MODELLING MULTI-ION PLASMA GUN SIMULATIONS OF TOKAMAK DISRUPTIONS

by

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FUSION POWER PROGRAM

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Fusion Power Program/Technology Development Division**

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David A. Ehst

ABSTRACT

The effect of impurity ions in plasma gun ablation tests of various targets is considered. Inclusion of reasonable amounts of impurity (~10%) is adequate to explain observed energy transmission and erosion measurements. The gun tests and the computer code calculations are relevant to the parameter range expected for major disruptions on large tokamaks.

1. Motivation for Model Improvements

Recent experiments [Bolt] have confirmed earlier studies [Suzuki] which showed that the source plasma provided by a plasma gun may be an important self-shielding entity - a dense cloud of "recycled gas" - which serves as a dominant vapor shield to protect the plasma gun target from the high power incident heat pulses. Indeed, this self shielding occurs even in the absence of target ablation; so the transmitted energy density is greatly attenuated, even below the threshold for target material erosion. Such behavior already has been included in the vapor shield physics models [Ehst] included in the DESIRE computer code.

The major defect in the earlier version of DESIRE was the restriction to a pure hydrogen source plasma. This limited the code's application to cases with typically low incident proton energies, $E_{H_0} \lesssim 50$ eV. At higher kinetic energies hydrogen is fully stripped and the photon radiation of this plasma is so low that radiation transport to the target surface is unrealistically small. In fact, real plasmas always have impurities which strongly radiate, even at much higher temperatures. This report describes the inclusion of non-hydrogen ions in the source mixtures modelled by DESIRE. Comparisons with plasma gun experiments show good agreement with the measured data of the improved DESIRE code.

2. Model Improvements

The new version of DESIRE includes up to three atom species in the source plasma. The source opacity at each wavelength is the sum of the opacities of the component species, weighted by the density of each species. The opacity is calculated [Ehst] with three contributions to photon emission and absorption: free-free, free-bound, and electron-atom Bremsstrahlung. Likewise, multiple species are included in the computation of the vapor's heat capacity. At low temperature ($\theta \lesssim 1$ eV) the vapor is only partly ionized, while at higher temperature the plasma becomes fully ionized. However, at a given temperature the charge state differs for various species, depending on the respective ionization potentials of the species. The code computes the average charge state for each species, in equilibrium at a given temperature. The vapor's heat

capacity is the sum of the free electron and ion kinetic energies and the density-weighted sum of the ionization energy input to form each average charge state.

The appropriate average charge state for each respective species is used in the calculation of the free-bound opacities. Moreover, DESIRE now retains six charge states in the free-bound opacity. For example, Al vapor at ~50 eV with $Z_{av} = 8.2$ contains charge states $Z = 6$ through $Z = 11$. The relative density of charge states is determined by Z_{av} and the six contiguous ionization potentials [Zeldovich]. Typically only the nearest states to Z_{av} have substantial densities, the farther populations being exponentially small.

A tremendous simplification in the analysis occurs by our neglect of detailed calculations of bound-bound contributions to opacities. Thus, our radiation transport considers only continuum radiation and ignores lines. While this at first appears to be a somewhat cavalier treatment, this approximation is in fact very reasonable for many cases of interest. For example, the spectral emission intensity of the source vapor of thickness Λ_s is $e_s(\lambda) = B_s(\lambda) [1 - \exp(-\alpha_s \Lambda_s)]$, where $B_s(\lambda)$ is the black body spectral emissivity at the source temperature and $\alpha_s(\lambda)$ is the source absorption coefficient at each wavelength. For many plasma gun tests (and for ITER-relevant disruptions) the source plasma density is large ($\gtrsim 10^{25} \text{ m}^{-3}$), and the source plasma depth is thick ($\gtrsim 1 \text{ cm}$); and in these cases the computed continuum optical depth is $\alpha_s \Lambda_s \gg 1$, except at very short λ where $B_s(\lambda)$ is exponentially small. In these cases the source vapor is already opaque - nearly a black body - from continuum radiation alone. No significant improvement in accuracy can be achieved by including cumbersome line radiation calculations. This neglect of line radiation is monitored by DESIRE at each time step in the calculation; in general our treatment is accurate, except for typically short initial periods ($\lesssim 10 \mu\text{s}$), when the source and target vapors are still at low density and relatively transparent.

An example of the opacity of an argon/sodium vapor at $\theta = 10 \text{ eV}$ is shown in Fig. 1. The upper curve, from a detailed calculation of opacity [Peterson], displays several emission lines in addition to the continuum, whereas the lower curve is the DESIRE result. Four (recombination) absorption edges are prominent in the DESIRE curve (Ar^{+3} , Ar^{+4} , Ar^{+5} , Ar^{+6}). At the specified

temperature the density is barely above the Saha critical density, [Ehst] and the average charge states computed in DESIRE ($Z_{Ar} = 4.65$ and $Z_{Na} = 2.98$) may be somewhat low. This could account for the overall computed low value of α compared to Peterson's result (n.b., $\alpha \sim Z_{av}^3$). At very long wavelengths ($h\nu \ll 1$ eV) the DESIRE value deviates further from Peterson's since DESIRE does not correct for frequencies below the plasma frequency. Such corrections are insignificant as vapors of interest to us radiate very little power at such low photon energies. In practice DESIRE only computes radiation transfer at wavelengths where the black body factor, $B(\lambda)$, is significant; we generally consider two hundred energy groups, uniformly spaced over the interval $0 \leq h\nu \leq 20$ eV. Note in the case illustrated, for a vapor thickness $\Lambda \gtrsim 10$ cm the opacity $\alpha \Lambda \gtrsim 1$ for most photon energies less than 1 keV, so such a vapor would radiate essentially as a black body at 10 eV.

3. Comparison of DESIRE with Experiments

A variety of observable parameters may be measured in plasma gun experiments, [Ehst] including target erosion depth, vapor energy transmission fraction, and vapor thickness, temperature, density, and pressure. Transmission fraction and ablation erosion are most frequently reported in plasma gun experiments and will serve for this report to illustrate the accuracy of DESIRE calculations. The source vapor cloud thickness Λ_s is monitored, and the vapor is allowed to expand until $\Lambda_s = d_g = 0.20$ m. (We denote the distance from the gun electrodes to the target surface as d_g .) At this point a particle and kinetic energy sink turns on [Ehst] in order to account for the source plasma leakage to its surroundings, such as the gun electrodes.

Consider first erosion studies with plasma gun tests of tungsten samples. The data points in Fig. 2 show measured erosion, from mass loss, with two different working gases, Ar vs. H. The steel electrodes in the PLADIS experiment are thought to be the source of Fe impurity atoms observed in these tests [Gahl (1995)]. We model the experiments by adding a 500 eV Fe minority to the working gas. Preliminary analysis of these experiments suggests all ions emerge at approximately the same speed, so in DESIRE we select ion energies to vary roughly according to the ion mass ratios. Electron energies are always set at 1 eV in this report. (Pulse widths in all these experiments is $t_d \equiv 100$ μ s.) An

additional observation in plasma gun tests is that the impurity fraction increases at higher capacitor bank energies, so for the DESIRE calculations in this figure we selected an impurity fraction $f_{Fe} = 0.10$ at 11.5 MJ/m^2 and $f_{Fe} = 0.30$ at 15.1 MJ/m^2 . Both measured and calculated erosion indicate a material ablation loss of $\delta \cong 1 \text{ }\mu\text{m}$ at $U \gtrsim 14 \text{ MJ/m}^2$, with Ar resulting in somewhat higher values of δ . However, these energy densities are near the damage threshold for tungsten. Consequently the DESIRE result is not expected to be entirely accurate around the threshold, $U \cong 10 \text{ MJ/m}^2$.

Figure 3 shows similar data [Gahl 1992] and modelling, except with a graphite target. Again there is considerable agreement between measurement and theory. Note that the ablation threshold is lower for this target material. The similar values of measured erosion for different majority gases (Ar vs. H) are persuasive evidence that erosion is not sensitive to details of the line radiation in the emission spectrum.

Plasma guns of different construction will contribute different impurity species. Whereas PLADIS, at the Univ. of New Mexico, sees Fe contaminant, the VIKA experiment sees a carbonfluoride (CF_2) component [Bolt]. For comparison with the $U = 11.5 \text{ MJ/m}^2$ point in Fig. 4 with H (20 eV, 90%) + Fe (500 eV, 10%), for which DESIRE finds $\delta = 0.72 \text{ }\mu\text{m}$, we ran cases with minority species C (150 eV, 10%) and the mixture C (150 eV, 3.3%) + F (150 eV, 6.7%). These latter runs resulted in $\delta = 0.30 \text{ }\mu\text{m}$ and $\delta = 0.34 \text{ }\mu\text{m}$, respectively. Such a quantitative variation in erosion results with minority content should be kept in mind when comparing experimental results on different guns.

The variation of impurity content with gun energy U , is very uncertain. Figure 4 shows, for W, the variation in energy transmission fraction, T , to the target computed versus U with constant values, $f_{Fe} = 0.01$ (dashed) and $f_{Fe} = 0.10$ (solid); at the highest energy density the plot includes T values with f_{Fe} up to 0.30. Evidentially T increases with f_{Fe} , other conditions being equal. A large increase from $f_{Fe} \cong 0$ at low U to $f_{Fe} \gtrsim 0.30$ at 15 MJ/m^2 is necessary to explain the observed [Suzuki] monotonic increase of T on PLADIS - the solid points.

Figure 5 shows the measured erosion of W on PLADIS (solid triangles) as well as the calculated values of δ at $f_{Fe} = 0.01$ (dashed) and $f_{Fe} = 0.10$ (solid). Again, as demonstrated also by the open points, the calculated erosion increases with impurity content. Note how the measured erosion on a similar experiment, VIKA [Barabash], also displays increasing damage at higher U but with substantially larger measured losses. Subtle differences in experimental conditions make it difficult to exactly reproduce measured values with the DESIRE code. One important agreement among the calculations and measurements in Figs. 4 and 5 is that T remains ~ 0.10 even below the ablation threshold (i.e., for $U < 10 \text{ MJ/m}^2$), which confirms the self-shielding effect of the dense cloud of source particles [Bolt].

Calorimetry measurements were also performed on PLADIS with C targets [Suzuki], and these (solid) points are shown on Fig. 6. The DESIRE calculations show the same trend as previously, generally requiring an increase of f_{Fe} with U in order to agree with measurement. At low energy density exceptionally clean plasma gun discharges ($f_{Fe} \leq 0.01$) are calculated to expand so much ($\Lambda_s \geq d_G$) that source particle energy is predominantly lost to the surroundings. The experimental ablation depths of C vary considerably, as shown in Fig. 7, possibly due to differences in thermal conductivity and other material properties of the selected targets. (Among POCO samples there is also a factor of two difference in ablation depths between experiments on PLADIS and VIKA [Gahl 1992].) Nevertheless, it seems clear that increasing f_{Fe} with U in DESIRE reproduces the general experimental trend.

One final issue is the sensitivity of the DESIRE results to the kinetic energy of the source particles, a quantity not well known in the experiments. For both W and C targets we varied the energies of the H majority (10-50 eV) and of the minority Fe (100 eV - 1000 eV) and found that both T and δ increase with kinetic energy of either species. Yet, the increases are not as big an effect as varying f_{Fe} , the impurity concentration. As an illustration of this, Fig. 6 includes two open triangles (with $f_{Fe} = 0.03$) at $U = 15.1 \text{ MJ/m}^2$. Although an increase of kinetic energy with U is plausible, due to increasing capacitor bank voltage, this is not clearly seen in the experimental observations.

4. Conclusions

Plasma guns present considerable variation in measured results. Besides the scatter in data (Fig. 5 and 7) there is typically a factor of five or more discrepancy between the maximum crater depth from profilometry and the average depth inferred from mass loss [Gahl 1992]. Due to the simple source plasma geometry employed in DESIRE it seems appropriate to compare the average (mass loss) ablation depth with the calculated δ , as done here. Our calculations are encouraging in their reasonable agreement with measured values of T and δ , despite a general lack of detailed knowledge of the species and kinetic energy content of plasma gun sources.

We conclude that a hydrogen plus impurity mixture, as modelled in DESIRE and other disruption codes [Hassanein], can explain the results of plasma gun simulations of disruptions. The impurity concentration has an important effect on the calculated results, more so than the kinetic energies of the source particles. Both experiments and these calculations are relatively insensitive to source species (majority H or Ar; impurity Fe, C, or F) which indicates that the ionized gases are nearly black (and independent of detailed line radiation) over most of the spectrum, at the high particle densities supplied by these plasma guns.

Below the ablation threshold both experiment and calculation show the self-shielding effect - ~5% energy transmission without target vaporization. This threshold region ($U \lesssim 10 \text{ MJ/m}^2$) of energy density is of interest in present-day tokamaks which are marginal for producing disruption erosion of plasma facing surfaces; and this will be the topic of future work with the DESIRE code.

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References

H. Bolt, V. Barabash, A. Gervash et al., "Energy absorption and material damage evolution under pulsed energy deposition in a plasma accelerator," in: K.H. Spatschek, J. Uhlenbusch, Eds., Contributions to High-Temperature Plasma Physics (Akademie Verlag, Berlin, 1994) pp. 216-228.

S. Suzuki et al., J. Nucl. Mat. 200 (1993) 265.

D.A. Ehst and A. Hassanein, Argonne National Laboratory Rep. ANL/FPP/TM-268 (1993).

Ya. B. Zel'dovich and Yu. P. Raizer, Physics of Shock Waves and High-Temperature Hydrodynamic Phenomena, (Academic Press, New York, 1967) Chap. III.

R.A. Peterson and G.A. Moses, Comput. Phys. Commun. 28 (1983) 405.

J. Gahl, private comm. (1995).

J. Gahl et al., J. Nucl. Mat. 196-198 (1992) 692.

V.R. Barabash et al., Fusion Eng. and Design 18 (1991) 145.

A. Hassanein and I. Konkashbaev, J. Nucl. Mat. 220-222 (1995) 244.

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Fig. 1 Absorption coefficient vs. photon energy for $1 \times 10^{25} \text{ m}^{-3}$ Ar with $2 \times 10^{22} \text{ m}^{-3}$ Na at a plasma temperature of 10 eV; upper curve from Peterson and Moses, lower curve from DESIRE.

Fig. 2 Ablation of W by Ar and by H plasma guns (PLADIS); calculation assumes Fe impurity (10% at low energy density, rising to 30%).

H(20eV) or Ar(400eV) on C

Fig. 3 Same as Fig. 2, but for a C target.

H(20ev) + Fe(500ev) on W

Fig. 4 Measured (PLADIS) and calculated energy transmission fraction with a W target; calculation assumes various Fe impurity concentrations.

H(20eV) + Fe(500eV) on W

Fig. 5 Measured and calculated erosion depth with a W target; both PLADIS and VIKA experiments are reported.

H(20eV) + Fe(500eV) on C

Fig. 6 Same as Fig. 4, but for a C target.

H(20eV) + Fe(500eV) on C

Fig. 7 Measured and calculated erosion depth with a C target; various graphites are reported experimentally from PLADIS.

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