Development of X-Ray microscopy systems based on laser plasma sources

Martin Richardson, Andrew Vasil'ev, Steven Grantham,
Kai Gabel, & Masataka Kado

Center for Research & Education in Optics & Lasers,
University of Central Florida, Orlando, FL 32826, USA.

ABSTRACT

We report progress in two areas of technology relevant to the development of high-resolution x-ray microscopy techniques based on laser plasma x-ray sources for the analysis of wet and dry biological specimens. The approach we discuss involves the use of ultrashort x-ray emission from a laser plasma source. Precision x-ray optics are used to collimate and filter this light onto the specimen. Imaging and image magnification are accomplished with a combination of x-ray and electron-optical systems. We discuss our progress towards establishing a flexible laser-plasma x-ray source for the development of biological imaging and contact microscopy, and progress we have made towards the development of an electro-optical imaging system having high magnification and spatial resolution.

1. Introduction.

X-ray microscopy in principle will avoid many of the limitations of present-day electron microscopy techniques for analyzing biological material. Principal among these are the small depth of field and the need to significantly treat samples (drying, dying, sectioning, coating etc.,) before analysis. While being limited to the resolution in the 100A range, the ability of x-ray microscopy to probe the internal structure of *in-vitro* assemblies provides biologists and life scientists the opportunity to observe complex features in their natural, even live state. Most x-ray microscope development has so far been made using large synchrotron sources. The latter limits x-ray microscopy to being primarily a limited research tool centered around a complex beam line located at a major synchrotron facility. The use of a laser-plasma x-ray source, however, makes plausible the development of a compact x-ray microscope having a size and cost comparable to a conventional electron microscope. We have previously discussed several approaches towards x-ray microscopy based on laser plasma x-ray sources[1]. In this paper we describe progress we have made at the Laser Plasma Laboratory at CREOL towards constructing a flexible laser-plasma-based facility for the development of x-ray microscopy techniques, and the progress we have made in electron-optical image tube technology that will hasten the development a compact real-time imaging system for x-ray microscopy.

2. A laser-plasma x-ray source for the development of x-ray microscopy.

The primary advantages of a laser plasma x-ray source for x-ray microscopy system from it's compactness and flexibility. The spectral brightness of laser plasma x-ray sources can be comparable to the brightest available synchrotrons[2]. Laser plasma x-ray sources have the advantage of being compact, moveable and tolerable of modest vacuum requirements. Compared to synchrotrons they are much cheaper to install and to operate. The x-ray emission spectrum of laser plasmas is rich in bright broad continuum emission and in narrow atomic emission lines,

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and can easily be varied to suit specific microscopy needs. This selectivity in x-ray wavelength has a potential high dividend for x-ray microscopy in facilitating elemental analysis of features within biological structures by difference imaging with emission at two different wavelengths. Laser plasmas are point sources which can be highly reproducible, a requirement for precision x-ray optical systems having extremely high alignment specifications. Lastly pulsed laser plasmas introduce the time domain element into x-ray microscopy. Whereas exposure times for microscopy with synchrotrons are measured in seconds, laser plasmas can provide x-ray emission in pulses ranging from several nanoseconds duration to less than one picosecond. This introduces the possibility of capturing kinetic, chemical, or morphological changes in biological structures in time frames of interest to understanding complex biological processes. Moreover the influence of radiation damage on image reliability is avoided by using exposure times short enough to prevent the sample responding to the damaging radiations. No other source for x-ray microscopy can offer this capability.

Although many measurements of the x-ray emission from laser plasmas have been made in the spectral regions of interest for biological microscopy[3-6], that is in the so-called 'water window' (2.3-4.4nm), and at other, element specific wavelengths., many of them have been made with laser and target characteristics more germane to other applications of laser plasmas. Moreover these studies have not had reason to consider the effects of plasma and particulate blowoff from the laser plasma, an important additional issue for microscopy, as it is for the use of laser-plasmas x-ray sources for lithography[7,8] where the integrity of expensive x-ray optics in close proximity to the target must be preserved. At CREOL we have initiated a broad program of development of laser plasma x-ray sources for lithography and microscopy. This program includes addressing not only the efficient generation of x-ray emission at specific wavelengths, but also addressing the issues of target debris mitigation and inhibition, and the engineering issues associated with routine high repetition rate operation that are required for many of these applications. For x-ray microscopy of biological material, we have commenced a detailed study of optimum laser plasma conditions for constructing a source of x-rays in the water window and at shorter wavelengths. The laser system that we will use for these studies is shown in Fig.1.

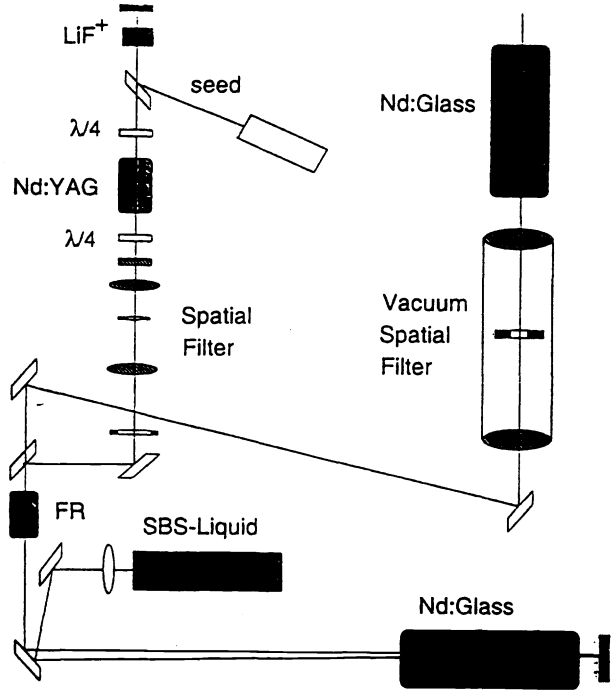

Fig.1. 700 MW solid state laser incorporating nonlinear wavefront correction by stimulated Brillouin scattering (SBS.

The laser incorporates an oscillator followed by several amplifier units in a fully imaged optical beamline. The Nd:YAG oscillator is Q-switched with a solid-state passive saturable absorber (LiF^+) [9], and is frequency injection locked with the output of a diode-pumped cw Nd:YAG laser. Its output consists of a 12 ns duration laser pulse in a diffraction limited beam of peak power 1 MW. The output of this laser is imaged-relayed through an air spatial filter to a four-pass amplifier which utilizes a Faraday rotator (FR) as the final output element. This amplifier stage also incorporates a phase-conjugation mirror which preserves the wavefront quality of the output of the oscillator as it passes through four consecutive passes of the 410 mm long Nd:glass amplifier. The 150 MW output of this amplifier is them relayed through a 1:1 vacuum spatial filter to a single-pass 16 mm diameter 410 mm long amplifier. The output of the laser has a peak power of up to 700 MW with a pulse duration of ~7 ns, the [pulse-shortening being due to the influence of of gain saturation and the nonlinearity of the phase conjugation mirror[10]

Experiments will be carried out in the experimental chamber shown in Fig.2. The laser beam is focused onto targets with a f = 14 cm focal length lens, producing intensities in the range $1 \times 10^{12} - 5 \times 10^{13}$ W/cm^2. Biological samples are exposed to x-rays from the target by encapsulating them in a hydrated cell of the type shown in Fig.2(b), situated 2 cm from the target. an array of x-ray diagnostic instrumentation including x-ray diodes, an x-ray crystal spectrograph, an x-ray pinhole camera and a flat field grating spectrograph is used to characterize the x-ray radiation.

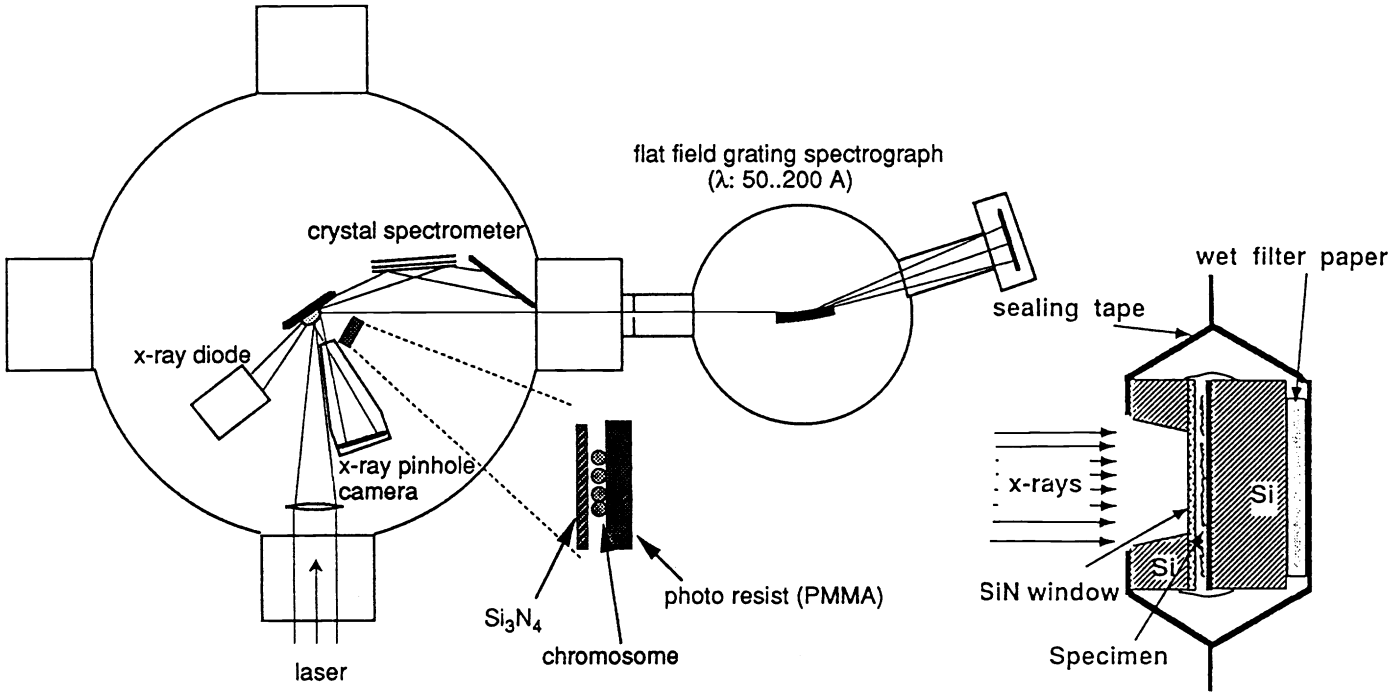

Fig.2. (a) Experimental set up used for initial biological x-ray microscopy experiments at CREOL. (b)Hydrated cell for exposing biological material for contact imaging.

3. A high resolution, high magnification electron-optical x-ray imaging system.

In determining the specifications of x-ray optical components in a laser plasma-based x-ray microscope, we first establish the primary performance requirements of the overall system. We assume that the required resolution must be in the range of current imaging capabilities, ~50nm. This resolution, or better, has been demonstrated with Fresnel zone-plate imaging[11,12], contact imaging[13,14], and, at longer wavelengths, with normal incidence reflective optical imaging[15]. Moreover we assume that the system must be capable of real-time image acquisition.

Current advanced image array detectors have pixel sizes in the 6μm range. Assuming a minimum image contrast ratio of ~10, this implies the need for an overall image magnification of 10^3-10^4 This level of image magnification cannot easily be met with x-ray optics alone. Although most x-ray microscopes today rely primarily on optical elements having modest image magnification and long-time image processing of an image recorded on resist, film, or through image scanning, the optimum microscope will require real-time image acquisition and thus will incorporate a combination of x-ray image magnification and electron-optical image magnification. Such a system is shown schematically in fig. 3. The specimen to be analyzed will be irradiated with monochromatic radiation from the laser plasma source. This could be facilitated by either a normal incidence multilayer mirror collector or a zone-plate condenser. An image of the specimen in the backlit radiation is then created with either a Schwarzschild microscope or Fresnel lens with a magnification (20-50) commensurate with the cathode resolution capability of an electron-optical image magnifier such as an x-ray-sensitive zoomtube[16] or an x-ray photoelectron microscope[17,18]. A zoomtube having an image magnification of 40-200 and a cathode resolution of ~1μm has already been demonstrated[16]. Moreover, a photoelectron microscope having a resolution of 0.1μm and a magnification of 1200 should be developed in the near future[19]. At some loss in resolution, but with considerable gain in sensitivity and simplicity, the latter could be used in a simple contact or 'proximity' imaging mode.

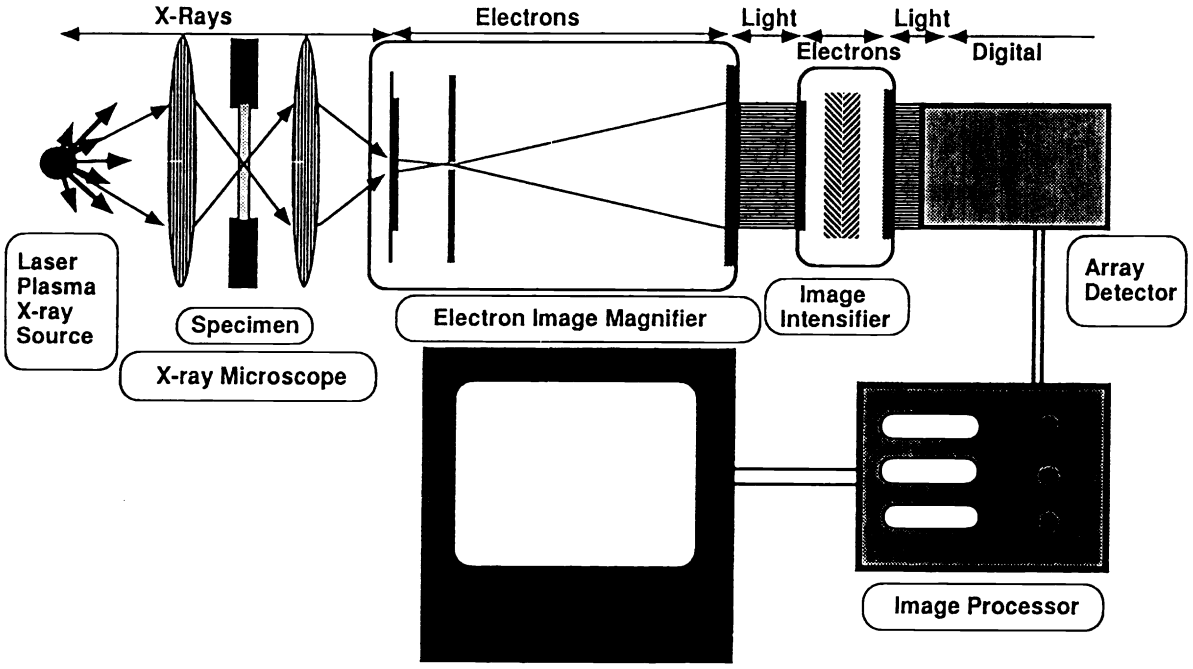

Fig.3 Possible structure of an x-ray - photoelectron-optical microscope.

An electron-optical image magnification tube of the type shown in Fig.3. is currently being built at the National Institute for Standards and Technology (NIST) for use with the SURF II synchrotron light source in a microscope for the observation of masks made for the optical alignments of soft x-ray lithography systems[20]. We are participating in this development by developing the high resolution soft x-ray photocathodes required for this system. These photocathodes must resolve features of 0.1 μm at a wavelength of 13.5 nm. We have therefore assembled at the Laser Plasma Laboratory at CREOL a dedicated x-ray photocathode fabrication

facility for the development of efficient x-ray photocathodes for high resolution electron-optical systems. We have also tested some of these new types of photocathodes on a calibrated beamline of SURF II[21]. Fig.4 shows the photo-emissive yield in electrons/photon in the wavelength range adopted for the NIST Conversion Microscope for a number of photocathode materials.

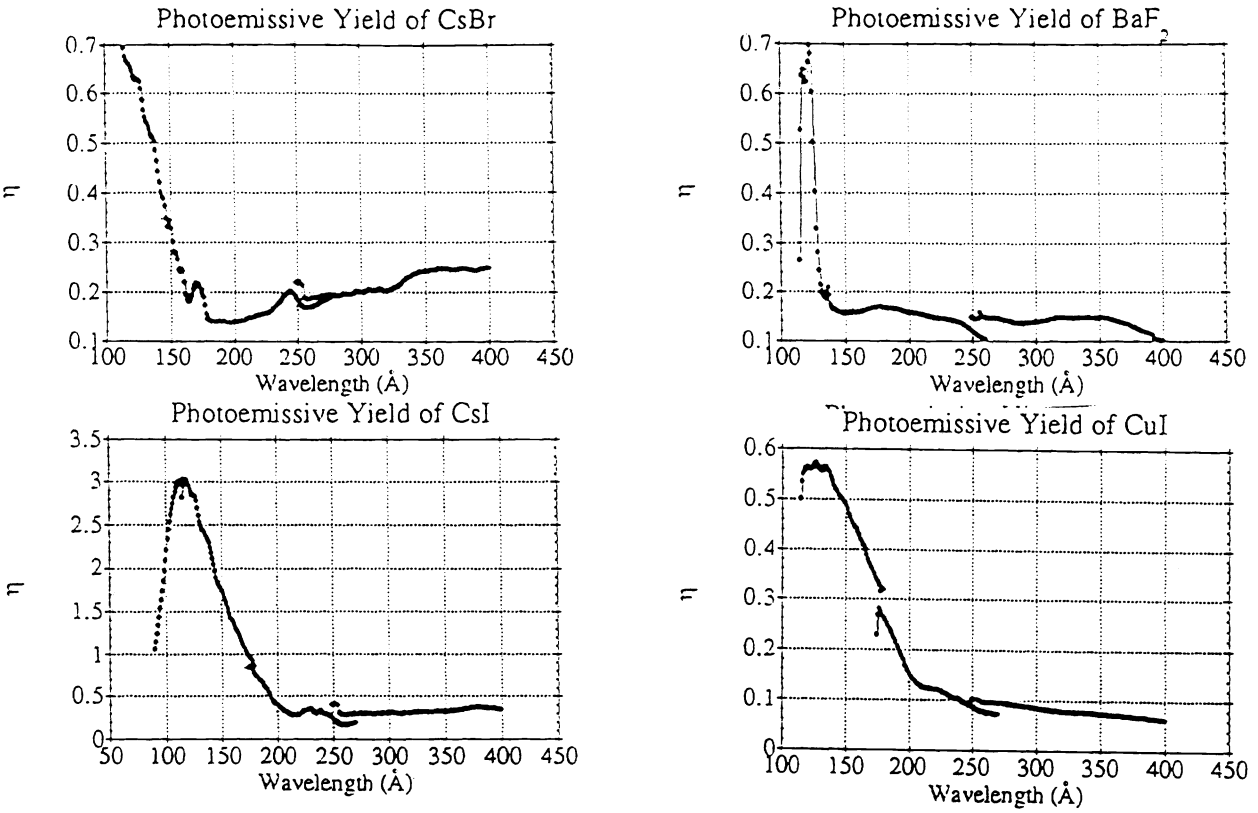

Fig. 4 Photoemissive yields of various photocathodes as measured on SURF II.

We intend to adapt the design of this electron-optical imaging system for applications to biological imaging. Although the electron optical imaging system will remain the same, we will develop new x-ray photocathodes for the water window and shorter wavelengths.

4. Summary

We have presented in this paper the progress we have made toward the development of x-ray microscope technology based on laser plasma point x-ray sources. We have established at the Laser Plasma Laboratory at CREOL a solid state laser system dedicated to the development of optimum point sources for biological x-ray microscopy. This source is currently being used to make progress in the use of contact microscopic techniques, and will also soon be used for advanced x-ray imaging systems incorporating multilayer coated Schwarzschild optics and high resolution zone plates. Towards the development of high resolution, high magnification electron-optical imaging systems for x-ray imaging applications we have established a dedicated x-ray photocathode fabrication facility and wish soon to adapt electron-optical designs of the soft x-ray conversion microscope at NIST for a similar instrument sensitive for x-rays in the water window and of shorter wavelength. These developments will bring closer the realization of a compact real-time x-ray imaging microscope for the biological and life sciences.

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