and as a result, have better spectral resolution.

Figure 3 shows the proposed model of a gas-ionization EUV spectrometer with 8 electrodes and a diode detector.

Figure 3. A 2D cut through proposed gas-ionization chamber. A system of electrodes (1-8) allows to focus, align and control the photo-electrons in the required range of their energies (input solar radiation). The beam originates on the photo-ionization area (1) and goes to the detector (9). The top half shows the beam produced by the photon-gas ionization area with diameter 6 mm and the beam’s elevation angle of 54.7 deg. The bottom half shows the ionization area diameter 12 mm and the elevation angles in a range of -54.0 to -55.4 deg. All electrons have energies 19.6 eV, corresponding to the He II spectral line (30.4 nm).

The same input conditions as in the Figure 1 B, bottom half for the ionization area and elevation angles were modeled for the electrons with energy of 19.6 eV, which corresponds to the He II 30.4 nm spectral line.
The output detector (9) may be installed with a limiting diaphragm to correspond the output beam profile and the spectral resolution. Comparing Figure 1 B with Figure 3, one can see that having the same differences on the input ionization area and elevation angles for the bottom beams, the bottom beam (Figure 3) comes to the detector with about the same profile as the top (reference) beam.

The system of electrodes includes an input electrode (1) required in the SIMION modeling tool, four circular concentric electrodes numbered from 2 to 5 and three axial electrodes 6-8. The position and configuration of electrodes was determined to solve the task of focusing electrons in the required range of energies (8.9–40.3 eV) or radiation (40.6–20 nm) with controlling the beam by changing the potential on a single electrode (6) of the system.

The potentials on electrodes for the configuration shown in Figure 3 is presented in Table II.

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<th>Electrode number</th>
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Table 2. Potentials on the electrodes (see Figure 3) optimized for the spectral band centered at 30.4 nm

Two examples of electron beam for the low and high-energy edges of the required spectral bandpass 20–40.6 nm are shown in Figure 4. Figure 4 shows quite good focusing at the edges of the spectral band with both normal and wide ranges of the ionization area and elevation angles. The focusing system’s potentials are the same (Table II) for the shown range (20.0–40.6 nm) of input EUV radiation.

Figure 4. Focussing of low- and high-energy electron beams. Bottom halves show examples with a large (12 mm) ionization area and the elevation angle deviation of ±0.7 deg. A) Electrons with energies of 8.93 eV (40.6 nm). Potential on the control electrode is set to 190 V. B) Electrons with energies of 40.33 eV (20.0 nm). Potential is set to 1090 V. 
3.1. Modeled spectral resolution of the spectrometer

One of the goals in building of the model of EUV spectrometer with an advanced focusing system was to get a wide range of EUV spectrum around the strong He II (30.4 nm) spectral line with a spectral resolution comparable to that obtained with a modern EUV grating spectrometer, e.g., about 0.4 nm or better. Following this goal, the focusing system was optimized to the spectral band centered at the 30.4 nm. This optimization was mainly done by determining the appropriate potentials on focusing electrodes rather than changing the electrodes configuration. Figure 5 shows a zoomed view of two electron beams with energies 19.157 eV (top) and 18.825 eV (bottom). They correspond to 30.4 nm and 30.65 nm with the 0.25 nm difference.

![Figure 5. A zoomed view of two electron beams with the spectral difference of 0.25 nm. A square box, which represents a photodiode detector, e.g. AXUV-HS5 has size 1×1 mm. A vertical line in front of the detector represents a diaphragm with diameter 0.8 mm.](image)

The bottom electron beam (Figure 5) has an aperture of about 0.6 mm diameter at the focal plane (Figure 5 shows a 2-D cut through a half of the beam). The radial separation between this beam and the other (top beam) produced by photo-electrons originated from a radiation with 0.25 nm difference is about 0.41 mm. It means that a spectral resolution of about 0.25 nm may be reached with a limiting diaphragm of 0.8 mm diameter. Smaller apertures (either diodes, e.g. AXUV-HS1 with a sensitive area size of 0.22×0.22 mm² or with a smaller diaphragm) may allow even better spectral resolution in the model for the solar EUV radiation centered around of the 30.4 nm He II spectral line.

Spectral resolution at the both low- and high-energy edges of the band is a function of the detector position at the X-axis as the focal plane location is a function of electron energies for a fixed set of potentials. For the shown position of the detector, which was optimized to the center of the band (Figure 5) and the same diaphragm with 0.8 mm diameter, the modeled spectral resolution for the low- and high-energy edges is about 0.5 and 1.0 nm respectively.

3.2. Controlling of the electron beam

The proposed spectrometer was designed and modeled to develop the highest spectral resolution in the spectral band of 20.0–40.6 nm centered at 30.4 nm. Another requirement was to control the position of the beam (to scan
through the spectrum) with a single electrode. These requirements were realized using the system (Figure 3) with eight electrodes. A plot of a scan through the wavelengths of the band by changing the control electrode’s potential is shown in Figure 6.

**Figure 6.** An electrical field’s dispersion of the spectrometer as a function of control electrode’s potential. The plot shows voltage on electrode 6 (Figure 3 and Table II).

Potentials on non-control electrodes (Table II) may be changed to another set of voltages for shifting the spectrometer’s spectral range to either lower-energy or higher-energy photons. Figure 7 shows two examples for such shifting: A) and B) represent the focusing of the photo-electrons ionized by 50.0 and 5.0 nm radiation respectively. The corresponding sets of electrode voltages are shown in Table III. The focusing of the electron beams (Figure 7) produced by the 50.0 and 5.0 nm radiation were optimized to these two edges of the EUV spectrum. The beams shown in Figure 7 are focussed with the same quality or even better than correspondent beams for the ‘softer’ 40.6 and 20.0 nm edges of the spectrum shown in Figure 4. This demonstrates that an appropriate combination of the electrode potentials allows not only shifting of the edge of the spectral band to
Table 3. Potentials on the electrodes (Figure 3) modeled for the 50.0, 10.0, 7.5, and 5.0 nm photon energies (Figure 7).

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<th>Electrode number</th>
<th>Potential for 50.0 nm, V</th>
<th>Potential for 10.0 nm, V</th>
<th>Potential for 7.5 nm, V</th>
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more extreme values but also it may be used to optimize the output beam parameters in the required region and get improved spectral resolution there. If the spectrometer should work in a wider spectral band, e.g. 5.0–50.0 nm, an appropriate look-up table may be created to scan through this spectral region by changing a set of potentials at some wavelengths.

3.3. Spectral contamination of the modeled spectrometer

Any type of the EUV spectrometer is sensitive to the spectral contamination, meaning detecting out-of-band wavelengths either from a neighbor region or from different spectral orders. Filter-based and grating spectrometers use appropriate metal filters for preventing unwanted radiation being detected. A spectrometer with an electron focusing system may employ an additional tool - some spatial selecting of the electrons with different energies by the focusing system and detector. We have modeled a few examples (Figure 8) to show that the modeled spectrometer is not sensitive to spectral contamination from the edges of the spectral band.

Figure 8. Two examples of contamination-free configuration for the low- and high-energy edges of the band. A) The system is set to detect the electrons with energies 8.93 eV (40.6 nm) - bottom beam. The 40.33 eV high-energy electrons (20.0 nm) - upper beam are collected by electrode 3. B) The system is set to to detect high-energy electrons (upper beam). Low-energy electrons (bottom beam) are collected by electrode 4.
Electrons from neighbor regions of the spectrum may be collected by a diaphragm that covers the detector. It prevents spectral contamination from any off-axis beam created by electrons with different energies.

4. A PRELIMINARY DESIGN

A preliminary design of the EUV spectrometer may be based on the modeled configuration (Figure 3). The design of the system would have a cylindrical shape with diameter 140 mm and length 200 mm. These dimensions do not include a required tank for compressed gas with a gas delivery system, power supply, magnetic and electrical field filters.

A three-dimensional view of the spectrometer is shown in Figure 9.

5. CONCLUSIONS

We have analyzed existing prototypes of EUV spectrometers based on a gas-ionization chamber. The prototypes used two-electrode focusing systems to work in either a monochromator regime or to detect solar radiation in some range of the EUV spectrum. A model of the toroidal electrostatic analyzer showed that its effectiveness in a spectral range of a few nanometers or more is low as electrons with different energies are scattered in a wide area and cannot be collected by a reasonable size detector (e.g., 60 mm diameter MCP). The output beam in the monochromator regime became quite unfocussed if some wider input conditions (photon-gas ionization area, elevation angles) are applied. The model showed that some optimization of the electrical field of the monitor is required to focus the electrons in a wider range of their energies.

A model of an eight-electrode focusing system was developed to serve as a prototype of an EUV spectrometer. The model satisfied two major requirements, on the spectral resolution (about 0.4 nm or better for the region of the strong solar line He II 30.4 nm) and a spectral band about 20 nm centered at this line. The spectral resolution in the center of the 20.0–40.6 nm band is about 0.25 nm and about 0.5 nm and 1.0 nm at the low- and high-energy edges of the band respectively if the same set of potentials is used for all wavelengths of the band. The electrical scan through wavelengths of the band is performed in this case by a single control electrode.
The proposed system may be re-aligned to other spectral regions by changing potentials on focussing electrodes. Two examples for the 5.0 and 50.0 nm radiation were modeled with improved focusing at these edges of the spectral band. The optimization of the potentials may be done at either a wavelength of interest or during a scan through a wide spectral region to enhance the spectral resolution there.

A simplified analysis of spectral contamination showed that low- and high-energy parts of the photo-electron beam are not overlapped at the detector. Selecting the required wavelengths without contamination may be done by both the focusing of the beam and by the choosing the detector’s entrance aperture diaphragm.

The proposed model of the EUV spectrometer with an eight-electrode focussing system has the following dimensions (gas delivery system is not included). Diameter is 140 mm and length is 200 mm.

REFERENCES

