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TITLE: 1. NONDISPERSIVE X-RAY DIAGNOSTICS OF SHORT LIVED PLASMAS

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AUTHOR(S): Robert H. Day

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Los Alamos Los Alamos National Laboratory
Los Alamos, New Mexico 87545

1. NONDISPERSIVE X-RAY DIAGNOSTICS OF SHORT LIVED PLASMAS

Robert H. Day

Los Alamos National Laboratory

Physics Department

Post Office Box 1663

P-14 MS 0410

Los Alamos, New Mexico 87545

1. NONDISPERSIVE X-RAY DIAGNOSTICS OF SHORT LIVED PLASMAS

1.1 Introduction

In this NATO Advanced Study Institute, we have discussed in detail the diagnosis of many pulse power machine properties, including their electrical behavior, grounding and shielding, and related data acquisition techniques. The purpose for many of these machines is to create high temperature/high density plasmas and, therefore, the subsequent behavior of these plasmas is of critical concern. The energy density of these plasmas is such that they will naturally radiate in the x-ray regime and thus the diagnosis of their x-ray emission is a crucial measurement of the entire system performance. In this lecture, I will describe the general techniques used to perform nondispersive x-ray diagnostics of these short lived plasmas.

First, let's put the issue of x-ray diagnostics into a general framework which will guide our discussions. As in any diagnostic application, there are three basic types of information that can be acquired: 1) the energy distribution of the plasma emission, 2) the temporal history of the x-ray emission, and 3) the spatial distribution of the emission. The precision with which each of these parameters must be measured, varies greatly depending upon the application. For example, the plasmas of interest at this institute have time scales from a hundred picoseconds for laser produced plasmas to microseconds for relativistic electron beam sources. Similarly, the spatial scale can be microns for laser plasmas to centimeters for relativistic electron beam sources. The requisite energy resolution can also vary from a few parts in a thousand to totally energy integrated.

The topic of high resolution x-ray spectroscopy is an important separate issue and a whole chapter is devoted to its discussion. In particular, the sections by Hans Griem and Giovanni Tondello will describe the types of information which can be deduced from the details of the energy dependent emission. My comments here will, therefore, be restricted to broad band spectroscopy with or without time and spatial resolution.

The three coordinates of time, energy, and space, which I have described, are shown schematically as the two, 2x2 matrices of Fig. 1. These matrices represent all classes of information which can be returned depending upon whether one integrates over the parameter of interest or resolves information in that parameter. In the upper left hand corner of each matrix element, I've tried to indicate some of the major physics issues which are illuminated by the measurement indicated; while in the lower right hand corner of each entry, I've tried to indicate some of the diagnostic techniques which will return this type of information.

As we move from the upper left to the lower right in this figure, we progress from information integrated over all three coordinates to information resolved over all three coordinates. In general, it is not possible nor necessary to return complete information about all three coordinates so the majority of diagnostics will integrate over one or more of them. In this section, we will be primarily concerned with the diagnostics and physics issues which are illuminated by the spatial and time coordinates. We will, however, also cover the low resolution spectroscopy applications in the lower half of this matrix. In particular, we will cover time resolved low resolution

spectroscopy in some detail and discuss the application of layered synthetic microstructures, LSM's, to x-ray diagnostics measurements. In section 1.8, I will also outline the techniques which are available to characterize the instrumentation described below.

1.2 Bolometry

Bolometry is the simplest type of x-ray diagnostic and can only return information about the total amount of x-ray emission integrated over time, energy and space. This data yields information on the energy balance and conversion efficiency of the plasma in turning pulse power into x-rays. Though this is not a very descriptive indication of detailed plasma performance, it is frequently one of the most important numbers that can be returned on the overall performance of a plasma experiment. The two devices which are used to measure this parameter are the flat energy response calorimeter and simple bolometers.

Recently, James Degnan^[1] has developed a system to perform pulse bolometry to measure the total soft x-ray conversion efficiency of an imploding liner experiment at the SHIVA capacitor bank at the Air Force Weapons Laboratory, AFWL. The advantage of such a system is its simplicity for measuring total radiated power with an integration time of approximately 1 microsecond.

A schematic of this device is shown in Fig. 2a. The measurement is based upon the principle that as a material is heated, its resistivity change is only dependent upon its temperature. The resistivity change is measured as the change in voltage drop across the foil experienced by a constant current passing through the foil. A magnetic field is frequently applied parallel to the surface of the foil to suppress the emission of photoelectrons created by the incident x-rays.

The voltage drop, ΔV_B , across the foil is given by the expression:

$$\Delta V_B = \frac{\Delta \rho}{\Delta E} \frac{1}{\rho x^2} \frac{\ell}{w}$$

where $\frac{\Delta \rho}{\Delta E} = 13.2 \times 10^{-9} \Omega\text{-cm per Joule-gram}$. The foil length = ℓ , x = the foil thickness, w = the foil width, and ρ = the foil density. Aluminum foil was chosen for this application because of its availability, well known specific resistivity and ease of use.

A cross sectional view of this device is shown in Fig. 2b. The foil is mounted on a modified High Voltage Engineering 2 inch diameter vacuum flange with an HN vacuum feedthru connector. The bolometer is suspended between the center conductor and ground of an HN connector. A magnetic field is supplied by external magnets. The device is built as part of a 50 ohm coaxial transmission line and the coaxial cable connected to the HN connector leads to a current source and oscilloscope recording station.

This device is used as a routine diagnostic to measure total x-ray yield under a wide variety of implosion conditions. The validity of this measurement of total x-ray yield has been tested by comparing the bolometer x-ray yield with the x-ray yield measured by integrating over the spectrum with a filtered detector spectrometer. The filtered detector spectrometer will be described below in Section 1.4 in greater detail. The results of this comparison are shown in Fig. 3 where the ratio of yields measured by the two techniques is plotted versus the equivalent black body temperature of the plasma. The temperatures in this plot vary by a factor of five which means that the x-ray output will vary by more than a factor of 600, and yet the agreement between the two techniques is within 15% across this entire range. This implies that the pulse bolometer is a very reliable and simple diagnostic for total x-ray conversion efficiency measurements.

1.3 Flat Response XRD's

The foil bolometer which is described in Section 1.2 integrates the x-ray emission over time for most of the high temperature plasma sources of interest today. In order to answer more detailed questions about the time evolution of the plasma x-ray emission, it is necessary to utilize more sophisticated x-ray diagnostics. As we move from the upper left cell of Fig. 1 to the upper right cell of Fig. 1 we are asking to return information on the time evolution of the space and time integrated x-ray emission of the plasma. This type of data answers questions related to the time dependent energy partition within the plasma. A diagnostic that returns this type of information for short lived pulsed plasmas, is the flat response x-ray diode, XRD.

We will find x-ray diodes used in a variety of applications and it is appropriate to describe this important class of detector before proceeding. In their most basic form, these detectors are very simple as shown schematically in Fig. 4. The x-rays from a plasma source are made to impinge on a metallic photocathode after passing through a transmission filter between the x-ray source and the detector. An x-ray transparent anode, usually consisting of a partially transparent metallic mesh is placed a short distance from the photocathode so that the photocathode is biased negative with respect to the anode photoelectrons are accelerated emission away from the cathode. The return current flowing into the photocathode to replace the electrons emitted from the surface are then a measure of the incident x-ray flux. Detailed descriptions of the time and energy response of these systems are given elsewhere.[2,3,4]

The inherent energy sensitivity of such a system is determined by the energy dependence of the surface photoemission and has been shown semiempirically[5] to fall as the energy of the photon, E , multiplied by the photoelectric absorption coefficient $U(E)$. This intrinsic response is then modified by the transmission of the filter placed between the plasma source and the photocathode as shown in Fig. 5. It was noted by Harry Kornblum and William Slivinsky[6] that by appropriately filtering different fractions of a gold photocathode it was possible to create a response function which was flat to $\pm 20\%$ when expressed in units of coulombs per kilovolt over the energy range from 100 eV to 1 keV as shown in Fig. 6. This type of device is then a flat response calorimeter but it is also possible to construct it with very high time response.[4] Bandwidths have been achieved with these devices in excess of five gigahertz for a half inch diameter diode.

The slow roll off of the high energy response of this system can cause significant error if the spectrum being measured doesn't also fall fast enough. In several versions built by Slivinsky[6], this high energy response was further suppressed by including a critical angle x-ray mirror between the detector and the plasma source. For the device shown in Fig. 5 the angle of incidence and material of the mirror was chosen to give a cutoff energy of 1.5 keV. This was achieved with a highly polished beryllium mirror at 1 degree with respect to the incident x-ray beam. The reflectivity of this mirror is in excess of 80% from 109 eV to 1.5 keV and then rapidly falls to near zero reflectivity.

The flat response XRD has been used on a wide variety of laser plasmas in the Lawrence Livermore National Laboratory, LLNL, laser fusion program. The inferred flux from this time resolved calorimeter has also been compared like the foil bolometer of Section 1.2 with the output of a filtered detector spectrometer. As with the bolometer, agreement to better than 20% has been achieved between the two detectors over more than a decade variation in total x-ray output.

1.4 Filtered Detector Spectroscopy

In the last section, I described how it was possible to compensate for the inherent energy selectivity of the XRD detector by appropriate choice of filters to achieve a constant energy sensitivity. It is also possible to accentuate this energy selectivity of the basic XRD detector to build a system which has low spectral resolution. This type of detector yields low resolution spectral information with high temporal resolution and begins to return information on the time evolution of the plasma spectral emission.

Spectral selectivity is achieved by interposing appropriate filters between the plasma and the photocathode. These filters are selectively transparent to x-rays in different regions of the spectrum and therefore the current measured from that XRD is a measure of the x-ray fluence in that region of the spectrum. The various response functions shown in Fig. 7 for an aluminum photocathode filtered by several different materials are typical of the kind of systems that can be built and resolving powers of one to a few are achievable by careful selection of filters and cathodes.

A spectral measurement is made by simultaneously measuring the detector current from a variety of such channels whose response has been optimized in various regions of the spectrum. We have built a seven channel system of this type at the Los Alamos National Laboratory, LANL, to measure the x-ray emission from laser fusion targets and similar systems have been used to measure the x-ray emission from a variety of pulsed plasma power machines.

To infer a time dependent spectrum from this data it is necessary to carefully common time the emission from all channels and then iteratively deconvolve the spectral response of each channel to derive the true spectral nature of the emission. This deconvolution process must be handled with great care and a variety of techniques have been developed to process this type of data.[7]

An example of the time evolution of the x-rays emitted from a simple 300 micron diameter gold coated nickel microballoon illuminated by 2.3 kilojoules of 10.6 micron laser light in a 1 nanosecond pulse is shown in Fig. 8. For the first nanosecond while the laser is on, the temperature of the emission increases

quickly to several hundred electron volts. After the energy source is turned off, we see a long decay of the emission from the radiative cooling of the heated target.

The use of XRD's in this type of system is not essential and similar measurements have been made with PIN solid state detectors[8], and photodiode/fluor combinations[9] as the x-ray to current transducers; but XRD's have several advantages including simplicity, high speed, and moderate to low sensitivity. Their use, however, depends upon measurements of their absolute efficiency.

The quantum efficiency of an XRD is defined as the number of electrons emitted from the photocathode for each incident photon. This parameter has been measured for a variety of materials[4,5] commonly used in detector systems and typical results are shown in Fig. 9. The surface of the XRD acts as a solid state ionization chamber and primary and secondary electrons which are created within an escape depth of the surface of the photocathode contribute to the signal. This implies that x-ray photoemission is a surface effect and the efficiency of the detector can be modified by small changes in the surface constituents.

The stability of the response of a typical aluminum XRD photocathode was investigated in the laser fusion environment. It was found that by standardizing photocathode preparation and controlling the handling of the surfaces these systems could be used reliably. The constraints on using this type of detector as an absolute instrument are:

- a) Prepare the photocathode surface by a standard procedure such as micromachining the photosurface with a clean tool and no machining lubricant.

- b) Careful preliminary x-ray calibration.
- c) Frequent refurbishment of the photocathode surface. (This may mean replacement on every shot on many pulse power machines.)
- d) Post calibrations to verify surface stability.

With these precautions it is possible to achieve calibration uncertainties of less than 15% in routine use.

The filtered detector system can also be used to return spatially resolved information by restricting the field of view of the instrument to only those source regions of interest. For example, on the multichannel instrument described earlier a series of seven lines-of-sight, LOS's, were established by a series of precisely aligned pinholes to only view a region of 400 micron diameter on the surface of the target. With such a system it is possible to measure the specific emissivity of the source in units of watts per square centimeter and perform detailed comparison of measured x-ray spectra to models of the emission process.

With a collimated filtered detector instrument, it is possible to return low resolution data on all three parameters of energy, space, and time yielding: the time dependent x-ray spectral emission from a small region on the source.

1.5 Filter/Fluorescer Spectroscopy

For many applications, such as spectral deconvolution, it is desirable to have simpler response functions and higher spectral resolution than that available from the filtered detector system described in Section 1.4. For measurements of x-ray emission

above 1 KeV, filter/fluorescer spectroscopy is an attractive alternative to significantly increase the measurement resolution.

This type of system is shown schematically in Fig. 10. The x-ray emission from the source is limited by an LOS similar to the type described in Section 1.4 for the filtered detector system. The detector package on each LOS consists of a filter in the primary x-ray beam to crudely define the x-ray spectrum and a fluorescer to provide a threshold energy for x-ray detection. The fluorescent photons are then detected through a post filter by a detector which is provided to transduce the x-rays into electrical current. The advantage of this system is improved spectral resolution while the disadvantage is a reduced sensitivity of at least several orders of magnitude.

The way in which each element shapes the response of a channel is shown in Fig. 11. A 1 keV black body spectrum is shown for reference as the initial x-ray source in the LOS. The effect of the prefilter is to suppress the spectrum at energies above the absorption edge of the filter. These are usually K-edge filters. The effect of the fluorescer is then to establish a threshold energy for the detection of x-rays corresponding to the K-edge of the fluorescer material. The post filter is used to suppress low energy scattered radiation and is usually a K_β filter for the fluorescent photons. The detector is chosen to optimize the system response to the fluorescent photons as much as possible. XRD's with photocathodes made of elements with Z just below the fluorescent energy are a frequent choice because of their sharply peaked energy response.

Proper optimization of prefilter, fluorescer, postfilter, and detector can result in a channel with nearly flat energy response between the K-edges of the fluorescer and the prefilter.

The resolving power of this type of system can be as high as ten and is a significant improvement over the filtered/detector system.

1.6 Spatial Resolution

All of the systems described above have, at best, poor spatial resolution, and yet information on the spatial distribution of x-ray emission is an important measurement of energy distribution and evolution within the plasma source. The collimated LOS geometries can, at best, give an indication of the energy density at a single location within the source. A number of systems have been devised to return data on the spatial distribution of x-ray emission and I will describe two such instruments, the pinhole x-ray camera and the imaging spectrograph.

By far, the simplest x-ray imaging instrument is the pinhole camera; and this device has been applied in many plasma diagnostics. In its simplest form, the pinhole camera uses x-ray sensitive film for a detector and provides little information on the time evolution of the plasma, though extremely good spatial resolution approaching ten microns can be achieved with precision pinholes in laser fusion applications.

The sensitivity of a time integrated pinhole camera is, however, strongly biased to the time of peak plasma temperature. This results from the fact that for a typical black body emitter the intensity of x-ray emission varies as the fourth power of the plasma temperature and, therefore, the majority of emission will occur at peak temperature. X-ray pinhole cameras have been used extensively to diagnose both quantitative and qualitative features of plasmas related to the nature of energy deposition and transport.

As the techniques of x-ray optic fabrication improve more sophisticated imaging devices are beginning to find widespread use. Other papers in this volume, such as those by Dr. Price describing Kirkpatrick-Baez, Fresnel zone plate, and Wolter x-ray optics are examples of more advanced systems. These instruments combine moderate to high spatial resolution with high collection efficiency. More general application of these instruments awaits perfection of techniques for generating precision microstructures and ultrasmooth precision surfaces.

Another class of imaging instrument combines good spatial resolution with monochromatic imaging[10]. The system requires that the emission spectrum of the source have characteristic lines and the source is imaged at the energy of these lines. A schematic of one such instrument[11] is shown in Fig. 12.

For this technique to be successful, the source must produce intense characteristic emission which will diffract from the crystal in the instrument geometry shown. The source is placed on a sphere of radius R and the crystal is bent to a spherical curvature of $2 \times R$ and the surface is ground to the spherical radius R . A real image is then created on the spherical surface beyond the crystal for a source which is dominated by line emission. This type of device has high throughput but it is possible to build similar monochromatic imagers with lower throughput using simple flat crystals. A particularly useful application of this technique is to seed the plasma with materials chosen to be imaged by the instrument. By measuring the absolute intensity of the resulting spatial distribution of emission a map of the local plasma conditions can be achieved.

to meet the diagnostic requirement rather than to modify the diagnostic to fit the properties of available crystals.

The technology for building these systems has been available for many years[12]; however, it is only recently that thin film depositions have achieved the requisite perfection and control necessary for LSM manufacture. The techniques of sputter deposition and e-beam evaporation have both been used to manufacture metal multilayers of sufficient perfection to achieve high efficiency x-ray diffraction. Dr. Eberhardt Spiller of the IBM Watson Research Laboratory[13] uses an e-beam evaporation system with insitu monitoring of the x-ray diffraction efficiency to optimize the deposition process. Dr. Troy Barbee of Stanford University[14] uses the precise control available from sputter sources to lay down the layers of the LSM.

The present state-of-the-art in LSM construction allows the manufacture of systems with 2d spacings as short as 30 Å. The 2d of the layers has been modified by as much as 10% from the top to the bottom of the stack and a 50% length variation of 2d has been achieved along the multilayer. LSM's have also been deposited on curved x-ray optics with radii of curvature in excess of 1 m. Numerous materials have also been used in their construction including high Z layers of tungsten, tungsten carbide, silicon carbide, titanium, molybdenum, niobium, palladium, rhenium, and others. Low Z layers have been constrained to carbon and boron, but beryllium layers may be possible.

The diffraction properties of LSM's can be modeled using classical electromagnetic diffraction theory where material 1 is characterized by a thickness d_1 and a complex index of refraction $n_1 = 1 - \delta_1 - \beta_1$ and δ and β are the standard unit decrements. Material 2 is characterized by an index of multilayer refraction

$n_2 = 1 - \delta_2 - i\beta_2$. Underwood and Barbee[15] have summarized classical diffraction theory to predict metal multilayer's performance. If x-rays are incident on the material/vacuum interface of the metal multilayer at a Bragg angle of θ with s and p polarization components of the electric field of E^s and E^p respectively, then the x-ray reflection from the boundard between layer ℓ and $\ell + 1$ is predicted by the Fresnel equations:

$$F^s = (g_\ell - g_{\ell+1}) / (g_\ell + g_{\ell+1})$$

$$F^p = (g_\ell/n_1^2 - g_{\ell+1}/n_1^2 + 1) / (g_\ell/n_1^2 + g_{\ell+1}/n_1^2 + 1)$$

$$\text{where } g_\ell = (n_1^2 \dots \cos^2\theta)^{\frac{1}{2}}$$

with the Fresnel coefficients we can define a parameter $R_{\ell,\ell+1}$ which described the reflection including absorption in the substrate for an x-ray of wavelength λ :

$$R_{\ell,\ell+1} = a_1^4 \frac{R_{\ell+1,\ell+2} + F_{\ell,\ell+1}}{R_{\ell+1,\ell+2} F_{\ell,\ell+1} + 1}$$

$$\text{where } a_1 = \exp(-i\frac{\pi}{\lambda} g_\ell d_1)$$

At each interface within the LSM four waves are present. The wave incident from the surface, the wave scattered towards the surface, the wave incident from below, and the wave propagating towards the rear surface of the LSM. The boundary conditions on the bottom of the LSM are such that no wave is incident from below. Therefore, by starting at the lower surface and solving for the reflectivities recursively one can solve for the intensity, $I(\theta)$, of the wave leaving the surface in terms of the wave incident on the surface, I_0 , and thus derive a reflectivity of the structure:

$$\frac{I(\theta)}{I_0} = (R_{1,2})^2$$

For systems with uniform structure along the path of the x-ray, it is possible to sum this recursion relationship explicitly[16] and derive a closed form solution for the reflectivity of the LSM.

Use of these theories, however, presupposes accurate knowledge of the optical constants of the materials. A thorough summary of these parameters has been compiled by Henke[17] in the energy range from 100 eV to 2 keV; however, there is still significant uncertainty in these parameters in the regions of anomalous dispersion near absorption edges. Outside of these regions, acceptable comparison of theory and experiment is achieved. For example, Fig. 14 shows a comparison of measurement and theory for a molybdenum/carbon multilayer at a photon energy of 1.487 keV. The agreement between theory and measurement is quite good with the residual difference is probably due to substrate imperfections and surface roughness[14].

These systems are beginning to find widespread application in the plasma diagnostics community. One of the first systems to use these devices was a simple multichannel spectrometer built by Gary Stradling[18] as a front end dispersion element for an x-ray sensitive streak camera. This system was a high time resolution x-ray spectrometer in the LLNL laser fusion program.

The instrument consisted of six discrete channels each with a uniform d-spacing crystal to define the energy range of interest. The crystals had a resolving power of approximately 40 and the d-spacings were engineered to cover the energies of several hydrogen and helium-like resonances lines in the plasma spectrum.

At Los Alamos, we have also been developing LSM technology to build a unique diagnostic instrument which would not be possible with conventional crystal spectrometers. This device is shown schematically in Fig. 15. An LSM is placed in a beam of x-rays with a natural divergence of 1 milliradian or less. The LSM is placed at a 7 degree Bragg angle with respect to the beam and the d-spacing of the crystal is 50% longer on one end of the crystal as on the other. The output beam of the spectrometer is a parallel beam of x-rays with an energy of 1.5 keV on one side and 2.5 keV on the other.

A detector with eight discrete channels intercepts the output beam and measure the time evolution of the spectrum with a resolving power of approximately 10. This design is simple, and compact with high throughput and large signal-to-noise ratio. This level of simplicity in design would not be possible without the unique ability to create variable d-spacing crystals provided by LSM technology.

Obviously, this new class of x-ray diffractors opens up many new possibilities of instrumentation for plasma diagnostics. We've only begun to touch on the possibilities of instrument design. Other new instruments will include focusing x-ray optics with monochromatizing surface coatings, high collection efficiency optics at high energy, and many others we have just begun to imagine.

1.8 X-ray Characterization

In this section, I have described a variety of diagnostic instruments to measure the spatial, spectral, and temporal histories of plasma emission. Acquiring absolute measurements of any of these parameters, will usually require that the instru-

ments have calibrated responses. No single x-ray source is capable of performing all these calibrations and so a number of systems has been developed to optimize its properties for this variety of purposes.

There are five major classes of x-ray generators: the electron impact source, the ion impact source, the electrically driven plasma source, the laser pulsed plasma x-ray source, and the electron storage ring synchrotron source. The major parameters of intensity, spectral character, and time structure for each of these sources is listed in Table 1. In this subsection, I will outline the major properties and use of each of these sources.

1.8.1 Electron impact generators. The electron impact generator is the oldest and simplest type of x-ray generator and it is still in common use today. The technology of the electron impact generator is versatile and can be applied to a variety of applications, including high intensity DC sources and short pulse high brightness x-ray generators.

The x-ray generation scheme is very simple utilizing a source of electrons either from a hot filament or field emission. A potential is established between the cathode and the anode and the electrons are accelerated into the anode. The anode material is chosen to either optimize the continuous bremsstrahlung spectrum or the characteristic line emission. In typical DC applications the anode is water or air cooled to achieve higher power levels. These systems can dissipate tens of kilowatts electrical resulting in hundreds of watts of x-rays.

The output of such sources can be used directly or further monochromatized. Monochromatization can be enhanced by simple

characteristic line filtration or by use of x-ray monochromators. However, this results in a concomitant loss in intensity.

The parameters of this source are listed in the first column of Table 1 and the electron impact generator is obviously not the system of choice to optimize any one parameter. However, the simplicity of construction and use of this type of source frequently makes them the system of choice for characterization applications.

These systems have been used in many different applications. The quantum efficiency curves shown in Fig. 9, for example, were measured with electrical impact generators for the data above 100 eV.

1.8.2 Ion impact x-ray sources. The ion impact x-ray generator works in a way analogous to the electron impact x-ray source when it is used for characteristic line generation. The difference is that the primary vacancy is created by the impact of an ion instead of an electron.

In use the electron source of the electron impact generator is replaced by a light ion accelerator. The ion energy is typically one to a few MeV per atomic mass unit. Power densities approaching several kilowatts per square centimeter are typically achieved and characteristic photon energies in the range from 100 eV to several kilovolts are generated.

The advantage of the ion impact x-ray source is the improved purity which can be achieved in comparison to the electron impact generator. The knock-on electrons created during ion deceleration will have a maximum energy given by the ion energy multiplied by the electron mass divided by the ion mass. Thus,

for an MeV ion the maximum electron energy will be below 1 keV. These electrons create less bremsstrahlung background than the typical electron impact source. The purity of the system is improved from 90% for a typical electron impact generator to better than 98% for a light ion generator.

The ion accelerators which are the heart of the ion impact generator are in use in numerous laboratories for nuclear and atomic physics research. A few dedicated facilities have been commissioned solely for the generation of x-rays. One such facility is the LLNL IONAC source, a picture of which is shown in Fig. 16. It utilizes a beam energy of 300 kV and is used to produce x-rays of energy below 1 keV.

By reviewing the properties of Table 1 it can be seen that when the ion impact source is optimized for power dissipation the resulting x-ray beams have comparable intensity to traditional electron excited sources. The major advantage of the ion impact source is its improved purity.

1.3.3 Electrically driven plasma sources. In order to achieve the highest x-ray intensities, it is necessary to raise a material's temperature until it attains the plasma state. Several such plasma x-ray sources are under development[19,20]; however, none of these have been optimized for x-ray laboratory characterization purpose.

These systems usually consist of a Marx generator to create a high current and high voltage source of pulse power which is then coupled to various plasma loads such as gas Z-pinches or wire arrays. The characteristic emission of this plasma will consist of both thermal emission from the plasma as well as characteristic line emission from the optically thin regions of the plasma.

We can see by comparing the parameters in Table 1 that this electrical pulsed plasma source is one of the most intense x-ray sources and is particularly useful for characterizing systems with time response of a few nanoseconds or longer. To date, this type of machine has been used as a flash radiography source for backlighting[21] and as a lithography source.

1.8.4 Laser pulsed plasma x-ray source. High temperature plasmas can also be achieved with short pulse lasers. When focused to submillimeter dimensions, lasers can create plasmas with electron temperatures of hundreds of volts and 100 ps duration. Such plasmas can generate intense line radiation useful as a characterization source. On the other hand, if lower intensity illumination is used it is possible to create quasicon- tinuum sources of radiation in the VUV and low energy x-ray region using rare earth targets[22].

Again, reviewing the parameters of Table 1 it is seen that laser plasma x-ray sources can provide the shortest duration x-ray pulses of 100 ps or less. They also provide the brightest x-ray sources because of their high energy density and small size. This type of source is the system of choice where high bandwidth temporal response is paramount. Such an application was the bandwidth measurement of the risetime of the high band- width x-ray diodes discussed in Sections 1.3 and 1.4[4].

1.8.5 Synchrotron x-ray sources. A new class of x-ray source based upon the synchrotron emission of electrons in high energy storage rings has become increasingly important in recent years. This radiation source is being applied to many of the x-ray characterization needs typically handled by conventional sources. The properties of synchrotron sources are a unique combination of high brightness, high intensity, continuous energy coverage, tunable polarization, low divergence, and pulsed time structure.

The intensity of synchrotron radiation is shown in Fig. 17. The two curves are for the two electron storage rings at the Brookhaven National Laboratory's, National Synchrotron Light Source, NSLS. One ring has a storage energy of 2.5 GeV and a maximum current capability of 500 mA. This ring produces the highest energy photons and is optimized for generating x-rays between 1 and 25 keV. The second ring has a 1 amp capability and a storage energy of 750 MeV to optimize it for x-rays of energy lower than 2 keV. In their range of optimum intensity, each source is several orders of magnitude brighter than conventional electron impact generator.

Synchrotron radiation has been used as an absolutely calibrated x-ray source in only a limited number of experiments. Some of the first of these included the measurement of surface quantum efficiencies of x-ray diodes at the Synchrotron Ultraviolet Radiation Facility, SURF II, at the National Bureau of Standards[23]. With the advent of numerous synchrotron beam lines, more are being dedicated to absolute measurements. Facilities being built by Los Alamos at the Brookhaven National Laboratory, and by Livermore at the Stanford Synchrotron Radiation Laboratory will also have an absolute radiometric capability to provide additional facilities for absolute calibration.

1: NONDISPERSIVE X-RAY DIAGNOSTICS OF SHORT LIVED PLASMAS

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1. NONDISPERSIVE X-RAY DIAGNOSTICS OF SHORT LIVED PLASMAS

- Fig. 1a and 1b: One can measure spatially, temporally and/or spectrally resolved information about the x-ray emission from a plasma. The type of physics information that is required will determine what measurement and instrument is needed. The physics information is shown in the upper left corner of each box and the types of instruments to perform these measurements are listed in the lower right corner.
- Fig. 2a. Schematic of a thin foil pulse bolometer.
- Fig. 2b. Cross sectional view of a thin foil pulse bolometer as built by James Degnan at the Air Force Weapons Laboratory.
- Fig. 3. A comparison of x-ray yields inferred from a pulse bolometer and a filtered detector spectrometer for a variety of plasma conditions.
- Fig. 4. A schematic of an x-ray diode detector.
- Fig. 5. The intrinsic response of an XRD is modified by the filters placed between the photocathode and the plasma source.
- Fig. 6. The response function of a "Flat Response XRD" before being filtered by a critical angle x-ray mirror.
- Fig. 7. Spectral selectivity can be enhanced with an XRD by appropriate filtering of the plasma emission.
- Fig. 8. X-ray emission from a 326 μm diameter Au coated Ni micro-balloon illuminated by 2.3 kJ of 10.6 μm laser light in a 1 ns pulse.
- Fig. 9. The energy dependent quantum efficiencies of various surfaces which are useful as XRD photocathodes have been measured.
- Fig. 10. Schematic of a generic filtered-fluorescer detector system.
- Fig. 11. This shows the way in which each element of filter/fluorescer channel modifies the incident spectrum.
- Fig. 12. Schematic of an imaging spectrograph.
- Fig. 13. LSM's are the manmade analogs of the natural diffraction crystal. Alternating layers of high and low Z material take the place of the three dimensional array of atoms in the natural crystal.

Fig. 14. A comparison of experimental measurement and theoretical reflectivity of a 30 layer pair Mo/C LSM of 110.6 Å 2d spacing. Al K_α radiation was used for the measurement.

Fig. 15. A unique x-ray spectrometer utilizing LSM diffractors with 2d spacing which varies from one end to the other. This instrument covers the energy range from 1.5 to 2.5 keV.

Fig. 16. Lawrence Livermore National Laboratory has installed a 300 keV proton accelerator to excite characteristic sub-kilovolt x-ray lines. This is their "IONAC" low energy x-ray facility.

Fig. 17. The source intensity of the two synchrotron storage rings at the Brookhaven National Laboratory. These sources are continuous in x-ray emission and several orders of magnitude more intense than conventional sources.

Table 1. Typical source parameters.

fig. 1a

fig. 1b

fig. 2a

Fig 2b

-fig. 3

17 B.4.

Fig. 5

Fig. 6

fig 7

8
fig

Fig. 9

Fig 10

fig. 11

Fig. 12

Fig. 13

Fig. 14

Fig. 15

ION ACCELERATOR-SUBKILOVOLT X-RAY FACILITY

Fig. 16

Fig. 17

TABLE 1

TYPICAL SOURCE PARAMETERS

	Electron Impact Generators	Proton Impact Generator	Plasma Sources		Synchrotron
			Electrical	Laser	
Intensity (Photons) sec	$\sim 10^{12}$ direct $1'' \phi @ 12''$ (10^8 fluoresced)	5×10^{11} $1'' \phi @ 12''$	$< 10^9$ /pulse $1'' \phi 12''$	$< 10^9$ /pulse $1'' \phi @ 12''$	$> 10^{14}$
Photon Energy	K L Lines .1 - 100 keV	K L Lines .1 - 100 keV	Lines .1 - 2 keV	.01 - 300 eV	continuously tunable
Purity	> 90%	> 95%	> 90% monochromatized	> 90% monochromatized	> 98%
Divergence	2π	2π	4π	4π	3×10^{-3}
Time Structure	DC, chopped or pulsed to < 50 ps	DC or RF accelerator	~ 10 ns	50 ps - 50 ns	Pulsed < 300 ps - 2 ns