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PRELIMINARY DESIGNS FOR X-RAY SOURCE MODIFICATIONS FOR THE MARSHALL SPACE FLIGHT CENTER'S X-RAY CALIBRATION FACILITY

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ABSTRACT

The objective of this investigation is to develop preliminary designs for modifications to the X-ray source of the MSFC X-Ray Calibration Facility. Recommendations are made regarding: (1) The production of an unpolarized X-ray beam, (2) Modification of the source to provide characteristic X-rays with energies up to 40 keV, and (3) Addition of the capability to calibrate instruments in the extreme ultraviolet wavelength region.

ACKNOWLEDGEMENTS

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UNPOLARIZED X-RAY SOURCE

Requirements for a source to produce an X-ray beam which is 100% unpolarized were investigated by J. H. Kitterman.[1] He made an extensive survey of commercial X-ray tubes and found that an end-window toroidal cathode tube manufactured by Machlett Laboratories should have the desired properties if electrons are emitted from the cathode uniformly and are focused onto the anode symmetrically. Important features of the tube are illustrated in Figure 1.

This tube was designed as a source for use in X-ray fluorescence spectrometry and is said to provide an intense broad-spectrum X-ray beam. The theory of production of continuous (bremsstrahlung) X-rays is given by Compton[2] and Dyson[3] and is summarized by Kitterman. According to this theory, the plane of polarization of X-rays produced at points 180° apart on the annular shaped area of the flat target which is bombarded by electrons will be in the same direction but will be perpendicular to that of X-rays produced at the 90° and 270° positions. Thus when contributions to the X-ray beam are summed around the annular area of electron bombardment, the result should be an unpolarized beam if the source is axially symmetric.

While the Machlett tube should produce an unpolarized X-ray beam it is not without problems. The tube was designed to operate between 20 and 75 kV and Kitterman reports that the designer of the tube is uncertain if the intensity will be adequate at much lower voltages. Since the operating characteristics of this tube at low voltages have not been determined, the spot-size (area of X-ray emission) is unknown. The spot-size for normal operating voltages is reported to be 1.0 to 1.5 Cm o.d. A spot this size would subtend an angle at the optical bench pivot which is 10 to 15 times as large as the $\sim$0.7 arc seconds of the present source. This spot size would appear to be too large for some applications. Targets are not easily interchangeable in this tube so a series of tubes with targets of different elements would be required to provide characteristic X-rays of the desired energies. Since tubes cost approximately $12,000 each, this series of tubes would be expensive.

Kitterman pointed out that another possible X-ray source is a modified electron-beam-evaporator and he obtained literature on one produced by Vacuum Generators. This model has a toroidal cathode and its geometry is basically the same as that of the Machlett tube. However, it is designed for easy disassembly and has a crucible for holding the different materials which are to be evaporated. A brief search of the literature revealed only one example of a modified electron beam evaporator being used as an X-ray source and it was this model by Vacuum Generators.[4] No details of modifications or operating characteristics were reported. However, it should be a straight-forward procedure to modify this evaporator to accept interchangeable flat faced target anodes which would screw onto the water-cooled stem where the crucible is normally located.

This evaporator is designed to operate at voltages up to 10 Kv but the literature indicates that in practice these evaporators are usually operated below 5 kV to reduce arcing in the vapors which are produced when materials are being evaporated. In applications as an X-ray source where target evaporation is avoided, operation at the 10 kV upper limit of the power supply should be possible. Information from the factory indicates that it might be possible to push this evaporator to a maximum voltage of 15 kV which is the rating of the high voltage electrical feed-throughs.[5] This low maximum operating voltage is a serious limitation on the useful energy range of this X-ray source. It does have a focus adjustment which allows a spot size of 1 mm diameter. This evaporator would be a much more economical X-ray source since the evaporator and power supply cost less than one Machlett tube.

Inquiries to several suppliers of electron beam evaporators led to one other one for possible use as an X-ray source. Dr. R. Bakish of Bakish Materials Corporation indicates that his line of evaporators is often used as X-ray sources.[6] An axial electron-gun with magnetic focusing and magnetic beam turning through 90° will result in a geometry which produces unpolarized X-rays. This is due to the fact that when a parallel beam of electrons strikes a flat target perpendicular to the plane of the target-face that there is no preferred direction of scatter of the electrons. The X-rays, produced by these randomly scattered electrons, which are observed at 0° and 180° with respect to the preimpact velocity of the electrons will be unpolarized due to symmetry.[7] Figure 2 shows a sketch of such an arrangement. An electron beam focused by a magnetic lens in the electron gun is bent through 90° by a uniform magnetic field external to the gun and perpendicular to the original beam direction.

The main advantage of the Bakish system is that electron guns that operate up to 60 kV are available. A discussion of electron-guns and electron beam apparatus is contained in books by Bakish[8] and Schiller, et.al.[9]

The 90° rotation of the unpolarized source which is required to check for asymmetries should be obtained by mounting the source on a special rotatable vacuum flange such as one manufactured by Ferrofluidics.

The X-ray Calibration Facility provides primarily characteristic X-rays which are known to be unpolarized.[10] These characteristic X-rays are superimposed on the bremsstrahlung continuum which is partially polarized. Thus it is only the continuum X-rays which contribute to the polarization of the present X-ray beam. Kitterman estimates that polarization of the present beam from an Al target is only 0.3%. Estimates of the polarized X-ray component in the beams from other targets should be made since Reily reports that the Al line is one of the cleanest.[11]

In the opinion of the author of this report, it is highly unlikely that the "unpolarized sources" discussed by him or Kitterman will be known to be 100% unpolarized with an accuracy greater than 0.3%. While the author of this report is not an expert on polarization measurements of celestial X-ray sources, he is not aware of measurements with an uncertainty as small as 0.3%. Therefore, I suggest that careful discussions with principal investigators be held to be sure that it is really necessary to go to the considerable trouble and expense to try to improve on the present source as a generator of an unpolarized X-ray beam. In my opinion, the polarization characteristics of the present beam should be measured with a polarimeter before proceeding to other alternatives.

Since the unpolarized characteristic X-rays are superimposed on the partially polarized continuum, the relative amount of polarized X-rays accepted will be a function of counter resolution and "window-width." These can be varied in the experiment to study the polarized contribution to the X-ray beam.

40-KEV X-RAY MODIFICATION

In order to extend the energy capability of the X-ray facility to 40 keV, modifications will have to be made in the X-ray source and beam monitor. The efficiency of Production of Characteristic K X-rays is proportional to: $(E_o/E_k-1)^{1.63}$, where E_o is the energy of the projectile electrons and E_k is the binding energy of the K-shell orbital electrons.[12] From this, it is clear that for the efficient production of K X-rays at 40 keV, accelerating voltages of at least 80 kV will be necessary. Since the high voltage power supply for the present source has a maximum value of 60 kV it will be necessary to obtain a new power supply with perhaps a 100 kV maximum output.

The energies of the Characteristic K X-rays increase with the atomic number, Z, of the target material. Thus targets of higher Z-values than those used in the past will have to be obtained. To help select promising target and filter materials, I have surveyed the elements in the periodic table of the elements starting from where the HEAO-2 targets stopped out through samarium which has a K X-ray energy of about 40 keV. Table I includes a list of these elements with comments regarding their possible usefulness as targets.

These higher X-ray energies will require that a different beam monitor be used. The Xenon proportional counter designed to operate at energies up to 10 keV for the AXAF calibration will not be adequate.[21] Extrapolation of the efficiency vs. energy curve for this Xe counter indicates that its efficiency is essentially zero at approximately 22 keV. Two possible detectors for use up to 40 keV are NaI(Tl) crystals coupled to photomultiplier tubes, and solid state detectors. Thin NaI(Tl) scintillation crystals coupled to photomultiplier tubes are available from Tennelec and Harshaw. These detectors are rugged, reliable, have moderate energy resolution and are relatively inexpensive. High purity germanium (HPGe) solid state detectors can provide excellent efficiency from approximately 3 keV to energies well above the 40 keV of interest. These HPGe detectors can be shipped and stored at room temperature without damage but are operated at the temperature of LN_2. These HPGe detectors have a great advantage over the older lithium drifted germanium detectors which were ruined when brought up to room temperature. These detectors

TABLE I SOME INFORMATION RELATIVE TO ELEMENTS SUITABLE AS X-RAY TARGETS

CHEMICAL SYMBOL	ATOMIC NO.	ENERGY $K_{\alpha 1}$ (kev)[13]	USEFUL AS TARGET?	ELECTRO-PLATE?	REFERENCES	COMMENTS[14]
Co	27	6.93	yes	yes	15(p.328)	
Ni	28	7.48	yes	yes	15(p.317)	have filter from HEAO-2
Cu	29	8.05	yes	yes		have from HEAO-2
Zn	30	8.64	yes	yes	16(p.198-207)	
Ga	31	9.25	no	no	20(p.71)	(Alloys with metals!) liquid near room temperature
Ge	32	9.89	maybe	?	20(p.71)	Vacuum evaporate
AS	33	10.54				
Se	34	11.22			20(p.74)	may contaminate vacuum system
Br	35	11.92	no	no		liquid at room temperature
kr	36	12.65	no	no		gas
Rb	37	13.40	no	no		liquid near room temperature
Sr	38	14.17	no	no		keep under kerosene, oxidizes rapidly
Y	39	14.96				relatively stable in air
Zr	40	15.77	yes			have from HEAO-2
Nb	41	16.62		?	20(p.73)	vacuum evaporate
Mo	42	17.48	yes			known to have been used as X-ray target
TC	43	18.37	no			not found in nature
Ru	44	19.28	yes	yes	18(p.227)	in platnium group
Rh	45	20.22	yes	yes	18,21(p.167)	proposed source at 2.6-kev
Pd	46	21.18	yes	yes	18(p.213)	platnium group
Ag	47	22.12	yes	yes		have from HEAO-2
Cd	48	23.17	yes	yes	16(p.95-102)	
In	49	24.21	yes	yes	17(p.161)	
Sn	50	25.27	yes	yes		have from HEAO-2
Sb	51	26.36	yes	yes	17(p.150)	stable in air at room temperature
Te	52	27.47	?		20(p.75)	P-type semiconductor
I	53	28.61	no	no		volatizes at room temperature
Xe	54	29.78	no	no		gas
CS	55	30.97	no	no		liquid near room temperature
Ba	56	32.19	no	no	19(p.512)	(vacuum evaporate BaO) oxidizes easily, keep under oil
La	57	33.03	no	no		oxidizes rapidly in air
Ce	58	34.28	no	no		oxidizes readily at room temperature
Pr	59	36.03	no	no		keep in oil or sealed in plastic
Nd	60	37.36	no	no		keep in oil, quickly oxidizes in air
Pm	61	38.72	no	no		not naturally occuring
Sm	62	40.12	maybe			reasonably stable in air, used as a neutron absorber in nuclear reactors

are rugged, reliable, have excellent energy resolution and are very expensive. Two sources of these detectors are ORTEC and Canberra. An efficiency curve for a Canberra planar HPGe detector is shown in Figure 3.

Experimenters need to be aware that electrical shock hazards and radiation hazards may be greater at these higher voltages and thus should exercise appropriate precautions.

ULTRAVIOLET SOURCE

There is growing interest by astronomers in studying the universe in the extreme ultraviolet wavelengths. Measurements must be made from above the earth's atmosphere which is opaque at these energies and orbiting observatories are the most effective means for long term studies. Figure 4, adapted from J.A.R. Samson's classic work on vacuum ultraviolet spectroscopy indicates the relationship between the Vacuum UV, Extreme UV and SOFT X-Ray regions of the electromagnetic spectrum.[22] It should be noted, however, that these wavelength boundaries are not universally accepted.

Wavelength specifications of some Vacuum UV instruments on several orbiting observatories are shown in Table II. Results of International Ultraviolet Explorer investigations of comets, satellites, planets, the sun, stars of all types, supernova remnants, the interstellar medium, nebulae, clusters, galaxies, quasars, etc. in the wavelength range 1150-3200 Å have been reported.[16] Astronomers now want to study these and other interesting objects in the extreme UV region. At this time the Extreme Ultraviolet Explorer (EUVE) is being developed to survey the entire celestial sphere for astronomical sources in the extreme UV region (100-1000 Å). An interest has been expressed in extending the capability of the MSFC X-Ray Calibration Facility for instrument calibration into the extreme UV region.[25] This extension would be reasonable and the possibility deserves consideration since the EUV region overlaps the soft X-ray region where a capability already exists.

Although facility requirements in this energy range have not been well defined, it is clear that a source of EUV radiation, a grazing incidence monochromator to select energies, and a detector to measure the flux will be ncesssary. As a modest first step in investigating the possibilities of developing a capability in the EUV region, I have surveyed suppliers of UV equipment to find what items are commercially available and what companies can supply them.

Several Samson designed UV sources are available from Minuteman Laboratories. However, it appears that perhaps the best source for this application is a continuous discharge Penning source with emission lines between 50 and 300 Å which is described in the literature but is not available commercially.[26] Grazing incidence monochromators for the EUV region are available from McPherson, Acton Research, Minuteman Laboratories and Instruments S.A. If off-the-shelf models are not satisfactory, these companies have considerable experience in supplying custom monochromators.

Detectors of several types including channel electron multipliers, multichannel plates, photodiodes, photomultiplier tubes, thin window proportional counters and ionization chambers are available from Galileo Electro-Optics and Minuteman. Appendix A contains a list of company names, addresses, telephone numbers and sales representatives of suppliers of VUV equipment. A number of companies listed in "Research and Development's Telephone Directory" and "Physics Today's Annual Buyers Guide" were contacted for descriptive literature. Only those companies with products that looked promising are listed.

Since some personnel of the X-Ray Calibration Facility are not familiar with EUV instruments and terminology; a list of definitions from manufacturer's literature and other sources are listed in Appendix B.

Table III lists some useful filter materials for the extreme ultraviolet region.[27]

RECOMMENDATIONS

1. I recommend that the polarization of X-rays from the current source be studied to see if they might meet the needs for an unpolarized source. These X-rays are primarily characteristic X-rays which are inherently unpolarized and may satisfy the requirements within the uncertainty limits of some measurements.

2. If it becomes necessary to acquire an additional X-ray source for the production of low energy unpolarized X-rays, I recommend that a vacuum generators electron beam evaporator be purchased and modified as an X-ray source. It would be worthwhile to determine if this apparatus can be modified to operate at significantly higher voltages than the 15-kv upper limit currently set by the rating of the electrical feed throughs. An axial electron gun such as that of Bakish Materials Corporation is worth consideration as a source of high energy unpolarized X-rays.

3. If there is continued interest in the calibration of instruments in the extreme ultraviolet region, I recommend that serious consideration be given to developing the capability to perform calibration in this region. This would appear to be a natural extension of the present capability. A first step should probably be to consult experts in optics and UV spectroscopy here at MSFC for recommendations regarding sources, monochromators and detectors.

TABLE II
WAVELENGTH AND ENERGY RANGES FOR SOME UV AND X-RAY EXPERIMENTS

EXPERIMENT	LAUNCH DATE	WAVELENGTH RANGE	ENERGY RANGE
Apollo-Soyuz[26]	July 1975	50-1000Å	12.4 - 248ev
IUE[23]	Jan 26,1978	1150-3200Å	3.9 - 10.8ev
HEAO-2	Nov. 1978	2-67Å	0.185 - 6.2kev
Space Telescope	1986	1100-3200Å	3.9 - 11.3ev
EUVE[24]	198_	100-1000Å	12.4 - 124ev
AXAF	199_	1.24 - 100Å	0.1 - 10kev

TABLE III
FILTERS FOR THE EXTREME ULTRAVIOLET REGION[26]

MATERIAL	BAND ev	Pass nm
Parylene N	83 - 225	5.5 - 15.0
Be/Parylene N	83 - 109	11.4 - 15.0
Aluminum Plus Carbon	20 - 73	17 - 62
Tin	16 - 25	50 - 78
Barium Fluoride	8.0 - 9.2	135 - 154

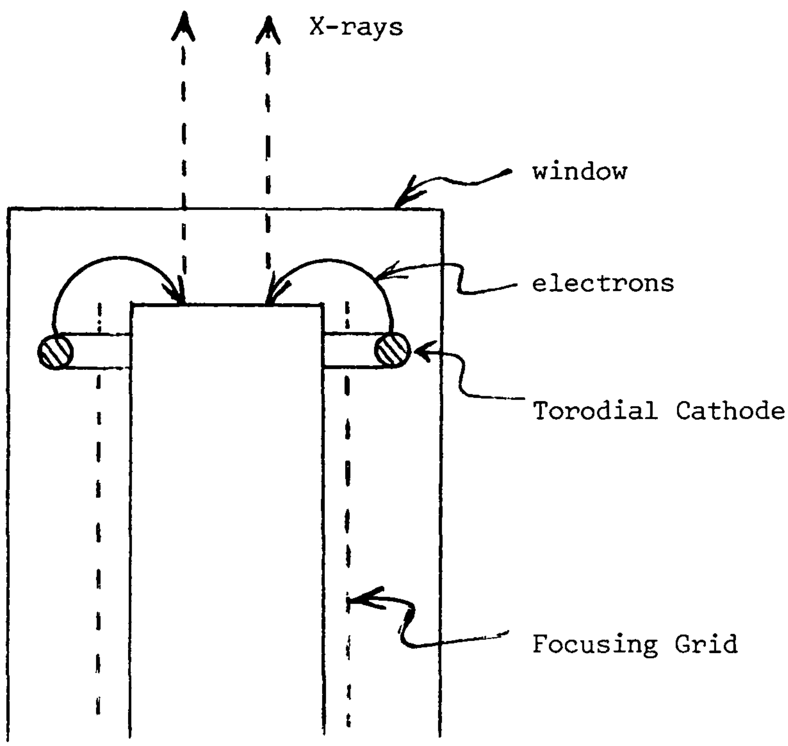

Figure 1 FEATURES OF AN END WINDOW TORODIAL X-RAY TUBE

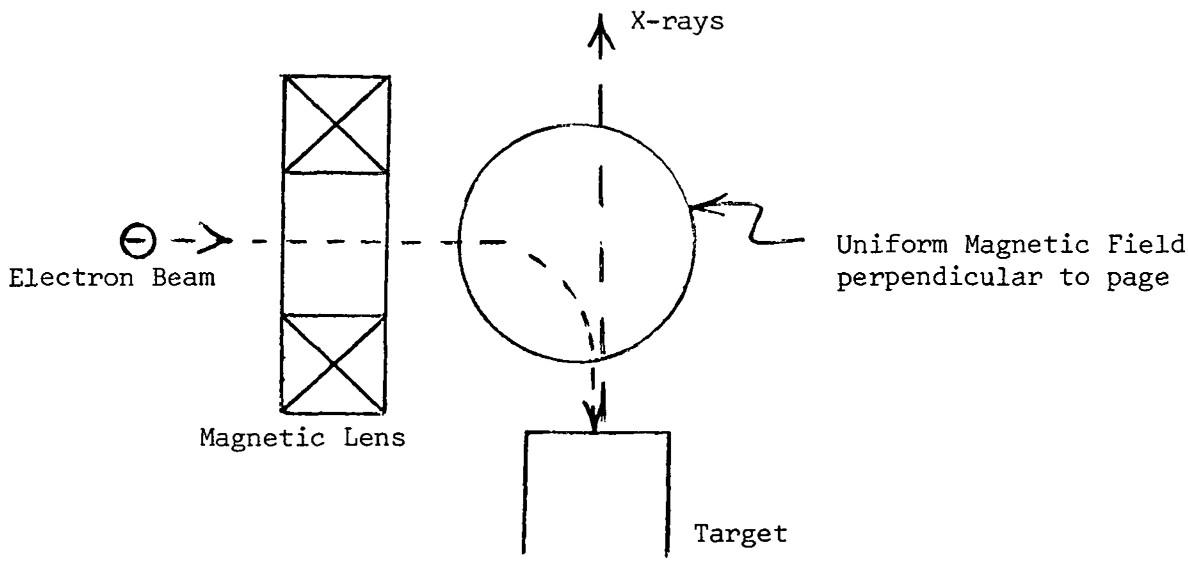

Figure 2 Axial Gun with Magnetic Focusing and Magnetic Beam Turning by 90°

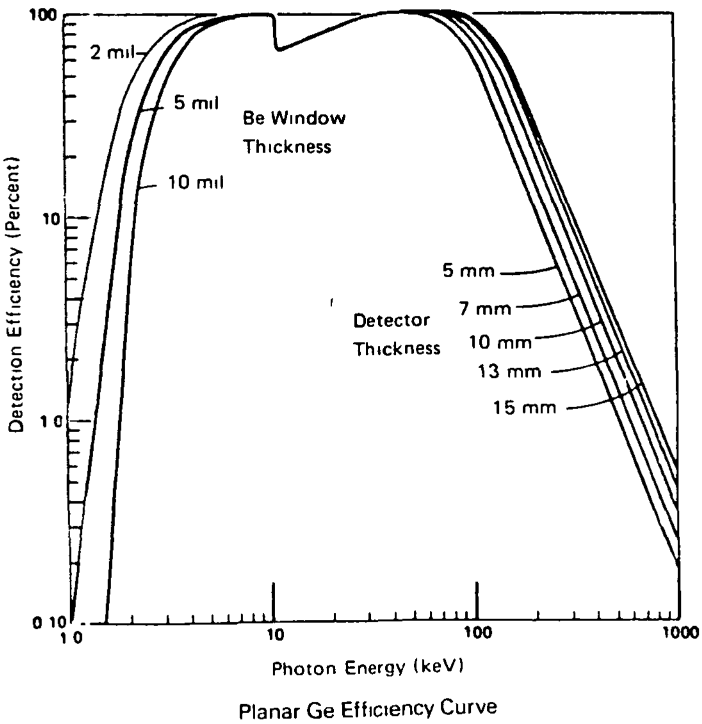

Figure 3 Planar Ge Efficiency Curve

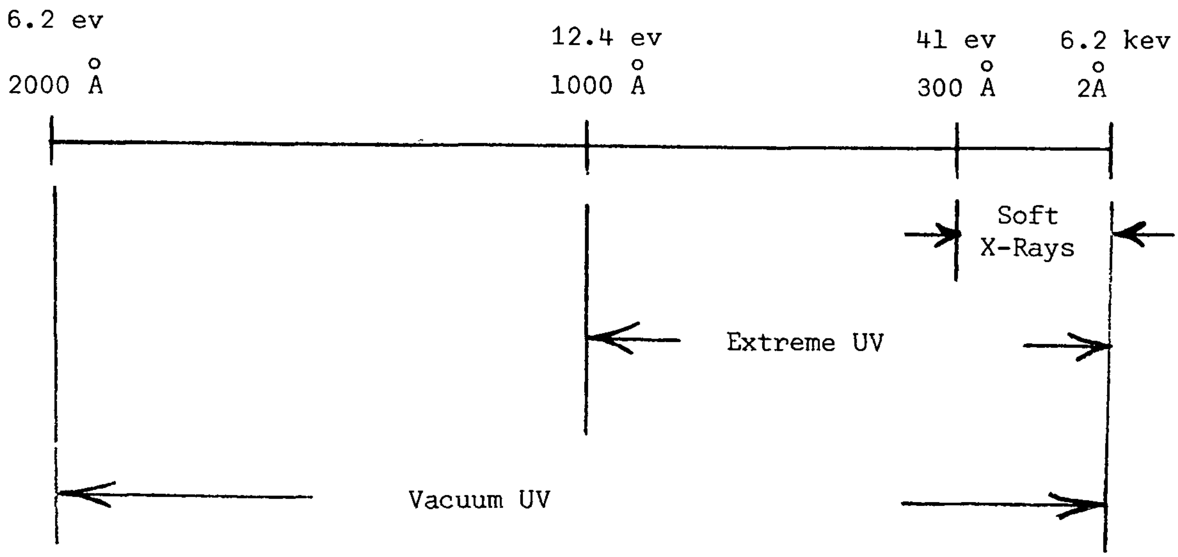

Figure 4 Energy and Wavelength Relationships in the Vacuum Ultraviolet

APPENDIX A

SOURCES OF SOME EQUIPMENT OF INTEREST

Electron Guns

Dr. R. Bakish
Bakish Materials Corporation
171 Sherwood Place
P.O. Box 148
Englewood, N.J. 07631
(201-567-5873)

Mr. Mike Flinko, Product Manager
UHV Components
Kurt J. Lesker Company
5635 Horning Road
Pittsburg, PA 15236
(412-655-9500)
(800-245-1656)
(Exclusive Distributor for Vacuum Generators, LTD)

Grazing Incidence Monochromators

Mr. Richard W. Merk
Operations Manager
Acton Reserach Corporation
Box 215
525 Main Street
Acton, Mass. 01720
(617-263-3584)

Mr. John Gilmore
Vice President
Minuteman Laboratories, Inc.
916 Main Street
Acton, Mass. 01702
(617-263-2632)

Mr. Jack Parmley
Sales Representative
S.I./McPherson
530 Main Street
Acton, Mass. 01720
(617-263-7733)
(800-255-1055)

Thin Window NaI(T1) X-Ray Detectors

Mr. J. E. Bradley
Sales Engineer
Tennelec, Inc.
601 Oak Ridge Turnpike
Oak Ridge, TN 37830-2560
(615-483-8405)

Rotatable Vacuum Flange

Ferrofluidics Corporation
40 Simon Street
Nashua, NH 03061
(603-883-9800)

Detectors for Extreme Ultra Violet Radiation

Mr. Richard E. Shepardson
Contracts Administrator
Galileo Electro-Optics Corp.
Galileo Park
Sturbridge, Mass. 01518
(617-347-9191)

APPENDIX B

DEFINITIONS RELATED TO MONOCHROMATORS

Aberrations are imperfections in slit image formation resulting from optical design, limitations of a configuration, or imaging at high aperature.

Aperture or f/Number is the ratio of the focal length of the monochromator to the grating diameter. The smaller the f/number, the larger the aperture and vice versa. A large aperture features a wide collection angle - making it more effective in gathering light while less effective in resolving it. A small aperture gathers only a small amount of light but finely resolves it.

Bandpass in nm is the actual resolution of a monochromator as a function of its slit width. It is the product of linear dispersion and the slit width.

Blaze Wavelength is the wavelength at which the grating is at its maximum efficiency. The useful range of a grating can be described by the "2/3-3/2 Rule" which gives the range of a grating to be: lower limit = $2/3\ \lambda_{blaze}$; upper limit = $3/2\ \lambda_{blaze}$. It is sometimes possible to operate the grating with reasonable efficiency above the 3/2 value, but operation below the 2/3 value is not recommended.

Dispersion is classically defined as the amount of the focal plane, expressed in mm, taken by one nm of light. Now it is more common to refer to dispersion as how well the monochromator spreads the light spectrum over the focal plane of the exit plane, this is expressed in the amount of spectrum (in nm) over a single mm of the focal plane.

Focal Length is the distance between the slit and the focusing component of the monochromator. Generally, the longer the focal length, the greater the linear dispersion.

Holographic grating is a grating produced by interference fringes from a laser beam. The holographic process produces gratings which are virtually free of spacing errors. Holographic gratings have been produced with efficiencies very near those of classically ruled gratings. Holographic gratings are most useful when a more dense groove spacing is required and efficiency is not of great concern.

Order number is an integer representing multiples of a given wavelength. When a monochromator is set to pass a wavelength of 800 nm, for example, integral multiples of other wavelengths (such as the second order of 400 nm) will be allowed to pass. In cases where transmission of higher orders causes a problem, bandpass filters can remove unwanted radiation.

Resolution is a measure of how finely a given monochromaton differentiates between spectral lines - the minimum detectable difference between peaks. While theoretically resolution can be approximated by multiplying slit width (in mm) by dispersion (in nm/mm), actual resolution rarely equals this due to aberations inherent in monochromators.

Rowland Circle is a circle which contains the concave grating and the entrance and exit slits in most monochromators. The circle has a diameter equal to the radius of the grating which is mounted tanget to the circle.

Throughput is the overall effectiveness with which a monochromator transmits light. It is defined as the ratio of the amount of light passing into the entrance slit to the amount of light passing out of the exit slit. Mathematically this is defined as:

$$T = \frac{\pi D h}{4(f/number)^2 R_1 R_2 R_3 \cdots R_n R_x}$$

where

D = dispersion (expressed classically as mm/nm), h= slit height in mm, $R_1 \ldots R_n$ = reflectivities of various mirror surfaces and R_x = the spectral efficiency of the grating.

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