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**THERMAL ABLATION OF PLASMA-FACING SURFACES IN TOKAMAK
DISRUPTIONS: SENSITIVITY TO PARTICLE KINETIC ENERGY**

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Thermal Ablation of Plasma-Facing Surfaces in Tokamak Disruptions: Sensitivity to Particle Kinetic Energy

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ABSTRACT

Ablation damage to solid targets with high heat flux impulses is generally greater for high-energy electron beam heat sources compared to low-energy plasma guns. This sensitivity to incoming particle kinetic energy is explored with computer modelling; a fast-running routine (DESIRE) is developed for initial scoping analysis and is found to be in reasonable agreement with several experiments on graphite and tungsten targets. If tokamak disruptions are characterized by particle energies less than ~ 1 keV, then we expect plasma guns are a better analogue than electron beams for simulating disruption behavior and testing candidate plasma-facing materials.

I. Particle Energy - Effect on Thermal Erosion

Both electron beams ($\lesssim 100$ keV) and plasma guns (plasma energies $\lesssim 100$ eV) have served as convenient test stands to examine thermal damage to candidate target materials in experimental simulations of high-heat-load tokamak disruptions. Both types of heat source can readily supply energy densities of several megajoules per square meter in short pulses (~ 0.1 ms), which is the range of interest to large tokamaks. However, the erosion effects are remarkably different. For example, in [Barabash 91] tungsten targets are tested with both sources. Whereas an electron beam of 4.0 MJ/m^2 energy density erodes $10 \text{ }\mu\text{m}$ of material, a higher energy density (7.0 MJ/m^2) plasma gun ablates only $0.3 \text{ }\mu\text{m}$. Such a strong dependence on particle kinetic energy is due to the different processes which govern power transfer and vapor shielding of the ablating target at high versus low particle energies. In computational simulations [Hassanein 92, Hassanein 94] of thermal erosion it is thus important to retain a generality of the treatment such that particle energy is an explicit input parameter and so that comparisons with test stand results can be made.

Actual tokamak disruptions may likewise involve particles of various kinetic energies. Runaway electrons are often measured to be well above 1 MeV during the current decay phase of a disruption, and these runaways may cause more severe damage than an equivalent energy density delivered by low-energy plasma ($\lesssim 1 \text{ keV}$). The thermal decay phase of a disruption offers additional uncertainties, as the particle energies are not well characterized in tokamak disruptions. A survey of experimental data [Najmabadi] suggested electron energies may be typical of the electron temperature on the last closed flux surface, $\sim 50\text{-}350 \text{ eV}$ in present-day machines. The best indication of ion energies has come from analysis [Bastasz] of the implanted hydrogen flux to the DiMES probe on DIII-D during argon-radiation triggered disruptions. The probe data show deuteron energies are $\sim 100 \text{ eV}$ during these disruptions on DIII-D. However, it is not obvious how particle energies will scale to larger, hotter plasmas in future tokamaks, such as ITER.

This report analyzes erosion behavior with heat sources of various kinetic energies, as computed with the DESIRE code [Ehst 93]. This work extends the DESIRE calculations to arbitrary kinetic energy, including relativistic electron

beams. The code results are compared to test stand measurements; and tokamak disruption results are predicted as a function of particle kinetic energy.

For more comprehensive and self-consistent analysis, the computer code A*THERMAL-S is recommended and should be used. The A*THERMAL-S code solves a multi-moving boundary problem coupled with target thermodynamics, vapor magnetohydrodynamics, and both continuum and line radiation transport in the vapor cloud and target regions [Hassanein 95].

II. Enhancements to DESIRE

At high kinetic energies incoming source particles lose energy by collisions [Hassanein 82, Hassanein 92] with the target vapor atoms which shield the ablating surface. The DESIRE code approximates this energy loss process with the following expressions:

$$\begin{cases} \frac{dE_e}{ds} = \frac{-k_e n_T}{a + E_e} \\ \frac{dE_i}{ds} = -k_i n_T \frac{\sqrt{E_i}}{\sqrt{m_i}}, \end{cases}$$

where subscripts e and i denote electron and ion species, E is the kinetic energy, n_T is the density of target vapor atoms, and m_i is the source ion mass (in amu). The electron formula is valid for $0.1 \text{ keV} \lesssim E \lesssim 100 \text{ keV}$, and, using standard stopping power tables, we fit the constants for various target species. For tungsten, for example, we use $a = 5.079 \text{ keV}$ and $k_e = 5.584 \times 10^{-21} (\text{keV} \cdot \text{m})^2$. The ion slowing down expression is likewise valid for $0.1 \text{ keV} \lesssim E \lesssim 100 \text{ keV}$, and a fit to the W data is $k_i = 4.5 \times 10^{-22} (\text{keV})^{1/2} \cdot \text{m}^2$. The failure of both formulas for $E \lesssim 0.1 \text{ keV}$ is accommodated in DESIRE by reverting to the low-energy, radiation (photon) transport model in [Ehst 93], once the incoming particles are slowed to such low kinetic energies. In fact, the breakdown of the slowing down formulas is related to angular scattering and straggling which lead to thermalization of the incoming particles as a source vapor cloud whose energy transfer property is best modelled as photon transport.

The slowing down formulas state particle energy loss along the path length s . Simple normal incidence through a target vapor of thickness Λ_T would have a path length equal to Λ_T . If source particles are incident at an angle or if a magnetic field adds a Larmor gyration to the charged particle motion then the path length may greatly exceed the cloud thickness, Λ_T . We account for this geometric effect by allowing a ratio, G , between total path length and the normal thickness, Λ_T , of the target vapor. Typically G is taken between two and ten, to represent oblique, magnetized source flow. Analytic solutions to the slowing down equations show that the slowing down is a function of the line average density of target vapor – $N_T = \int_0^{\Lambda_T} n_T(x) dx$ – normal to the ablating surface; slowing down does not depend on the spatial extent of the target vapor. Passing through the vapor shield, the source particles arrive at the ablating surface with energies

$$\begin{cases} E_e = \sqrt{(E_{e0} + a)^2 - 2 k_e G N_T} - a \\ E_i = \left(\sqrt{E_{i0}} - \frac{1}{2} k_i G N_T \right)^2, \end{cases}$$

where E_{e0} and E_{i0} are the initial kinetic energies of the incoming particles. For a singly charged source beam or plasma heat source, the power density from the source is $q_0 = J_e(3\varepsilon/2)(E_{e0} + E_{i0})$, where J_e is the source (electron) current density and $\varepsilon = 1.602 \times 10^{-19}$ J/eV. The target vapor shields the eroding surface, and the transmitted heat flux is $q = J_e (3\varepsilon/2)(E_e + E_i) < q_0$. At each time step, DESIRE updates E_e and E_i , as given by the above functions of N_T .

The code starts with a negligible line average density of target vapor, $N_T = 2 \times 10^{16} \text{ m}^{-2}$, typical of an ambient density of atoms in a distance of a few centimeters above the divertor surface in a typical tokamak scrapeoff/vacuum layer. The initial heat load, with a power density q_0 , raises the target temperature, and, as time goes on, continued heating results in ablation and an increase in N_T . The slowing down calculation continues as long as either $E_e > 0.3 \text{ keV}$ or $E_i > 0.3 \text{ keV}$. Once both species are slowed to energies below 300 eV then the code monitors angular scattering of the source particles. Slowing down continues until both electrons and ions encounter vapor clouds

adequately thick that the mean free path for 90° scattering is less than either the target or the source vapor cloud thickness; this occurs for either $N_T \sigma_{iT} \geq 1$ or $N_S \sigma_{jS} \geq 1$, where σ_{ji} is a standard momentum transfer cross section for incident particles j of energy E_{j0} against field particles i of atomic number Z_i . DESIRE presently uses an approximation, $\sigma_{ji} = 1.954 \times 10^{-22} [Z_i^2 / E_{j0}(\text{keV})^2] \text{ m}^2$. At longer times the incoming source particles form a thermal reservoir, and energy transfer continues via the photon transport mechanism [Ehst 93].

An additional parameter enters our calculation for high energy source particles. In contrast to low energy (~ 10 eV) plasma pulses which compress the vapor cloud—typically with megapascal pressure—due to high momentum impulses, for higher energy particles the momentum input is much smaller so the vapor clouds' thickness, Λ , is governed more by inertial expansion. As a function of time, t , the source vapor cannot expand further than $\bar{\Lambda}_S = t v_s / G_x$, where v_s is the speed of an average ion in the thermalized source vapor cloud. Now we use G_x to indicate the ratio of path length to cloud thickness (Λ_S) for source ions moving freely away from the target surface. When the ions are magnetized $G_x > 1$; and we generally set $G_x = G$ when running DESIRE.

In generalizing the earlier version of DESIRE [Ehst 93] to accept a wider range of input variables ($E_{e0}, E_{i0} > 1$ keV), the opacity calculations of hot vapor clouds have also been upgraded. One improvement generalizes the electron-neutral Bremsstrahlung which determines the opacity of low temperature, partially ionized vapor; now the momentum transfer frequency for electron-atom collisions is taken to be proportional to the atom's atomic mass. Another modification to the opacity calculation is inclusion of the advance of the series limits [Griem], which shifts the continuum absorption edges towards the red at high densities.

The main enhancement to the opacity calculation is including more detail in the free-bound contribution. In addition to retaining six charge states of each species in the source vapor cloud, recombination to the lowest four principal quantum number states is computed for the two dominant charge states. The general expression for the free-bound opacity contribution is thus, in terms of the free-free opacity, α_{es} ,

$$\alpha_{fb}(\lambda) \propto \left\{ \sum_{s=1}^3 f_s \sum_{k=Z-2}^{Z+3} f_k W_{sk} \alpha_{es}(\lambda) g \right\},$$

where s denotes atomic species, k denotes charge state (the sum taken, for example, from $k = 4$ to 9 for Al with an average charge state of 6.3), and f_s and f_k are the fraction of species and charge state for each species in the vapor. The ratio of free-bound to free-free Gaunt factors is given by g [Ehst 93]. For each charge state of each species of temperature θ

$$W_{sk} = \sum_n \left(\frac{\chi_n}{13.58 \text{ eV}} \right)^2 \frac{\zeta_n}{Q_n} \exp(\chi_n / \theta) H(\omega_n),$$

where the indices s and k are suppressed. Here Q_n is the shell of the outermost electron ("principal quantum number") after recombination; $n = 1$ denotes ground state recombination and we set $Q_{n+1} = Q_n + 1$. The ionization potential of the excited states is approximated as $\chi_n = \chi_1 (Q_1/Q_n)^2$, where χ_1 is the ground state potential. The factor ζ_n is the number of vacancies in the shell capturing the electron [Bekefi], and $H(\omega_n)$ is the Heaviside function (zero below the advanced absorption edge frequency and unity above). The sum is taken over the four lowest recombination energy levels ($n = 1, 2, 3, 4$) for the two charge states, Z and $Z + 1$, which bracket the average charge for that species. Only $n = 1$ is calculated for the other charge states. A maximum of twelve absorption edges may thus appear in the opacity for each of the source species. With up to three source species there is consequently considerable structure in the opacity as a function of wavelength.

Figure 1 shows the opacity calculated in DESIRE (dotted) for a pure Al plasma at 50 eV and a density of $6 \times 10^{26} \text{ m}^{-3}$ for a 1 mm slab. For comparison with the more accurate value of opacity [MacFarlane], the solid curve, an average $\bar{Z} = 6.3$ was assumed for the vapor. Note that DESIRE computes opacities within a factor of two or three of the more accurate values, although line radiation is not included. This accuracy is considerably improved over the original DESIRE results (cf. [Ehst 93]). Another comparison, Fig. 2, at 10 eV , shows the opacity and emission spectrum for C at $1. \times 10^{23} \text{ m}^{-3}$ density from a slab 100 cm

thick. The DESIRE result, with $\bar{Z} = 4.0$, deviates from the more accurate result [Peterson] for the continuum at extremely short wavelengths, $hc/\lambda \gg 10 \epsilon \theta$. This error arises from the difficulty of calculating the fractional density of high charge states. In this example the recombination at a photon energy of 392 eV is due to C^{+5} , which has an exponentially small population at $\theta = 10$ eV. What matters, though, is the opacity for photon energies of order $hc/\lambda \cong \epsilon \theta$, where black body radiation would peak. The emission spectrum clearly illustrates the good agreement in this range. Of course DESIRE underestimates the radiated flux by not including line radiation, which constitutes 49% of the total in this example.

Another illustration of emissivity is given in Fig. 3, where the DESIRE result (assuming $\bar{Z} = 2.0$) is shown for Be at 5 eV and a density of $1 \times 10^{23} \text{ m}^{-3}$ in a 100 cm slab. The continuum agrees reasonably well with the more accurate finding [Peterson], and in this case line radiation contributes much less than 50% of flux, due to the small number of bound electrons. Figure 4 is slightly different, the DESIRE result for a Be slab of 10 cm thickness at 3 eV and $1 \times 10^{24} \text{ m}^{-3}$ density. Although the shape of the emission spectrum differs in detail from a more accurate calculation [Koniges] the actual power density radiated is similar: DESIRE (setting $\bar{Z} = 1.85$) finds 35 GW/m² while [Koniges] reports 42 GW/m², of which only about 11% is due to lines.

A lesson in these comparisons is that the thermal ablation/vapor shielding calculation is insensitive to certain atomic physics details, since the radiated power density is an integral over the emission spectrum. Another example underscores this conclusion. Figure 5 is the DESIRE calculation for a more typical ablation cloud, a Be target vapor at 1 eV, and a density of $1 \times 10^{24} \text{ m}^{-3}$ in a 10 cm slab. At this density and temperature the plasma is only partially ionized (68% ionization is assumed here) and is approaching a black body. The integral of the spectrum computed by DESIRE is 913 MW/m² which can be compared to 766 MW/m² found by more detailed calculations [Koniges].

The actual ionization degree, Φ , or effective charge state in Figs. 1-5 was chosen to achieve the best fits to the published results in the cited references. As outlined in [Ehst 93] the DESIRE code performs its own calculation of Φ and $\bar{Z}$ at each time step, and it is helpful to compare our results with other, more

detailed equations of state. The solid curves in Fig. 6 are the average number of bound electrons of a Be plasma, as given in [Koniges]. The upper triangle at a density of 10^{18} cm^{-3} is the result of a kinetic calculation (A*THERMAL-S code [Hassanein 95]) with details of ion population states in LTE and non-LTE at 1 eV, while the circle is the Saha solution; note that the Saha result overestimates the degree of ionization. The lower triangle is the kinetic result at 3 eV. The DESIRE results (dotted curves) are quantitatively different from the other results but display the correct behavior versus density and temperature. DESIRE presently solves for a Saha equilibrium, which inaccurately calculates the ionization at low densities (e.g., $< 10^{18} \text{ cm}^{-3}$ at 10 eV). At such low densities a coronal equilibrium would be more typical.

III. Ablation Results from Varying Particle Kinetic Energies

The DESIRE calculations which follow deal with two different target materials, tungsten (W) and carbon (C). These two targets are interesting because there exist test stand erosion data for both materials and because they are both candidates for plasma-facing armor in large tokamaks like ITER. For simplicity we assume an energy density of 7.0 MJ/m^2 is delivered to W and 5.0 MJ/m^2 is incident on the C target; these energy densities are similar to those delivered by electron beam and plasma gun tests. The pulse width is taken to be 0.100 ms, as in the tests and also typical of tokamak disruptions; and the source geometry is a cylindrical column of 2.3 cm diameter (similar to test stands). The source particle mix is taken to be a majority deuterium species (75%) with a 15% addition of Ar and a 10% iron content; such an ion mixture is not unlike many plasma gun sources and might, as well, represent an actual disrupting tokamak plasma. This electron-ion plasma source is used up to electron kinetic energies of $E_{e0} = 50 \text{ keV}$; at 50 keV and above the calculation takes only an electron beam source (no ions) in order to compare with electron beam tests.

For each target material, calculations of erosion are done for a large variety of input particle kinetic energies. At the lowest energies ($E_{e0} < 2.0 \text{ keV}$) the particle kinetic energies are in the ratio $E_{e0} < E_{D0} < E_{I0}$, this being the normal experience in plasma guns. For calculations of plasma gun conditions we assume normal incidence with an unmagnetized plasma ($G = G_x = 1$).

Our simulations of tokamak disruption conditions assume oblique field lines with a magnetized plasma ($G = G_x = 10$), and these calculations extend up to $E_{e0} = 50$ keV. In the mid-energy range (multi-keV) we adjust the kinetic energy ratio to reflect our expectations for ITER-scale disruptions: when $E_{e0} \geq 2.0$ keV, then $E_{e0} = E_{D0}$ and $E_{I0} \equiv 5.0$ keV.

For the electron beam calculations ($E_{e0} \geq 50$ keV) we assume normal incidence with $G = G_x = 1$.

Thus the results of the calculations serve two purposes. First, predicted target erosion from guns and beams may be compared to the actual values measured on test stands; this will serve to assess the accuracy of the DESIRE code. Second, the predicted erosion for the disruption conditions will serve to illustrate the sensitivity of ablation results to the incoming particle kinetic energy, a parameter which is difficult to extrapolate to ITER-scale disruptions.

Figure 7 displays the results for 7.0 MJ/m^2 incident on W. Circles are the calculations for a plasma gun ($E_{e0} \leq 1.3$ keV); the code predicts the erosion depth due to vaporization, δ , to be rather insensitive to source particle kinetic energy over this range. The shaded areas indicate the range of measured erosion on two plasma gun facilities. On VIKA [Barabash 91] the experimental $\delta = 0.3 \text{ } \mu\text{m}$, although the energy density, U , is imprecisely known, $U = 7.0 \pm 2.0 \text{ MJ/m}^2$. The PLADIS results [Crawford], $\delta \lesssim 0.1 \text{ } \mu\text{m}$, are very uncertain and represent a rough extrapolation from the actual tests at $U \geq 11.6 \text{ MJ/m}^2$. In both test stands the actual particle kinetic energies are also uncertain but are probably in the range of 10 eV to 100 eV. In addition, the PLADIS energy density is uncertain because the plasma stream often wanders off the target center. Squares are electron beam calculations. The larger erosion loss at higher E_{e0} is due to the velocity dependence of the electron slowing down process - higher energy electrons lose less energy in passing through the W vapor cloud. The calculated δ with a 100 keV electron beam is two orders of magnitude larger than plasma gun damage. This effect is likewise seen on test stands, the shaded area being an extrapolation of data [Barabash 91] obtained with a 60 keV beam at $U = 4.0 \pm 0.2 \text{ MJ/m}^2$. The "disruption" erosion calculations, shown by the plus signs, display little dependence on kinetic energies up to $E_{e0} \equiv E_{D0} \equiv 2$ keV. The dip in the calculated δ near 8 keV is due to the low momentum input to the

vapor clouds at relatively high particle kinetic energy, which allows the clouds to expand and radiate much of the incoming power sideways, away from the W surface. Higher particle energy disruption results are dominated by the slowing down equations. Note that at $E_{e0} = 50$ keV a pure electron beam is expected to produce ten times as much erosion as a magnetized plasma with $E_{e0} = E_{D0} = 50$ keV.

Carbon-based materials are difficult to model due to a number of factors. For one, material properties such as thermal conductivity vary highly, depending on the detailed graphite fabrication process. It is also unclear whether C sublimation is dominantly monoatomic or whether multi atom clusters are emitted. Furthermore, a time-dependent surface hardening sometimes occurs. That is, the first thermal pulse to virgin material often produces four times as much loss as the average per-shot loss when the sample is hit by ten shots in repetition. Adding to these difficulties is the fact that experimental results often vary considerably, despite similar looking conditions. Thus, electron beam erosion of C, reported in [Barabash 91], was typically less than 10% of that found in [Engelko]. The former experiment found erosion to be unusually sensitive to the pulse width (50-200 μ s), and it may well be that the electron beam did not impact the test sample on center. As with the W targets, a final ambiguity is whether DESIRE should be matched to the maximum crater depth (measured by profilometry) or to the average material erosion (mass loss measurements), there being typically a ratio of three between these two values. For these several reasons there is considerable scatter in the experimental results to which the DESIRE calculations are compared.

The results of 5.0 MJ/m² incident on C are given in Fig. 8. Again the circles show plasma gun erosion, which is generally $\delta \approx 0.2$ μ m provided particles energies are less than ~ 1 keV. Experimental data, at $E_{e0} \lesssim 3$ eV, on PLADIS show considerable variation: erosion reported for three different graphites [Suzuki] varies in the range $\delta = 0.56 - 1.6$ μ m, where a linear interpolation to $U = 5$ MJ/m² is taken. The highest loss value may be large due to the sample being a low density graphite felt. In contrast, the same PLADIS facility tested POCO graphite [Gahl] at $U \lesssim 8$ MJ/m², and a crude extrapolation to 5 MJ/m² might suggest $\delta \approx 0.1$ μ m for this material. Hence the shaded experimental region in the figure at $E_{e0} \lesssim 3$ eV encompasses a variety of tested

graphites. VIKa, a plasma gun with higher energy particles (hydrogen ions at 30-75 eV) reports [Barabash 91] δ between 1-2 μm for four different graphites at 5 MJ/m², yet a test on a fifth type (POCO), reported in [Barabash 92], at ≥ 7.5 MJ/m² would suggest $\delta \lesssim 0.1 \mu\text{m}$ if linearly extrapolated to 5 MJ/m². Since plasma gun publications rarely cite the target material density it is obviously difficult to compare with DESIRE, which assumes a fixed value (8.98×10^{28} atoms/m³ for C).

As with the W target, DESIRE predicts electron beam damage (~ 100 keV) to be two orders of magnitude higher than plasma gun erosion of C. The experimental range, $\delta = 32\text{-}36 \mu\text{m}$, on Fig. 7 at 110 keV is a slight extrapolation beyond the data cited in [Engelko] at $U = 4.4$ MJ/m². The agreement is quite good.

The disruption calculation results are similar for C and W targets. Again, at $E_{e0} = 50$ keV an electron beam produces ten times as much erosion as a magnetized plasma with $E_{e0} = E_{D0} = 50$ keV.

IV. Conclusions

The DESIRE code has been upgraded to accept an arbitrary kinetic energy for source particles which supply ablation-producing power densities to target surfaces. This permits studies of various tokamak disruptions (high-energy electron or lower energy plasma thermal dumps) and allows us to compare the DESIRE physics treatment with test stands (electron beams and plasma guns).

A comparison of DESIRE subroutines [Ehst 93] with more elaborate calculations was illustrated by the opacity functions and emissivity spectra in Figs. 1-5. Despite the simple, fast-running nature of the DESIRE code, the opacity and emissivity fall within a factor of two or three of the more accurate findings. Furthermore, the radiated power density, from the plasma-vapor to the ablating surface, is an integral of the emissivity spectrum; performing the integral eliminates details of disagreement between different computed spectra. This was seen, for example, in Figs. 4-5 in which the power density found by DESIRE was within 20% of that given by [Koniges]. Equally important, the line contribution to radiated power is small at $\theta \lesssim 5$ eV for low Z atoms, and this

validates the simplified treatment in DESIRE which computes opacity only from the continuum. Heavy atoms at high temperature will have a larger line radiation fraction, and in this case DESIRE may be less accurate. A more detailed treatment of line radiation and its transport is given in the A*THERMAL-S code [Hassanein 95] which will be employed in future studies.

The charge state and ionization degree are inputs to the opacity calculation, and Fig. 6 shows results from four different calculations. The small discrepancies among models are probably insignificant. For example, the ionization degree Φ is an exponential function of the vapor temperature when $\theta \lesssim 1$ eV, so the result determined by a given model is very sensitive to the exact θ value.

Reference to Figs. 7-8 shows a good match of DESIRE to experimental erosion depth for electron beam tests (~ 100 keV), with small extrapolations of the measured data to the stipulated $U = 7$ MJ/m² on W and $U = 5$ MJ/m² on C. The match of calculations to the plasma gun erosion is also reasonably good, although the experimental data show a large scatter. In sum, the DESIRE predictions fall within the range of experimental observation for both high- and low-kinetic-energy source particles, and this gives us confidence that disruption conditions are also reasonably well handled by the code.

Turning to the magnetized plasma/disruption results (plus marks) in the figures we can conclude three points:

- a. Electron beams (~ 100 keV) do not duplicate the results expected for tokamak disruptions; even at $E_{e0} = E_{D0} = 50$ keV the plasma disruption may produce only one-tenth as much erosion as an electron beam.
- b. Unmagnetized plasma guns as expected to duplicate the ablation results of moderate kinetic energy tokamak disruptions ($E_{e0} \lesssim E_{D0} \lesssim 1$ keV). An important finding on DIII-D [Bastasz] was that $E_{e0} \equiv E_{D0} \equiv 100$ eV during disruptions when the central plasma temperature was ~ 3.5 keV, which may suggest that particle energies will be of order 1 keV in large high temperature disruptions (ITER, TFTR, JET, with central temperatures ~ 35 keV).

- c. For E_{e0} and E_{D0} below ~ 1 keV the erosion depth is insensitive to the actual particle energy. This further emphasizes the usefulness of plasma gun test stands, and it de-emphasizes the need to know the actual particle kinetic energy spread in a tokamak disruption. In essence, power flow is dominated by photon radiation in this regime, and incoming particle kinetic energy is effectively eliminated as an important variable.

In closing we remark that many factors conspire to obscure the comparison of erosion measurements with code predictions, some being experimental uncertainties and some being shortcomings of present-day modelling. The factors, to be studied more thoroughly in future work, include:

1. Experimental devices deliver energy densities which are often poorly known (e.g., 7 ± 2 MJ/m² for VIKA [Barabash 91]), and most data in our Figs. 7-8 are extrapolated from the test stands' reported energy densities.
2. For many materials $U \cong 5$ MJ/m² is near the threshold for ablation damage, where δ is a sensitive function of U .
3. In certain cases the source beam does not squarely impact the target surface; this results in a lower U than anticipated and leads to less erosion than full-footprint deposition.
4. Experiments sometimes report an average ablation depth over several shots, including occasional off-center strikes; shot-to-shot variation is large in experiments, whereas the calculation is for ideal (worst-case) conditions.
5. Graphite ablation on the first shot may exceed the average ablation over multiple shots by a factor of three [Linke]; such surface hardening is not always detailed in the experimental reports and is also difficult to model.

6. Maximum crater depth from profilometry exceeds the average depth from mass loss measurements, and the experiments are occasionally unclear as to which is being reported; experimental ranges in Figs. 7-8 include both types of measurement, and it is also unclear whether DESIRE should be compared to the maximum or the average erosion depth.
7. Plasma gun experiments frequently do not specify whether the working gas is hydrogen or deuterium; more importantly, the impurity content is generally not known, and this should significantly affect the erosion depth [Ehst 95].
8. The spread of kinetic energies, especially in plasma guns, is poorly known or reported in the literature, although we have found δ is insensitive to kinetic energies when $E_{e0} \lesssim E_{D0} \lesssim 1$ keV.
9. Accurate ablation calculations require temperature-dependent material properties, heat capacity and thermal conductivity, as well as density and the heat of vaporization; DESIRE uses "typical" properties of W and C (although graphites vary widely), whereas the experiments generally cite none of this information in their publication.
10. Metallic erosion measurements may include some loss of the melted layer, which is not accounted for in the present calculation. This issue is explored better with computer codes such as SPLASH [Hassanein 95].
11. Cracking and spallation is reported in some experiments; such phenomena can enhance the erosion but are not included in the code model.
12. Multi-atom clusters may be emitted during graphite vaporization; this would increase the erosion rate but is not included in the DESIRE calculation.

13. Some target vapor may recondense at the end of the high heat flux pulse, a factor not considered in the present model.

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Figure 1 Optical depth vs. photon energy for aluminum plasma at 50 eV and a density of 6×10^{26} atoms/m³ for a slab of 1 mm thickness. Solid curve is from [MacFarlane] and dotted curve is DESIRE, assuming $Z_{\text{eff}} = 6.3$. At this density the plasma is nearly a black body (optical depth greater than one for energies $\lesssim 1000$ eV) so emission and absorption are independent of detailed shape of the curves.

$$T = 10 \text{ eV}, n = 10^{17} \text{ cm}^{-3}, L = 100 \text{ cm}$$

Figure 2 Optical depth and emission spectrum for carbon plasma at 10 eV and 1×10^{23} atoms/m³ for a 1 m slab thickness. Solid curves are from [Peterson] and dotted curve is DESIRE, assuming $Z_{\text{eff}} = 4.0$.

$$T = 5 \text{ eV}, n = 10^{17} \text{ cm}^{-3}, L = 100 \text{ cm}$$

Figure 3 Emissivity of beryllium plasma at 5 eV and $1. \times 10^{23}$ atoms/m³ for a 1 m slab; solid curve is from [Peterson] and dotted is DESIRE, assuming $Z_{\text{eff}} = 2.0$.

Figure 4 Emissivity of beryllium plasma at 3 eV and $1. \times 10^{24}$ atoms/m³ for a 10 cm slab, as calculated in DESIRE, assuming $Z_{\text{eff}} = 1.85$. Power density radiated from the slab surface (the integrated emissivity over all wavelengths) is 34.6 GW/m².

Figure 5 Emissivity of a partially ionized beryllium vapor at 1 eV and $1. \times 10^{24}$ atoms/m³ for a 10 cm slab, as calculated in DESIRE, assuming 68% ionization fraction. The power density radiated from the slab is 913 MW/m², nearly 89% of the intensity of a black body at 1 eV.

Figure 6 Ionization degree in a beryllium plasma at several temperatures. Solid curves are a Saha solution [Koniges], while dotted curves are the DESIRE result at 1 eV and 3 eV. A Saha result from A*THERMAL at 1 eV (circle) lies close to the other codes; a more accurate kinetic calculation at 1 eV and 3 eV (triangles) results in less ionization than the Saha models.

Figure 7 Erosion of tungsten, by vapor loss only, from a 7 MJ/m² impulse delivered in 0.1 ms by a source of 2.3 cm diameter, considering three different energy sources. At the highest energies, electron kinetic energies $E_e \gtrsim 50$ keV, a pure electron beam of normal incidence is shown by boxes. At lower kinetic energies plasma sources are considered, always assuming an ion mix: 75% deuterium + 15% argon + 10% iron; the ratio of electron to deuterium to impurity particle energies varies nonlinearly as given by the three abscissas. Circles represent plasma gun calculations with normal incidence of an unmagnetized source. Plus signs denote a magnetized plasma source, similar to a tokamak disruption. Shaded areas indicate the range of experimental erosion data, plasma guns residing at low energies and electron beams near $E_e \approx 100$ keV.

Figure 8 The same as Fig. 7, except for 5 MJ/m² incident on a graphite target.

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