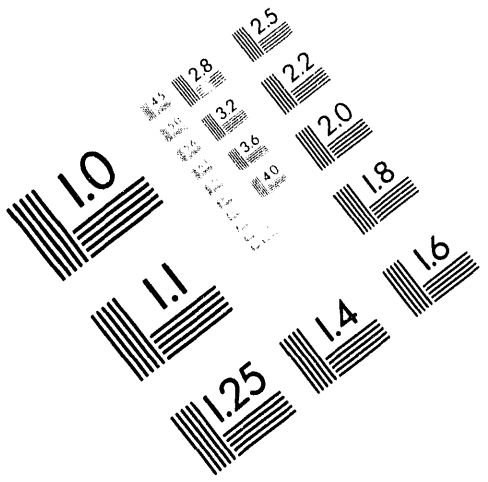

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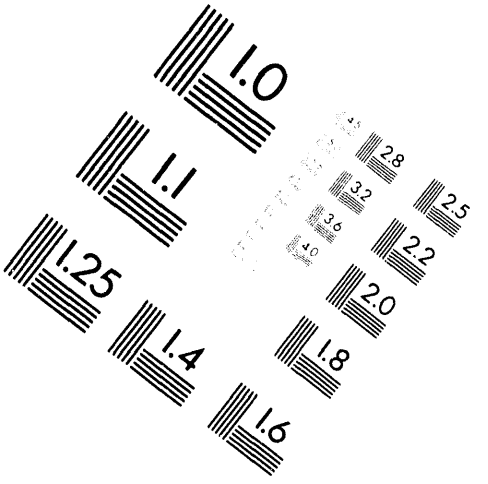

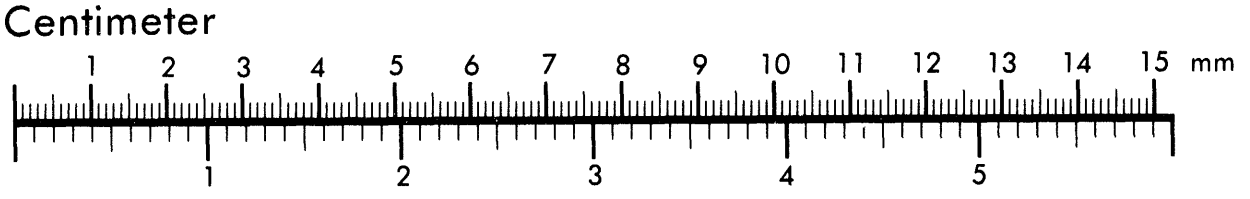

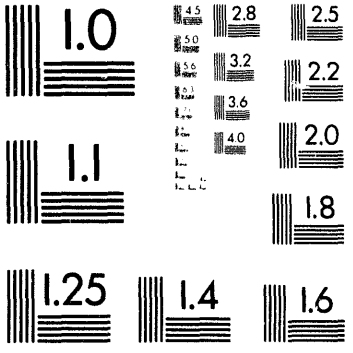

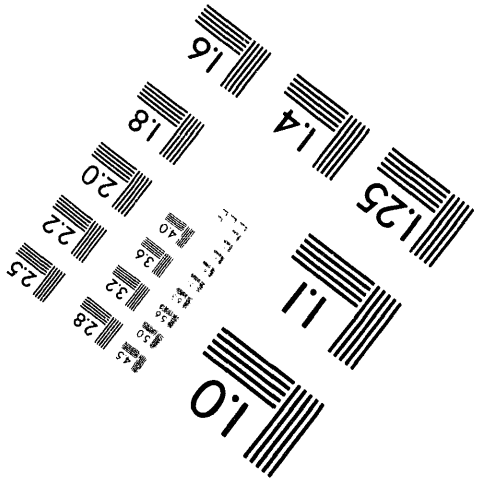

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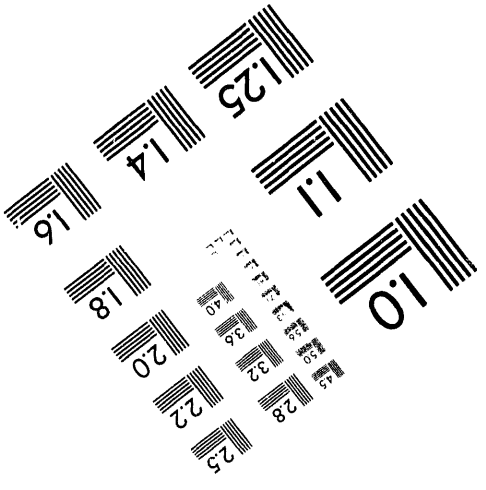

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Studies of the Ablated Plasma from Experimental Plasma Gun Disruption Simulations

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ABSTRACT

Extensive simulations of Tokamak disruptions have provided a picture of material erosion that is limited by the transfer of energy from the incident plasma to the armor solid surface through a dense vapor shield. Radiation spectra were recorded in the VUV and in the visible at the Efremov Laboratories on VIKA using graphite targets. The VUV data were recorded with a Sandia Labs transmission grating spectrograph, covering 1-40 nm. Plasma parameters were evaluated with incident plasma energy densities varying from 1-10 kJ/cm^2. A second transmission grating spectrograph was taken to 2MK-200 at TRINITI to study the plasma-material interface in magnetic cusp plasma. Target materials included POCO graphite, ATJ graphite, boron nitride, and plasma-sprayed tungsten. Detailed spectra were recorded with a spatial resolution of ~1 mm resolution. Time-resolved data with 40-200 ns resolution was also recorded. The data from both plasma gun facilities demonstrated that the hottest plasma region was sitting several millimeters above the armor tile surface.

94-1874C
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I. Introduction

Experimental disruption simulations have continued to be an important component of the International Thermonuclear Experimental Reactor (ITER) program.[1] We have been attempting to characterize the plasmas used in experimental disruption simulations, rather than to simply measure their effect upon candidate plasma facing component (PFC) armor tiles. The plasma-material interaction for two plasma guns was studied with vacuum ultraviolet (VUV) spectroscopy to infer plasma conditions both close to and far from the tile surfaces. The results of this work are reported in this paper.

We wished to compare detailed measured plasma conditions to those observed in computational simulations of disruptions. Such code validation would then render future code results more credible in accessing a larger parameter space. Also, there has been much controversy about the similarity of various plasma disruption simulation sources to actual Tokamak disruption plasmas.[2-4] Thus we intended to compare the plasma characteristics observed in plasma gun irradiation to those plasmas observed in pulsed electron beam irradiation experiments.

We performed measurements of VUV spectra with a transmission grating spectrograph that possessed both space- and time-resolution. One experiment centered upon the VIKA plasma gun at the D. V. Efremov Laboratory in St. Petersburg, Russian Federation. VIKA could provide 100 μsec pulses in a hydrogen plasma with energy densities from 2-100 MJ/m^2 on target. The other experiment focused upon the two-

sided plasma gun 2MK-200 at the TRINITI laboratory in Troitsk, Russian Federation. 2MK-200 exposed a larger area with a 20 μsec pulse in a hydrogen plasma with only 2 MJ/m^2 on target.

Target materials included POCO graphite, ATJ graphite, OFHC copper, plasma-sprayed tungsten, and boron nitride. None of the materials had been baked out. The spectral region covered by our spectrograph was 15-400 Å, which permitted viewing of carbon IV , V, and VI, and of oxygen VI and VII. 2MK-200 permitted use of time-resolved spectroscopy with 200 nsec resolution, along with spatial resolution of 1-2 mm at the target. VIKA permitted the use of spatial resolution on all shots, but integrated the plasma interaction in time.

Analysis of the data revealed the importance of impurities in understanding the characteristics of each plasma under study. For instance, the dominant species that appeared in the VIKA plasma gun interaction was fluorine, not the target material. Teflon insulators were contributing fluorine to the incident plasma beam from photodesorption. In the spectra on 2MK-200 impurity lines of oxygen were mixed with lines from magnesium and sodium, which apparently came from hand oils. These spectra demonstrated that some plasma sources may not be purely hydrogen sources, and that all targets in future spectroscopic studies should be cleaned well before evaluation.

II. Transmission Grating Spectrograph Geometry

These experiments utilized very fine gold transmission gratings that were fabricated in the laboratory of Prof. Henry I. Smith in the Physics Department of Massachusetts Institute of Technology. The grating d-spacings were 2000 Å and the grating thicknesses were 2200 Å. (This latter dimension made measurements near 100 Å difficult, because of phase interference effects near the gold O-shell edges.)

Grating heights were 10 mm, which permitted the use of a spatially-resolving slit. Target plasmas were imaged in the plane normal to the target surface. This permitted a recording of the plasma spectra from 15-400 Å as a function of vertical distance from the target surface. In addition a 100 μm slit was placed perpendicular to the imaging slit to maximize spectral resolution.

Figure 1 demonstrates the orientation of the grating, the dispersion slit, the imaging slit, the collimating slit, and the target. The collimating slit and the dispersion slit defined the angular view of the spectrograph. This in turn established the spectral resolution of the dispersed data. A lack of certainty of signal strength motivated the choice of relatively large collimation slits (300-500 μm) and reduced spectral resolution (~3-4 Å) in these experiments. Future experiments will operate with smaller collimating slits

~100 μm and resolutions of ~1 Å. The imaging slit could be moved, permitting observation of as little as 0-2 cm above the target to as much as 0-7 cm above the target.

Time integrated data were recorded on Kodak 101 film that was developed with standard procedures.[5] The results were digitized on a Perkin Elmer PDS Microdensitometer with 58 μm spatial resolution at the film. Spectra could then be measured at varying heights off the target to infer plasma temperature as a function of distance from the target surface.

In addition time resolved data was obtained by utilizing a gold-coated single-stage gated microchannel plate (MCP) intensifier supplied by the TRINITI laboratory. The MCP replaced the Kodak 101 film and provided 200 nsec gating at five different times during the 20 μsec pulse of 2MK-200. Thus we were able to obtain time- and space-resolved data at the 2 MJ/m^2 energy density that 2MK-200 could produce.

Second order contributions of 10-25% were clearly visible in the data recorded during these experiments. While, theoretically, even orders should be excluded in these equal bars and spaces gratings, in fact the non-rectangular cross-sections of the grating bars, and their somewhat irregular spacing often results in significant even order contributions.[6] Thus higher order effects were estimated and removed from most data prior to analysis.

III. Experiments performed on VIKA

The VIKA plasma gun operated in the deflagration mode, producing a plasma beam via **J x B** forces that moved towards the target with velocities corresponding to 100 eV energies. A rapid gas valve puffed hydrogen into the coaxial gun chamber just prior to discharge. Charging voltages were varied from 2-4.7 kV, producing incident energy densities on target of 6-100 MJ/m^2 over a 1.3 cm FWHM spot in 100 μsec. Figures 2 and 3 show the profiles of energy on target and of the incident electron density. The electron density profiles were obtained with a Mach-Zehnder interferometer using a HeNe laser, and by assuming azimuthal symmetry. Energy profiles were obtained with a ballistic calorimeter, optical spectroscopy, and interferometry.

Pressure measurements and optical measurements indicated that directed velocities of the plasma incident upon the target was 100 eV. VUV spectroscopic data indicated that fluorine was contaminating much of the discharge. This was found to derive from photo-induced erosion of Teflon insulators around the electrodes. Spatially resolved optical spectra showed CF_2 in the incident beam. By using the imaged spectral data, and by assuming that the total hydrogen mass on target was the same at all voltages, an estimate could be made of the fractional energy contribution of the two species.

Fifty eight shots were recorded with targets that included POCO graphite, OFHC copper, plasma sprayed tungsten (1mm thick) on copper, and no target. Some shots were overlaid on the same film, but no blurring of the spectra were noticed.

The spectra on VIKA were not suitable for inference of the target plasma conditions. As seen in Figure 4, spectra recorded at the same intensity, but with different targets had the same form. All lines observed were identified as fluorine and low ionization levels of carbon. No target spectra were ever confirmed in VIKA spectra. Recent experiments suggest that the VIKA-generated target plasma is at low temperature due to the low incident ion energy (~100 eV). No evidence of CV or CVI was observed here, as was later seen on 2MK-200, a source of more energetic ions.

As intensity on target was increased, increased ionization stages of fluorine were observed (Figure 5), but still no spectra were seen from the original target plasma. Target plasma was clearly being generated as evidenced by the significant erosion observed after several shots in the same area of a target. Yet most observed lines corresponded to FVI, FVII, and FVIII, not carbon or tungsten.

IV. Experiments on 2MK-200

2MK-200 at TRINITI consisted of a two-sided deflagration plasma gun with two magnetic cusps to filter out heavy ions from the incident plasma beam. A deuterium plasma discharge was forced down two ~10 meter drift tubes contained by a solonoidal magnetic field. Each plasma beam was directed from opposite ends of the tube towards the middle where the two cusp fields lay. The light ions of deuterium were deflected into the cusp while heavier impurity ions continue down the drift tube. This resulted in an incident plasma of pure deuterium with temperatures of ~1 keV and a density of ~1 x 10^{16} cm^{-3}, yielding an on-target energy density of 2 MJ/m^2. The cusp radius was 35 cm with peak pressure reached at a radius of 18 cm over a width of 2 cm in a pulse lasting 20 μsec.

Thirty four shots were taken, eleven of which were time-resolved with the TRINITI gated microchannel plate intensifier. Targets included ATJ graphite, POCO graphite, plasma-sprayed tungsten (1 mm thick) on copper, and bulk boron nitride. The spectra on 2MK-200 were unaffected by the impurity problems observed on VIKA. All observable lines appeared to arise from the target, rather than the incident plasma. Null shots, i.e. shots with no target present, showed a trace contribution from carbon, which may have come from the cusp walls at late time, rather than from any incident plasma.

Tokamak disruptions are rarely shorter than 100 μsec, and the short 20 μsec pulse of 2MK-200 has always been used to criticize its credibility as a disruption simulation testbed. The relevant question is thus: is 20 μsec sufficient time to stabilize an outgoing flow of ablated plasma? The question was answered by our time-resolved spectra.

By 8.2 μsec material on the surface has been ablated and formed a plasma of several eV (required to ionize to C IV and O VI). After nine microseconds, a strong C V signal appeared, indicating a rise in plasma temperature to several tens of eV. A barely resolved C VI signal at 33.7 Å confirmed the existence of 20-40 eV temperatures, much higher than previously expected. These data represent the penetration of a radiation wave into the material, heating the surface as more plasma is incident from above. One should note that these temperatures are being formed with only 2 MJ/m^2 incident, suggesting that energy density is not the appropriate parameter with which to scale disruption effects.

The evidence of this data is that the disruption simulated plasma is well formed by 8-10 μsec and can be used to estimate the erosion from a longer disruption pulse. However, the spectrally-observed heating effects ended at 14.7μsec rather than at 20μsec. This should be taken into account when comparing net erosion on 2MK-200 to simulators of longer duration.

The TRINITI lab has performed extensive measurements of plasma characteristics with time-resolved laser interferometry and time-resolved optical spectroscopy. One of their data on graphite appeared as seen in Figure 6.[7] Other data showed that these profiles stabilized at approximately twice the density of this figure at a time of 4.5 μsec. This information combined with the time-resolved spectra showed that while the density profile was set up early, the heat wave from the incident disruption plasma moved through to the target plasma on a longer time scale, releasing cool debris early and warm debris in high ionization stages at later times.

V. Discussion and Conclusions

The use of VUV spectroscopy has elucidated the presence of impurities, the spatial extent, and the temporal dynamics of plasma gun disruption simulators. Such simulators have been shown to be ITER equivalents even at short pulselengths. This work confirmed prior speculation that the relevant parameter in driving material erosion was not energy density, but instead was power density. It was power that determined plasma temperature and that resulted in increased ablation velocities and erosion. It was power that fueled the hydrodynamic impulse that shocked beryllium and graphite armor samples on PLADIS at the Univ. of New Mexico.[8] The peak power in both VIKA and 2MK-200 was 1-20 x 10^7 W/cm^2.

Spectroscopy on VIKA was difficult to interpret because of the presence of fluorine in the incident plasma, apparently photodesorbed from internal insulators of Teflon. It was possible that the relatively high Z plasma was opaque to the carbon and oxygen radiation from the graphite target. Optical emissions from carbon IV were clearly observed, but we were unable to detect any VUV emissions in the 20-300 Å region. The

lower temperature of the incident plasma (100 eV compared to the 1 keV 2MK-200 plasma) may have resulted in lower levels of ionization of target material in VIKA. The concomitant long characteristic wavelengths would experience a higher opacity in the incident plasma. Target erosion took place at similar rates between these two plasma gun simulators, indicating that similar energy was reaching our targets.

The 2MK-200 plasma was elementally more pure and only showed the presence of atomic species that originated from the target. Much oxygen appeared at early times in graphite irradiation, probably from entrained water. None of the target samples had been baked out prior to use. Time integrated shots taken with boron nitride showed bright lines of B V, B IV, N V, and N IV, demonstrating that the spectra were real and not the artifacts of the recording process.

Time resolved data demonstrated the progression of a heat wave through the ablating plasma. Temperatures were inferred to be in the 20-40 eV range in order to produce the high levels of ionization observed in both graphite and boron nitride. These species only appeared near the peak of the power pulse, as would be expected. The interaction plasma in 2MK-200 extended at least 40 mm above the surface of the target.

The results of this work indicated that both plasma guns could simulate the effects of a disruption in ITER, but that the purity of the magnetically swept 2MK-200 gun was far higher. Simulator pulselength was found to be less important than simulator power on target. The VUV emissions from the plasma interaction at the surface appeared to be a useful signature for that simulator and would be usefully applied to other sources, such as, electron beam and laser sources. Finally, these results contained detail sufficient to provide useful comparisons with code predictions.

Future work in this area will use a redesigned grating spectrograph to improve spectral resolution by a factor of three to four. This should permit the inference of plasma temperature from isolated lines as a function of height above the target surface. Studies will be made to reduce the effect of insulator impurities in the linear VIKA-type of plasma gun. PLADIS has a similar design to VIKA, but uses lexan insulators rather than teflon. Thus a future spectroscopic study of PLADIS will also aid in evaluating the utility of this gun for disruption simulation.

VI. Acknowledgments

The authors wish to thank the many individuals who supported and aided us in producing the data of this report. They include Dr. Y. Prokofiev , Dr. V. Litunovsky, and the members of the VIKA team at the D. V. Efremov Scientific Research Institute of Electrophysical Apparatus in St. Petersburg, RF, Dr. S. Tserevitinov, Dr. Y. Skvortsov, and the 2MK-200 team of the TRINITI laboratory of Troitsk, RF, and Dr. R. T. McGrath of Sandia National Laboratories in the US.

This work was supported by the Department of Energy under Contract #DE-AC04-94AL85000.

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List of Figures

4. Comparison of VUV spectra of POCO Graphite and Tungsten at 60 MJ/m^2. Note the similarity of signals and the lack of any features unique to either target type.

5. Comparison of VUV spectra of POCO Graphite at two different incident plasma gun intensities. Note the higher stages of ionization of fluorine in the higher intensity interaction.

6. Time-resolved laser interferometry recorded this sequence of electron density profiles above a graphite target on 2MK-200.

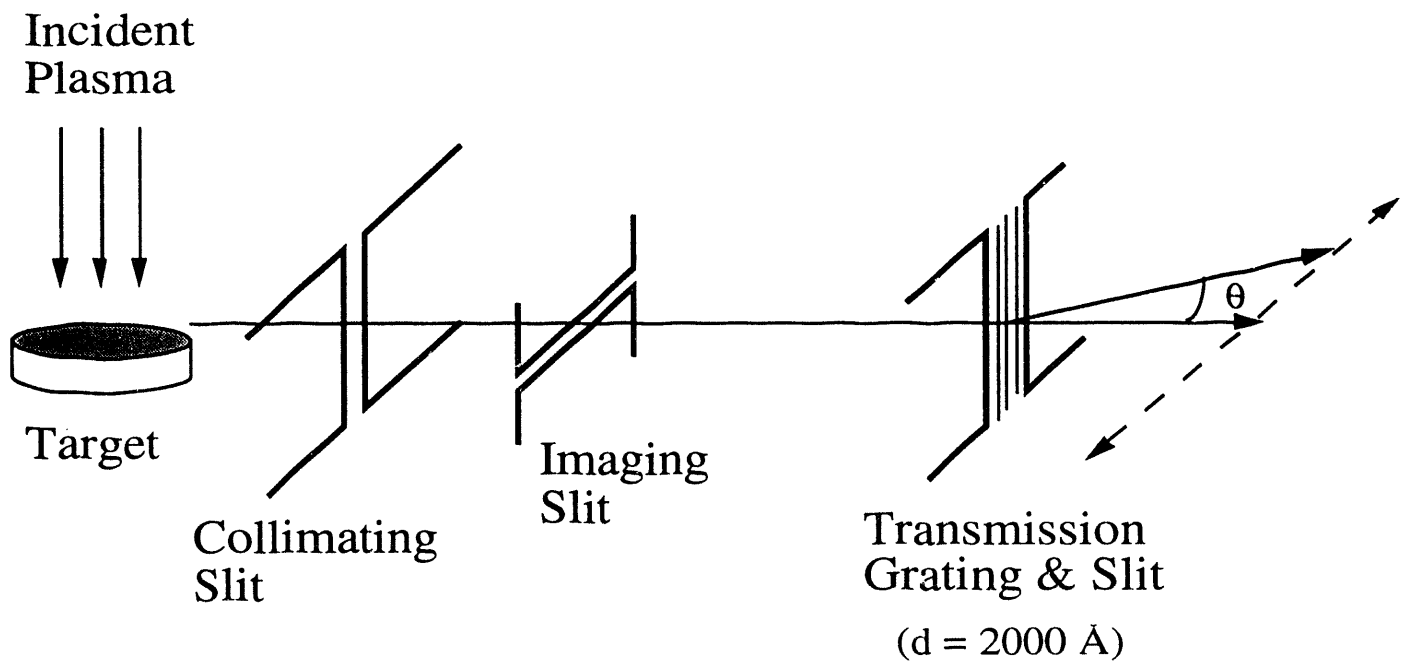
Incident
Plasma
Target
Collimating
Slit
Imaging
Slit
Transmission
Grating & Slit
(d = 2000 Å)
θ

Figure 1

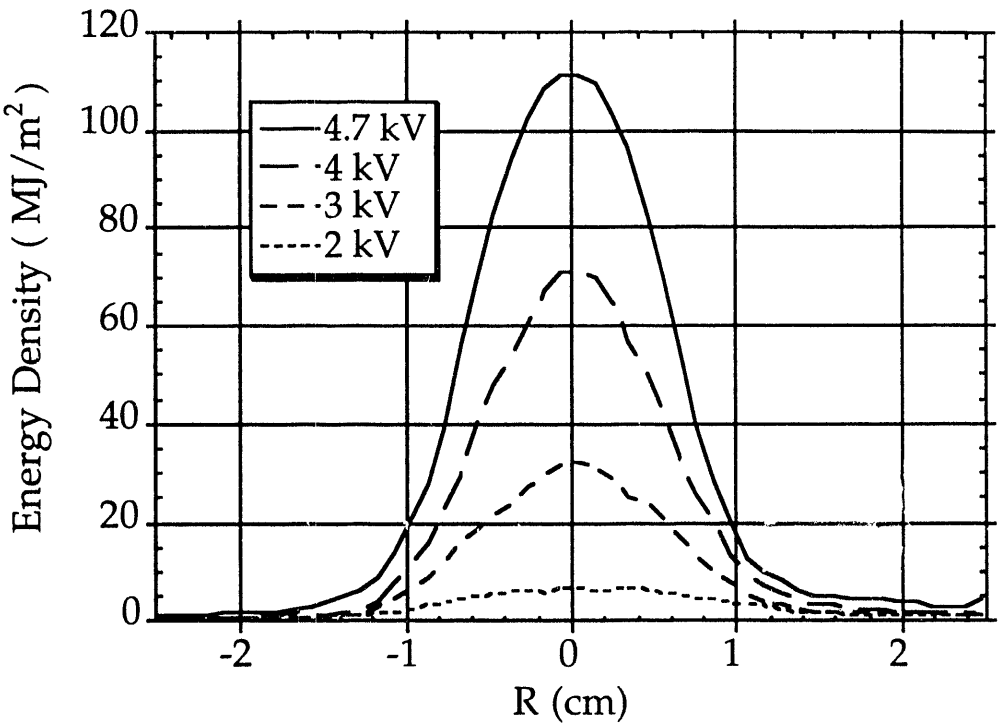
120
100
80
60
40
20
0
-2
-1
0
1
2
Energy Density (MJ/m^2)
R (cm)
4.7 kV
4 kV
3 kV
2 kV

Figure 2

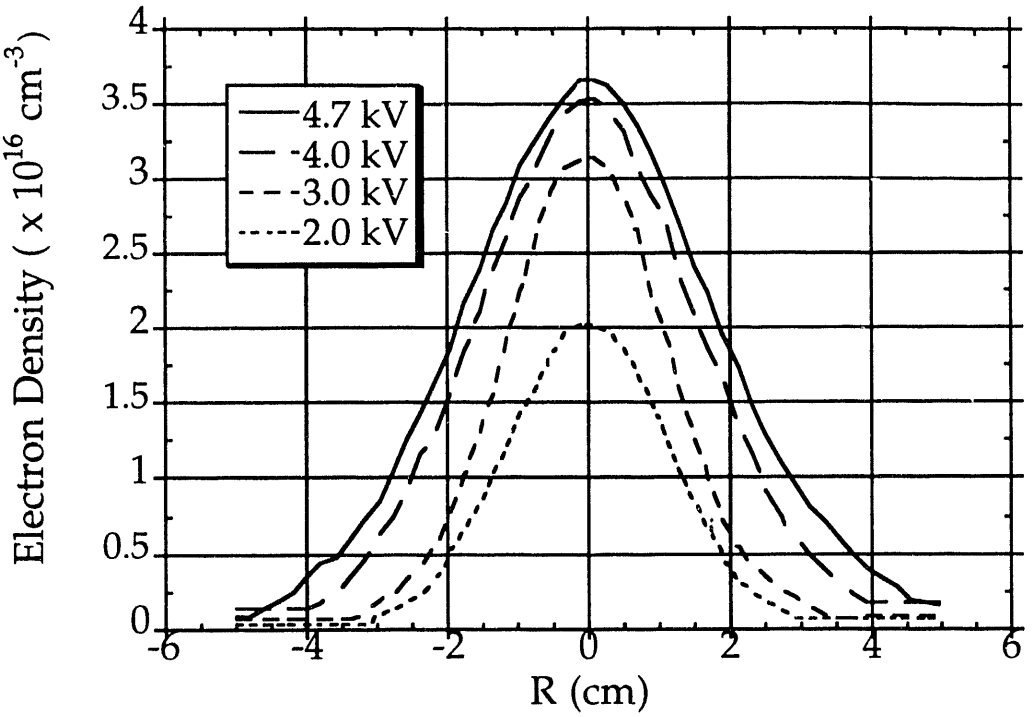
Electron Density (x 10^16 cm^-3)
4
3.5
3
2.5
2
1.5
1
0.5
0
-6
-4
-2
0
2
4
6
R (cm)
4.7 kV
-4.0 kV
-3.0 kV
-2.0 kV

Figure 3

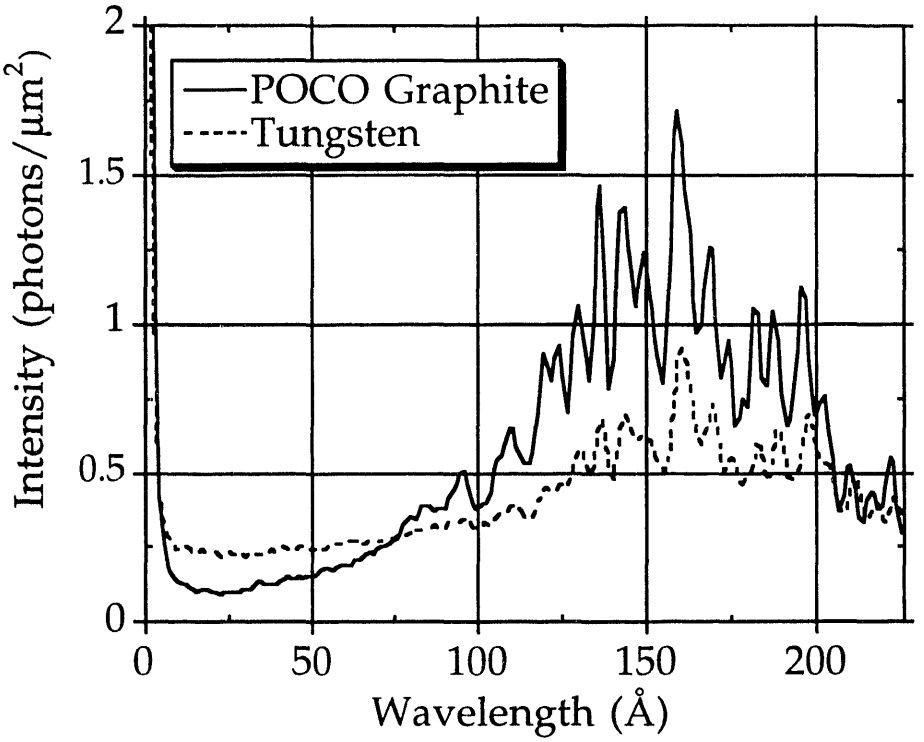
POCO Graphite
Tungsten
Intensity (photons/μm²)
Wavelength (Å)
0
0.5
1
1.5
2
0
50
100
150
200

Figure 4

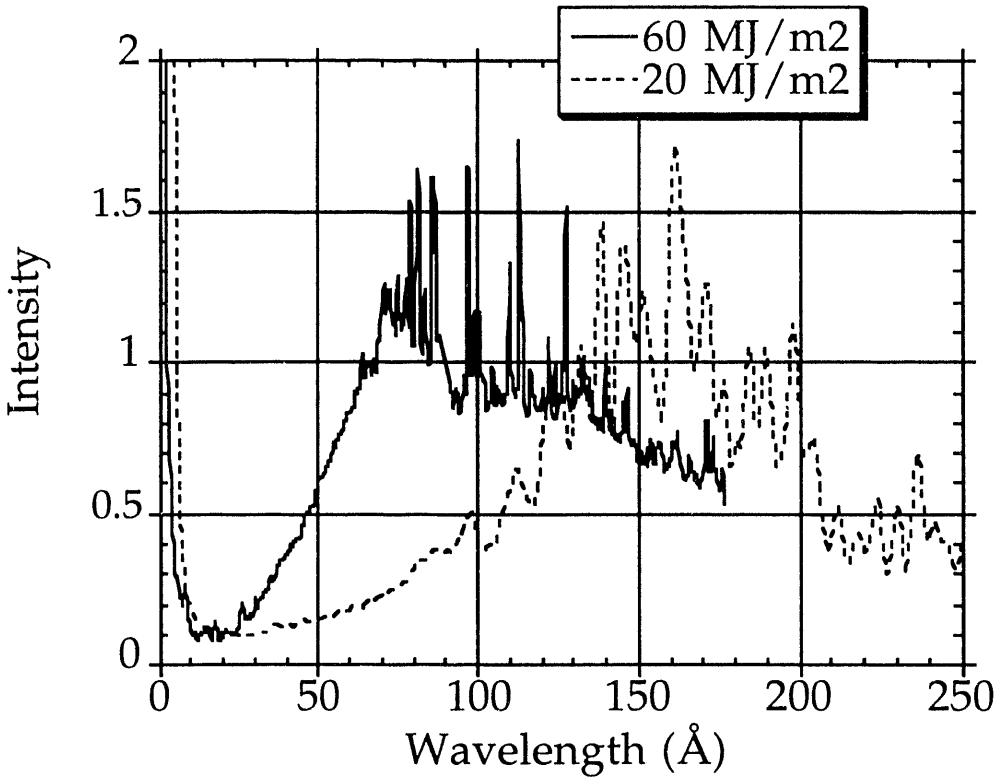
60 MJ/m2
20 MJ/m2
Intensity
2
1.5
1
0.5
0
0
50
100
150
200
250
Wavelength (Å)

Figure 5

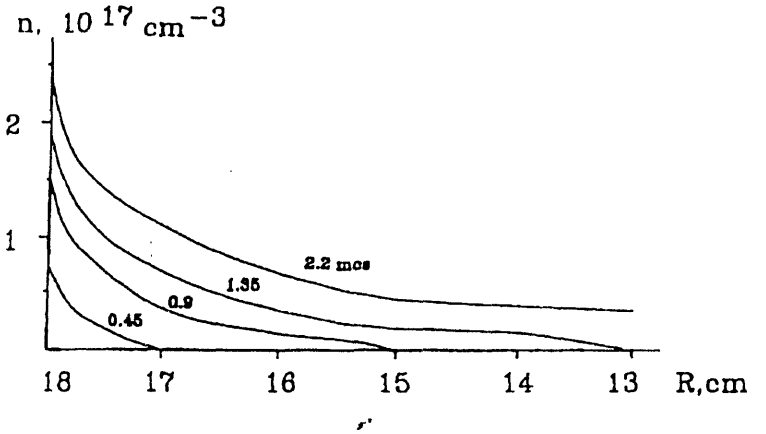

Fig. 17 Electron density distribution in front of graphite sample (R – CUSP radius).

Figure 6

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