192
1/2/80

DR. 460

LA-8117-MS

Informal Report

**Ultra-Soft X-Ray "Light Pipes"
for Space-, Time-, and Energy-Resolved Imaging
of High-Density Plasmas**

MASTER

University of California

LOS ALAMOS SCIENTIFIC LABORATORY

Post Office Box 1663 Los Alamos, New Mexico 87545

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

LA-8117-MS
Informal Report
UC-20f
Issued: November 1979

Ultra-Soft X-Ray "Light Pipes" for Space-, Time-, and Energy-Resolved Imaging of High-Density Plasmas

C. A. Ekdahl

DISCLAIMER

This document contains information developed by an agency of the United States Government. It is hereby stated that the United States Government and its employees make no warranty, express or implied, of the accuracy, reliability, or legal liability of the information contained herein, or of the use of the information for purposes not intended by the agency. The information is provided for informational purposes only and is not to be used for any other purpose. Reference herein to any specific product, process, or service, by trade name, trademark, or otherwise, does not constitute a recommendation, endorsement, or approval by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

ULTRA-SOFT X-RAY "LIGHT PIPES" FOR SPACE-, TIME-,
AND ENERGY-RESOLVED IMAGING OF HIGH-DENSITY PLASMAS

by

C. A. Ekdahl

ABSTRACT

By use of the Ultra-Soft X-ray (USXR) analog of "light-pipes" it is possible to obtain space- and time-resolved measurements of plasma radiation in the high-energy region of the emission spectrum. Using fast analog-to-digital converters, computerized data acquisition and processing, and the techniques of computer-aided tomography, it is possible to reconstruct from these data the time evolution of a spatially distributed x-ray source. A conceptual design of an apparatus using USXR pipes for obtaining spatially resolved data from the ZT-40 toroidal pinch is described.

The pipes also have the property of acting as a dispersing element, and a means of using this feature to obtain information about the spectral properties of the plasma source is described.

I. Introduction

Time-resolved plasma luminosity measurements are a useful diagnostic technique for high- β plasmas, such as pinch discharges. Spatially-resolved measurements of emitted plasma radiation in the visible portion of the spectrum have classically been made using streak camera photography.^{1,2} More recently, the problem of quantification of the spatial resolution has been solved by using fiber-optic arrays and individual detectors to obtain data simultaneously using parallel recording channels.^{3,4,5} With the advent of fast

analog-to-digital converters ("transient recorders") and on-line computerized data acquisition and analysis, this diagnostic has become a powerful technique for inference of plasma properties. For example, it is entirely feasible to perform on-line Abel inversion of the spatially-resolved data, and thus obtain a time history of the plasma-emission density spatial profile for a single discharge.^{6,7}

The most intense radiation from high-temperature plasmas occurs in the x-ray region of the spectrum,⁸ and a similar evolutionary process has accompanied the development of soft x-ray diagnostics used on high-temperature tokamaks. These measurements were originally made with a detector viewing the plasma through a resolving pinhole aperture, and the spatial resolution was obtained by reorienting the line of sight between discharges.⁹ The more recent use of multiple detector arrays viewing the plasma through a pinhole, along with computerized data acquisition and analysis has resulted in an important means of "looking" at these tokamak discharges. Inversion techniques have been developed from the methods of computer assisted tomography,¹⁰ and have been applied to the reconstruction of plasma emission profiles. As an example, use of this technique has been responsible for the identification of internal disruptions and the reconstruction of surfaces of emissivity.¹¹

The x-ray emission spectrum also contains additional information on other plasma properties such as the electron temperature, T_e .^{12,13} Using filter techniques in the x-ray energy region, it is possible to infer the electron temperature of high temperature plasmas which have a low impurity content and hence an emission spectrum that is dominated by free-free bremsstrahlung, rather than free-bound recombination and line radiation.^{12,14} A complication of using single filters in the x-ray regime is that they are transparent to energies above a cutoff determined by the photon absorption cross section and material thickness, and in addition have stop-bands resulting from the absorption edges in the x-ray regime. In many experiments it is possible to use band-pass filters made by using combinations of different absorber materials,¹³ or by combining absorbers with thin detectors, which detect only the lower energies.

An Ultra-Soft X-Ray (USXR)* diagnostic instrument has recently been put into operation on the Los Alamos toroidal Z-pinch, ZT-40. This apparatus is intended to provide a broad survey of the USXR emission properties of the ZT-40 discharges. It is a versatile instrument, incorporating two high-sensitivity detectors that view the plasma through a collimating pinhole to provide spatial resolution. A filter wheel can be adjusted from outside the vacuum system to position a variety of absorption filters in the line-of-sight of one of the detectors thereby providing for coarse energy resolution of the detected radiation.

However, the spatially-resolved "picture" of the ZT-40 discharge must be developed on a shot-to-shot basis by repositioning the line of sight between shots. A further limitation on the spatial resolution is that due to the geometry of the ceramic tubulations incorporated in the ZT-40 ceramic liner, no instrument depending on a straight, vacuum line of sight can view the entire cross section of the plasma volume for the entire history of the discharge. It is the purpose of this note to propose a means of overcoming these limitations by extending into the USXR region of the emission spectrum the fiber-optic array method of obtaining simultaneous space- and time-resolved luminosity data. It will also be shown how the dispersion characteristics of the USXR analog to the optical light-pipe can be used to obtain energy resolution of the detected signals.

II. Ultra-Soft X-Ray "Light Pipes"

It has recently been demonstrated that USXR radiation can efficiently be transported through hollow glass tubing by grazing incidence internal reflections.^{16,17} Because of the dependence of the critical angle for total reflection on energy, these pipes are natural low-pass filters that can be used

*For convenience, the entire portion of the spectrum defined by $10 \text{ eV} < h\nu < 1 \text{ keV}$ is referred to here as Ultra-Soft X-Rays (USXR), although in other papers the lower energy range ($h\nu \lesssim 100 \text{ eV}$) is sometimes called the extreme ultra-violet (XUV).

in conjunction with thin-film absorption filters to perform simple band pass energy discrimination.

Figure 1 illustrates the geometry of a straight pipe for use with an USXR source. Radiation from the source, S, located at an angle, θ , off of the axis of the tube, which has inner radius, a , and length, l , is incident on the inner surface at the angle θ , and transported by multiple internal reflection to the detector D, which may be a scintillator-photomultiplier combination, x-ray diode (XRD), silicon barrier-diode, PIN diode, or other suitable detector for the energy range and radiation intensity of interest. A thin filter, F, can be placed at the output of the pipe to provide a low-energy cutoff of the detected radiation.

For incident radiation in the energy range of interest, the critical grazing angle of reflection from a solid is determined by the free-electron cutoff frequency at the surface, and is given by¹⁸

$$\sin \theta_c = \lambda / \lambda_p = 3 \times 10^{-15} \lambda \sqrt{n} \quad , \quad (1)$$

where $\lambda_p = 2\pi c / \omega_p$ is the cutoff wavelength. Here $\omega_p = (4\pi n e^2 / m)^{1/2}$ is the plasma frequency for a free-electron density $n(\text{cm}^{-3})$ at the surface. In Eq. (1), λ is expressed in Å units. In the simple theory reflection is total for all grazing angles less than the critical angle, but for grazing angles greater than θ_c the reflectance is very low. As an illustration of the energy dependence of the critical grazing angle and the low-pass filter property of the pipe, glass has a free electron density $n \sim 8 \times 10^{23} \text{cm}^{-3}$, and for small angles Eq. (1) gives $\lambda(\text{Å}) \sim 6.5 \theta_c^0$. Thus, x-rays with energy, $h\nu$, greater than 1 keV ($\lambda = hc/h\nu = 12.4 \text{ Å}$) will be highly attenuated as they are transmitted down the pipe if the incident angle is greater than about 2° .

Actually, the transition from total to no reflectance is a smoothly varying function of incident angle in the vicinity of θ_c .^{19,20} For glass in the energy range (100-500 eV) investigated by Lukirskii,²⁰ the reflectance can be closely approximated by

$$R \sim 1 - \frac{4}{5} \frac{\theta}{\theta_c} \quad , \quad (2)$$

where the critical angle is inferred from measurements to be $\theta_c \sim 2.1 \lambda(\text{\AA})$ in milliradians or $\theta_c^0 \sim 0.12 \lambda(\text{\AA})$.

Following Mosher¹⁷, one notes that for a single ray incident at the angle θ the intensity at the exit of the pipe, I_{out} , is related to the intensity at the entrance, I_{in} , by a transmission efficiency

$$\eta_1 \equiv \frac{I_{out}}{I_{in}} = R^N \quad , \quad (3)$$

where N is the number of specular reflections occurring in the length of the pipe. From the geometry of Fig. 1 the number of reflections is

$$N = \frac{l \tan \theta}{2a} \sim \frac{l\theta}{2a} \quad . \quad (4)$$

The single-ray transmission efficiency, η_1 , given by Eq. (3) and Eq. (4) is shown as solid curves in Figs. 2-6 for aspect ratios ($l/2a$) from 50 to 800, and energies, $h\nu$, from 12 eV to 800 eV. Also graphed in these figures as dotted curves is a useful approximation to Eq. (3) that was pointed out by Mosher,¹⁷

$$\eta_1 \sim \exp[- (\theta/\hat{\theta})^2] \quad . \quad (5)$$

It is evident that for high aspect ratio pipes, this is a very close approximation.

Our analysis of Lukirskii's critical angle data gives a value for the e-folding angle, $\hat{\theta}$;

$$\hat{\theta}^2 = \frac{2a}{l} \frac{32.6}{h\nu} \quad , \quad (6)$$

where the energy, $h\nu$, is expressed in eV. The value of $\hat{\theta}$ from Eq. (6) differs from that obtained by Mosher by less than 2%.

It is clear from the graphs of the single-ray transmission efficiency that these pipes are exceptionally effective for defining a restricted field of view in the USXR energy regime. Using a pipe with aspect ratio of 400 for example, the e-folding angle for 200 eV radiation from Eq. (6) is $\hat{\theta} \sim 20$ mrad. This divergence defines a full width of the observed plasma volume of only ~ 1.6 cm at a 40-cm distance from the entrance to the light pipe. The numerical aperture for this example would be $NA \sim \sin \hat{\theta} \sim \hat{\theta} = 2 \times 10^{-2}$, and the corresponding $f/\text{no} = 1/2NA \sim 50$.

This simple treatment has not considered the finite aperture size of the tube and the resultant spread in angle of the rays accepted from a point source, $\Delta\theta \sim 2a/d$, where d is the distance of the source plane from the aperture (see Fig. 1). For $d \gg a$ the accepted rays can be considered to be parallel and the transmission efficiency is essentially that of a single ray. The angular spread in the accepted radiation is less than the divergence determined by the transmission efficiency when $d \gtrsim 2a/\hat{\theta}$. For the 200 eV example above, the source must be ~ 50 diameters from the pipe entrance to reduce the transmission problem to that of a single ray.

Bending the USXR pipe will further reduce the transmission efficiency. Mosher and Stephanakis¹⁷ estimate this reduction to be at least as great as

$$\eta_b \sim \exp(-\phi/2.5\theta_c) \quad , \quad (7)$$

where ϕ is the bend angle, which is made with a radius of curvature, R , such that the bend aspect ratio, $R\phi/2a \gg 1$. The total transmission efficiency for a bent pipe is then expected to be less than $\eta = \eta_b \eta_1$.

A reduction in transmission efficiency is also expected for inside surface imperfections.²¹ A quarter-wave distortion in the reflected wave-front is caused by a surface imperfection with amplitude $\delta = \lambda/(8\sin\theta) \sim \lambda/8\theta$. A simple

estimate is that the critical angle is the maximum angle of incidence for which this effect is important, because waves with higher incidence angles are strongly attenuated in any case. This gives $\delta \sim 60 \text{ \AA}$ at the grazing angle independent of wavelength. Surface imperfections of this size are impossible to avoid, and, therefore, can be expected to reduce the transmission efficiency. Nevertheless, experiments have shown efficiencies nearly that predicted without regard to surface roughness.^{16,17}

III. Application of USXR-Pipes to Space- and Time-Resolved Emission Measurements

Figure 7 shows a conceptual design for space- and time-resolved emission measurements in the ZT-40 toroidal, reversed-field pinch. The USXR pipe array consists of 11 pipes, each with its own detector. Each pipe is constructed from 1-mm inside diameter by 2-mm outside diameter quartz tubing, and has an aspect ratio ~ 300 . To "see" the ceramic wall in the plane of the plasma requires a bend in the outermost pipes of about 25° resulting in a loss of efficiency of about 74% at 200 eV, as predicted by Eq. (7). From Eq. (6), the acceptance angle is $\sim 23 \text{ mrad}$, which defines a mean halfwidth of the plasma volume viewed of $r \sim 0.5 \text{ cm}$.

The radiation collected through this clear aperture from a pencil of uniformly emitting plasma is approximately

$$P \sim \frac{\pi a^2}{4 \pi D_1 D_2} P_v \pi r^2 (D_1 - D_2) \quad (8)$$

where r is the mean radius of the pencil of plasma viewed, D_1 is the distance from the pipe to the farthest point in the plasma, and D_2 is the distance to the nearest plasma point. For the ZT-40 geometry the radiation collected by the vertical pipe, which views the greatest depth of plasma, is $P \sim 1.7 \times 10^{-5} P_v$ where P_v is the power emitted per unit volume. This value is roughly 1/16th of the calculated power that should be collected by the present

ZT-40 USXR-survey instrument. Consequently, an observed signal output from the present instrument that is 16 times greater than the minimum useful signal level should indicate the feasibility of the proposed system, which has the advantage of single-discharge space- and time-resolution.

An additional technological advantage gained by using these pipes is that they provide an easy means of maintaining a high vacuum at the x-ray detectors using differential pumping. The mode of operation of ZT-40 and many other plasma experiments is to fill the discharge with a static fill pressure of 1-100 mTorr of gas. It is difficult to provide for a high vacuum at the x-ray detectors by differentially pumping across a space-resolving pinhole because of the high conductance of the pinhole, and this limits the types of detectors one may use. For example, the most attractive detector available for this diagnostic is a windowless metallic-photocathode x-ray diode (XRD) coupled to a high-gain, multiple-dynode electron multiplier that can provide an essentially noise-free gain of the order of 10^5 or more. This detector has many advantages, not the least of which is the ready availability of the energy response of the cathode as a result of much recent calibration work to characterize the energy response of XRD photocathodes.^{22,23} It cannot, however, be used with the present survey instrument without using a high-strength, and therefore highly attenuating, vacuum window in order that a high vacuum ($p \leq 10^{-5}$ Torr) can be maintained at the cathode and multiplier structures. Use of USXR pipes can obviate the necessity for a vacuum window.

For the pressure range 1-100 mTorr the mean free path, λ_{mfp} , for H_2 gas is $1 \text{ mm} \leq \lambda_{\text{mfp}} \leq 10 \text{ cm}$, and the flow in the 1-mm ID tube is generally in the molecular flow range which is defined by $2a < \lambda_{\text{mfp}}$. The tube conductance in this range is given by $C \sim 3.2 (2a)^2 (2a/\ell) \sim 10^{-4} \ell/\text{s}$. The conductance of the parallel combination of tubes is thus $C \sim 10^{-3} \ell/\text{s}$ for the 30-cm long tubes proposed. The corresponding leak rate from the discharge chamber at 100 mTorr pressure is 10^{-4} Torr ℓ/s . This is also the gas load to be differentially pumped to an ultimate pressure $\leq 10^{-5}$ Torr in the detector chamber. The required pumping speed to maintain this ultimate pressure is only $\sim 100 \ell/\text{s}$, which can easily be provided.

IV. Application of USXR-Pipes to Energy-Resolved Measurements

Assuming specular reflections in an USXR pipe, it follows that the radiation emitted from the exit end of the pipe has the same angular distribution as is plotted in Figs. 2-6. This suggests a conceptually simple method of obtaining simultaneous energy analysis along with space and time resolution. It is noted in advance that to practically accomplish this one probably has to give up some of the spatial resolution.

The radiation intensity angular distribution at the USXR pipe exit is proportional to $\eta_1(\theta, h\nu)$ for a discrete radiated energy, and to an integral transformation of η and the emitted power spectrum otherwise. That is, in general the radiation pattern at the output of the USXR pipe is given by

$$I(\theta) = \int \frac{dI_0}{d(h\nu)} \eta(\theta, h\nu) d(h\nu) \quad (9)$$

where $dI_0/d(h\nu)$ is the spectral distribution of the radiation collected by the pipe. Thus, the pipe acts as a dispersing element for USXR radiation, and the radiant energy distribution may in principle be resolved by the use of suitable spatially-resolved detectors.

As an example of this technique, it will be applied to the problem of determining the electron temperature from the ideal free-free (bremsstrahlung) continuum emission spectrum using a detector array of a particular geometry.

In Fig. 8 the single detector of Fig. 1 has been replaced by a "bull's-eye target" array of detectors with annular sensitive regions that are coaxial with one another and with the USXR pipe. This array could be made by stacking silicon barrier-diode disks with different radii, each backed with a dense metal USXR stop, and with the smallest diode located closest to the pipe. The smallest diode and stop would effectively block USXR radiation from the central portion of the next larger diode, etc. Instead of diode detectors, one could similarly stack an array of scintillator disks of different radii backed with heavy metal USXR obstructions. Each disk could then be connected to a photomultiplier by light guides. Or alternatively, it may be possible to

fabricate annular coaxial scintillators that are optically isolated from each other, and are connected to individual photomultipliers by means of light guides.

Although it is not essential to this technique, fabricating the detector array so that each annular sensitive area is the same simplifies the analysis somewhat. This condition is satisfied if each of the nested annular detectors has an outer radius which is related to the radius of the smallest disk, r_1 , by

$$R_n = \sqrt{n} r_1, \quad (10)$$

where R_n is the outer radius of the n th detector. Each detection then has area $A = \pi r_1^2$. The outer edge of the n th detector is located at an angle θ_n given by

$$\theta_n \sim \tan \theta_n = \sqrt{n} r_1 / D, \quad (11)$$

where D is the distance of the detector array from the exit of the USXR pipe. In Eq. (12), the electron density, n_e , is in cm^{-3} and the electron thermal energy, kT_e , is in eV. For a $Z=1$ plasma, the bremsstrahlung emission spectrum is,

$$\frac{dI_0}{d(h\nu)} = 1.66 \times 10^{-32} \int n_e^2 \frac{1}{\sqrt{kT_e}} \exp[-h\nu/kT_e] d^3x \quad (\text{W/eV}) \quad (12)$$

where the volume integral extends over the plasma volume viewed by the USXR pipe. Assuming n_e and kT_e to be constant over this volume, V , and using the approximate form for η (Eq. (5)) in Eq. (9) yields:

$$I(\theta) = \frac{1.66 \times 10^{-32} n_e^2 V}{\sqrt{kT_e}} \int_0^\infty \exp(-h\nu/kT_e) \times \exp\left(-\frac{\ell}{2a} \frac{\theta^2}{32.6} h\nu\right)$$

$$= \frac{1.66 \times 10^{-32} n_e^2 V}{\sqrt{kT_e}} \left(\frac{1}{kT_e} + \frac{\ell}{2a} \frac{\theta^2}{32.6} \right) \quad (13)$$

Integration of this angular intensity distribution over the equal-area concentric annular detector array produces the expression for the power incident on the nth detector,

$$P_n \sim \frac{1.66 \times 10^{-32} n_e^2 V \pi r_1^2}{\sqrt{kT_e}} \left[\frac{1}{kT_e} + \frac{r_1^2}{4D^2} \frac{\ell}{2a} \frac{(2n-1)}{32.6} \right] \quad (W). \quad (14)$$

From Eq. (14) it is evident that a linear regression of the data from several annular detectors of equal area will give the temperature from the intercepts, if the geometrical parameters are known. For a sensitive determination of kT_e independent of the density and volume, one would like the geometry to be such that the second term in Eq. (14) is at least of the same order as the first,

$$kT_e \sim \frac{2a}{\ell} \frac{4D^2}{r_1^2} 32.6 \quad \text{eV} \quad . \quad (15)$$

For increasing electron temperatures this favors higher resolution detectors and lower aspect ratio pipes. For example, the 200-eV plasma expected in ZT-40 and the 300/1 aspect ratio pipes proposed for the space- and time-resolved measurement would require $D \sim 20 r_1$ to meet this requirement. The same pipe used with a 1-keV plasma, however, would require $D \sim 50 r_1$ for the same energy resolution.

As for any dispersing or energy-resolving instrument, calibration using a variable monochromatic radiation source of known intensity would be essential for the interpretation of the data obtained using this technique. The recent

availability of synchrotron radiation sources such as SURF-II,²⁴ which cover an energy range from 40 eV to 310 eV, makes such a calibration feasible.

V. Conclusions

A method of extending the light-pipe space- and time-resolved visible luminosity measurement technique into the ultra-soft x-ray region of the emission spectrum has been suggested. The means of accomplishing this is based on the use of grazing-incidence internal-reflection USXR pipes. These pipes have been shown to have the property of providing the necessary restriction of the field of view for the geometry and energy range of interest, i.e., for use on the ZT-40 toroidal z-pinch. In addition, it has been shown that it is possible to make use of the energy dispersion characteristics of those pipes to obtain energy resolution of the transmitted radiation.

Acknowledgments

The author is indebted to R. J. Comisso, P. Foreman, K. B. Freese, F. C. Jahoda, and R. E. Siemon for useful advice and stimulating discussions.

Fig. 1.

Ultra-Soft X-Ray pipe geometry. The USXR pipe, with radius, a , and length, l , collects radiation from the source, S , and transmits it to the filtered, F , detector, D , by means of multiple internal reflections.

Fig. 2.
Single ray transmission efficiency for a pipe with aspect ratio $l/2a = 50$ for several photon energies $12 \text{ eV} < h\nu < 800 \text{ eV}$.

Fig. 3.
Single ray transmission efficiency for a pipe with aspect ratio $l/2a = 100$
for several photon energies $12 \text{ eV} < h\nu < 800 \text{ eV}$.

Fig. 4.
Single ray transmission efficiency for a pipe with aspect ratio $l/2a = 200$ for several photon energies $12 \text{ eV} < h\nu < 800 \text{ eV}$.

Fig. 5,
Single ray transmission efficiency for a pipe with aspect ratio $l/2a = 400$ for
several photon energies $12 \text{ eV} < h\nu < 800 \text{ eV}$,

Fig. 6.
Single ray transmission efficiency for a pipe with aspect ratio $l/2a = 800$ for several photon energies $12 \text{ eV} < h\nu < 800 \text{ eV}$.

Fig. 7.
 Conceptual design for space- and time-resolved USXR emission detector system for use on the ZT-40 toroidal pinch,

Fig. 8.
Possible geometry for construction of segmented detector with annular sensitive areas for use in energy analysis of radiation emerging from USXR pipe,

References

1. E. A. McLean, Appl. Opt. 6, 2120 (1967).
2. A. D. Beach et al., Nucl. Fusion 9, 215 (1969).
3. A. Eberhagen and M. Keilhacker, in Proceedings of the Sixth International Conference on Ionization Phenomena in Gases, T. Hubert and E. Crémien, Eds. (Bureau des Editions, Centre d'Etudes Nucléaires des Saclay, Paris, 1964), Vol. II, p. 537, 577.
4. D. J. Dancy and M. Keilhacker, Culham Laboratory Publication CLM-M 55 (1965).
5. G. A. Sawyer, V. A. Finlayson, F. C. Jahoda, and K. S. Thomas, Phys. Fluids 10, 1564 (1967).
6. R. C. Amsden, K. B. Freese, and F. C. Jahoda, Bull. Am. Phys. Soc. 20, 1344 (1975).
7. K. B. Freese, W. R. Ellis, and G. I. Chandler, in Proceedings of the First Topical Conference of High Temperature Plasma, Knoxville, TN, 1976, Paper A-9.
8. R. F. Post, Rev. Mod. Phys. 28, 338 (1956).
9. S. von Goeler, W. Stodiek, and N. Sauthoff, Phys. Rev. Lett. 33, 1201, (1974).

10. N. R. Sauthoff and S. von Goeler, IEEE Trans. on Plasma Science PS-7, 141 (1979) and references therein.
11. N. R. Sauthoff, S. von Goeler, and W. Stodiek, Nucl. Fusion 18, 1445 (1978).
12. K. Boyer, E. M. Little, W. E. Quinn, G. A. Sawyer, and T. F. Stratton, Phys. Rev. Lett. 2, 279 (1959).
13. H. R. Griem, A. C. Kolb, and W. R. Faust, Phys. Rev. Lett. 2, 281 (1959).
14. F. C. Jahoda, E. M. Little, W. E. Quinn, G. A. Sawyer, and T. F. Stratton, Phys. Rev. 119, 843 (1960).
15. D. C. Johnson, Rev. Sci. Instr. 45, 191 (1974).
16. P. J. Mallozzi, H. M. Epstein, R. G. Jung, D. C. Applebaum, B. F. Fairand, W. J. Gallagher, R. L. Uecker, and M. C. Muckerheide, J. Appl. Phys. 45, 1891 (1974).
17. D. Mosher and S. J. Stephanakis, Appl. Phys. Lett. 29, 105 (1976).
18. A. H. Compton and S. K. Allison, "X-rays in Theory and Experiment," (Van Nostrand, Princeton, NJ, 1935).
19. R. W. Hendrick, J. Opt. Soc. Am. 47, 165 (1957).
20. A. P. Lukirskii, E. P. Savinov, O. A. Ershov, and Yu. F. Shepelev, Opt. Spectros. 16, 168 (1964).
21. J. S. Pearlman and R. F. Benjamin, Appl. Opt. 16, 94 (1977).
22. R. B. Cairns and J. A. R. Samson, J. Opt. Soc. 56, 1568 (1966).
23. E. B. Saloman and D. L. Ederer, Appl. Opt. 14, 1029 (1975).
24. D. L. Ederer, E. B. Saloman, S. C. Ebner, and R. P. Madden, J. Res. Natl. Bur. Std. 79A, 761 (1975).