JOURNAL OF X-RAY SCIENCE AND TECHNOLOGY **1**, 3–6 (1989)

GUEST EDITORIAL

The Early Days of X-Ray Optics—A Personal Memoir

ALBERT V. BAEZ

58 Greenbrae Boardwalk, Greenbrae, California 94004

Received August 29, 1988

INTRODUCTION

The 1986 report of the Center for X-Ray Optics at Berkeley discusses the following topics of investigation, among many others: zone plates, x-ray mirrors, soft x-ray microscopy, holographic and contact microscopy, and x-ray microchemical analysis. All of these topics were the subject of experiments and discussion in the early 1950s at the University of Redlands—a small liberal arts college with no track record in research. We were caught up in a tidal wave of world-wide interest and activity in what is now called x-ray optics. This will be a personal, incomplete, informal, and anecdotal memoir. It is not a review article and it does not claim to do justice to all the significant work that was being done in this field in many other laboratories around the world. It is intended to evoke the flavor of the times as we experienced them.

THE EARLY WORK AT STANFORD

For us it started in the late 1940s when two independent investigators were developing techniques which would eventually link x-ray microscopy and holography. While Dennis Gabor in the United Kingdom was trying to improve the resolution of the electron microscope through holography, Paul Kirkpatrick was developing the first reflection x-ray microscope at Stanford University.

X rays had already been reflected at grazing incidence from flat mirrors, but the books still said it was impossible to focus x rays. Kirkpatrick and others did focus them in several ways, but he was the first to show how two curved mirrors can focus x radiation from a point source to a point image. One mirror squeezes x rays from a point source down to a line, but if the radiation is allowed to hit a second mirror at right angles to the first, the line is squeezed down to a point. An extended object is focused into an extended x-ray image. Kirkpatrick was once illustrating this phenomenon at a physics colloquium at Stanford in the 1940s by using visible light and cylindrical lenses instead of mirrors. The object was an illuminated rectangular wire mesh. The image it produced on a projection screen using a single cylindrical lens consisted only of a set of parallel lines. Kirkpatrick predicted that when he introduced a second cylindrical lens into the beam at right angles to the first the combination of cylindrical lenses would behave like a single convergent spherical lens. There was a flurry of

0895-3996/89 $3.00

disbelief among members of the audience, which included at least one future Nobel Prize winner in physics. When Kirkpatrick introduced the second cylindrical lens into the beam a clear image of the entire rectangular mesh appeared on the projection screen and the audience applauded.

It was my privilege as a graduate student at Stanford to share in the excitement of the earliest experiments in x-ray focusing. With dark-adapted eyes I observed, on a fluorescent screen, how the x-ray beam reflected from a single mirror narrowed down to a line as I manipulated a device which curved the mirror by bending it. Eureka! We had focused x rays! In those days it was still possible to perform some meaningful experiments, as Rutherford had said, ". . . with love and string and sealing wax."

THE COSSLETT–NIXON POINT PROJECTION X-RAY MICROSCOPE

After Stanford my interest in teaching took me to the University of Redlands, but the Research Corporation encouraged me to do research with undergraduates, and Kirkpatrick suggested that a good way to begin would be to repeat Gabor's experiments using filtered light from a point source. He also brought to our attention Gabor's prediction that a hologram produced with radiation of wavelength λ_1, and reconstructed with radiation of wavelength λ_2, would produce a magnification λ_2/λ_1, a ratio of the order of 1000 when the radiations used are light and x rays, respectively. This opened up another approach to x-ray microscopy based upon Gabor's idea of reconstructed wavefronts. We figured it should be possible to make an on-line hologram with x rays as we had done with a point source of visible light if we could get an x-ray source with a sufficiently small diameter. Remember that the x-ray laser was still about 30 years in the future.

Cosslett and Nixon of Cambridge University had developed an x-ray tube with a focal spot of about 1 μm in diameter. They were willing to build one of their tubes for the University of Redlands. When I discussed my proposal for making an x-ray hologram with the National Academy of Sciences they said they would send a physicist to Redlands to explore the possibility.

The physicist—whose name I have unfortunately forgotten—arrived as I was about to teach a class so I asked my student Don Robinson to entertain him while I was engaged. I had unwittingly done the best thing possible to impress our visitor. Don, a junior who had guided our research while I had been on leave of absence in Baghdad for Unesco, explained holography so clearly to him that when he returned to Washington he must have said "Give Baez the money for the Cosslett–Nixon tube," because we did, indeed, receive a grant of $1000 to order the tube from Cambridge. What can you buy today for $1000, I wonder?

In due course the tube arrived at Redlands with William Nixon of Cambridge to help us set it up. The tube found multiple uses. It served as the source of x rays for a curved crystal spectrometer designed by Lou Zeitz for microchemical analysis and as the point source for the first attempts at x-ray holography by Hussein El Sum. In the hands of William Nixon it served as a projection x-ray microscope and produced spectacular radiographs of biological and metallurgical specimens. Nixon gave lectures on x-ray microscopy which were well attended by scientists from Southern California, and we received small grants from the Research Corporation, the National

Science Foundation, the National Research Council, the Office of Naval Research, and the American Cancer Society.

THE FIRST INTERNATIONAL SYMPOSIUM ON X-RAY MICROSCOPY AND MICRORADIOGRAPHY

By the mid-1950s interest in x-ray microscopy and related fields had reached such a peak of world-wide interest that an international symposium held at the Cavendish Laboratory of Cambridge University attracted over 70 participants. My Redlands associates M. A. El Sum and Lou Zeitz, my students, and I worked feverishly to finish reports of our work to present at the Symposium. We submitted papers dealing with resolving power in x-ray holography, x-ray microchemical analysis, and the use of a computer in designing an x-ray mirror.

Although Gabor had not worked in x rays the nature of his research in holography, for which he would receive a Nobel Prize almost 20 years later, made him a welcome and honored guest at the Symposium. The assembled participants were greeted at the formal inaugural dinner by Professor Mott who said, tongue-in-cheek, pointing to the impressive portrait of King Henry the Eighth on the wall, that it was very appropriate for a group of investigators to be assembled beneath the portrait of "the great experimenter."

The "Proceedings of the Symposium" containing all 72 submitted papers is still worth reading as a starting point in x-ray optics. Many of the modern developments in the field are extensions of work that had its beginnings then.

X-RAY ZONE PLATES

El Sum's attempts to produce a good x-ray hologram were frustrated by the fact that even a 1-μm focal spot was much too large to produce the necessary spatial coherence. We could not register sufficient interference fringes to produce good resolution. If we had understood temporal and spatial coherence better, we probably would not have even tried to obtain the Cosslett–Nixon tube and would have been deprived of the fun of using it for other experiments related to x-ray optics!

Since we had observed Fresnel zones on so many holograms made with visible light, I got the idea that we might set out deliberately to produce a zone plate for x rays. Attempts to produce one by the standard technique of photographing a drawn zone plate pattern failed for several reasons, one of them being that the soft x rays of interest did not go through the film backing. Hard x rays went through both the emulsion and the backing. I finally hit upon the idea that a metal zone plate with empty spaces for the transparent zones could be made self-supporting by connecting the circular bands with struts. The technology for doing this by using photo resist and electrochemical deposition was commercially at hand by the late 1950s. With financial support from the Smithsonian Astrophysical Observatory and the technical assistance of the Buckbee Mears Co. we produced the first self-supporting gold zone plate. It was tested with ultraviolet radiation. G. Möllenstedt of Tübingen subsequently borrowed this zone plate to reduce it further by electron optical means and produced a structure that could focus x rays with a wavelength of about 5 Å.

X-RAY ASTRONOMY

In 1960 H. Friedman published an x-ray picture of the sun taken with a pinhole camera from a rocket. This increased our excitement about the much greater resolution that could have been obtained if he had used our zone plate with 19 zones. Or, think of what he could have done with one of the modern plates whose smallest features are of the order of 1000 Å!

It was also obvious that Kirkpatrick's crossed-mirror system could be used as an x-ray telescope. The longer wavelengths that carry interesting information from space do not get through the atmosphere, so it became clear that the ultimate platforms for x-ray telescopes would be satellites. At the October 1960 meeting of the Optical Society of America I read a paper on this topic based in part on an x-ray astronomy conference we had organized at the Smithsonian Astrophysical Observatory in May of 1960. A proposal for a "venetian blind" x-ray telescope was published in the September 1960 issue of the *Journal of Geophysical Research.* This was my last foray into research before moving into the field of international science education with Unesco.

Since then, the field of x-ray astronomy has moved, for valid astronomical reasons, in the direction of devices that maximize the x-ray flux that can be collected from a given source rather than in the direction of image-forming devices.

CONCLUSION

Now, almost 40 years after Gabor and Kirkpatrick started their separate investigations, it is evident that great strides have been made both in holography and in x-ray optics as well as in new and then unheard of directions. The new x-ray sources afforded by synchrotron radiation and plasmas, the research on x-ray lasers, and the opportunities to detect x-rays in space, as well as other developments, promise (and demand) stimulating developments in these areas of optics. It is pleasant to look back and realize that we were among the many investigators who got the process started. It is especially pleasant for me to give credit to Paul Kirkpatrick who was the source of many of the original ideas and who got so many of us started in this interesting field.