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Configuring NIF for Direct Drive Experiments

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ABSTRACT

The National Ignition Facility (NIF) is a proposed 1.8 MJ laser facility for carrying out experiments in inertial confinement fusion, currently designed for indirect drive experiments. The direct drive approach is being pursued at the 30 kJ Omega facility at the University of Rochester. In this paper we discuss the modifications to the NIF laser that would be required for both indirect and direct drive experiments. A primary concern is the additional cost of adding direct drive capability to the facility.

1. OVERVIEW

The National Ignition Facility (NIF) is a project whose primary mission is to provide an above-ground experimental capability for maintaining nuclear competence and weapons effects simulation, and to pursue the achievement of fusion ignition utilizing solid state lasers as the energy driver. In this facility a large number of laser beams are focussed onto a small target located at the center of a spherical target chamber. The laser energy is delivered in a few billionths of a second, raising the temperature and density of the nuclear materials in the target to levels where significant thermonuclear energy is released. The proposed project is described in a conceptual design report (CDR) that was released in May 1994.

There have been two main approaches to achieving significant thermonuclear yield in ICF. The first is to enclose a small spherical shell containing the fuel inside a cylindrical container (indirect drive). The laser beams heat the cavity to several hundred eV and the associated X-ray flux on the capsule causes it to implode and ignite. In the second approach the laser beams illuminate the capsule directly, (direct drive) heating the corona to a significantly higher temperature. Based on a long history of experience from existing glass lasers, primarily

Nova, and from the Halite/Centurion series of underground tests devoted to ICF physics, the primary ignition campaign on the NIF will use the indirect drive approach. However, the indirect drive approach represents a less well studied but realistic alternative. The Omega laser at the University of Rochester is nearing completion and will add significantly to the scientific data base for direct drive. Present information indicates that direct drive can reach ignition at the energy and power of the NIF. If experiments at LLE and elsewhere confirm this there would be a strong interest in carrying out ignition experiments in direct drive also.

To configure the NIF for direct drive[1] involves adding 24 beam ports to the target chamber to make a total of 72 ports, as illustrated in fig. 1. Different subsets of these ports would be used for direct and indirect drive illumination. We would maximize the laser bandwidth by adding FM bandwidth to each of the four wavelengths present in a cluster. The bandwidth during the foot would be increased to improve the early time smoothing. The laser cavity and transport optics would remain the same. The added beam divergence associated with the beam smoothing does not appear to cause a significant reduction in the peak power on target. The oscillator and Front End would be modified to incorporate the beam smoothing hardware.

An additional advantage of adding ports to the target chamber is that other hohlraum designs can be contemplated, in particular tetrahedral and octahedral hohlraums.

2. STRATEGY FOR DIRECT DRIVE ON THE NIF

The strategy for modifying the NIF laser to accommodate direct and indirect drive should address several concerns. These include: (1) the additional cost associated with adding the hardware required to meet the additional target requirements should be kept to a minimum, (2) the modified system must be compatible with the indirect drive requirements, and (3) the plan must be flexible enough to respond to information obtained in the future, from the Omega laser at the University of Rochester and elsewhere, regarding the laser parameters that will lead to ignition. A particularly important issue to resolve is whether direct drive should be included as an upgrade to the NIF, to be completed at a later date after indirect drive experiments have begun; or whether it should be built into the facility during construction.

The main differences in the laser system requirements have to do with the target illumination geometry and the need for smoothing to control both imprinting and the spherical distortion at ignition. The illumination geometry is almost certainly incompatible with the port locations required for indirect drive. One approach is to build a second target chamber. Another is to add ports to the indirect drive chamber to accommodate the need for more even illumination. A third possibility is to simply repoint the beams from the indirect drive port locations so that some of the beams are not directed radially. The last possibility can be dismissed as ineffective. The second option is the least expensive for several reasons. A second chamber will require two complete sets (48 beams + 48 beams) of transport optics, whereas adding ports will certainly require the addition of less than 48 transport paths and ports, (probably 24) to the existing chamber. And adding the direct drive capability at a later date will require a full reconstruction of the transport optics with considerable hazard to the optics, and a delay in experiments of between six and twelve months. The most reasonable option is to build into the NIF at the outset the extra ports required for direct drive and at the same time add the mechanical capability to switch from one illumination geometry to anther. It is therefore a high priority to determine the desired port locations before engineering design is started.

The beam smoothing strategy is less certain. Experiments have not been conducted to

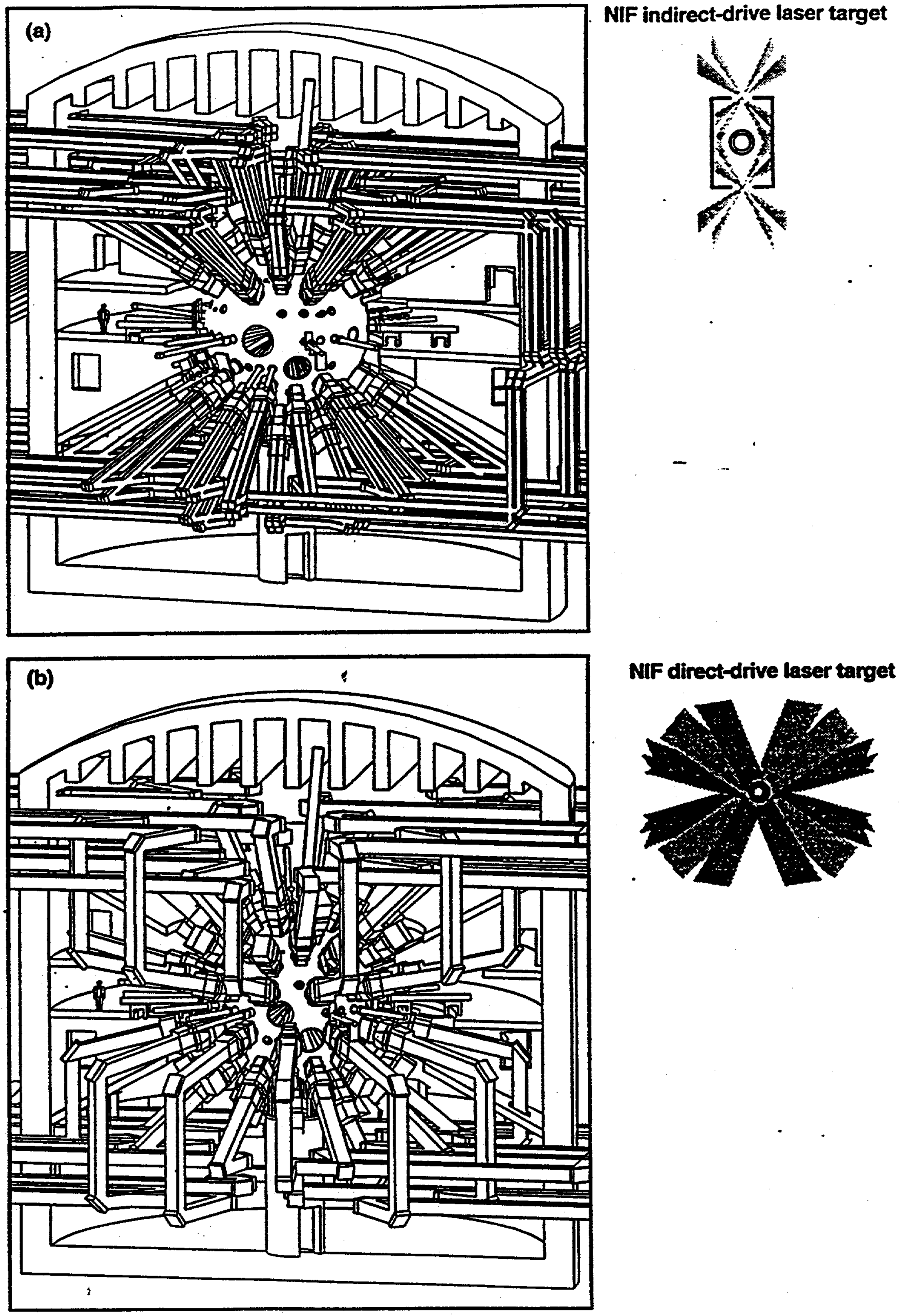

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Figure 1 NIF target illumination designs meet both the direct-drive and the indirect-drive requirements verify that propagation of suitably modulated beams through a NIF-like laser architecture is possible at the desired pulse energy and peak power. Also it is likely that data from Omega and elsewhere will indicate a preference byf spherical targets for smoothing with particular characteristics. It is clearly desirable to remain flexible with respect to the beam smoothing implementation. The Front End would be designed to accommodate those schemes that are believed at the present time to be attractive. The scheme selected in the light of future scientific data would be implemented at a later date closer to the direct drive experimental campaign. Implementation costs would be borne by operating funds or taken out of construction funds held over for this purpose. It is likely that the cost of implementing a smoothing scheme will be compatible with either approach.

Thus the laser strategy for direct drive is to design the target chamber at the outset to handle both indirect and direct drive illumination geometries and to design the Front End to accommodate such changes that can be foreseen today in implementing the modulation required for beam smoothing.

We believe that this strategy will result in a flexible system for direct drive experiments. In the laser modifications we envision the temporal pulse shape will be continuously variable, and the bandwidth will be adjustable between the foot and the main pulse. The spatial profile of the beams at the target can be changed by using different phase plates. The size of the beams can be adjusted in the same way. The average shape of the beams at the target (elliptical vs. circular) can be controlled in a time-dependent manner by adjusting the parameters of the smoothing hardware. The illumination geometry can be fine-tuned by repointing beams so that they are sightly non-radial at the target. This represents a sufficiently large adjustment, despite the time dependence of the beams' apparent position, to fine tune the time-dependent uniformity for optimum target performance. The power and energy of individual beams can be adjusted for further control of uniformity. The system we envision will have considerable flexibility within the basic constraints of frequency converted glass lasers to optimize the drive uniformity and control target instabilities. It will easily support the projected experimental campaign.

3. DIRECT DRIVE REQUIREMENTS AND TARGET CHAMBER MODIFICATIONS

A high degree of illumination uniformity is required to suppress hydrodynamic instabilities in the imploding target. Surface perturbations in the thin shell arise from fabrication methods and imprinting of the laser speckle pattern into the shell. These are amplified by the Rayleigh-Taylor instability as the shell is accelerated inwards. If the deformations are too large the target will not ignite; it is essential to control these instabilities.

The spectrum of spatial wavelengths in the surface perturbations is critical - the outer and inner surface perturbations participate sequentially in the growth of shell deformations. The outer surface perturbations grow while the shell is accelerated, whereas the inner shell perturbations grow as it decelerates prior to ignition. The initial outer shell perturbations contain a wide range of spatial wavelengths (L-modes) of which only a portion, mostly high L-modes (50-300) are significantly unstable. At the inflexion point between acceleration and deceleration the shell perturbations must be small enough that the shell remains whole. After the inflexion point the outer shell perturbations transfer to the inner shell where they add to the fabrication structure and are further amplified. It is mostly the low L-modes that transfer to the inner shell, and it is predominantly the low L-modes that determine whether the fuel ignites. Thus there are two components to the uniformity requirement. First, the high L-modes in the outer shell must be controlled to prevent shell break-up, and second, if the shell does not break up, the low L-modes must be controlled to ensure ignition. The high L-modes are controlled using beam smoothing techniques, but the low L-mode terms are determined predominantly by system tolerances such as beam pointing and beam-to-beam power balance. Simulations and theoretical arguments indicate that the uniformity requirement on the low L-mode ($L<20$) nonuniformity 1% at all times in the implosion, and that for the high L-modes ($21<L<500$) the speckle nonuniformity is 1% (when integrated over about 1 ns) for the foot of the pulse, and somewhat higher during the main pulse when laser imprinting is less significant.

Many laser parameters contribute to the uniformity, and all must be controlled. Table 1 illustrates a typical nonuniformity budget for the NIF, which is a 48-beam facility. Also included are the laser parameters necessary to meet the speckle or high L-mode requirements.

Table 1: Uniformity from Various Sources

Parameter	Nonuniformity Allocation (%)
Port Locations on Chamber	0.2
Beam pointing, centering	0.5
Beam-to-beam power balance	0.5
Beam envelope errors	0.5
Target Position (L=1)	0.5
Speckle Content (1ns)	1.0 (foot) ~ 2.0 (main pulse)
Bandwidth	2Thz (foot) < 1 Thz (main pulse)
Polarization	Mixed
Wavelength	351 nm

These must be added in an RMS sense, so that the low L-mode uniformity is 1%. Note also that the laser absorption radius decreases by about a factor of two during the pulse; this makes the laser uniformity requirements time-dependent.

The nonuniformity budget associated with the port locations can be achieved over a range of designs that includes the high performance indirect drive geometries. For indirect drive the ports are arranged in four cones in each hemisphere, at roughly 22°, 31°, 46°, and 58°, containing 4,4,8,and 8 ports respectively. For direct drive we would add a fifth cone of 12 ports at about 75°, using that ring and the rings at 22° and 46° to obtain uniform illumination. Figure 2 shows the nonuniformity achieved with this 4,8,12 geometry as a function of the two smaller cone angles, the third being fixed by the requirement of minimizing the nonuniformity. There is clearly considerable flexibility in the selection of the cone angles, sufficient to encompass the indirect drive geometry.

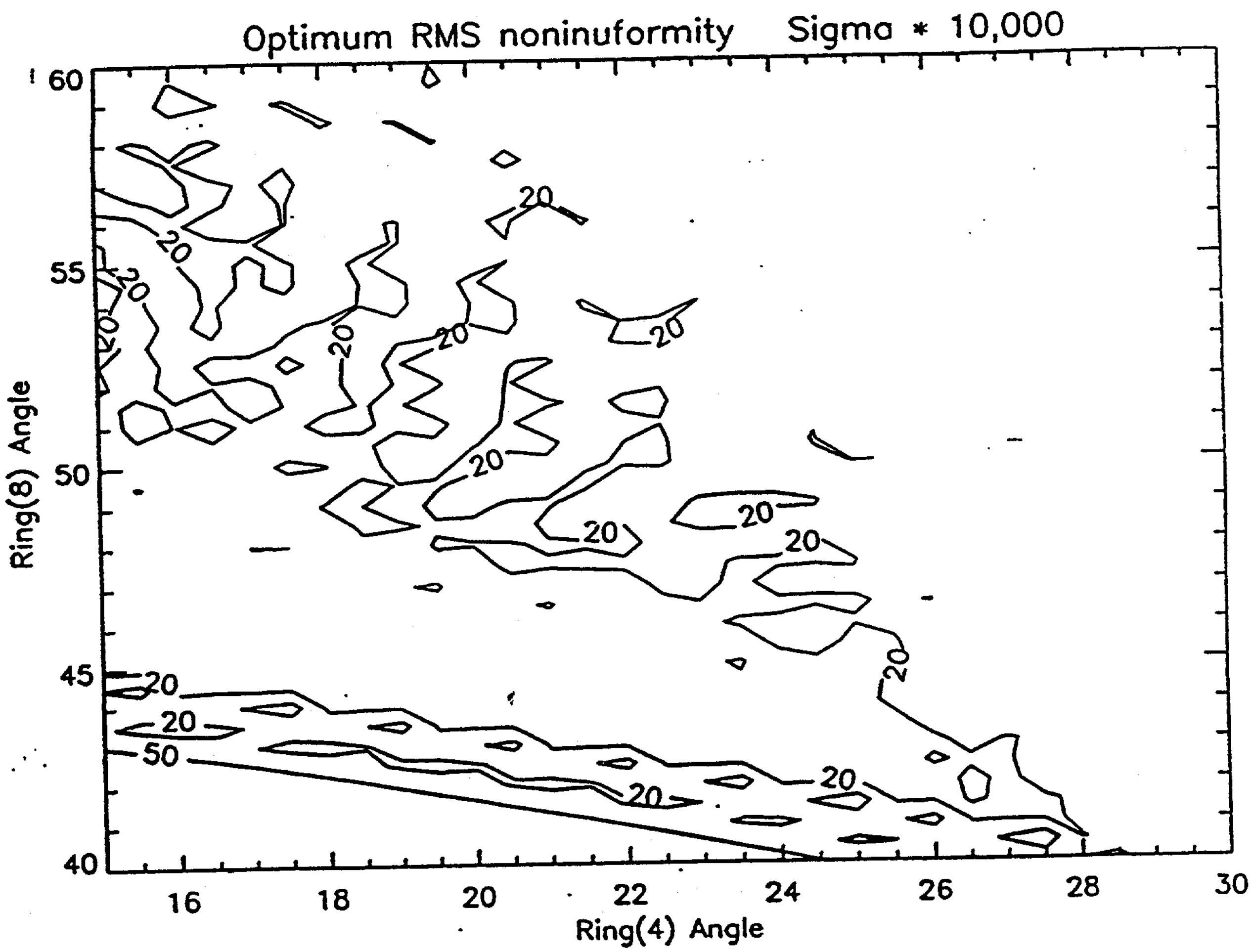

FIGURE 2 : Contour plot of Nonuniformity as a function of Ring angles. The third ring is optimized and is around 80 degrees.

From Table 1, it is clear that the port locations do not take up a significant part of the low L-mode nonuniformity budget. The dominant terms derive from beam pointing and beam-to-beam power balance. Note that the NIF has 192 beamlets grouped into 48 clusters of four. The nonuniformity depends on the correlations between the four beamlets within one cluster. Figure 3 shows the effect of pointing and power imbalance on the low L-mode uniformity for the case of 48 independent beams, and 192 independent beams, and taking the relevant target radius to be the initial radius (1.5 mm) or the laser absorption radius at ignition (0.8 mm). It is evident that the RMS tolerances must be significantly tighter if there are correlations between the beam errors. Currently target studies suggest that the appropriate radius to use is the initial radius. Thus with completely uncorrelated beams, the baseline NIF tolerances must be tightened to meet the low L-mode uniformity requirement.

4. BEAM SMOOTHING LASER MODIFICATIONS

Beam smoothing is used to control the high L-mode structure in the ablative pressure on the shell. The physics of imprint and its connection with the speckle smoothing implementation is a complex subject that will not be discussed further here. Some aspects are discussed in an accompanying paper[2]. The implications of beam smoothing for the laser system are the necessity for including high bandwidth up to 2 Thz, transporting multimode, modulated beams in the laser amplifiers, and incorporating appropriate modifications to the Front End to generate appropriately modulated beams. Moreover, the peak power and total energy on target must be maintained above the requirements,(450 TW, 1.5 MJ) after these feature have been included.

The spatial propagation of the beams the NIF amplifiers is affected by the smoothing modulation applied to the beam. The modulated beam has both bandwidth and an added beam divergence associated with the additional spatial modes. As a result the peak power delivered by the NIF is compromised by modulation. Bandwidth causes intensity modulation through group velocity dispersion and the added beam divergence causes spatial and temporal intensity variations associated with nonlinear ripple growth or beam clipping in the spatial filter pinholes or a near field aperture. At low intensity, large intensity modulation is permissible without compromising the performance. However, at high intensity an additional variation in the fluence across the beam aperture increases the risk of damage and requires the total power and energy to be reduced. The power and energy on target will be a maximum if the smoothing technique preserves pure phase modulation at high power.

A beam with phase modulation develops intensity modulation with propagation distance. Beams with SSD develop intensity modulation as a result of beam divergence as well as GVD in the laser glass. For direct drive the fractional bandwidth might be 0.0005, and the added beam divergence is about 10 X the diffraction limit, or about 50 μrads. For these parameters we estimate that the intensity modulation is $dR/dz = 0.0004$ per meter. The propagation distance in the relayed cavity is never more than the total cavity length, 45 meters, for which $R = 1.8\%$. During transport to the target chamber, the distance might be as large as 90 meters, for which $R = 3.6\%$. This modulation increases roughly as the square of the added beam divergence.

The time integral of the intensity modulation is small and therefore it has very little direct effect on the fluence, and hence on the maximum power and energy. On the other hand the peaks in the local intensity are large relative to the spatial wavelength of those ripples that experience significant Bespalov-Talanov nonlinear growth. In these circumstances, the ripple growth depends on the local intensity and varies locally over the beam aperture and in time

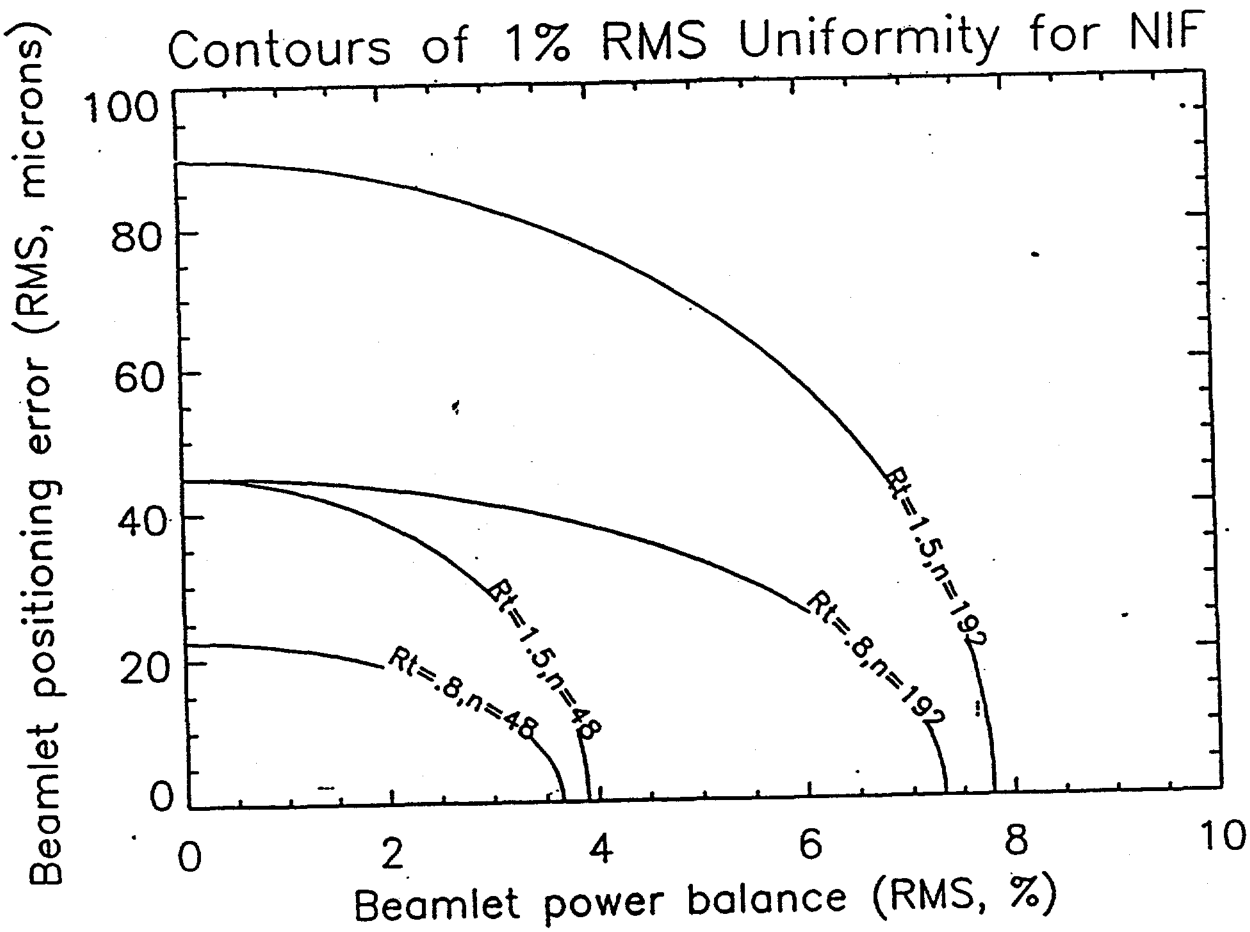

FIGURE 3 : 1% Nonuniformity curves for beam pointing and power balance. The baseline specifications are 50 μm positioning and 8% beam power RMS. The direct drive specifications are 50 μm psotioning and 5% beam power RMS.

within the pulse. Ripple growth is superlinear with intensity, and so the net effect of the intensity modulation is to increase the effective ripple growth. As a result, the modulation affects the local fluence indirectly through ripple growth, adversely impacting the peak power and energy. The increase in the peak fluence as a result of enhanced ripple growth is of order R^2 which is of order 0.0004 or less in the cavity. Even if the local nonlinear growth factor B is 2 or higher and the baseline ripple is 30%, the effect on the power and energy is not important.

A potentially more significant effect is the effect of modulation on the function of the spatial filter pinholes. The added beam divergence brings the beam closer to the edge of the pinhole and also permits partial passage of ripples at angles greater than 100 μrads that would ordinarily not pass in the absence of SSD. Both effects increase the spatial modulation at the frequency convertor. Simulations of the propagation of tilted beams show that adding 50 μradians to the beam and pinhole diameter does not increase the ripple growth significantly; it may even reduce it. Calculations of the performance of the baseline NIF cavity with 200 μrad (full width) pinholes, using monochromatic beams offset in angle by up to 60 μrads, indicate that at about 10-12 times the diffraction limit the spatial modulation on the beam begins to limit the power and energy. This calculation is conservative in that the beam energy is spread out by the added divergence rather than tilted off, and the NIF cavity may transmit beams of larger added divergence without loss. Thus it appears that the pinhole radius could be increased by up to 50 μm without exacerbating nonlinear growth. In that case, the clipping limit would move out to 100 μrad added divergence, well beyond the direct drive smoothing requirement. These calculations suggest that the NIF cavity will indeed handle the modulated beam without loss in energy or power. However, we note that as the NIF cavity design is refined, the ability to transport modulated beams with 50 μrad of added divergence remains a significant design constraint that must be included.

The frequency converter is sensitive to bandwidth. At the nominal bandwidth of 160 GHz at 1ω, the conversion efficiency is substantially reduced. The energy conversion efficiency for a picket fence pulse with a temporally flat main drive, and where the peak 1ω intensity is set to 3.25 GW/cm^2, is 0.70, and falls to 0.47 at a bandwidth of 160 GHz. The peak power conversion drops from 0.88 to 0.57, over the same range. The peak power is a very significant parameter for direct drive targets, and this loss in conversion efficiency, which translates linearly into a reduction of about a third in peak power, is very significant. Another feature of large bandwidth, apart from the loss in energy and power on target, is the strong power modulation that appears on the 3ω beam at the RF frequency. However, this modulation is skewed in time and probably does not affect the hydrodynamics of the target.

There are several ways to recover from this loss in peak power. The first is to redesign the tripler to be thinner. With a thinner tripler the foot converts less efficiently, but the main drive is essentially unaffected. Data from experiments on a 10.5 mm / 8.1 mm tripler is shown in Figure 4. The peak conversion efficiency for the given pulse shape and divergence drops from over 70% to about 60%, a loss of about 20%, a considerable improvement. There are also other frequency conversion schemes that offer some improvements, such as high dynamic range designs that increase the conversion efficiency for the foot of the pulse, without significantly compromising the conversion efficiency at its peak. One design that accomplishes this is a three-crystal design with two type I doublers arranged in an alternating-Z configuration, and a single type II tripler. In the alternating-Z doubler configuration the z-axes of the two doublers are in inequivalent directions, and their angular offsets in opposite senses. The thicknesses and angular offsets of the three crystals are listed in Table 2. The three lengths are L2, L2z, and L3, and

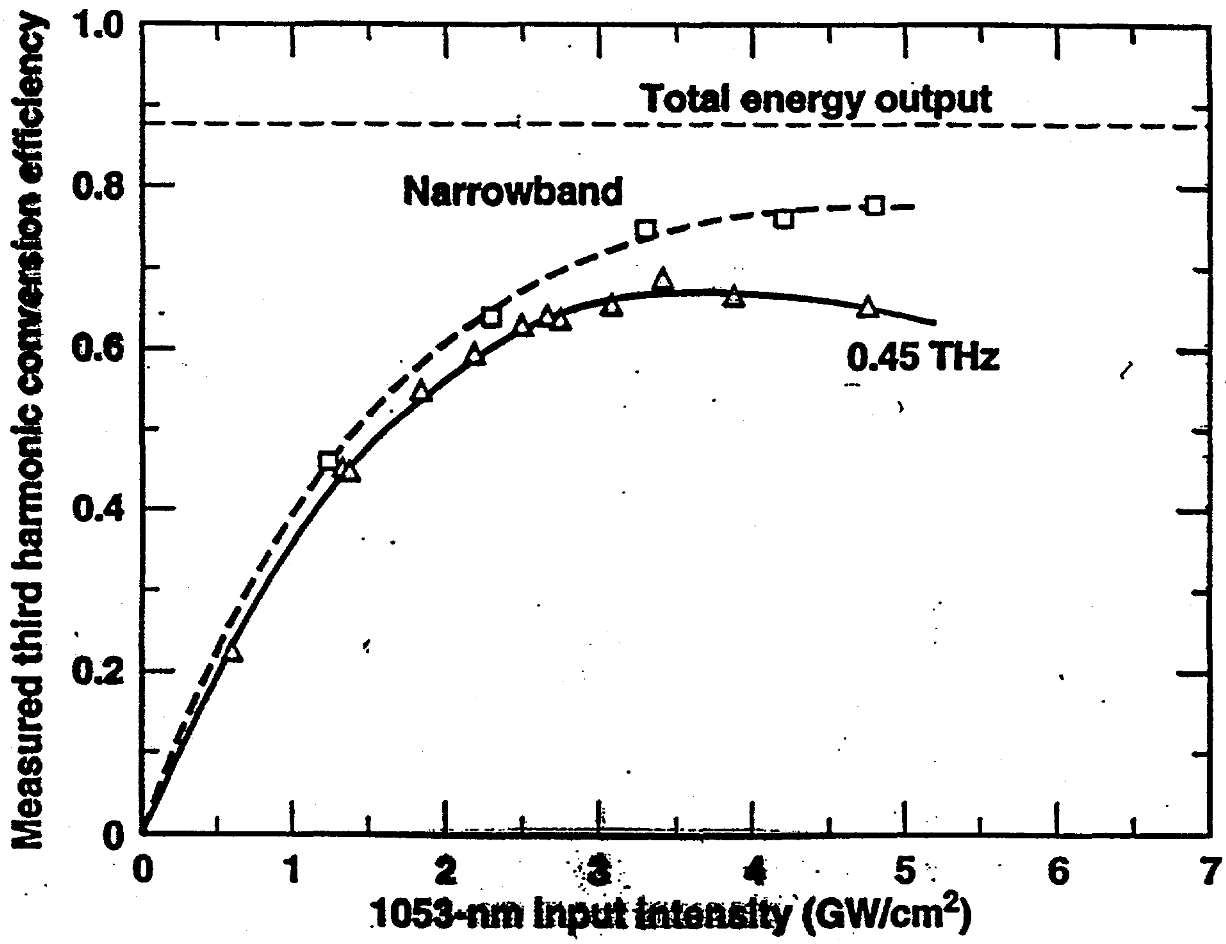

FIGURE 4 : Experimental data on the baseline NIF converter at 0.45 THz blue. The crystals had more loss than NIF crystals.

the associated angular offsets are Th2, Th2z and Th3. Also listed are the baseline, and a thicker crystal baseline that improves low intensity conversion by sacrificing the high intensity performance. Two advanced designs are shown. The second advanced design uses deuterated crystals to offset the increase in optical absorption for thicker crystals.

Table 2 : High Dynamic Range Frequency Tripling Designs for NIF

Set	D(%)	L2	Th2	L2z	Th2z	L3	Th3	Efficiency
1	0	11	250	-	-	9	30	66.5
2	0	13	210	-	-	10	30	69
3	0	13	400	10	-520	13	30	74
4	70	13.5	380	10	-510	13	30	75

Units: Length in mm, Angles are internal in microradians

These designs maintain about a 5% higher conversion at high bandwidth than the baseline conversion scheme.

There are other three-crystal tripling schemes that offer improvements in bandwidth such as single doubler followed by two triplers. Calculations of these tripling schemes are presented in another paper at this conference[3]. They suggest that the single beam bandwidth can be as much as 1 Thz at 3ω, with only a 5% penalty in conversion efficiency for the appropriately shaped pulses. The possibility of a system bandwidth in excess of 4 Thz is exciting and work is ongoing.

Another approach is to vary the bandwidth during the pulse. During the imprint phase, the bandwidth can be high, perhaps as much as 200 GHz (2.4THz for a cluster of four beams at 3ω) without seriously impacting the energy efficiency. After the imprint phase the bandwidth can be reduced to about 100 GHz (1.2THz per cluster) to allow high conversion efficiency for the main pulse, partially recovering both the energy and the peak power. This is perhaps the least expensive option for recovering from the bandwidth sensitivity of the triplers, and is attractive if it is acceptable to the target.

Figure 5 shows a contour plot of the peak power as a function of the bandwidth and added beam divergence. (We have assumed a thinner tripler than the baseline in anticipation of the needed redesign. The bandwidth penalty for the thinner tripler is assumed to be about half that for the baseline.) For SSD schemes, the bandwidth and added divergence are linearly related; if the bandwidth is reduced the beam divergence is also reduced. The interrelation of bandwidth and beam divergence implies that as the bandwidth is varied the added beam divergence may be different along the x- and y-directions so that beam in the pinhole may not be square. It can become a (time-dependent) rectangle. For figure 5 the relevant parameter is the maximum of the added divergences in any direction. As the bandwidth is varied, the system follows a line such as AB in figure 5. For the main pulse, the operating point should lie within a high power contour. During the foot, the peak power limits here are not the most significant, rather pinhole clipping and other linear sources of spatial modulation become important. Thus for higher bandwidth, the operating point can lie where the peak power is quite low. The key

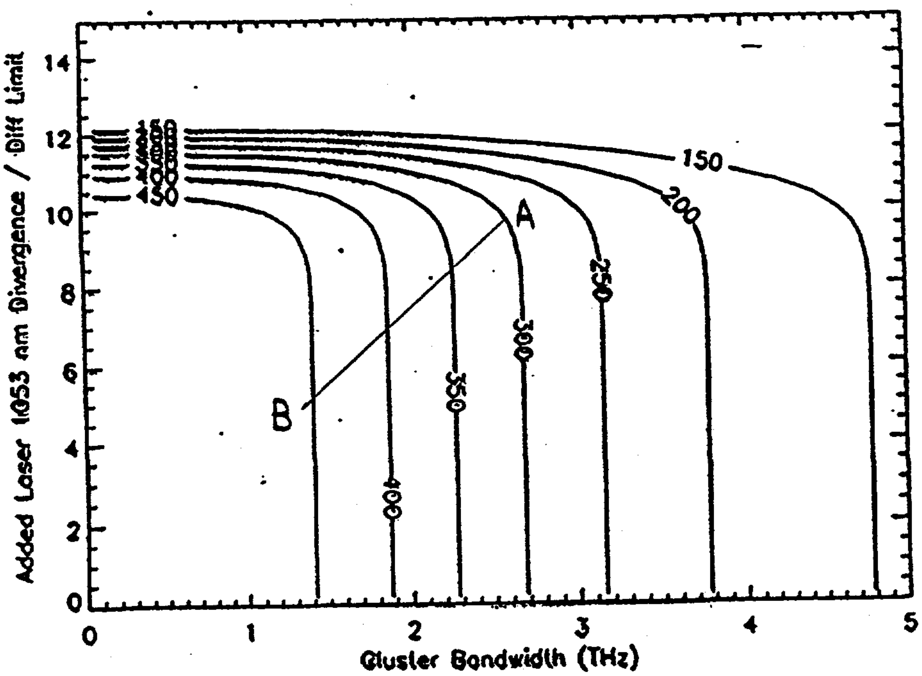

FIGURE 5 : Contour Plot of Peak Power as function of cluster bandwidth and added divergence. The point A refers to the foot operating point, the point B to the main pulse operating point.

figure of merit determining allowable extent of bandwidth variation is essentially the high l-mode smoothness requirement for the main pulse. The target requirements for the main pulse alone have not yet been explored.

5. SUMMARY

We have described a cost-effective approach to modifying the NIF laser design to enable direct drive experiments. While much design work remains, it appears that the strategy of using the same target chamber, but with 72 ports rather than 48, and designing the laser to accommodate the generation and propagation of modulated pulses, will enable direct drive experiments at about 1.5 MJ and 1% smoothness. Target modeling studies at the University of Rochester strongly suggest that under these conditions direct drive targets will ignite and achieve significant gain.

6. ACKNOWLEDGEMENTS

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1. LLE and LLNL joint publication "Configuring the National Ignition Facility for Direct Drive", David Eimerl, Editor, UCRL-ID-120758
2. J.E.Rothenberg,"Illumination Uniformity Requirements for Direct Drive Inertial Confinement Fusion at the National Ignition Facility", paper T11, this conference
3. P.W.Milonni, "Frequency Conversion with Spatially and Temporally Varying Beams", paper T18, this conference