REVIEW OF SCIENTIFIC INSTRUMENTS VOLUME 72, NUMBER 3 MARCH 2001

X-ray transmission through a plasma window

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(Received 7 June 2000; accepted for publication 4 December 2000)

Traditional solid window materials used for x-ray synchrotron beamlines may introduce undesirably high attenuation, or are subject to failure under high heat loads. A plasma window can in principle obviate these problems over a wide range of energies. Experiments were performed at the Brookhaven National Laboratory National Synchrotron Light Source on beamline X6A to study the transmission characteristics of a plasma window using argon as the arc gas. Measurements were made around the Ar *K* edge and far from resonance. The ''white-line'' absorption at the *K* edge was actually suppressed during arc operation as compared to room temperature gas at the same pressure. This is attributed to the high degree of ionization in the plasma. The relative strength of the white line to the edge jump does not seem to be a strong function of arc current at the argon *K* edge. Away from resonance (~3 times the edge energy) x-ray attenuation was negligible. © *2001 American Institute of Physics.* [DOI: 10.1063/1.1344598]

I. INTRODUCTION

Under certain circumstances, plasmas can function as windows. Plasmas can be confined in vacuum (by electric and magnetic fields) with minimal wall contact, yet provide impedance that can balance atmospheric (or even a few atmospheres) of pressure. The use of atmospheric arc plasmas to establish a vacuum-atmosphere interface has recently been demonstrated.[1] This ''plasma window'' establishes a barrier to gas flow by creating a hot plasma discharge that imparts a higher effective viscosity and a lower density than the working gas would exhibit at room temperature. Plasma windows can separate vacuum and atmosphere, or high and low vacuum, in a way that facilitates transmission of various particle beams and/or radiation from the low to high-pressure regions.[2]

The best high-pressure results have been obtained using argon as both the high-pressure ''target'' and arc gas. In one experiment a target at 5 bar was successfully separated from atmosphere.[2] Later, a target at 2.85 bar absolute was isolated from vacuum (0.6 mbar) using a 2.36 mm diameter 40 mm long arc. When coupled to a three-stage differential pumping system the background pressure of 5×10^{-9} bar was reached.[3] Transport of particles through plasma windows has also been demonstrated; a 175 keV electron beam was transported from the vacuum into the atmosphere through the plasma window.[1,2] More recently, a 2 MeV proton beam was successfully transmitted through a plasma window with negligible energy losses.[4] To prove their compatibility with sensitive instrumentation environments, a series of electromagnetic interference experiments revealed that radio frequency emission from the arc is negligible.[2] Collectively these results suggest a broad range of applications including isolation windows in synchrotron radiation experiments.

For some x-ray experiments, plasma windows offer significant advantages over the 0.25-mm-thick beryllium windows typically used on x-ray synchrotron beamlines. Because the atom density (or effective target thickness *nl*) of a plasma window is substantially lower than that of the Be window, the absorption of x rays is significantly reduced for x-ray energies below about 10 keV. For high heat load or high power density applications (like wiggler and undulator sources) the plasma window has merit because its performance is essentially unaffected by the little radiation it does absorb.

In absence of any atomic resonances, plasmas are transparent to electromagnetic radiation whose frequency exceeds the plasma frequency ω_p. At a plasma density (typical for a plasma window) of $1.5\times10^{17}\,\mathrm{cm}^{-3}$, $\omega_p=3.5\times10^{12}\,\mathrm{Hz}$. Therefore, radiation with a wavelength shorter than 86 μm is not affected by collective plasma processes. Cross sections for interaction of radiation from ultraviolet out into the hard x-ray regime, with individual particles is usually minuscule, e.g., for Thompson scattering $\sigma=2/3\,\mathrm{b}$ ($1\,\mathrm{b}=10^{-24}\,\mathrm{cm}^{-2}$). At resonance, however, some photoabsorption and photoionization cross sections can reach the 10^{-19}–$10^{-18}\,\mathrm{cm}^2$ level. The typical target thickness of a plasma window $nl\sim1.5\times10^{17}\,\mathrm{cm}^{-2}$ is about four orders of magnitude lower than that of a conventional 250 μm beryllium window with $nl\sim2.5\times10^{21}\,\mathrm{cm}^{-2}$. Electromagnetic radiation of an energy far from the absorption resonances of the working gas should have negligible interaction with a plasma window due to small target thickness coupled with low interaction cross sections.

Atomic resonances of the gas(es) in the plasma will be observed as characteristic absorption lines, however, their cross section can be substantially modified by the high degree of ionization in the plasma. Nevertheless, it may be possible to exploit the absorption characteristics of the plasma working gas in ultraviolet beamlines to provide an efficient filter. The gas could be chosen to attenuate higher-order diffracted light, which is often transmitted in the grating monochromators typically used in beamlines of this type. The rejection of ''high-order'' light is of significant benefit

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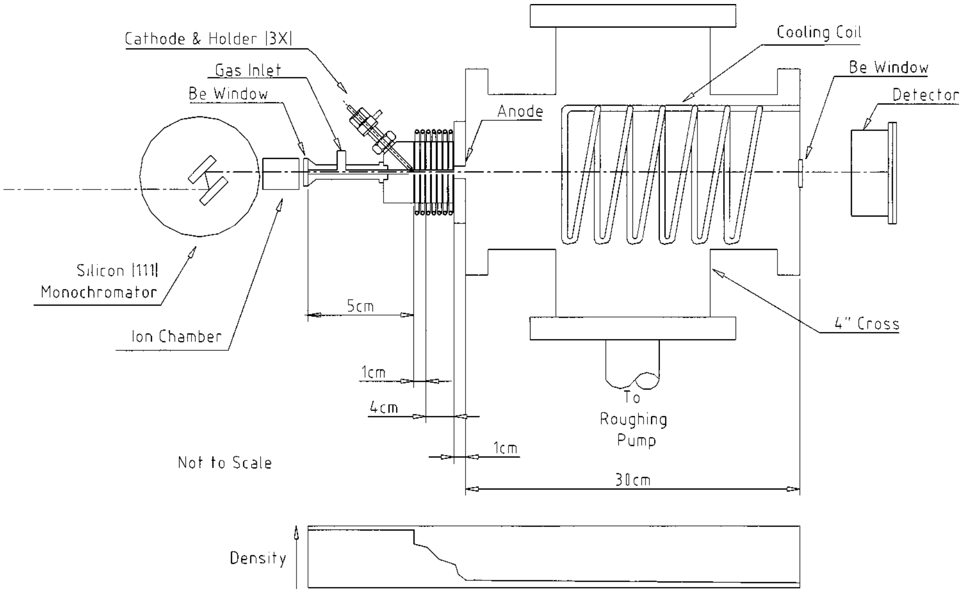

FIG. 1. Experimental schematic of the apparatus used to measure the transmission characteristics of the plasma window (no scale). The chart at the bottom of the figure qualitatively illustrates the anticipated gas density profile as a function of position along the apparatus. Note the precipitous decline in density through the arc itself.

to experiments like threshold photoionization spectroscopy, where harmonic content even at the 10^{-4} level can obscure the features of the spectrum of interest.

II. EXPERIMENTAL SETUP

The plasma window used for these experiments is a segmented wall-stabilized plasma arc[1,2] forming an interface between the higher gas pressure region of the gas cell and the vacuum. The plasma exhibits a high viscosity to gas flow, which results in the formation of a ''plug'' that can support a significant pressure differential. Transmission measurements were performed at the National Synchrotron Light Source on the X6A beamline. Figure 1 displays the experimental arrangement. A Si(111) channel-cut monochromator was used to select the energy of the x rays, which then pass through an ionization chamber that provides an incident intensity monitor. The beam then passes through a 0.25-mm-thick beryllium window and into a 54 mm long gas cell.

A centimeter of plasma separates the gas cell from a 4 cm long plasma window channel. The plasma is formed by striking a direct current arc from a set of cathodes to a single anode held at ground potential. The potential difference between the cathodes and the anode is distributed across several intermediate ''cascade plates'' made of copper that were allowed to float to their own potential. The arc used in these experiments has three sharp tip cathodes that are equally spaced around the beam path and just outside of its aperture. In this way a clear optical path 2 mm in diameter exists down the axis of the window. Each cathode has its own power supply for convenience in operation. The power dissipated in the arc can be substantial (the order of several kilowatts) so all of the arc components are water cooled.

The plasma window is mounted on an evacuated 4 in. cross. The cross is pumped by a Varian TriScroll roughing pump (300 l/m, base pressure $<10^{-2}$ bar). A second beryllium window is mounted 300 mm downstream from the plasma window anode. Photons existing this window are detected by a silicon photodiode. Due to limitations with the mounting of the first beryllium window (on the gas cell), the gas cell pressure had to be kept bellow 13 mbar. Hence, the highest gas pressure applied to the gas cell while at the beamline was 12 mbar of argon. Off-line measurements with the first Be window removed demonstrated that atmospheric pressure was effectively separated across this 2.36 mm diameter 40 mm long arc from a three-chamber differentially pumped system, with the pressure in the first chamber reaching 5.0×10^{-5} bar. The following two chambers reached pressures of 1.8×10^{-8} and 2.2×10^{-9} bar (chamber base pressure), respectively.[3] Argon was used as the working gas for all of the x-ray transmission measurements in this article. Further detail on the plasma window itself can be found elsewhere.[1–3]

III. RESULTS

Attenuation measurements were made with 9.6 keV x rays (approximately three times the Ar *K*-edge absorption) to obtain the ''off resonance'' results. When the gas cell (the volume between the Be window and the arc) was pressurized to 12 mbar the 4 in. cross pressure rose to 2 mbar. In this configuration the measured 9.6 keV x-ray transmission was reduced to 90% of the value obtained when the cross was pumped out to its base pressure of 7.9×10^{-5} bar. When the arc is switched on, the pressure in the cross drops to 2.6×10^{-4} bar, and the measured 9.6 keV x-ray transmission was 96% of the evacuated value. In addition to the obvious reduction in vacuum chamber pressure, a substantial decrease in density occurs in the plasma window channel due to heating.[1,2] On resonance with the arc off, no transmission of 3.2 keV x rays (argon *K* edge) could be observed until the gas cell pressure was reduced to 4.6 mbar or less.

Figure 2 plots the measured absorption for various arc currents, including no current. We define the absorption as ln ([incident intensity/transmitted intensity]). To compensate for the slightly different arc pressures at each current the data have been scaled to the same baseline absorption above and below the edge. The plot illustrates the dramatic affect of ionization on the measured absorption. Even at the lowest

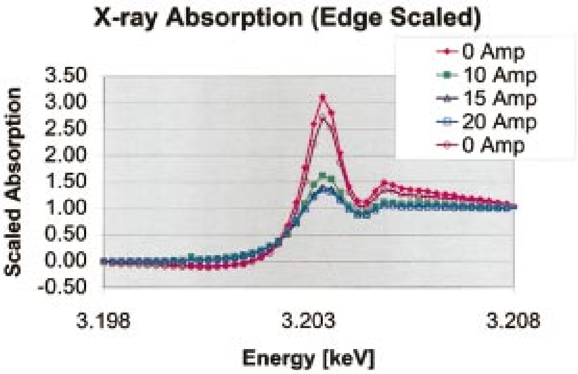

FIG. 2. (Color) Measured transmission at the argon *K* absorption edge for various arc currents (reported as current per cathode). The suppression of the white-line changes little as the arc current is increased from 10 A/cathode (solid squares) to 20 A/cathode (open squares) indicating a high degree of ionization even at the lowest operating current.

sustainable arc current of 10 A per cathode, the *K*-edge absorption is substantially reduced.

IV. DISCUSSION

A plasma window could be an extremely attractive way to isolate machine vacuum from the beamline for some types of synchrotron radiation experiments, as an alternative to presently used beryllium or SiN solid windows. As expected, the present results show that the plasma window is transparent to synchrotron radiation. The strong attenuation observed at gas resonance can be exploited as an efficient absorption filter for some specific energies. And, when needed, attenuation of those energies can be avoided with the proper choice of plasma window gas. In principle, x rays at any energy can be transmitted through a plasma window with very high efficiencies. In addition to providing low attenuation, plasma windows are free of spatial structure (e.g., scratches, defects, crystalline domains) common in conventional window materials that can interfere with some experiments, for example imaging and intensity correlation spectroscopy measurements. Plasma windows also have the benefit that they are impervious to thermal damage.

The observation that the absorption strength of the edge can be readily modified by changing the arc current suggests that the plasma is highly ionized, and further, that this property may be manipulated to benefit a particular experiment. Although this is an interesting problem, detailed analysis of the topic is beyond the scope of the present investigation.

ACKNOWLEDGMENT

This work was supported by the United States Department of Energy under Contract No. DE-AC02-98CH10886.

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