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SUBMILLIMETER-WAVE DUMPS FOR FUSION PLASMA DIAGNOSTICS

P. Woskoboinikow, R. Erickson
and W.J. Mulligan

Plasma Fusion Center
Massachusetts Institute of Technology
Cambridge, MA 02139

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ABSTRACT

An experimental study of submillimeter-wave dumps for high vacuum, constrained access fusion plasma diagnostics is presented. The experimental measurements were made at 385μm with a D_2O laser. Stainless steel, graphite, pyrex glass, window glass, and machinable ceramic are considered as dump materials. Several submillimeter radiation trapping structures are considered including a large Rayleigh horn, V-shaped grooves, and conical holes. Graphite dumps with a -10 to -18dB rejection were fabricated.

INTRODUCTION

The need for effective submillimeter wave (SMM) beam and viewing dumps for fusion plasma diagnostics is a well known problem. In collective Thomson scattering from thermal plasma fluctuations, to measure ion temperature, the scattered signal is only about 10^{-14} of the incident SMM radiation [1]. For this measurement stray radiation from the incident SMM beam is a severe problem in a constrained access plasma. In order for this diagnostic to succeed effective SMM beam and viewing dumps and/or a narrow linewidth rejection filter (the desired signal is Doppler broadened by the ion motions) are required. When the SMM source is a high power, optically pumped, molecular laser it has been shown that the low level laser linewidth can be quite broad [2]. This makes it necessary to have beam and viewing dumps for rejecting most of the stray SMM radiation rather than relying on a narrow linewidth rejection filter. Effective SMM viewing dumps would also be of value for electron cyclotron emission (ECE) measurements [3]. It would improve the usefulness of ECE from optically thin harmonics.

Many current fusion experiments have poor access for SMM diagnostics. Restricted port apertures and long propagation path length cause diffraction which makes it difficult to couple a SMM source beam or SMM field of view cleanly through the plasma to a dump. Also diagnostic ports on opposite sides of the plasma are not always available. These problems make it necessary to develop SMM dumps which can be located inside the vacuum chamber near the plasma. Therefore, the SMM dumps must be compatible with high vacuums, of compact design for constrained locations, able to withstand the harsh environment inside a fusion plasma vacuum chamber, and not be a source of high Z impurities. Most materials which are compatible with these requirements are also good reflectors at SMM wavelengths. This further requires that the dump be designed to trap the SMM radiation for many reflections to dissipate its intensity.

In this paper we present a limited experimental study of possible materials and designs for SMM dumps. We were motivated by the specific need to develop effective beam and viewing dumps for a 385μm D_2O laser Thomson scattering ion temperature diagnostic for the Alcator C tokamak. In this particular case only three materials are allowed in the limiter shadow: stainless steel, molybdenum, and graphite. These are allowed because they are already present in the vacuum chamber as first wall or limiter materials. Very little information about the SMM properties of these materials can be found in the literature [4]. Therefore, our first measurements were of the smooth flat surface reflectivity at 385μm of these and a few other easily obtainable vacuum materials such as ceramic and glass which might be acceptable in some plasma experiments. Most of the dump configuration studies were done using stainless steel and graphite because of their applicability to our requirements.

EXPERIMENTAL MEASUREMENTS

The set up for testing the SMM dumps is shown in Fig. 1. The output of a ~100mJ, 1μs pulsed 385μm D_2O laser [5] without a grating mirror was used as the SMM source. The laser beam diameter was restricted to be smaller in size than the dump under test by an aperture in a sheet of eccosorb [6]. A free standing wire grid polarizer (400 wires per cm) was used to insure that the laser beam was well polarized so that the polarization dependence of some of the dumps could be tested. The dump under test was illuminated by the laser beam at an angle of 10°-15° relative to normal incidence with the polarization in the plane of incidence. Dump effectiveness was determined by measuring the spectral reflection and scattered reflection and comparing this to the reflection from a gold-coated mirror substituted for the dump in the experimental set up. A Laser Precision type RK 3230 pyroelectric energy meter was used for these relative energy measurements. A 15cm diameter, 40cm focal length mirror focused the spectrally reflected component onto the energy meter. The scattered component was determined by scanning the detector away from the focal point of the mirror and at several different angles directly off the dump. From these measurements it was determined if the scattered radiation geometry was spherical or cylindrical. The total scattered reflection was then found by integrating over the half-sphere or half-cylinder of scatter.

The first set of measurements was of the flat surface spectral reflection of the candidate dump materials. Smooth flat samples were used that produced no scattered component. The results of these measurements are shown in Table 1. The materials that are acceptable in Alcator C (stainless steel, molybdenum, and graphite) are all good mirrors at 385μm. Of these the graphite sample has the lowest reflection of approximately 79%.

Ceramic and glass are good vacuum materials that have much smaller reflection at 385μm. Unfortunately, these are not allowed inside the Alcator C plasma chamber because they would contribute undesirable impurities to the plasma. Ceramic and glass may be usable in other experiments with more access for locating the dumps far from the plasma. Our measurement for the reflectivity of ordinary green-edged window glass of 18% is in agreement with previous measurements [7,8]. The sample of Macor [9] machinable ceramic was 2.1cm thick and the window glass was 0.6cm thick. No transmission of the 385μm laser beam through these samples was detected, placing an upper limit for transmission of 10^{-4}. The pyrex glass sample was only 1.7mm thick and 3.8% of the incident laser beam was transmitted, corresponding to an absorption coefficient of 12.8 cm^{-1}. When making a dump of this material it must be made thick enough to prevent transmission.

DUMP DESIGNS

Dump configurations that trap the SMM radiation for multiple reflections are clearly required for effective dumping. Several configurations were studied, the results of which appear in Table II. The spectral reflection and scattered reflection are each listed in terms of dB relative to the reflection from the gold-coated mirror. The scattered component was generally the dominant reflection. Eccosorb [6], a black plastic foam sheet with gold backing, is a standard millimeter wave absorber. It is not compatible with high vacuums and is listed only for reference purposes.

A cone is a standard configuration for trapping incident electromagnetic radiation [10]. A cone with a bend in it so that a ray incident along the cone axis is prevented from being reflected straight back out is known as a Rayleigh horn. If the cone dimensions are large relative to the wavelength, geometrical ray tracing can be used to determine the number of reflections an incident ray will have before exiting the cone. The smaller the apex angle of the cone the more reflections the ray will suffer. The effectiveness of the cone as a dump can be roughly estimated by raising the single surface reflection for the average reflection angle to the power of the number of reflections.

A pyrex glass Rayleigh horn as sketched in Fig. 2a with a 5cm aperture 50cm long, and 0.6cm thick walls was tested. For a normally incident laser beam 30 internal reflections are predicted for this horn. Only about 4 reflections near normal incidence from pyrex glass are required to give a rejection of better than -45dB. As expected no spectral or scattered reflection could be detected when the 385µm laser beam was directed into this horn. This was the best SMM dump we tested. Unfortunately, glass is not allowed near a fusion plasma. A graphite cone of similar dimensions would be expected to give a rejection between -20 and -30dB based on our measured reflectivity of graphite at 385µm, but the long dimension of a large cone makes it difficult to locate such a structure inside a plasma chamber.

The constrained space between the plasma chamber wall and limiter radius of most fusion plasma confinement devices requires a dump design with compact structure. We tested several such designs, one made out of stainless steel and the rest from graphite. The stainless steel dump was fabricated from sections of tubing to form a series of small slots with Rayleigh horn profiles as shown in Fig. 2b. The slot widths were 0.65cm with input knife edges. The total depth of this dump was 1.2cm. Geometrical ray tracing to predict the effectiveness of this dump would be uncertain because the incident beam very rapidly propagates into regions of the slots that have dimensions on the order of a wavelength. Experimental measurements showed this dump to be better than a flat stainless steel wall, but not much better. Almost half the incident SMM laser beam was unabsorbed and scattered.

The graphite dump designs, as expected, worked much better. First a nonsmooth surface of graphite was tested where the surface roughness was small in scale, caused by a coarse saw cut. The rough surface graphite showed significant improvement in SMM absorption over the smooth surfaced graphite and was even better than the stainless steel slot dump. The 5dB rejection though, is not adequate for most applications.

The machining of V-shaped grooves and small straight cones into blocks of graphite produced much more effective dumps. The machining of more desirable Rayleigh horn profiled grooves and cones was not possible. The V-grooved graphite dump as shown in Fig. 2c had a groove angle of 14°, a groove depth of about 1 cm, and groove spacing so that the walls between adjacent grooves would come to knife peaks. This dump was strongly polarization dependent, having a rejection of almost -18dB for polarization perpendicular to the grooves and only about -5dB rejection for polarization parallel to the grooves. A polarized dump would not necessarily be a disadvantage because many SMM sources and receivers are also polarized.

A graphite dump with small cones as shown in Fig. 2d was also tested. The cone angle was 20° and the cone depth was about 8mm. The cones were overlapped so that there were no flat surfaces between them. The machining of this dump design proved difficult because the sharp peaks between the cones tended to fracture. The best sample tested of this design had several fractured areas. This dump had a rejection of about 10dB which did not vary with polarization. Significant improvement in rejection of this dump design should be possible with improved machining. Also a smaller cone angle to improve the trapping of the incident SMM radiation would help, but the machining would be even more difficult because the peaks beween the cones would be narrower and more likely to break. A possible better way to fabricate a polarization independent dump similar to this design could be by binding together many small sharpened graphite rods.

CONCLUSIONS

A limited experimental study of SMM dumps that can be used for fusion plasma diagnostics has been presented. The requirements of fusion plasma diagnostics place severe limitations on the composition and size of acceptable SMM dumps. These dumps must be compatible with high vacuums, compact in size, and not be sources of high Z impurities. In most present fusion plasma experiments materials that are not already in the plasma chamber as first wall or limiter materials are not allowed for fear of introducing unwanted impurities. In the case of the Alcator C tokamak this limits the SMM dump composition to stainless steel, molybdenum, or graphite. We have shown that all these materials are good reflectors at 385μm. This makes it necessary that a SMM dump be designed to trap the incident radiation for many reflections to dissipate its intensity. We have tested several dump configurations and found that a V-shaped groove or conical hole structure in graphite gave the best SMM rejection compatible with our plasma diagnostic requirements on Alcator C. In other plasma experiments, with more access and relaxed requirements on dump composition a large Rayleigh horn made of glass or ceramic can be a very effective SMM dump. We have tested a pyrex glass Rayleigh horn with no measureable reflection at 385μm, which places an upper limit on rejection of -20dB based on our measurement capability.

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TABLE 1

SMOOTH FLAT SURFACE REFLECTION AT 385μm

Material	Reflection
Stainless Steel (type 304)	0.95 ± 0.05
Molybdenum	0.95 ± 0.05
Graphite*	0.79 ± 0.05
MACOR [9] Ceramic	0.14 ± 0.02
Pyrex Glass	0.07 ± 0.01
Window Glass	0.18 ± 0.02

* Poco Graphite, Inc. Grade AXF-5Q

TABLE 2

DUMP CONFIGURATION STUDY

		REFLECTION	
MATERIAL	CONFIGURATION	SPECTRAL	SCATTERED
Eccosorb [6]	Rough surface	<-45dB	-19.8dB
Pyrex Glass	Rayleigh horn	<-45dB	<-20dB
Stainless Steel	Rayleigh horn	-21.6dB	-3.7dB
Graphite*	Rough surface	-14.7dB	-5.0dB
Graphite*	V-grooves (polarization ⊥)	-19.8dB	-17.7dB
Graphite*	V-grooves (polarization 11)	-12.8dB	-4.9dB
Graphite*	Small cones	-18.6dB	-10.4dB

* Poco Graphite, Inc. Grade AXF-5Q

FIGURE CAPTIONS

1. Experimental setup for measuring dump reflection, E, eccosorb aperture, P, free standing wire polarizer, M, focusing mirror. A gold coated mirror replaces the dump to determine the relative dump efficiency.

2. Various dump configurations tested, (a) pyrex glass Rayleigh horn, (b) stainless steel Rayleigh profiled slots, (c) V-grooved graphite, and (d) conical holes in graphite.

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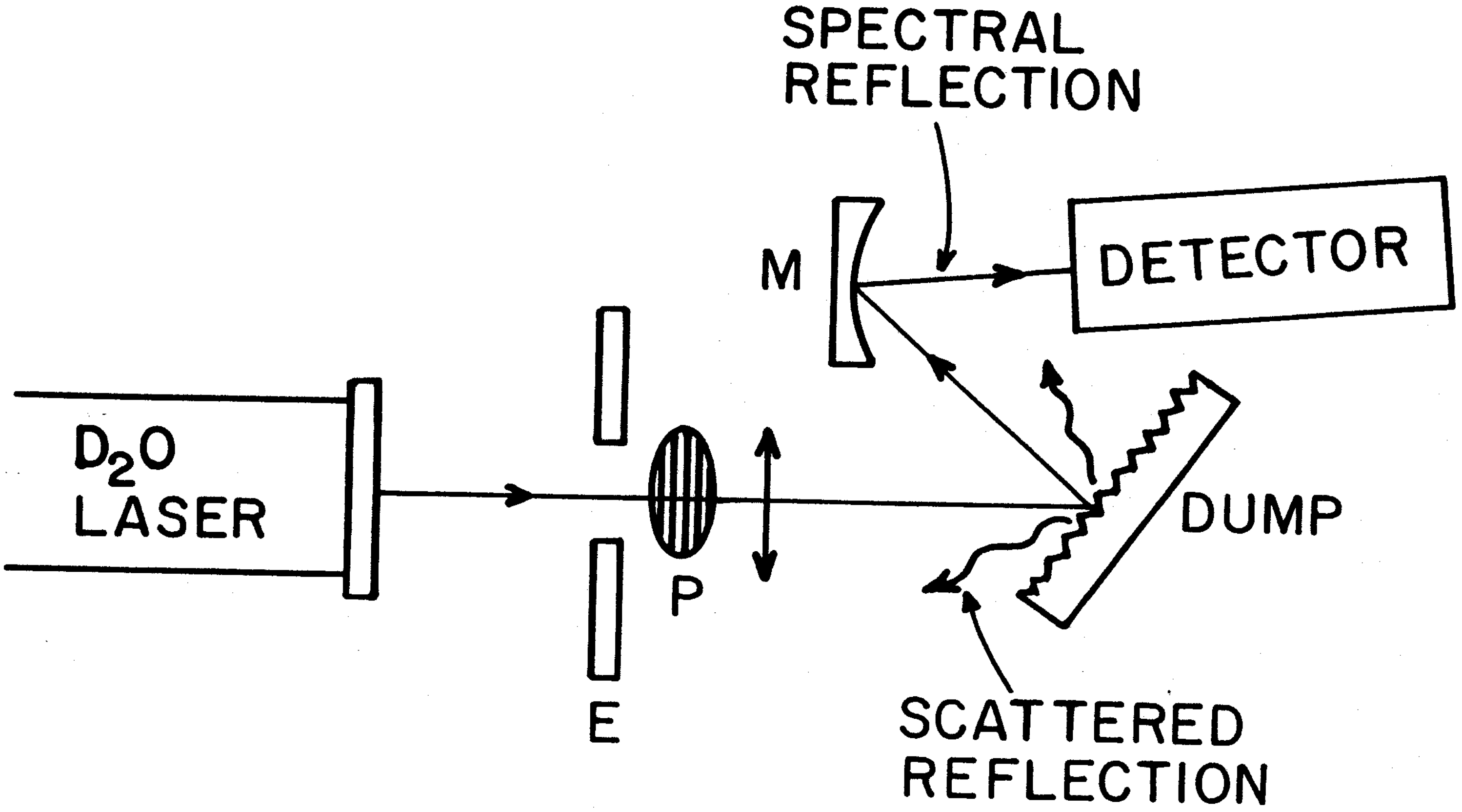
SPECTRAL REFLECTION
M
DETECTOR
D_2O LASER
P
E
DUMP
SCATTERED REFLECTION

Figure 1

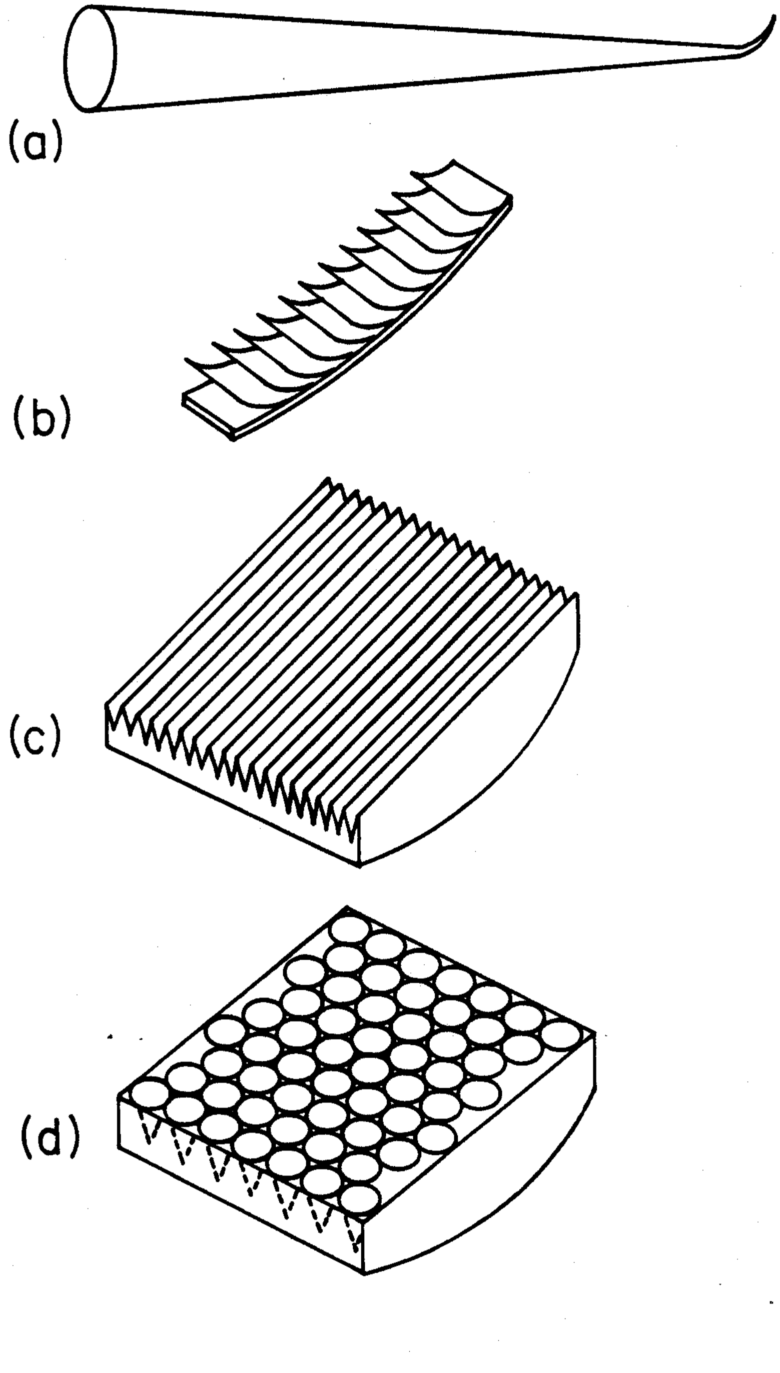

Figure 2