DIFFRACTION GRATINGS

Advanced technologies for the production of master and replica diffraction gratings

Innovations in optical design

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Founded in 1819, INSTRUMENTS SA JOBIN-YVON has defined the leading edge of the Optics of Spectroscopy.

Our pattern of leadership in optics has been hallmarked by the continuing development of both Classically Ruled and Holographic Grating Technology. This led to the introduction in 1967 of the Aberration Corrected Holographic Grating and subsequently Ion Etched and Blazed Concave and Plane Holographic Gratings.

As a result ISA JOBIN-YVON is able to offer dramatically superior gratings addressing the following technologies :

- *Flat Field Gratings for Array Detectors*
- *Spectroscopy : Emission and Absorption*
- *Ion Etched Gratings for the VUV*
- *Molecular and Dye Laser Gratings*
- *Gratings for Laser Chirped Pulse Compression, etc.*

Gratings from ISA JOBIN-YVON are found in synchrotrons, satellites, research centers, in spectrophotometers, clinical analysers, HPLC detectors, color monitors, emission spectrometers... the list seems end less.

In addition, as a vital service to our OEM customers, we can fully ray trace and optimize your total optical system from entrance optics through the grating to the detector.

CONTENTS

Advanced technologies for the production of master and replica diffraction gratings

Master grating production uses one or more of the following technologies :

- Mechanical ruling
- Holographic recording
- Ion-etching of a holographic master

The application usually determines which of the above methods will be employed to produce the optimum grating. For example, an f/2 spectrophotometer for use in the UV may demand an ion-etched supercorrected holographic grating whereas an Infra-Red laser may demand a master classically ruled grating. For routine use any grating may be inexpensively replicated.

MECHANICAL RULING

Master classically ruled gratings are produced by first evaporating a coating of Aluminum onto a highly polished and figured substrate and then "burnishing" grooves with a right angle apex with a diamond tool. It is essential that each groove be absolutely straight, parallel and equidistant from its neighbors. Instruments S.A./Jobin-Yvon employees double interferometers unto computer control to ensure the highest quality rulings.

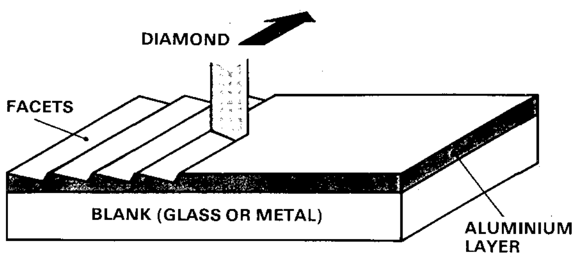


Figure 1 : Mechanical ruling using a diamond tool

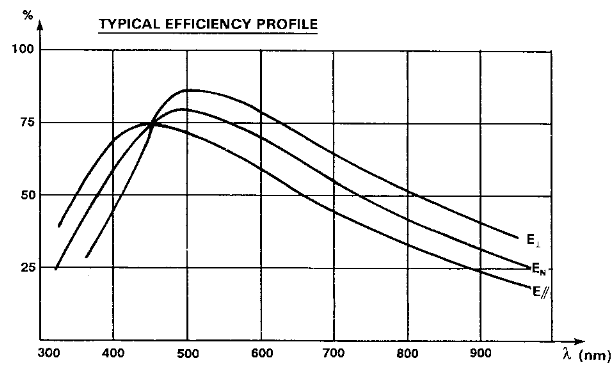


Figure 2 : Mechanically ruled grating
Blaze wavelength : 500 nm,
Number of grooves : 600 gr/mm
Deviation angle : 8 degrees

Classically ruled gratings are available up to 1800 gr/mm for use in virtually any spectral domain from the X-UV to the far infra-red.

HOLOGRAPHICALLY RECORDED GRATINGS

Holographic master gratings are produced by starting with a highly polished and figured substrate as with the ruled master gratings. In this case however, the blank is coated with a layer of protosensitive material and then exposed to interference fringes created at the intersection of two coherent laser beams. Chemical treatment of the protosensitive layer selectively dissolves the exposed areas forming grooves in relief. Following this, an evaporated metal coating is deposited on the surface and the grating is ready to use. The geometry of the laser wavefronts used to produce the interference fringes can be modified to produce a non linear groove distribution on the surface. This non linear groove distribution is used to correct aberrations. The shapes of the grooves produced by holographic recording have a sinusoidal shape.

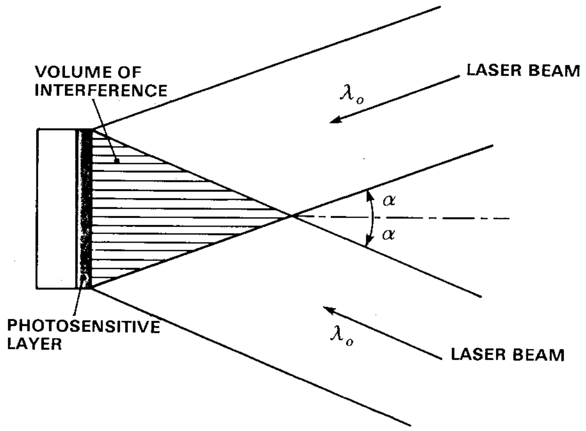


Figure 3 : Recording a plane holographic grating with straight and equidistant grooves.

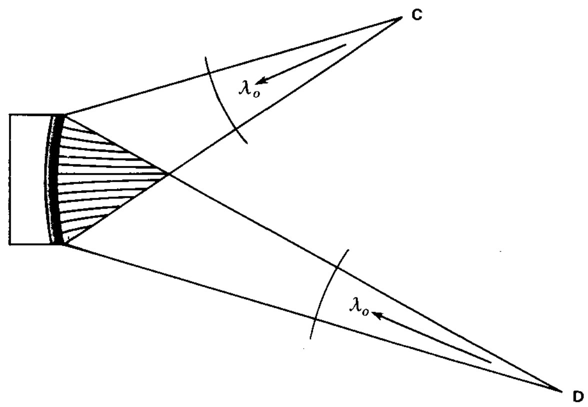
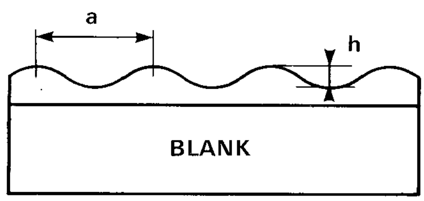


Figure 4 : Recording an aberration corrected concave holographic grating with non linearly spread curved grooves.



PHOTOSENSITIVE LAYER

a = GROOVE SPACING
h = MODULATION DEPTH

Figure 5 : Sinusoidal groove profile of a holographically recorded grating

The efficiency of a holographic grating is determined by the ratio of the wavelength and groove spacing λ/σ. In general if $\lambda/\sigma \geqslant 0.8$ the efficiency will be at a maximum from 85% in polarized light to about 50% in unpolarized light. When $\lambda/\sigma < 0.8$ maximum efficencies in non polarized light will be approximately 35% for the UV visible and near IR region of the spectrum.

Holographic gratings usually have a very long usable wavelength range.

On specific wavelength ranges, with polarized light, the efficiency of holographic gratings can be extremely high, provided that the right number of grooves has been selected : it is the case of the pulse compression gratings : a 1740 gr/mm, non blazed, holographic grating may have efficiencies as high as 97% at 1.06 μm and a 2000 gr/mm grating may be as high as 95% at 800 nm (see figures 6, 7, 8 and section on pulse compression gratings).

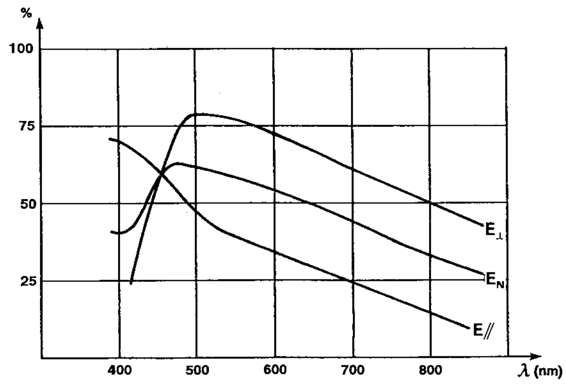


Figure 6 : Typical efficiency profile Holographic grating 1800 gr/mm. 450-800 nm

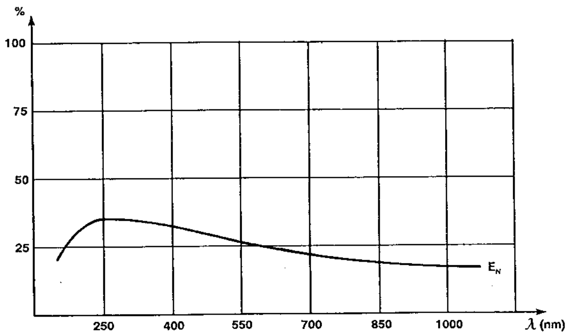


Figure 7 : Typical efficiency profile Holographic grating 1200 gr/mm. 190-1100 nm

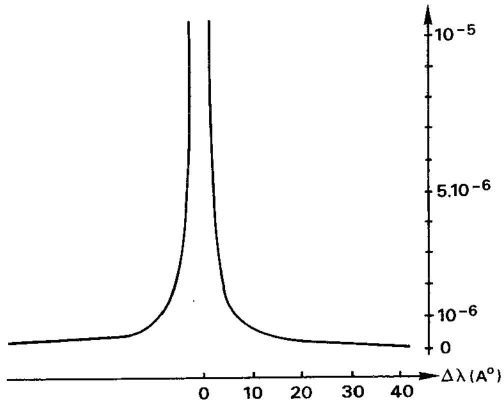


Figure 8 : Stray light rejection

STRAY LIGHT REJECTION

Holographic gratings provide excellent stray light rejection. The optical techniques used to produce them do not result in highly scattering grooves or periodic groove spacing errors that cause focused stray light or ghosts.

So holographic recorded gratings offer the user many significant benefits :

- **Perfect periodicity plus excellent micro-roughness of the surface elimitate ghost and enhance stray light rejection.**
- **Holographic recording permits the use of very high aperture including : concave spherical, toroidal, or aspheric surfaces.**
- **Grooves may be distributed non uniformly across the surface of the substrate, reducing or eliminating the normal aberrations of concave gratings or systems aberrations in the case of Czerny-Turner spectrometers.**
- **Allows the design of new imaging diffraction gratings for use in flat field spectrographs.**
- **Minimal groove errors permits very high resolution.**
- **Production of very high groove density gratings, currently up to 6000 gr/mm.**
- **Production of very large gratings, up to 450 mm in diameter.**

BLAZED ION ETCHED HOLOGRAPHIC GRATINGS

Ion etching permits the shape of the grooves on a holographic master grating to be "sculpted" as needed by an application. It is possible to produce blazed holographic gratings with many different groove shapes, including triangular and laminar profiles. The technique uses an ion etching machine to ablate surface atoms through a holographic mask. As before, the hologram is formed by the illumination, and subsequent chemical processing, of a laser generated interferogram in photoresist. The mask permits either a plane spherical or aspherical substrate to be used. The grooves being etched directly into its surface. The grating may be used as it is or be replicated.

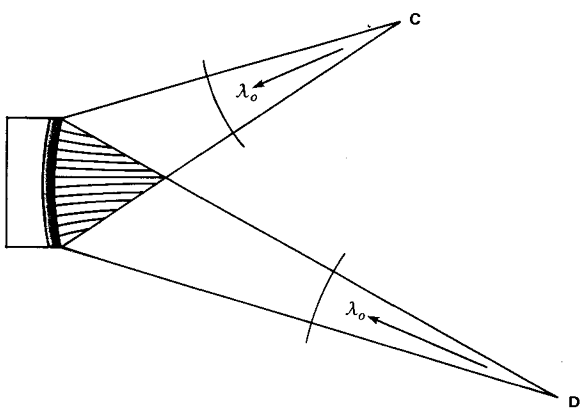
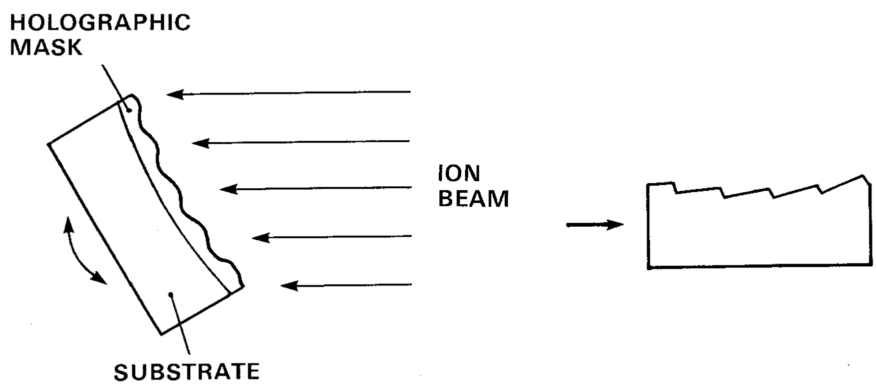


Figure 9a : Recording an aberration corrected concave holographic mask.



ION-ETCHING OF THE HOLOGRAPHIC MASK

RESULT OF ION ETCHING (SAW TOOTH PROFILE)

Figure 9

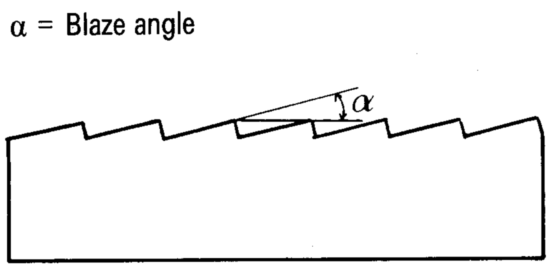


Figure 10 : Triangular groove profile of a blazed, ion-etched holographic grating

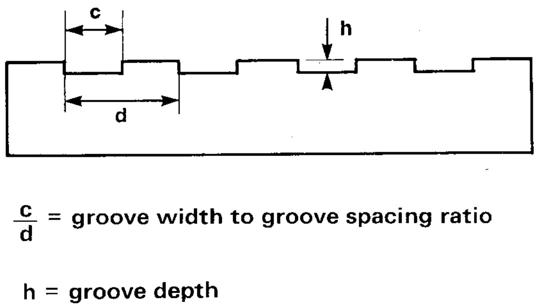


Figure 11 : Laminar groove profile obtained by ion-etching

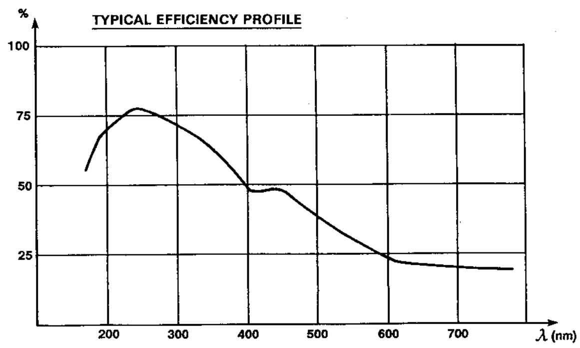


Figure 12 : Blazed, ion-etched, holographic grating
Blaze wavelength : 250 nm
Grooves density : 1200 gr/mm

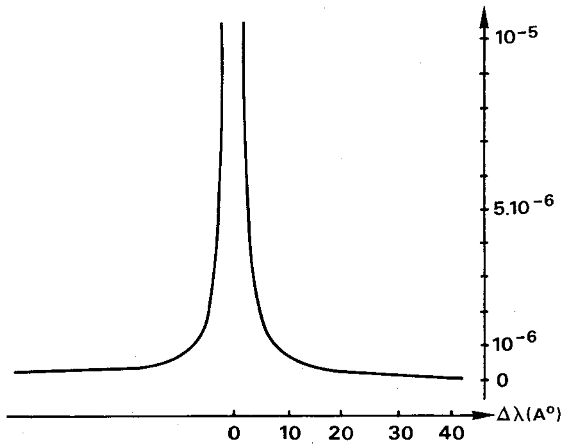


Figure 13 : Stray light rejection

Holographic ion etched gratings have all the advantages of conventional holographic gratings, (no ghosts, low stray light and aberration correction). They also offer additional benefits :

- **Very high efficiency over broad wavelength ranges.**
- **Groove profiles that are blazed at a wavelength of choice.**
- **Continuously variable blazing across a concave grating to enhance overall efficiency.**
- **The opportunity to etch the grooves directly into the substrate with subsequent removal of the photosensitive layer. Etching grooves into materials such as quartz, CVD silicon carbide and some metals produces gratings that can withstand high energy, optical flux, and temperature.**

REPLICATION OF MASTER GRATINGS

Once a master grating has been manufactured according to the techniques previously described, it can be replicated to produce many exact copies of the original. A replica blank of high optical quality is coated with a layer of epoxy and sandwiched together with the master. When the epoxy is cured the master and replica are separated with the epoxy layer staying attached to the replica. The epoxy layer is now an exact copy of the grooves of the master. This replica can now be coated with a reflective layer using vacuum deposition. It is possible to replicate gratings with many different shapes, including spherical and toroidal gratings.

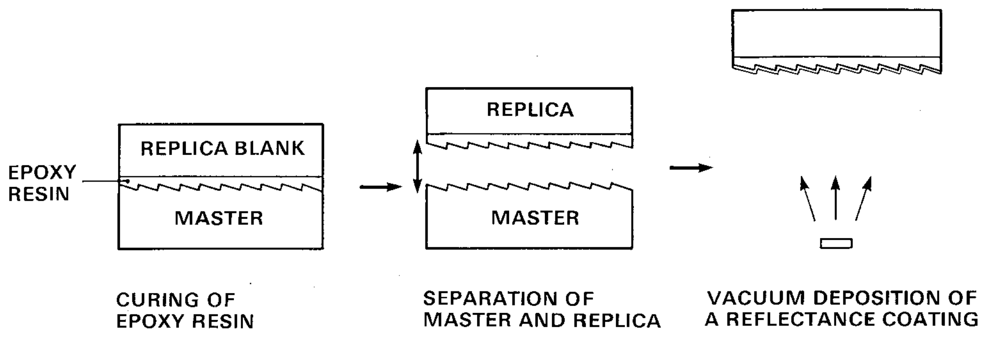


Figure 14

The replication process is highly accurate. Replica gratings retain the diffracted wavefront and efficiency of the master. In addition, the stray light is usually as good or better than the master.
It is possible to produce tens of thousands of identical gratings from a master. The reproducibility of replica gratings makes them ideal for OEM applications. There are no variations in performance or optical geometry. Replication also makes it possible to produce copies of sophisticated and expensive gratings in a very cost effective manner.

Innovations in optical design

PLANE GRATINGS

Instruments S.A./Jobin-Yvon offers a wide range of plane classically ruled, holographic and blazed ion-etched holographic diffraction gratings. Depending on the application plane gratings may be produced holographically to reduce or even eliminate system aberrations such as those found in Czerny-Turner spectrometers. In the VUV plane gratings with variable line spacing plus a toroidal mirror combination permit near astigmatic performance over a wide wavelength range. Holographic gratings may be up to 450 mm in diameter and up to 6000 gr/mm.

PLANE ABERRATION CORRECTING GRATINGS

All Czerny-Turner monochromators exhibit residual aberrations consistent with the use of spherical mirrors. The most serious is astigmatism although spherical aberration and coma may be significant depending on the instrument operating geometry and the wavelength of interest. The net result of any or all of these aberrations is a net loss in photon density and throughput. An application demanding excellent image quality will suffer, often unacceptably, under these constraints limiting the use of area detectors such as a CCD or CID array.

The solution to these problems may be found in a new type of plane grating in which the distribution of grooves on the surface is non linear such that the wavefont exiting the grating will exactly cancel the aberration present in the instrument. The image quality is significantly improved to the point, at some wavelengths, to be near stigmatic and diffraction limited. Please contact your Instruments S.A/Jobin-Yvon representative for more details.

CONCAVE GRATINGS TYPE 1

These gratings are holographically recorded on either spherical or aspherical susbtrates with equidistant and parallel grooves. Their geometric optical properties are the same as for classically ruled gratings and are interchangeable with them. Used on the Rowland Circle they demonstrate high stray light rejection and may be ion-etched to enhance efficiency.

Monochromator gratings

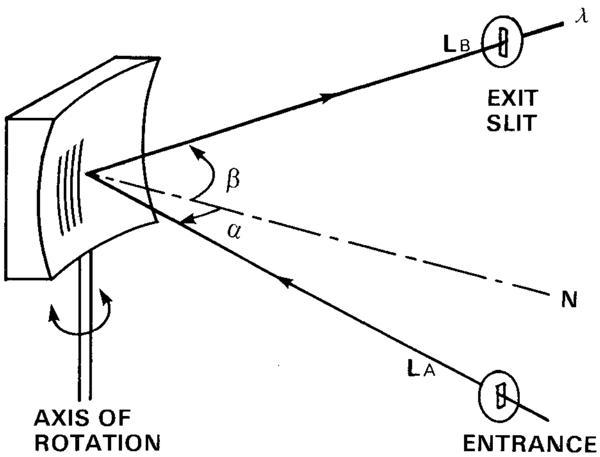


Figure 15

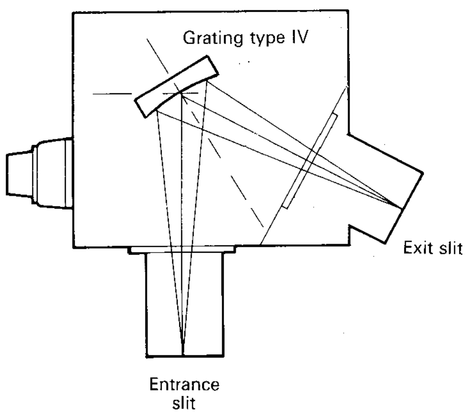
Traditionally called TYPE IV gratings a spectrum may be dispersed and submitted to a single element detector by simple rotation around an axis. The light source is imaged onto an entrance slit and the grating images the entrance slit onto an exit slit at the appropriate wavelength.

The groove spacing of these gratings are computer optimized to produce images at the wavelength of choice with a minimum of astigmatism, and coma. Consequently grooves are not equidistant or parallel nor would such a grating operate on the Rowland Circle.

Using this technique very large optically fast gratings are possible demonstrating superb light gathering power and high resolution.

As with most Instruments S.A./Jobin-Yvon holographic gratings efficiency may be enhanced by ion-etching.

Instruments S.A./Jobin-Yvon offers a wide range of standard gratings that operate from the UV to the near infra-red.



Monochromator model H10-61
Optical aperture : F/3
Focal length : 100 mm

ACH grating : Aberration Corrected Holographic grating

Figure 16 : A single optical element monochromator

HOLOGRAPHIC FLAT FIELD AND IMAGING GRATINGS

Flat field gratings are designed to focus a spectrum onto a plane surface. This property is well suited to take maximum benefit from solid state detectors with either a linear or area array of independent photosensitive elements. These gratings are produced with grooves that are neither equidistant nor parallel and as such may be computer optimized to form near perfect images of the entrance slit on the detector.

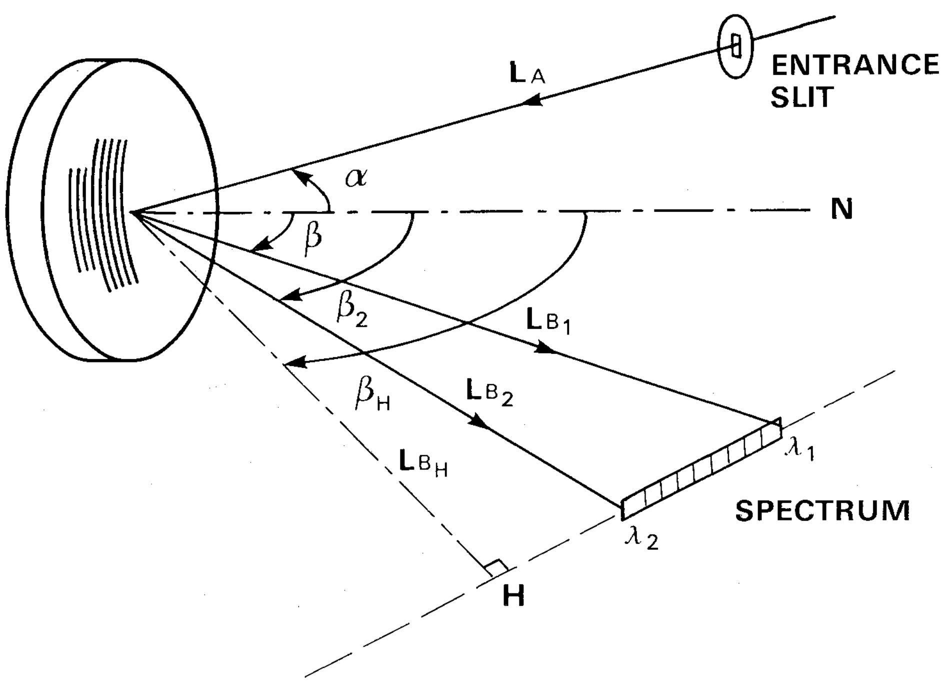


Figure 17

If an area array detector such as a CCD or CID is used then it is often possible to focus multiple sources onto the entrance slit and independently evaluate the spectrum of each against each other or a reference spectrum. A new generation of these gratings have been designed that are virtually free from astigmatism and often operate under conditions where the detector itself limits the resolution.

These gratings are referred to as "super-corrected holographic gratings". These gratings are available with aperture ratios down to f/1.2 depending on size, focal length and wavelength ranges. As with many holographic gratings it is often possible for them to be ion-etched to enhance their efficiency characteristics.

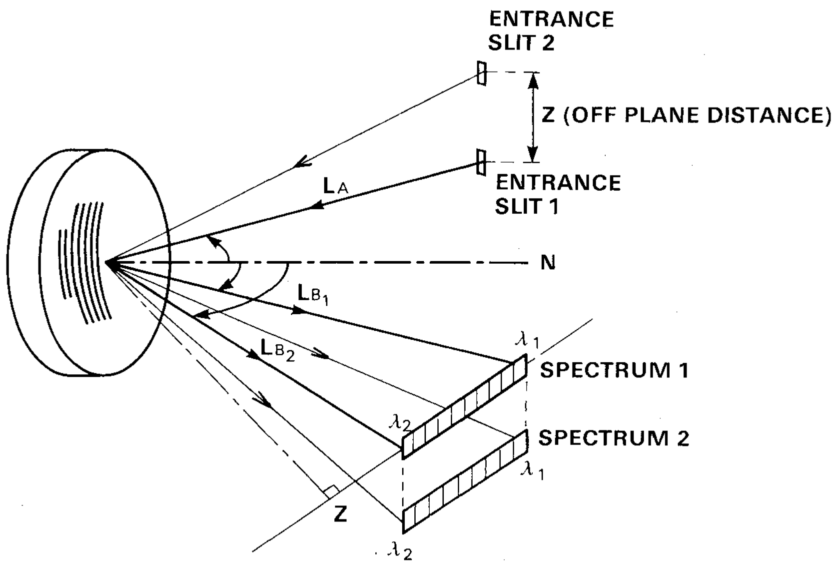


Figure 18

The above illustration shows a "super corrected holographic grating" imaging two independent sources onto two independent linear arrays. Spectrum 1 is a "sample spectrum" from slit 1 and spectrum 2 a reference spectrum from slit 2. These "slits" could well be fibre optic inputs.

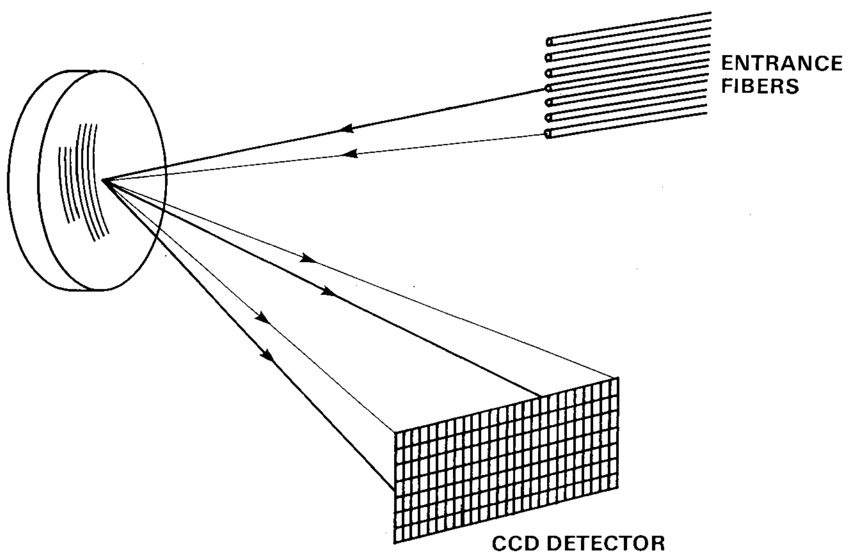


Figure 19

Fibres may be located along the height of the entrance slit or may themselves constitute the entrance slit. A CCD type detector may then independently monitor and display the spectrum from each fibre simultaneously.

All spectrograph and monochromator gratings may be purchased in prealigned mounts as shown in figure 20 and figure 21, or as a complete unit as shown in figure 22.

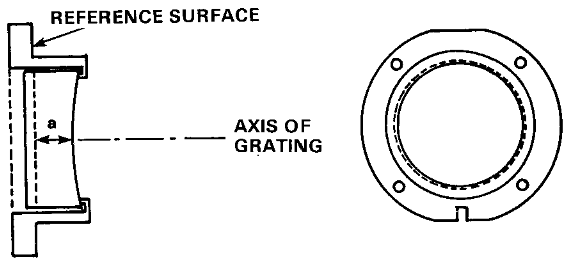


Figure 20 : Prealigned Spectrograph grating mount.

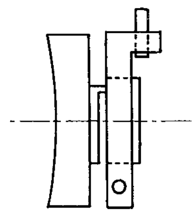


Figure 21 : Prealigned Monochromator grating mount.

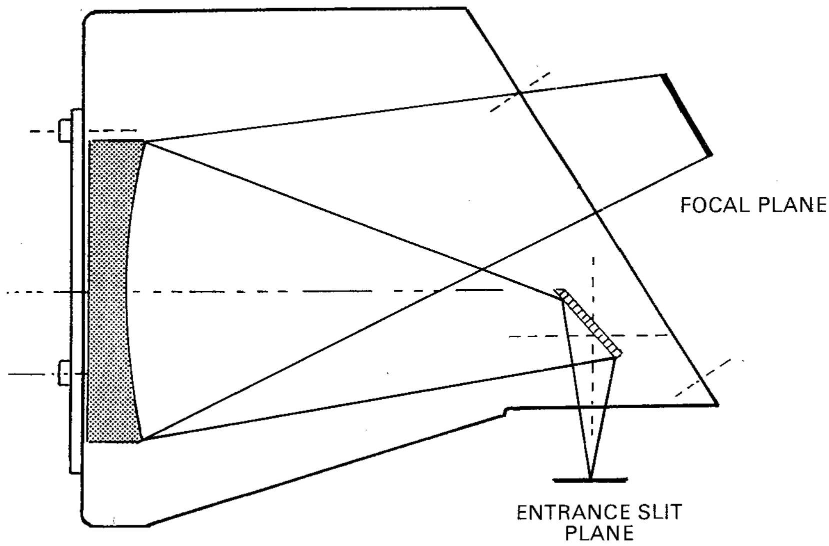


Figure 22 : CP 140 OEM Spectrograph
Focal length : 140 mm
Aperture ratio : f/2

The CP140 spectrograph offers the OEM customer a low cost, F/2, modular instrument with unsurpassed spatial resolution. High efficiency ion etched holographic gratings make this the perfect spectrograph for use with single or multiple fiber imputs, linear arrays and CCD type detectors. New models with shorter focal length (90 mm or even 40 mm) are also available.

Single element holographic gratings are now extensively used in color monitors, blood analyzers, radiometers, plasma monitors, HPLC detectors as well as esoteric applications in earth monitoring satellites and synchrotron radiation facilities.

GRATINGS FOR THE ULTRA HIGH VACUUM UV

Gratings and mirrors used in the far vacuum UV and soft X-RAY must be used in grazing incidence to enhance the reflectivity of the coatings. However, the traditional solution employing a Rowland Circle configuration with spherical gratings results in considerable astigmatism resulting in a loss of flux density and throughput. Excellent image quality is possible with spherical gratings used in conjunction with spherical or cylindrical mirrors : DRAGON type monochromator. Recent designs also permit good image quality with a toroidal mirror used with a non uniformly grooved plane grating.

Toroidal grating monochromators (TGM) spectrographs (TGS)

A non uniform groove distribution on a toroidal substrate can be designed to produce an image substantially free from astigmatism and significantly reduced coma. To change wavelength it is only necessary to rotate this aberration correcting grating around its axis - the spectrum is then either focussed on an array detector or fixed slit. In neither case is it necessary to move the detector to a new position to find the best focus of the wavelength of interest. The focal field may be essentially flattened to accomodate multichannel detectors in a spectrograph configuration.

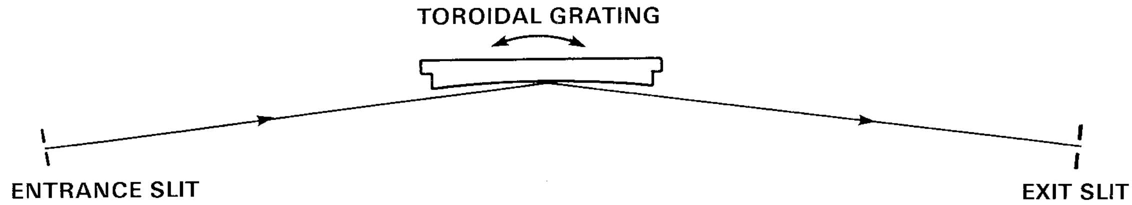


Figure 23 : Toroidal grating monochrmator

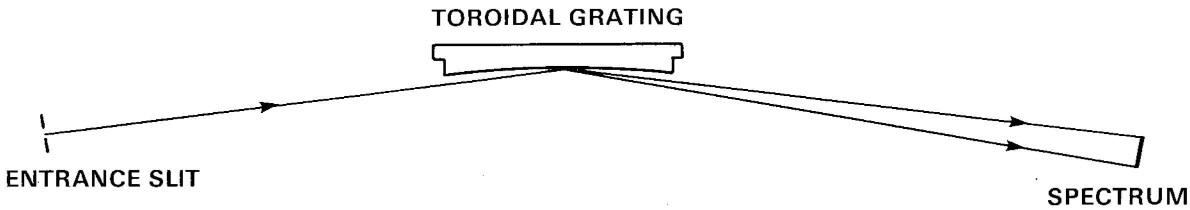


Figure 24 : Toroidal grating spectrograph

Plane grating monochromators (PGM) spectrographs (PGS)

Astigmatism may be nearly totally eliminated if a toroidal mirror is used in conjunction with an aberration correcting PLANE grating. As in the above solution the wavelength is changed by simple rotation of the grating around its axis with a fixed entrance slit and fixed exit. Resolution is high and the "straight through" configuration very convenient when space is restricted.

The systems can work as monochromators or as flat field spectrographs or both (monographs)

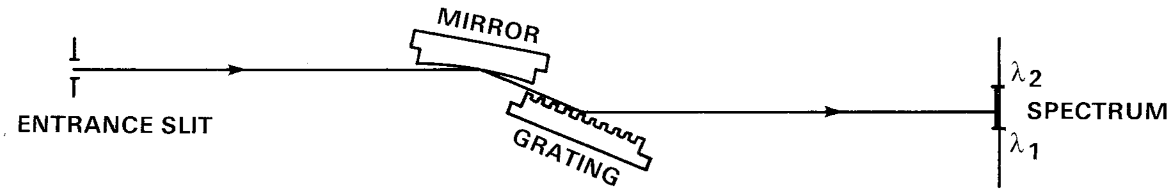
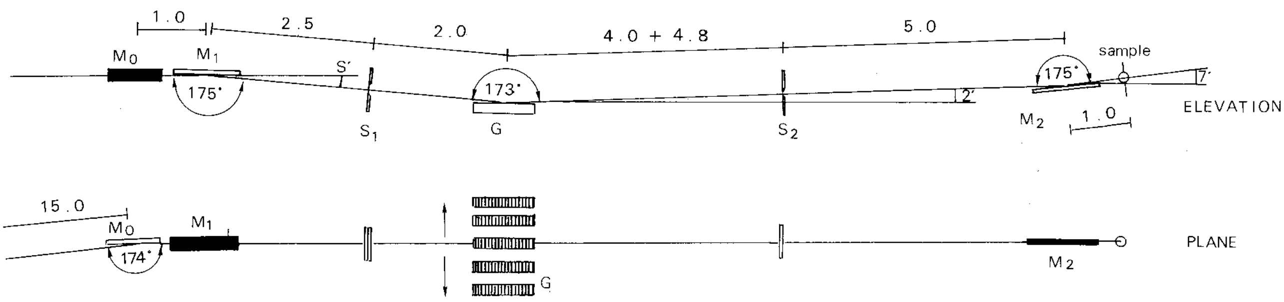


Figure 25

Spherical grating monochromators (SGM) spectrographs (SGS)-(DRAGON)

A spherical grating in conjunction with spherical or cylindrical mirror totally eliminates astigmatism and provides the highest possible resolution. These systems function as either monochromators or spectrographs.



M_o : Horizontal Focusing Spherical Mirror M_o (Focuses horizontally on exit slit S_2)
M_1 : Vertical Focusing Spherical Mirror M_1 (Focuses vertically on entrance slit S_1)
G : Spherical Gratings
M_2 : Toroidal Mirror

Figure 26

All the above holographically recorded gratings may be ion-etched to produce a laminar (square) groove profile. This significantly reduces the intensity of the 2nd order and 3rd order and makes a highly flux and temperature resistant grating. The blank material may be glass, fused silica, or CVD silicon carbide or metal depending on requirements. These blanks may be polished to an RMS roughness of 5 Å and a slope error of less than 0.25 arc second.

Grating blanks and mirrors polishing

Instrument S.A./Jobin-Yvon has developped full capabilities for polishing mirrors and grating blanks with required specifications for high resolution VUV monochromators as DRAGON. Possible shapes are plano, spherical, cylindrical or toroidal. Material can be glass, pyrex, zerodur, fused silica, CVD silicon carbide or metal.
Example of figure accurary measured on spherical grating blanks :

- Dimensions of blank were 170 mm length and 30 mm width
- Blank material : fused silica.
- Figure slope error $\leqslant$ 0.25 arc second RMS.
- Surface microroughness $\leqslant$ 4 Å RMS.
- Similar performances are obtained with bulk CVD silicon carbide.

LASER GRATINGS

There are many categories of laser gratings ranging from those used for pulse compression to those that form part of a laser cavity.

In general they must all withstand high power densities and produce excellent diffracted wavefront characteristics.

Molecular laser gratings

Because of the very high power density typically present in a molecular laser it is necessary to produce and use Master gratings on stainless steel, kanigen coated copper, silicon or Invar blanks. They may be either plane or concave and can incorporate a cooling system.

CO_2 laser gratings

These gratings are optimized for maximum efficiency from 9 to 12 microns and often exhibit efficiencies of up to 97 % absolute at 10.6 microns on E $\perp$ polarization. All CO_2 laser, gratings are tested with an actual CO_2 laser.
Waveguide laser gratings may be economically produced in large quantities.

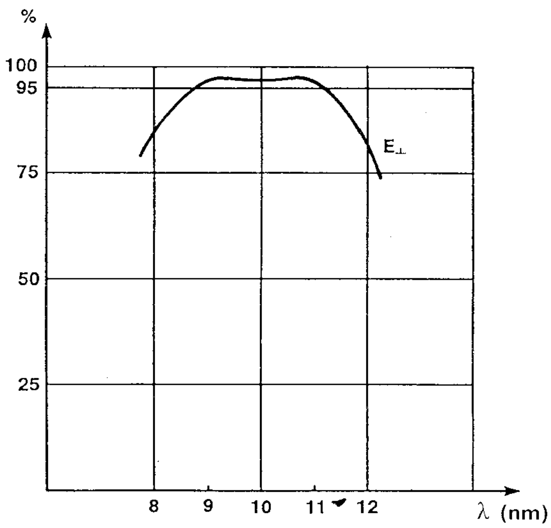


Figure 27 : CO_2 laser gratings (150gr/mm) Typical efficiency profile

Grating type	Laser power continuous	Laser power pulsed	Maximum Temperature
Replica on pyrex Aluminium coated	50 W/cm^2	10 MW/cm^2 on 20-30 ns	100°C
Replica on pyrex Gold coated	50 W/cm^2	10 MW/cm^2 on 20-30 ns	100°C
Master stainless Steel, alum. coated	1000 W/cm^2	60 MW/cm^2 on 20-30 ns	600°C
Master stainless Steel, gold coated	1200 W/cm^2	70 MW/cm^2 on 20-30 ns	1000°C

Figure 28 : Table of damage thresholds

Dye laser gratings

These gratings are designed for use in either Littrow (L series) or grazing incidence (G series) and are typically holographic.
Efficiency is highest when the incident energy is polarised perpendicular to the grooves as may be seen in figures 30 and 31.

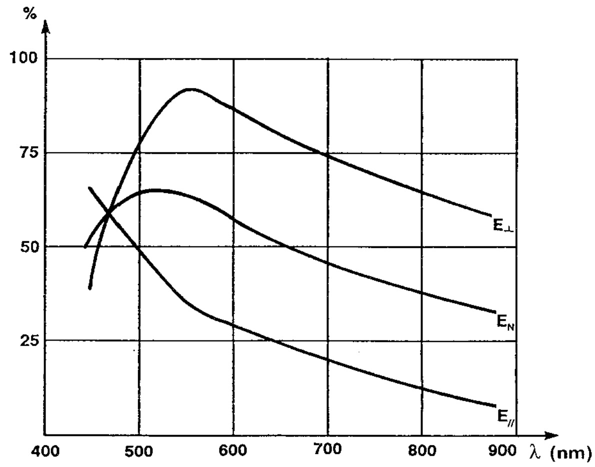


Figure 29 : Typical Efficiency Profile

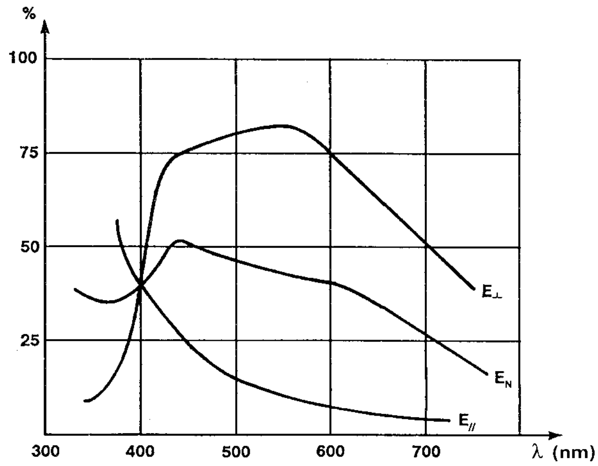


Figure 30 : Typical Efficiency Profile

Typical efficiency curves for 1800 gr/mm and 2400 gr/mm gratings.

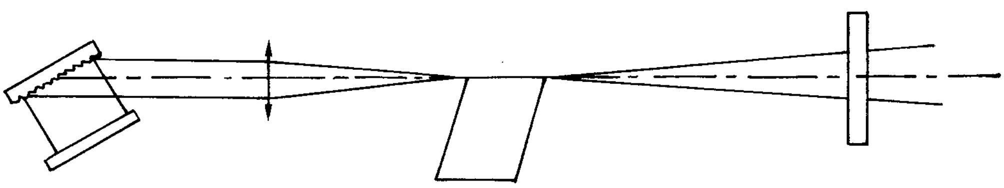


Figure 31

The depth of the groove is optimized to produce highest efficiency when operated in grazing incidence. In this case the angle of incidence is large.

Gratings for use in pulse compression

When used to either compress or stretch a chirped laser pulse it is necessary to employ two gratings as a pair. In this application maximum energy densities is desired. So damage resistance and good focussing properties are of the essence. To achieve the best result, it is necessary to demonstrate the highest possible efficiency, the minimum of energy absorption plus high wavelength dispersion and extremely good diffracted wavefront quality.

After detailed calculation is has been determined that the optimum groove density is 1740 gr/mm when used at 1.06 micron (or 1.053 micron) and 2000 gr/mm when used in the range 750-850 nm.

Typical performances of our gratings for laser chirped pulse compressor or strecher :

- Master holographic grating - Gold coated.
- Diffracted wavefront quality : better than F/8.
- Efficiency on E ⊥ polarization :
  a) with 1740 gr/mm gratings, efficiency ⩾ 95 % at 1.06 micron (or 1.053 micron).
  b) with 2000 gr/mm gratings, efficiency ⩾ 95 % at 800 nm and efficiency ⩾ 90 % in the range 750 nm to 850 nm.
- Littrow angle : 65 degrees for highest dispersion.
- Grating size : up to 200 × 360 mm

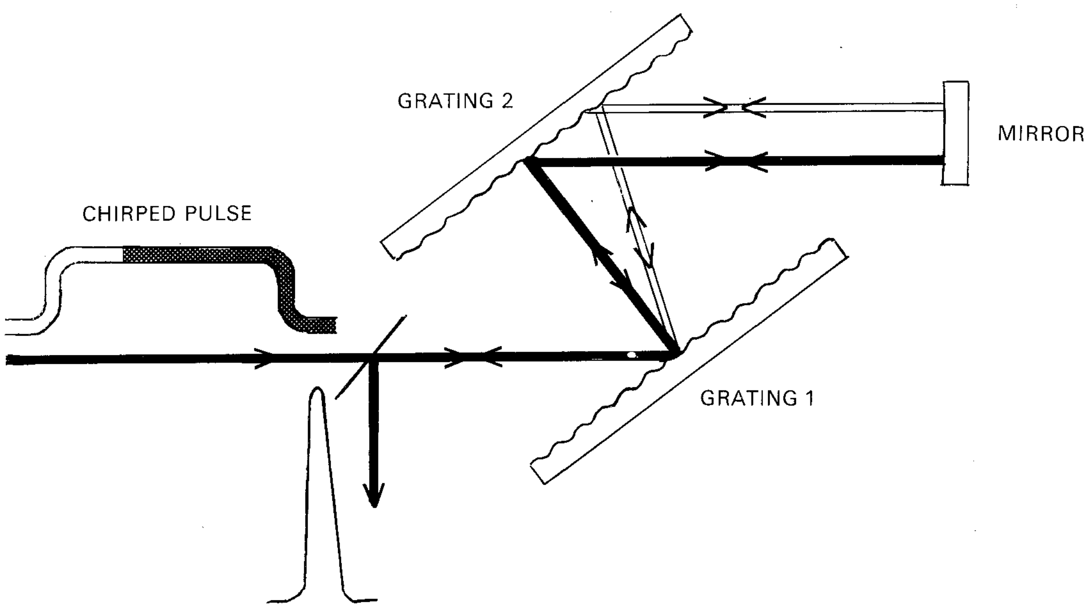


Figure 32 : Laser chirped pulse compressor.

CUSTOM MADE ABERRATION CORRECTED CONCAVE GRATING REQUEST FORM FOR CALCULATION

NAME ....

ORGANIZATION/COMPANY ....

LABORATORY/DEPARTEMENT ....

ADRESS ....

TELEPHONE .... TELEFAX .... TELEX ....

1) SPECTRAL RANGE: ....

2) CONFIGURATION OF USE
- MONOCHROMATOR ☐
- FLAT FIELD ☐
- MONOGRAPH ☐

3) NUMERICAL APERTURE: F/(or SIZE OF GRATING) ....

4) MAXIMUM OVERALL DIMENSION (MAX FOCAL LENGTH):

5) DESIRED DISPERSION (nm/mm): ....

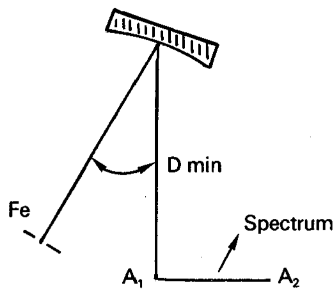
6) DESIRED RESOLUTION (nm): ....

7) ENTRANCE SLIT WIDTH: ....

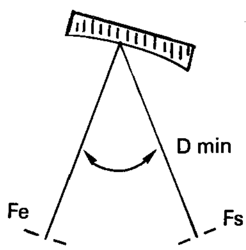
HEIGHT: ....

8) MINIMUM DEVIATION: ....

In general deviation has to be minimum to improve correction of astigmatism, so indicate possible minimum deviation when overall dimensions of source, sample chamber and detector are taken into consideration.



FLAT FIELD



MONOCHROMATOR

9) AT EXIT

IF MONOCHROMATOR, EXIT SLIT WIDTH: ....

HEIGHT: ....

IF FLAT FIELD, LENGTH OF DETECTOR: ....

HEIGHT OF PIXEL: ....

WIDTH OF PIXEL: ....

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