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Low Mode Surface Perturbation Tolerance of Ignition Capsule Implosions for the National Ignition Facility

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Abstract: The implosion stability for a NIF capsule to target fabrication defects in spherical harmonics modes L£12 is quantified in terms of a mode dependent tolerance to surface perturbations. Simulations of NIF capsule implosions with single mode perturbations on a single surface allow the determination of modal growth factors. Simulations with large initial perturbations were also done to determine how large a final perturbation could be tolerated. Combining the growth factors and tolerances determine specifications on initial perturbations. This allows an estimate of modal tolerance for each capsule surface and thickness variation for a polyimide ablator capsule design with central gas fills of 0.3 or 0.6mg/cc.

1. Introduction

Several inertial confinement fusion (ICF) capsule designs have been proposed as possible candidates for achieving ignition with indirect drive from the National Ignition Facility (NIF) laser[1]. These include a plastic (CH) ablator capsule with a small amount of bromine (Br) added and a beryllium (Be) plus sodium (Na) and Br capsule with graded doping[2, 3]. Krauser et al[4] described a Be ablator capsule designed by Wilson[5] with a small amount of copper (Cu) added. Dittrich et al[6] compared several of these designs and also proposed an undoped polyimide (C_{22} H_{10} N_2O_4) capsule, a Be plus graded Cu doped capsule, and a boron carbide (B_4C) capsule, all with a 300 eV drive. Dittrich et al[7] have also described Be plus graded Cu dopant capsule simulations with 250 eV drives. All of the ICF capsule designs described above are to be driven indirectly, i. e. the laser light is converted to x-rays in hohlraums[8, 9], and these x-rays then drive the capsule implosion.

Exhaustive analysis has been done on the growth and stabilization of the hydrodynamic instabilities of these capsule implosions. Most work has emphasized the most unstable modes (L between 10 and 150) which grow by factors of order one thousand. However, real capsules will have large perturbations at low modes, where L is less than ten. Even though these modes do not grow very much, it is still important to set a specification on how large these perturbations can be initially. That is the purpose of this work.

The capsule examined in this work is a baseline polyimide target, shown in Fig. 1. The capsule, enclosed in a hohlraum as described in (ref.2) is comprised of deuterium-tritium (D-T) gas innermost, frozen D-T solid fuel (ice), and an ablator outside the fuel. This NIF capsule design has an inner DT gas fill, 80 microns of DT ice, a 135 micron $C_{22}H_{10}N_2O_4$ polyimide uniform ablator of density 1.50 g/cc, and an outer radius of 0.1085 cm. (Note the polyimide density and ablator thickness that were used in the study were somewhat different from more recent estimates[10] of 1.40 g/cc, and an ablator thickness of 145 microns. We do not expect this difference to significantly change the results presented here, which at any rate will need to be updated and generalized for various NIF designs as they evolve.) A pulse shaped 300 eV spherical drive, shown in Fig. 2, is assumed for the implosion simulations analyzed here. This produces four shocks over about 17ns[1-6]. The drive is non-Planckian, based on simulations of a gold hohlraum. The solid fuel and ablator are assumed to have uniform density and composition. Two inner DT gas fill cases

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are considered, at triple point conditions, and at half that density, 0.6 or 0.3mg/cc respectively.

The uniform ablator capsule has three surfaces that can affect implosion stability—the inner gas/ice DT surface, the DT ice/ ablator interface, and the outer ablator surface. Variations of these surfaces from spherical and/or variations of the ice or ablator thickness from uniform will detrimentally effect capsule implosions. These variations from spherical can be described with the three interface radii $R_g(\theta,\phi)$, $R_i(\theta,\phi)$, and $R_a(\theta,\phi)$ for the interface of the gas/ice, ice/ablator, and ablator/outside respectively. The variations can also be described using the capsule outer radius, $R_a(\theta,\phi)$, and the ablator and ice thickness:

$$H_a(\theta,\phi) = R_a(\theta,\phi) - R_i(\theta,\phi), \qquad (1)$$

$$H_i(\theta,\phi) = R_i(\theta,\phi) - R_g(\theta,\phi), \qquad (2)$$

The use of R_a, H_a, and H_i, as variables allows explicit treatment of the case where the perturbations represent variations in capsule radius at constant thickness, which we might expect to be less important than variations in thickness. To systematically study variations from an ideal sphere, each thickness or the ablator surface is characterized by an expansion in spherical harmonics, where the radius as a function of angle is given by:

$$R(\vartheta,\phi) = \sum_{L=1} \sum_{M=-L}^{L} R_{LM} Y_{LM}(\vartheta,\phi) \qquad (3)$$

We concentrate on long wavelength modes on each capsule surface, and for a given surface consider only modes through L=12. The outside of the ablator can be located in the co-ordinate system such that the expansion coefficient for mode 1 of this surface is zero. The ablator and fuel are assumed to both have the desired average thickness but these may not be concentrically located. Hence the mode one expansion coefficient for the ice or ablator thickness is not necessarily zero.

The power spectrum for a mode (given L value) is defined as:

$$P_L = [1/4\pi] \sum_{M=-L}^{L} R_{LM}^2 \qquad (4)$$

The modal power reflects the contribution to the surface rms deviation for a given mode and is an important factor in determining the capsule stability during an implosion. As used throughout this paper, modal power denotes the initial deviation of a surface from spherical, as defined in eqn. (4). The growth of a given L, M mode is independent of M as long as the growth is linear with initial amplitude.

The yield of an implosion can be degraded by deformation of the hot spot surface at ignition. The hot spot surface has an average radius of about 28 microns at ignition for successful implosion simulations. When this hot spot surface is too convoluted or rough, the subsequent capsule implosion will not produce significant yield. The yield rapidly deteriorates when the hot spot surface rms exceeds 9 microns in low mode 2 D simulations of implosions for the point design NIF capsule. Several 2-D simulations of a capsule implosion were run with an initial perturbation of large amplitude on the inside surface of the DT ice for modes 2 and 6. With a gas fill of 0.3 mg/cc, the yields from these simulations form a single curve when plotted versus the initial surface rms times the linear regime growth factor at ignition, see Fig. 3. For the 0.6 mg/cc gas fill, the yield is more sensitive to mode 6 perturbations than for mode 2 perturbations, see Fig. 3b. The yield for mode 2 drops rapidly for a hot spot surface rms of 10 microns, but for mode 6, the cliff in yield is earlier, when the rms is about 4 to 5 microns. A mode dependent weighting factor will be introduced to account for this.

2. Simulation Details

2-D simulations of capsule implosions were run with the codes LASNEX[11] and Hydra[12]. The time when the ion temperature reaches 12 KeV and when also ρr is greater than 0.3 gm/cm^2 is taken as the ignition time. The hot spot perimeter is defined as the locus of points where the burn rate is 0.01 of the central burn rate at ignition time.

The simulations used Marinak few group opacities[13]. The time dependent drive flux and spectrum were adjusted so that the implosion time history and density profiles closely matched a 1D simulation with full radiation transport and fully converged radiation groups. Only one expansion coefficient on a single surface was taken as different from zero per simulation, with the other surfaces spherical, except for the deformed radius case where each surface has the same perturbation. The initial perturbation amplitude in the simulations is 1.0 10^{-9} cm. In these single mode simulations the shape of the hot spot surface mirrors the shape of the initially deformed capsule surface as it has the same Legendre polynomial shape deviation from spherical. Even L modes utilize a z-symmetric simulation of one half the capsule. Odd L modes are simulated by a 2D calculation of the full capsule.

3. Growth Factors

Growth factors numerically describe the coupling between initial perturbations from spherical of the DT ice or ablator surfaces and subsequent perturbations on the hot spot surface. These modal growth factors, as determined by numerical simulations for *L* up through twelve, are tabulated at the time of ignition for initial perturbations on the gas/ice interface, the ice/ablator interface, the ablator/outside interface, and for the deformed radius case of identical perturbations on each surface, see Table I. These columns tabulate results from separate simulations. A negative growth factor means the final perturbation has phase opposite that of the initial perturbation. Calculations were done for gas fills at the center of the capsule of 0.3 mg/cc, and 0.6mg/cc, the triple point density. Comparison of the growth factors shows that the gas fill at the center of the capsule has only a very minor effect on the growth factor.

The thickness growth factors are linear combinations of these growth factors. The gas/ice interface growth factor describes the case when the outer capsule radius and the ablator thickness are each independent of radius, but the DT ice thickness varies with angle. So this inside surface growth factor case is the same as the ice thickness growth factor. The radius growth factor should be equal to the sum of the three interface growth factors. The numbers in Table I show minor differences between the sum of the three interface growth factors and the radius growth factor, when the latter is calculated in a separate simulation. This difference represents a minor error in at least one of the four simulations required to do this check. The ablator thickness growth factor is the case where the ablator thickness varies with angle, but the outer radius and the ice thickness are each independent of angle. In the fifth column of Table I, H_{abl} is a derived growth factor for ablator thickness at constant outer radius and ice thickness, calculated as the ablator/outside interface growth factor minus the deformed radius growth factor. The last column of Table I, shown in brackets, [], is the other way to derive the growth factor for perturbations on the ablator thickness, H_{abl}: minus the ice/ablator interface growth factor minus the gas/ice interface growth factor. If all the growth is linear and the simulations were numerically precise, these two ways of calculating the ablator thickness growth factor would agree. The two calculations of ablator thickness growth factor agree to 5%, except when passing through zero. For applications below, we take the ablator thickness [H_a] growth factor as determined by the negative of the ice/ablator and the gas/ice growth factors. The other method of calculating the ablator thickness growth factor often requires taking the difference in magnitude of two large numbers, with some resulting loss of precision.

The growth factors vary smoothly with mode number, even through sign changes. The hot spot shape at ignition is more sensitive to initial perturbations on the outer part of the capsule. The ice thickness growth factors are typically an order of magnitude less than the growth factors for the ablator thickness or the ablator/outside interface. Growth factors for radius variations at constant thickness are somewhat smaller than growth from perturbations in ablator thickness because there is no mass variation to seed variations in acceleration. These growth factors are used to develop the modal tolerances for this capsule in the next section.

4. The Capsule Implosion Stability figure of Merit

The modal tolerances quantify whether a capsule can be expected to successfully implode to ignition. An implosion can fail from too much power in a single mode, or from the cumulative effects of power summed over the entire spectrum of modes. Linear growth of small amplitude modes allows the various modes to combine in linear summation. The hot spot surface rms can then be predicted using growth factors and the initial power spectrum. The predicted hot spot surface rms deviation from initial surface perturbations is:

$$\sigma = [\sum_{i=1}^{3}\sum_{L=1}^{12} G_{Li}^2 P_{Li}]^{1/2} \qquad (5)$$

where G_{Li} is the growth factor and P_{Li} is the power spectrum associated with the Lth mode on the ith capsule surface or thickness. One might try to use σ itself to determine whether a perturbation is acceptable. However this is not an adequate description since large initial amplitude simulations showed the polyimide capsule implosion stability for the 0.6mg/cc gas fill was more sensitive to higher modes, see Fig. 3b. To allow for this sensitivity of yield to mode number, a mode dependent danger factor, D_L is introduced. This danger factor, for gas fill 0.6mg/cc, is modeled as a linear increase from 1.0 for mode two to 1.5 for mode six, so D_L is $(6+L)/8$. The danger factor is unity for gas fill 0.3mg/cc since for this case the large initial amplitude simulations showed no modal sensitivity in yield versus ignition time perturbation. A modal tolerance is defined as:

$$T_{Li} = 9\mu m / D_L G_{Li} \qquad (6)$$

In Fig. 4, the yield divided by the yield from an ideal spherical capsule implosion is plotted versus the initial power over the square of the modal tolerance. This ratio is called yield over clean (YOC). Each curve represents the implosion YOC for a single mode perturbation with varying amplitude on the inner DT ice surface. Results are shown for mode 2 and 6 perturbations with central gas fills of 0.3 and 0.6 mg/cc. The YOC curves form a narrow band that monotonically decreases. The YOC remains high until the abscissa exceeds unity. These trends justify the 9μm scale and the danger factor introduced into the modal tolerance defined above.

Including simultaneous perturbations from all modes on all three surfaces of the capsule, a global specification for implosion instability of a capsule can be written in terms of the modal tolerances as:

$$\sum_{i=1}^{3}\sum_{L=1}^{12}[P_{Li}/T_{Li}^2] \le 0.1 \qquad (7)$$

The 0.1 on the right hand side above allows margin for other possible problems with the implosion, such as radiation asymmetry and high mode perturbations of the capsule fabrication. (Note that letting this quantity be unity would put the implosion right on the shoulder in Fig. 4.) Of course the limit 0.1 is arbitrary; it represents a reasonable allocation of margin to low mode capsule imperfections of the many sources of imperfection in the implosion. If the inequality above is satisfied, the left hand side being less than one tenth, then the capsule can be expected to undergo successful ignition with some margin in an ideal spherical drive. The sum is over the ablator outer surface and the ice and ablator thickness, and over each mode denoted by the indices L, i. If any one of these surface mode terms is saturated, that is if $P_{Li}/T_{Li}^2=0.1$, for any one mode, then the power in all the other modes would have to be zero. The other extreme circumstance is where each mode and each surface contribute equally to eqn. (7). The modal tolerances allocated for an equal contribution from each mode to exactly saturate eqn. (7) in combination are in Table II. These modal tolerances are determined from the growth factor for each thickness, the danger factor, and a figure of merit of 9 microns for a successful implosion. They include the 0.1 margin factor in power, and each is divided by ÷35 so that they represent an equal allocation of the perturbation budget to each surface and each mode. The outer radius of the capsule can be centered with respect to the origin, so mode 1 for the outer radius will not contribute to the quadrature sum. The different surface and mode perturbations can be traded off as long as eqn. (7) is satisfied. As a conservative estimate, if the growth factor is less than 2.0 in magnitude, it is replaced by 2.0 in determining the modal tolerance.

5. Summary

Simulations of NIF capsule implosions with single mode perturbations on a single surface allow the determination of modal growth factors and modal tolerances. The modal amplitude, final over initial, is the growth factor for a given mode. The capsule implosion tolerance to RT instabilities provides a criterion that the modal power spectrum must satisfy. An implosion can fail from too much power in a single mode, or from the cumulative affects of power summed over the entire spectrum of modes. Since the modal power depends only on the initial capsule shape, this provides a way to predict whether a given capsule, with aspherical surfaces, can be expected to successfully undergo ignition. Using the capsule radius, with the ablator and ice thickness to describe the perturbations, the modal tolerances for the ice thickness are the largest and the modal tolerances for the ablator thickness are intermediate. The tolerances for the capsule radius are generally the smallest. The gas fill 0.3 mg/cc capsule has marginally higher tolerances than does the 0.6mg/cc capsule. This offers one more advantage to initiate the implosions with a capsule cooled below the D–T triple point conditions.

6. Acknowledgements

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8. List of Figure Captions

1. The spherical Point Design capsule has a polyimide ablator, a D-T cryogenic layer, and an inner D-T gas fill.
2. Time dependent flux temperature of the radiative drive.
3. Yield versus expected hot spot rms in microns from 2-D implosion simulations with gas fill of 0.3 mg/cc for modes 2 and 6. "Expected hot spot rms" is the product of the initial rms and the linear regime growth factor. B) gas fill of 0.6mg/cc.
4. The YOC versus power over squared modal tolerance. Each curve is for a single mode perturbation with varying initial amplitude. The solid curves are for gas fill 0.3 mg/cc, dashed curves are for gas fill 0.6 mg/cc.

Table I. Surface modal Growth Factors at Ignition for the capsule Hot spot.
Ratio of perturbation on hot-spot boundary at ignition time to initial perturbation.
Gas fill at center of capsule: (0.3 mg/cc)

Perturbation on:	gas/ ice $=H_{ice}$	ice/abl	abl/out	Radius	H_{abl}	[H_{abl}]
Mode	GF	GF	GF	GF	$GF_{abl/out-wall}$	[$GF_{-gas/ice-ice/abl}$]
L=1	-2.55	-7.63	11.43	1.14	10.29	[10.18]
L=2	-1.73	-4.00	6.90	0.95	5.95	[5.73]
L=3	-1.20	-1.00	1.65	0.41	1.24	[2.20]
L=4	-0.66	2.05	-3.64	-1.47	-2.17	[-1.39]
L=5	0.28	6.10	-13.1	-5.62	-7.48	[-6.38]
L=6	1.21	10.2	-22.5	-13.0	-9.48	[-11.4]
L=7	2.20	14.8	-37.9	-22.3	-15.6	[-17.0]
L=8	3.19	19.4	-53.4	-31.7	-21.7	[-22.6]
L=9	4.31	24.9	-76.2	–47.2	-29.0	[-29.2]
L=10	5.43	29.5	-99.0	-62.5	-36.5	[-34.9]
L=11	6.47	34.5	-131.	–86.2	-44.8	[-41.0]
L=12	7.55	39.5	-163.	–110.	-53.7	[-47.0]

Gas fill at center of capsule = 0.6 mg/cc

Perturbation on:	gas/ ice$=H_{ice}$	ice/abl	abl/out	Radius	H_{abl}	[H_{abl}]
Mode	GF	GF	GF	GF	$Gf_{abl/out-wall}$	[$GF_{-gas/ice-ice/abl}$]
L=1	-2.63	-7.85	11.53	1.02	10.51	[10.48]
L=2	-2.00	-4.92	9.33	0.19	9.14	[6.92]
L=3	-1.33	-0.83	0.79	-1.07	1.86	[2.16]
L=4	-0.66	1.76	-3.90	-3.39	-0.50	[-1.10]
L=5	0.16	5.82	-12.7	-7.50	-5.20	[-5.98]
L=6	0.99	9.90	-21.5	-11.6	-9.94	[-10.9]
L=7	2.08	14.9	-37.5	-21.4	-16.1	[-17.0]
L=8	3.01	19.9	-53.6	-31.2	-22.4	[-22.9]
L=9	4.25	25.6	-78.8	–47.8	-31.0	[-29.8]
L=10	5.50	31.4	-104.	–64.4	-39.6	[-36.9]
L=11	6.71	37.8	-140.	–93.7	-46.3	[-44.5]
L=12	7.91	44.2	–177.	–123.	–54.	[-52.1]

Table II Surface Thickness Tolerance per mode for Implosion Stability

This set of tolerances represents an equal allocation of the allowed final perturbation between the various modes and surfaces. The actual perturbations may be traded off against each other as described in the text. The perturbations are specified as: (I) H_{ice}= perturbation in the ice inner radius with uniform ablator thickness and outer ablator radius spherical; (ii) H_{abl} = perturbation in the ablator thickness with the outer radius spherical and the ice thickness uniform; (iii) Radius = perturbation in the outer ablator radius with both ice and ablator thickness uniform.

Gas fill 0.3 mg/cc

Perturbation on:	H_{ice}	H_{abl}	Radius
Mode	T_{ice}(nm)	T_{abl}(nm)	T_R(nm)
L=1	190	47	-
L=2	240	81	240
L=3	240	220	240
L=4	240	240	240
L=5	240	75	86
L=6	240	42	37
L=7	220	28	22
L=8	150	21	15
L=9	110	16	10
L=10	89	14	7.7
L=11	74	12	5.6
L=12	64	10	4.4

Gas fill 0.6 mg/cc

Perturbation on:	H_{ice}	H_{abl}	Radius
Mode	T_{ice}(nm)	T_{abl}(nm)	T_R(nm)
L=1	180	46	-
L=2	240	52	240
L=3	210	200	210
L=4	190	190	110
L=5	170	58	47
L=6	160	29	28
L=7	140	17	14
L=8	91	12	8.8
L=9	60	8.6	5.4
L=10	44	6.5	3.7
L=11	34	5.1	2.4
L=12	27	4.1	1.7

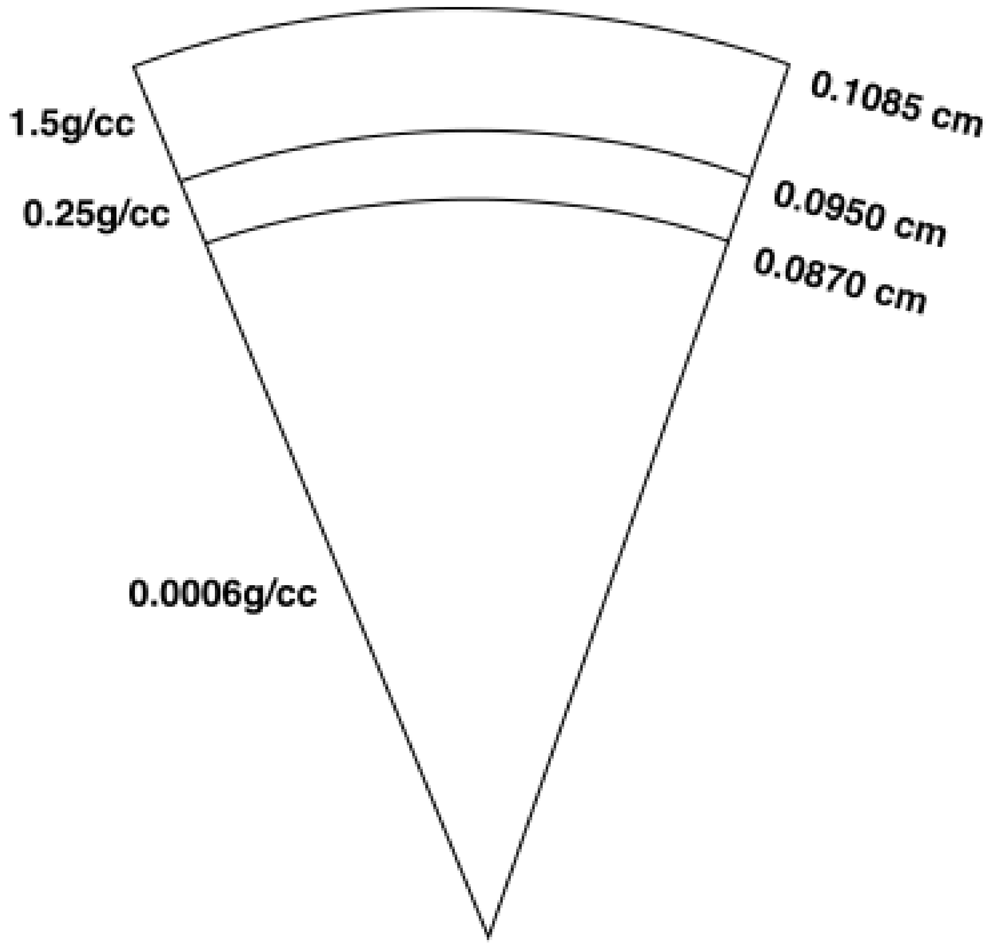

Figure 1. The spherical Point Design capsule has a polyimide ablator, a D-T cyrogenic layer, and an inner D-T gas fill.

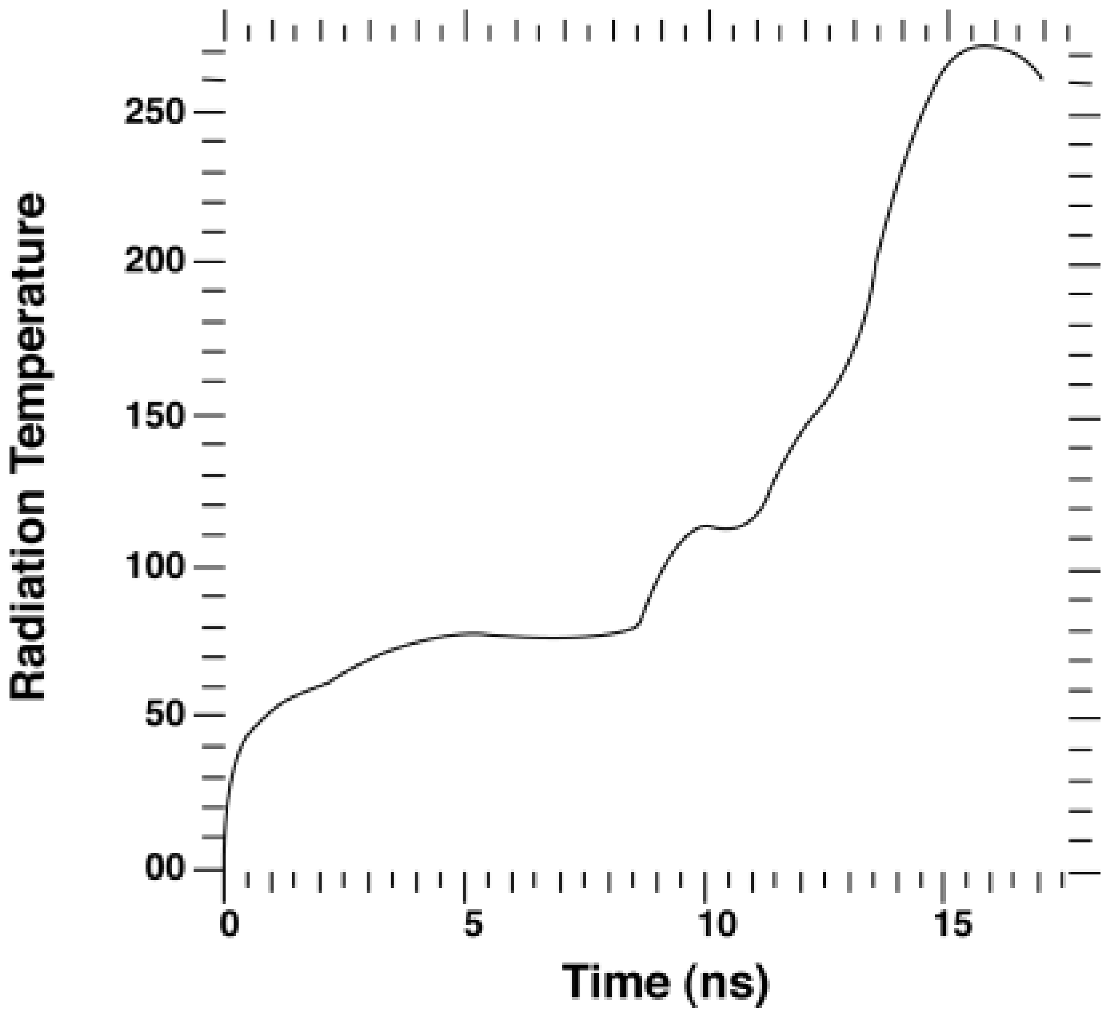

Figure 2. Time dependent flux temperature of the radiative drive.

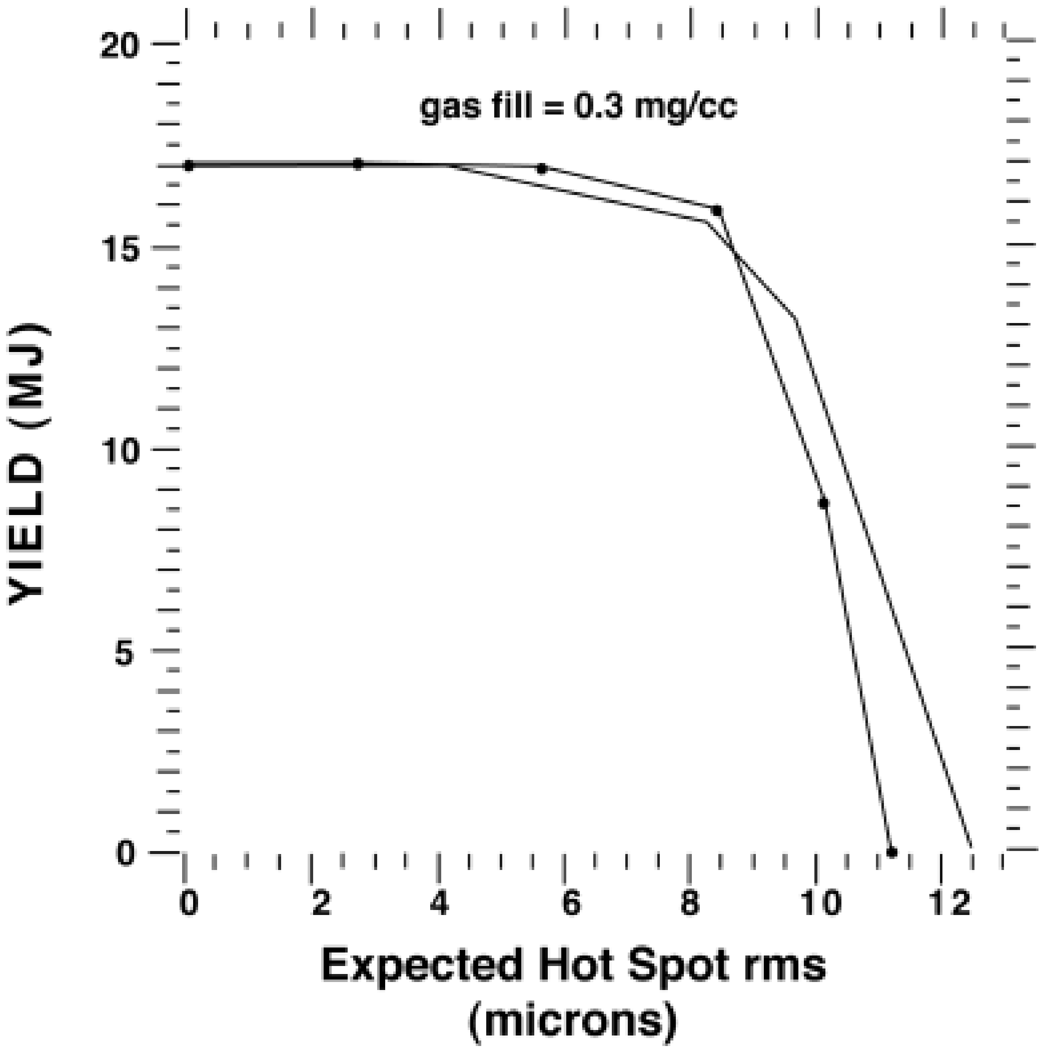

Figure 3a. Yield versus expected hot spot rms in microns from 2-D implosion simulations with gas fill of 0.3 mg/cc for modes 2 and 6. "Expected hot spot rms" is the product of the initial rms and the linear regime growth factor.

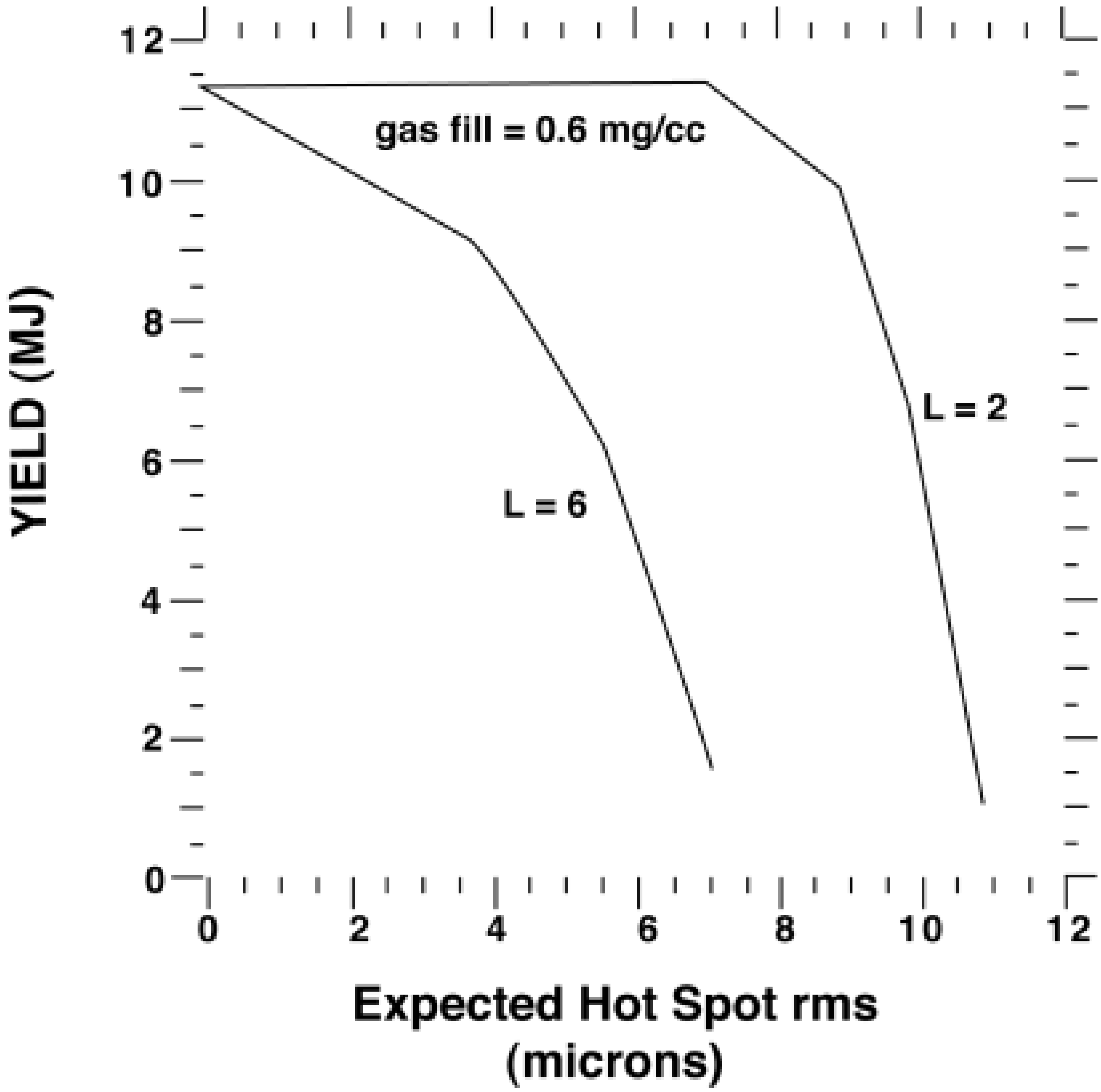

Figure 3b. Gas fill of 0.6 mg/cc.

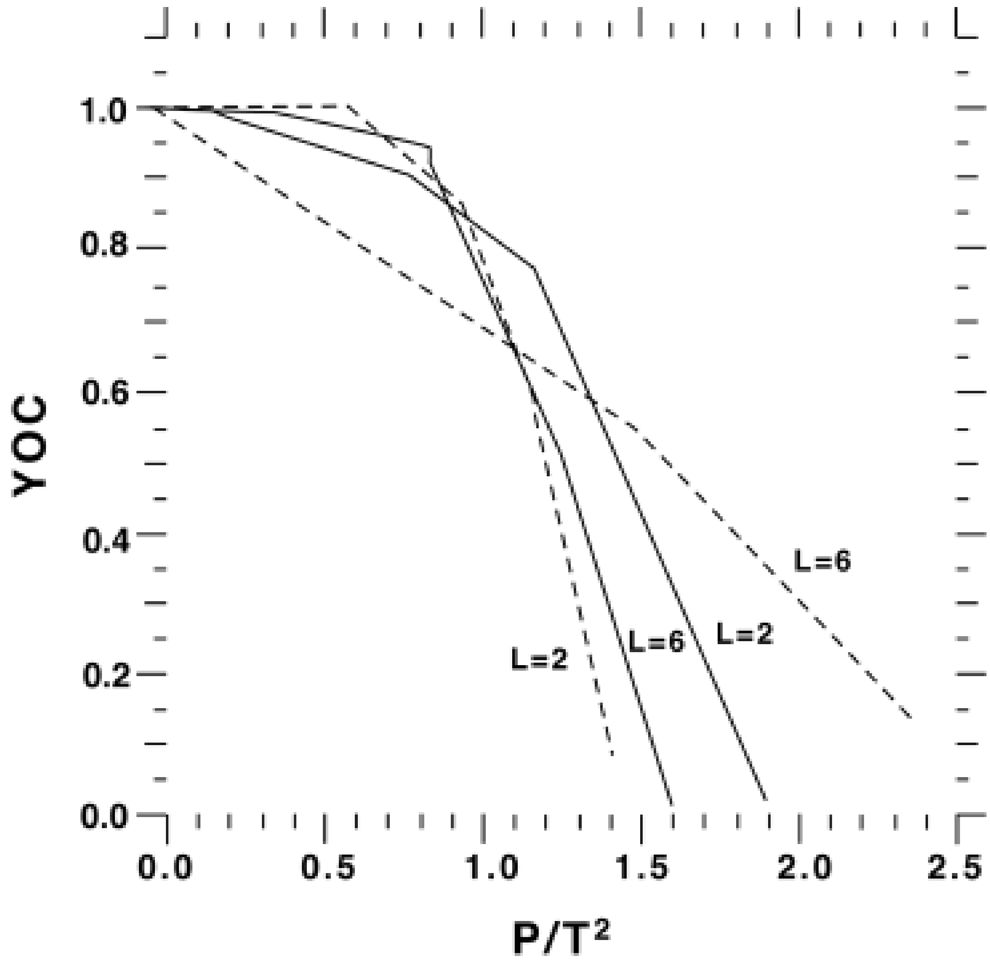

Figure 4. Yield over Spherical versus P/T^2.The YOC versus power over squared modal Tolerance. Each curve is for a single mode perturbation with varying initial amplitude. The solid curves are for gas fill 0.3 mg/cc, dashed curves are for gas fill 0.6 mg/cc.

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