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RADIATION TRANSPORT EFFECTS IN DIVERTOR PLASMAS GENERATED DURING A TOKAMAK REACTOR DISRUPTION

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ABSTRACT

Vaporization of material from tokamak divertors during disruptions is a critical issue for tokamak reactors from ITER to commercial power plants. Radiation transport from the vaporized material onto the remaining divertor surface plays an important role in the total mass loss to the divertor. Radiation transport in such a vapor is very difficult to calculate in full detail, and this paper quantifies the sensitivity of the divertor mass loss to uncertainties in the radiation transport. Specifically, the paper presents the results of computer simulations of the vaporization of a graphite coated divertor during a tokamak disruption with ITER CDA parameters. The results show that a factor of 100 change in the radiation conductivity changes the mass loss by more than a factor of two.

I. INTRODUCTION

The vaporization of material from tokamak divertors during disruptions is a potentially serious problem in the design of a tokamak reactor. For example, the ITER CDA estimated a peak energy fluence to the divertor of 1200 J/cm^2 during a thermal quench.[1] The ITER EDA attempts to avoid disruptions,[2] but the divertors should be designed with some attention paid to disruptions. In a thermal quench, the disruption energy reaches the divertor or other Plasma Facing Component (PFC) in the form of energetic hydrogen ions. The deposition occurs in a low enough areal density in the divertor material that, after the initial vaporization, the divertor is protected from the direct effects of the ions by the vapor. The divertor is, therefore, self-shielding. However, the vapor is heated by the deposition to the point that it can radiate energy to the divertor and heat the surface enough to vaporize more material,[3,4,5] as is depicted in Fig. 1. Since the range of the ions in the material is so short, if the radiation transport of energy to the surface is slow enough that no more vaporization occurs, the surface will lose less than 1 μm of material per thermal quench. If there is enough re-radiation of energy to the divertor, the divertor may experience excessive material loss. It is therefore very important to accurately calculate the physics of radiation emission and transport in the vapor plasma.

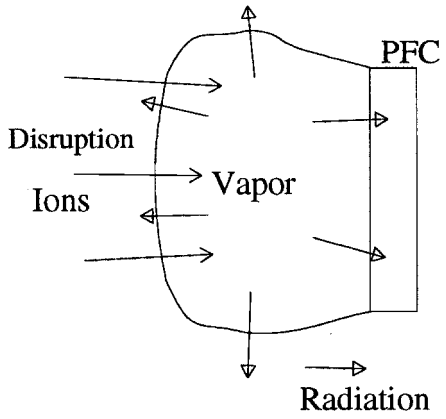

Fig. 1. Schematic of vaporization by disruption ion deposition in the vapor and reradiaton to the Plasma Facing Component.

Radiation transport is calculated in Cartesian coordinates with the transfer equation:[6]

$$\frac{1}{c}\left(\frac{\partial I_\nu}{\partial t}\right) + \vec{n}\cdot\vec{\nabla} I_\nu = \eta_\nu - \chi_\nu I_\nu. \qquad (1)$$

TABLE I

Parameters for Sample ITER CDA Problem

Geometry	Cylindrical
Radius (cm)	339
Initial plasma density (cm^{-3})	1×10^{13}
Divertor coating material	Graphite
Coating thickness (cm)	0.1
Temperature of back of coating (K)	773
Dirsuption ions	5 keV DT
Disruption fluence (J/cm^2)	1200
Disruption pulse width (ms)	0.1

Here I_ν is the spectral intensity of the radiation at frequency ν, χ_ν is the opacity coefficient, and η_ν is the emission coefficient. A great deal of atomic physics determines the crucial parameters χ_ν and η_ν. The populations of ionization and excited states can have important effects and even for a given state, the calculation of the energy levels and transition probabilities can be difficult, especially at higher atomic numbers. If the medium for transport (in this case the vapor) is cold enough, molecules can be present that greatly change the opacity.[7] These complications in the atomic physics lead to uncertainties in the transport parameters. In this paper, we present computer simulations that will test the sensitivity of the self-shielding effect of the vapor to changes in the opacity of the transport medium.

II. DESCRIPTION OF SAMPLE PROBLEM

A sample problem has been chosen to test the sensitivity of the vaporization of divertor material during a tokamak disruption thermal quench. We have tried to approximate the ITER CDA design as a cylinder 339 cm in radius. The parameters for this sample problem are listed in Table I. We assumed a 1200 J/cm^2 disruption thermal quench of 5 keV deuterium and tritium ions (fully ionized) in a flat top pulse 0.1 ms long. We assumed that these ions leave the center of the tokamak, which is a DT plasma at a density of 1×10^{13} cm^{-3}. We assumed that the divertor is made of some good conductor that is at a constant temperature of 773 K. This is coated with a layer of graphite 0.1 cm thick. The properties we have assumed for this material are consistent with H-451 graphite and are shown in Table II. We did not have any data for the Grueneisen coefficient and assumed that it is 1.0. Graphite does not melt, but sublimes and has no melting temperature. The other properties come from a number of standard references [8,9].

TABLE II

Properties of Graphite

Atomic number	6
Solid density (g/cm^3)	2.27
Initial density (g/cm^3)	1.80
Bulk modulus (MPa)	7900
Grueneisen coefficient	1.0
Lattice separation energy (J/g)	5.98×10^4
Debye temperature (eV)	0.2137
Vaporization temperature (K)	3922
Heat capacity (J/g/eV)	8240
Latent heat of vaporization (J/g)	5.973×10^4
Thermal conductivity (W/cm/eV)	1.55×10^4

III. COMPUTER CODES

Simulations have been performed with the CONRAD[10] computer code, which is a one-dimensional Lagrangian radiation-hydrodynamics code with x-ray and ion energy sources. CONRAD has been developed at the University of Wisconsin and used in several fusion plasma applications. Vaporization and condensation phenomena on a surface are modeled in the code. Radiation transport is calculated with a one-dimensional multigroup flux-limited diffusion method. Equations of state and opacities are interpolated from tables that are either supplied by the IONMIX[11] computer code, by the EOSOPC[12] computer code, or from the SESAME[13] tables. CONRAD also can calculate equations-of-state internally with models that are valid at solid and higher densities using a method used in the ANEOS[14] subroutines used in several codes at Sandia National Laboratories. The EOSOPC code can produce opacities that are valid for high density and high atomic numbers and is used in calculation of carbon opacities for the simulations discussed in this paper. The equations-of-state for these materials are calculated with the ANEOS methods that include lattice separation energies and electron degeneracy effects, and where the material pressure is zero when the material is cold and exactly at solid density. CONRAD has a single plasma temperature, and therefore assumes that the electrons and ions are at the same temperature. Time-dependent disruption ion spectra are used. Ion deposition is calculated in CONRAD with a modified Mehlhorn model,[15] that is valid to low particle energies. The charge state of the disruption ions is calculated in flight.

In radiation diffusion, the radiation transport model used in the CONRAD simulation presented

here, the opacity χ_ν is assumed to be large enough that radiation mean free path is small compared to the typical length scale for the transport medium. Under these condition, the radiation flow is approximately isotropic because photons undergo a random walk and they are continually emitted and absorbed in the medium. The time derivative term in the transfer equation is ignored and Eqn. 1 can be manipulated to yield a diffusion-like equation for the radiation flux[6], $\vec{F_\nu}$:

$$\vec{F_\nu} = -K_{R\nu}\vec{\nabla}E_{R\nu}\,. \qquad (2)$$

$K_{R\nu}$, the frequency dependent radiation conductivity, equals $c/(3\rho\sigma_{R\nu})$, where $\sigma_{R\nu}$ is the Rosseland opacity, c is the speed of light, and ρ is the mass density of the transport medium. $E_{R\nu}$ is the radiation energy density. This method is not valid if $\sigma_{R\nu}$ is small enough for any ν that the optical depth of the vapor for that frequency is less than unity. This situation is most likely to occur for ν correponding to atomic lines, and in that case lines should be removed from the spectra and transported separately. Even in the case where the whole spectrum is optically thick, it is not alway clear how the radiation conductivity should be calculated. In multigroup diffusion transport, $\sigma_{R\nu}$ must be averaged over a photon energy group. The lines and the continuum have absorption coefficients that differ by several orders of magnitude, making the averaging over the groups a problem. The Rosseland opacity is calculated with a method that more heavily weights low absorption parts of the spectrum in the group average, and is therefore often used to calculate transport. Other ways of performing the average will give different group opacities. Therefore, the choice of averaging method leads to an uncertainty in the group opacities in addition to the uncertainties in the basic atomic physics. In this study, we test the sensitivity of the vaporization of material from a divertor to variations in the group opacities by comparing results using the Rosseland opacities, as we calculate them with EOSOPC,[12] with the results where the opacities are arbitrarily multiplied and divided by ten.

The disruption plasma is treated as a beam of deuterium and tritium ions emanating from the center of a cylinder. The ions are assumed to be hydrogen with an atomic mass of 2.5 amu's at an energy of 5 keV. The ions are created within a pulse width that is defined by a piecewise linear function of time. The ions are parceled into packets, one packet for each source energy, species, and source time interval. The packets travel from the center outward toward the divertor, their current ion energies determined by energy deposition losses and their velocities determined by their current ion energies. The packets exist until they have spent all of their energy. As the ions deposit energy, they give energy and momentum to the medium in which they are depositing; they do not deposit mass. The mass of the source ions is ignored in CONRAD.

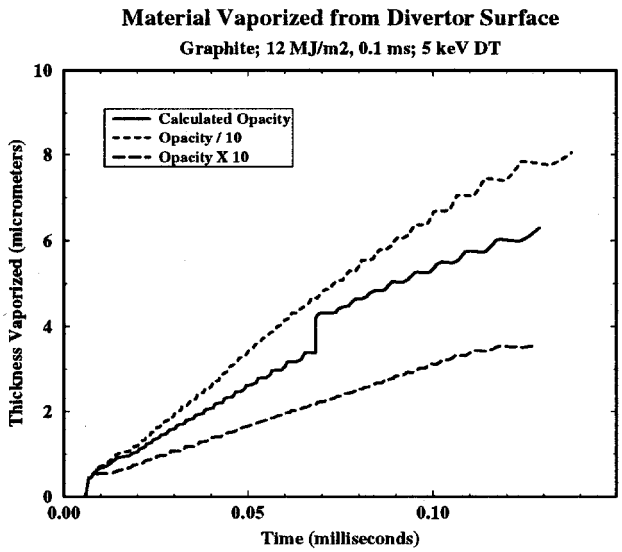

Fig. 2. Material vaporized from the surface of a divertor coated with 1 mm of graphite during a 1200 J/cm^2 disruption. The ablated thickness is shown as a function of time.

TABLE III

Results of CONRAD Simulations

Rosseland opacity	Calc.	/10	×10
Ion energy (J/cm^2)	1200	1200	1200
Vapor mass (mg/cm^2)	1.42	1.82	0.804
Thickness vaporized (μm)	6.28	8.05	3.56
Energy reradiated to surface (J/cm^2)	394	474	333
Run time (ms)	0.13	0.14	0.13

IV. RESULTS

The results of the three simulations are shown in Figs. 2 through 4 and in Table III. The three CONRAD runs all followed the evolution of the dirsuption vapor until after the disruption ion deposition was complete (1.3 ms, 1.4 ms and 1.3 ms respectively), which corresponds to 150000 time steps and required several hours on a workstation. By the ends of these runs, the case where the opacity/10 showed the greatest surface erosion (8.05 μm) and the opacity ×10

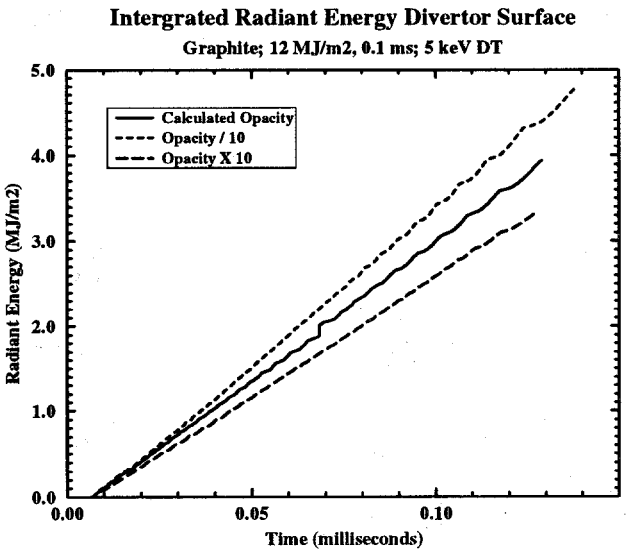

Fig. 3. Time-integrated re-radiated energy on the surface of a graphite coated divertor versus time during a 1200 J/cm^2 disruption thermal quench.

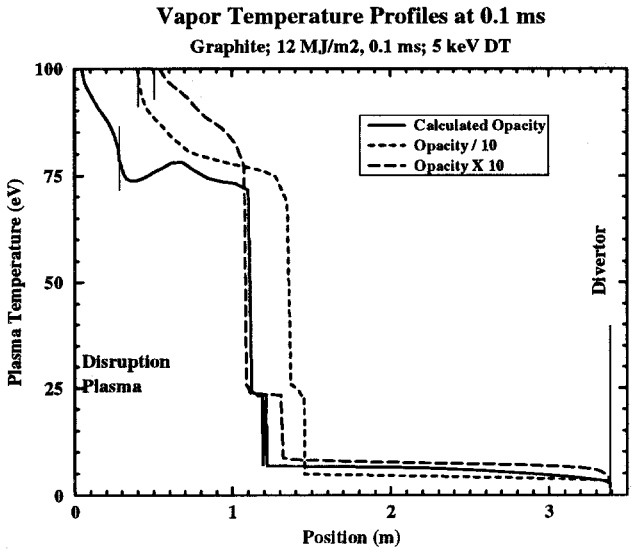

Fig. 4. Plasma temperature profiles at about 0.1 ms in the vapor in front of a graphite coated divertor during a 1200 J/cm^2 disruption thermal quench.

case showed the least (3.56 μm), with the calculated opacity case in between (6.28 μm). The thickness of divertor material is shown in Fig. 2 as a function of time. The material loss rate drops for all three cases after the end of ion deposition, but it does not vanish because the vapor continues to emit radiation, as is shown in Fig. 3. The low opacity case has a greater rate of re-radiation to the surface and therefore erodes more material than the higher opacity cases. The highest opacity case seems to have reached the point where the re-radiant power has dropped enough that thermal conduction in the material can keep the surface temperature low enough that the erosion has almost stopped. There is an unexplained rapid vaporization in the case using the calculated opacity at about 0.07 ms. We do not believe that this is a true result, but is a minor error in that run that we have yet to trace. The radiant energy to the surface does not vary by a factor of 100 between the high and low opacity cases, even though the radiation conductivity does. The results are less than linearly proportional to the opacity because the vapor temperature profiles, shown in Fig. 4, are not the same for all three cases. The radiation emission profiles will also be different for the three cases. In Fig. 4, the vapor temperature profiles are plotted at the time of the end of the ion deposition, about 0.1 ms. Actually the high, medium, and low opacity results are plotted at 0.098 ms, 0.10 ms, and 0.095 ms. The vertical marks on each profile between 30 and 50 cm represent the boundary between the vapor and the original tokamak plasma. The profiles have a very hot region of the vapor nearest the disruption ion source, due to the ion deposition in the vapor. The high opacity calculation has the hottest ion deposition region in the vapor, which is due to the lower rate that energy is carried away by radiation and also keeps the radiation emission rate higher. This high emission rate in part counteracts the lower radiation conductivity, causing less of a difference between the high and low opacity calculation than one would expect purely on the basis of the difference in the radiation conductivity.

V. CONCLUSIONS

We have performed computer simulations of the vaporization of tokamak divertor material during a disruption thermal quench for the ITER CDA parameters. The simulations varied the radiation conductivity to study the sensitivity of the vaporization of material to the particulars of the radiation transport. We have found that a factor of 100 decrease in the Rosseland opacity increases the amount of vaporization by more than a factor of two. The vapor temperature profiles are modified by the change in opacity, which make the effect on the vaporization less than one would have initially thought. In other studies,[16] line transport has been seen to greatly change the radiant heat transfer out of a plasma with similar temperatures and densities. This could be even more important than the effect of correct group opacity cal-

culations shown here.

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