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**Early time radiation symmetry tuning in the presence of cross-beam energy transfer in indirect drive ignition hohlraum experiments on the National Ignition Facility**

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**Abstract**

At the National Ignition Facility (NIF) we have successfully tuned the early time (~ 2 ns) lowest order Legendre mode ($P_2$) of the incoming radiation drive asymmetry of indirectly driven ignition capsule implosions by varying the inner power cone fraction. The measured $P_2/P_0$ sensitivity vs cone fraction is similar to calculations, but a significant -15 to -20% $P_2/P_0$ offset was observed. This can be explained by a considerable early time laser energy transfer from the outer to the inner beams during the laser burn-through of the Laser Entrance Hole (LEH) windows and hohlraum fill gas when the LEH plasma is still dense and relatively cold. A simple analytical model of $P_2/P_0$ vs cone fraction, tuned to match calculations and data, suggests >200% increase in inner beam power due to transfer. Measurements using two different NIF ignition hohlraum designs show similar $P_2/P_0$ sensitivity to cone fraction with an offset explained by changes in geometry and beam pointing, in agreement with our analytical model and calculations.

Capsule tuning experiments on the National Ignition Facility (NIF) [1] using 192 laser beams, with total energy ranging between 1 and 2 MJ, have been underway for the past couple of years [2]. The goal is to optimize the compression of a DT filled, 2-mm diameter capsule imbedded in a cm-long He-filled high-Z hohlraum [3,4] in an attempt to bring it to ignition and burn [5]. One of their main objectives is to achieve a capsule implosion with minimal low mode asymmetries in the imploded core. For the cylindrical hohlraum geometry employed at the NIF, the laser beam spots at the wall are arranged in three illuminating rings with nearly uniform azimuthal coverage due to the large number of beams per ring. As a result, the x-ray flux impinging onto the capsule has a high-degree of azimuthal uniformity and can be decomposed into Legendre polynomials $P_L$ [6,7]. Furthermore, since the beams are arranged symmetrically about the hohlraum mid-plane, the odd Legendre polynomials ($P_1$,$P_3$,…) are intrinsically small and mainly due to random imbalances of the laser beams. On the other hand, even low order modes ($P_2$, $P_4$) of the incoming radiation flux at the capsule need to be controlled by hohlraum geometry, relative cone powers and beam pointing [2]. Radiation-hydrodynamics simulations [8] have shown that the shape of the capsule at ignition time is mainly sensitive to radiation asymmetries occurring during the first 2 ns (picket) and during the peak of the ignition laser pulse while asymmetries at other periods of the laser pulse play a small role. The mitigation of early time asymmetries is needed since they are responsible for time-dependent swings of the $P_2$ and $P_4$ modes during the time of maximum compression leading to unacceptable levels of hot spot deformation [9, 10]. In addition, drive flux asymmetries are tantamount to non-uniformities in shock velocity and timing, leading to local increases in hot-spot entropy in excess of the ideal case. This effect is particularly important during the picket, which sets the arrival time and the

strength of the first shock at the inner surface of the DT ice, largely determining the implosion adiabat [11].

Initial indirect drive implosion experiments of cryogenic DT fuel capsules at the NIF found that round imploded cores could not be achieved solely by varying the ratio of inner to outer beam cone power balance during the peak of the laser pulse due to limitations in the available inner beam power. To achieve round implosions, current NIF experiments employ a complementary scheme whereby the inner cone power is further increased by crossbeam energy transfer (CBET) through the excitation of an ion acoustic wave (IAW) caused by the interference pattern of two laser beams having slightly different wavelengths [12]. While this process is geared at tuning the time-integrated symmetry dominated by the peak of the pulse, it is likely to change drive symmetry at other times. In particular, since the generation of the IAW is more effective when the plasma is dense and relatively cold [12], we expect the outer-to-inner CBET to be important during the picket when the laser beams burn through the hohlraum laser entrance holes (LEH) windows and gas fill.

To evaluate the effect of the picket symmetry on capsule performance we have performed a series of computer simulations where the ignition laser drive was artificially symmetrized after 2.5 ns. These simulations are routinely performed to assess the impact of different periods of the laser pulse on the final imploded core. The results are summarized in Fig. 1 which shows the variations of the $P_2/P_0$ of the incoming flux, integrated over the first 2 ns, as the incident cone fraction $CF_0$ (ratio between the incident inner and total laser beam powers) varies from the optimal value. The density maps of an ignition capsule at the time of maximum neutron production (insets in Fig 1) show relative fuel ρR-rms variations ($\Delta\langle\rho R\rangle$) of as much as 20% for 20% picket P2/P0. These variations in $\langle\rho R\rangle$ have dramatic implications on the performance of

an ignition capsule, with minimal yield degradation for $\Delta\langle\rho R\rangle$ <= 10% to almost 100% for $\Delta\langle\rho R\rangle$ > 20%. Thus, to stay within acceptable levels in capsule performance a $\Delta\langle\rho R\rangle$ < 10% is required, which translates to a cone fraction variation of ±0.035 or an allowable picket $P_2/P_0$ of ± 7.5% (Fig. 1). This is indicated by the blue region in Fig 1 and was adopted as our ignition requirement for the picket symmetry. Additionally, our calculations indicate that this variation in $P_2/P_0$ is equivalent to keeping the adiabat of the imploding capsule within 3% of the optimal value [2, 5].

In this letter we report on the measurement and control of the incoming radiation flux $P_2/P_0$ asymmetry impinging onto an ignition capsule during the picket drive phase of gas-filled NIF ignition hohlraums [2]. The lowest order moment ($P_2/P_0$) of the radiation flux during the first 2 ns of the laser pulse (picket) is tuned by changing the delivered laser cone fraction.

The measurement of the picket drive symmetry in NIF ignition hohlraums is performed using the re-emit technique [13] and the results are used to set the cone fraction for the first 2 ns of the laser pulse in ignition implosions [2]. The experimental layout is shown in Figure 2a, in which the ignition capsule is replaced with a high-Z sphere of similar dimensions. The asymmetry in the incoming flux at the capsule is inferred by measuring the soft x-ray re-emission pattern at the limb of the high-Z sphere. The target design uses a ~2 mm diameter Bi-capsule mounted in a He gas-filled (0.96 mg/cc) gold hohlraum having two 2.7 mm diameter diagnostic holes covered with 1 μm thick polyimide windows. The front hole is required for soft x-ray imaging, while the back hole is necessary to avoid contamination from the back-side wall emission. We tune the picket in two most recent ignition baseline hohlraum designs, referred to as scales 544 (5.44 mm diameter x 10.01 mm length) and 575 (5.75 mm diameter x 9.43 mm length), both having the

same 3.1 mm diameter LEHs. Data was acquired at four independent times in the 0.9-2.2 ns time interval using a 4-strip gated x-ray imager [14], placed 57 cm away from the re-emit sphere, set up with M=2x magnification and 100-270 ps imager exposure. The hohlraum is heated by ignition pulses terminated at 3 ns shown in Fig 2b which also includes a typical cone fraction vs time. The picket cone fraction $CF_0$ is defined at t=0.5 ns where the laser power is at its maximum. To avoid the x-ray background produced by the interaction of the laser beams with the diagnostic windows, 24 inner beams for the re-emit case are truncated just before they reach the hohlraum wall (at 600 ps), thus maintaining surrogacy with the ignition capsule case where all 192 beams are used to burn through the LEH windows and gas fill (see Fig 2a). The soft x-ray hohlraum flux in the picket measured by Dante [15] (Fig. 2c) reaches its maximum at 1.3 ns, 0.8 ns later than the peak of the laser power, since at early times a significant part of the laser energy is spent burning through the LEH windows and hohlraum gas fill. Calculations show that maximum x-ray drive at the capsule is reached at t=1.6 ns, i.e. 0.3 ns later than the peak hohlraum x-ray drive. The time integrated picket $P_2/P_0$ coefficient that we attempt to minimize (Fig. 1) is strongly weighted by the $P_0$ of the incoming x-ray flux at the capsule and thus dominated by the instantaneous $P_2/P_0$ in the 1.5-1.6 ns time range. Re-emission images are recorded at photon energies ($h\nu$) in the high energy tail of the Planckian spectrum allowing for amplification of the asymmetry of the spectrally-integrated radiation drive by $h\nu/4kT_{re}$, [13] where k is the Boltzmann constant and $T_{re}$ is the sphere re-emission temperature. The energy band chosen is a compromise between the increase in measurement sensitivity to the incident flux asymmetry and the reduction in the detected photon flux at higher energies that affects our photon-statistics-based accuracy. For the experiments presented here, our imaging system used 2.5 and 6 um thick Al filters paired with 50 and 100 um diameter pinholes respectively.

Convolving with a $T_{re} \approx 65$ eV Planckian expected for the typical picket Tr =75 eV, these filters select photon energies at 600 and 800 eV with a spectral width of ~300 eV, thus amplifying the $P_2/P_0$ Legendre mode coefficients by 2.1-3.2x.

Due to the differences in hohlraum geometry and laser beam configuration between the ignition and re-emit targets as described above, surrogacy was assessed by performing 3D radiation hydrodynamics simulations using HYDRA [17]. The results are summarized in the red-line shown in Fig 1, which shows the picket $P_2/P_0$ of the incoming flux integrated over 2 ns as a function of variations from the optimal cone-fraction. Calculations show that both ignition and re-emit $P_2/P_0$ have similar linear sensitivity with the Re-emit target having a ~6% higher $P_2/P_0$ for a symmetric ignition drive. This difference can be attributed to the presence of the diagnostic patches (+6% P2/P0), larger reemit x-ray albedo (-2% P2/P0) [5] and truncated inner cone beams (+2% P2/P0).

The picket symmetry tuning experiments in ignition gas-filled hohlraums on the NIF obtained re-emit images in both scales 544 and 575 hohlraums, for an inner-to-outer wavelength separation at 1ω of 5.5 Å. This wavelength separation was chosen to get the best time-integrated symmetry [2,12] at the time of maximum compression of an ignition capsule. Figure 3 shows the measured Re-emit images vs incident laser cone fraction in scale 544 hohlraums, obtained using the 800 eV photon energy channel at maximum x-ray flux time at the capsule (1.6 ns, Fig. 2b). It is clearly seen from Fig 3 that changing cone-fraction is tantamount to a change in the symmetry of the incoming flux from pole hot ($CF_0$ = 0.18) to waist hot ($CF_0$ = 0.25) going through the symmetric case for $CF_0$ = 0.22. From the measured photon collection statistics that was validated

experimentally in previous vacuum hohlraum re-emit experiments [13], the incident inferred $P_2/P_0$ accuracy is ±1%, which is well within the ±7.5% requirement (Fig 1).

The experimental tuning curve, compiled from the data (Fig 3) is displayed in Fig 4 showing incident inferred P2/P0 vs instantaneous cone fraction at t=1.6 ns. Fig 4 also includes our original simulation results without CBET (empty squares). Notably, simulations and data show a similar sensitivity to cone fraction, albeit with a significant offset in the cone-fraction ($\Delta CF_0$ ~ 0.2) for a symmetric drive. Previous re-emit experiments performed in scale 544 vacuum hohlraums [16] have shown that a symmetric drive was achieved by approximately equal power being distributed among the 2 laser cones, i.e. $CF_0$ ~ 0.31. For a gas-filled hohlraum, one must account for the energy spent burning through the gas. To first order, neglecting the difference in laser intensities between the inner and outer cones, the amount of energy spent in traversing the hohlraum gas is proportional to the path length through the hohlraum. Since the inner cone has a ~1.5 times longer path, one might expect that a $CF_0$ ~ 0.46 should be needed for a symmetric drive, consistent with our initial calculations without CBET (Fig. 4). In contrast, the cone fraction for a symmetric drive was determined experimentally to be $CF_0$ =0.27 for a scale 544 target (Fig 4). This large disagreement with predictions suggests that CBET must be operating not just during the peak of the ignition pulse [12], but during the picket in the vicinity of the hohlraum LEH's (see Fig. 2a) where inner and outer beams overlap, effectively changing the delivered cone-fraction at the hohlraum wall. This is certainly plausible since our experiment employed cones having different wavelength ($\Delta\lambda$=5.5 A) required to achieve symmetric ignition implosions. Recall, that power transfer occurs only when the laser beams interacting in a plasma environment have different wavelengths and/or the plasma has a velocity close to its sound speed in the direction of the beating wave [12].

Outer-to-inner CBET can be expressed as [12]:

$$\frac{dP_{inner}}{P_{inner}} = g(n_e, T_e)P_{outer}dx \qquad and \qquad \frac{dP_{outer}}{P_{outer}} = -g(n_e, T_e)P_{inner}dx \qquad [1]$$

where $P_{inner(outer)}$ is the initial inner (outer) cone power and $g(n_e, T_e)$ is the CBET coefficient that scales on resonance as the ratio of electron density ($n_e$) to temperature ($T_e$) of the plasma medium. The solution of Eq. [1] expressed in terms of incident cone fraction ($CF_0$), cone fraction after power transfer (CF) and total instantaneous laser power ($P_L = P_{inner} + P_{outer}$) is:

$$CF = \frac{CF_0 e^{GP_L}}{1+CF_0(e^{GP_L}-1)} \qquad [2]$$

where $G = \int g dx$ is the CBET gain coefficient integrated along the interaction path between the inner and outer beams.

Simulations including CBET are also shown in Fig 4 (solid squares) which calculate a symmetric $CF_0 \sim 0.32$ for scale 544 hohlraums. Again, data and the calculations including CBET show the same sensitivity but there remains a cone fraction offset $\Delta CF_0$ of 0.05 at $P_2/P_0 = 0$ for both scales 544 and 575 hohlraums. Calculations with cone-fraction arbitrarily enhanced by 25% are needed to agree with the measured $P_2/P_0$ which may suggest a similar discrepancy between measurements and calculations in ne/Te for the plasma region where CBET takes place.

To assess the experimental CBET gain coefficient, we employ an analytical view-factor model [16,18] to fit the observed $P_2/P_0$ using:

$$\frac{P_2}{P_0} = (5)\frac{\left[P_2^i \cdot S_2^i \cdot \epsilon + P_2^o \cdot S_2^o \cdot (1-\epsilon) - 0.65 \cdot P_2^{LEH} \cdot S_2^{LEH} \cdot \frac{A_{LEH}}{A_{wall}} \cdot F\right]}{(1+F)} \qquad [3]$$

where $P_2^x$ is the average value of Legendre mode 2 at the wall for inner and outer beams and LEH's, $S_2^x$ are the corresponding smoothing factors at the capsule of mode 2 in a spherical hohlraum approximation [5], ε is a geometry-weighted inner/total beams x-ray power fraction, $A_{LEH}$ is the total area of the LEH's, including diagnostic holes that have low x-ray albedo

($\alpha_{window}$=0.2), $A_{wall}$ is the total wall area including the high-Z Re-emit sphere assumed to have same albedo as the wall [16], and F is the ratio of the hohlraum x-ray re-emission to laser plasma x-ray emission [5,18]. F is given by [5, 18]:

$$F = \frac{\alpha_{wall}}{1-\alpha_{wall}+\frac{A_{LEH}+(1-\alpha_{window})\cdot A_{window}}{A_{wall}}} \cong \frac{\alpha_{wall}}{1-\alpha_{wall}+\frac{A_{LEH}+A_{window}}{A_{wall}}} \qquad [4]$$

where $\alpha_{wall}$ is the wall albedo (ratio of the re-emitted flux to incident flux). In the simplifying limit of the laser spots being optically thick Lambertian x-ray sources, oriented along the hohlraum wall, ε [16,18] can be expressed in terms of CF as:

$$\epsilon = \frac{(CF-\Delta/sin\theta_i)\cdot C_i\cdot sin\theta_i[1-sin\theta_i(1-\alpha_{wall})]/r_i^2}{(CF-\Delta/sin\theta_i)\cdot C_i\cdot sin\theta_i\frac{[1-sin\theta_i(1-\alpha_{wall})]}{r_i^2}+(1-CF-\Delta/sin\theta_o)\cdot sin\theta_o\frac{[1-sin\theta_o(1-\alpha_{wall})]}{r_o^2}} \qquad [5]$$

where $r_{i(o)}$ are the distances between inner (outer) beam spots and capsule center, $\theta_{i(o)}$ are the average angles subtended by the inner(outer) beams spots at capsule center with respect to the hohlraum axis. The term $\Delta/\sin\theta_{i(o)}$ in Eq. [5] accounts for the reduction of the inner (outer) beam power at the hohlraum wall due to absorption through the fill gas that scales as $1/\sin\theta$ for the different path-length of the two cones. $C_i$ is the ratio between the inner and outer beams x-rays conversion efficiency and is < 1, reflecting the inner beams turning point density, proportional to $\sin^2\theta$ [19] is lower than for the outer beams.

Scale 544 vacuum hohlraum Re-emit experiments performed on the Omega Laser Facility [16], where no CBET takes place and Δ=0 (Eq. 5), have validated both the 3D hydro-simulations and our simple view-factor model. Thus, for the gas-filled hohlraum experiments presented here, we first set $C_i$ and the power loss fraction in the fill-gas Δ in our model by matching the calculated $P_2/P_0$ vs incident cone fraction at each time in the absence of CBET. With optimized $C_i$ and Δ we then match the measured $P_2/P_0$ vs cone fraction at different times by adjusting the average cross beam power coefficient G in Eq [2] to evaluate the CBET time history.

Table 1 summarizes the inferred incident $P_2/P_0$ from our measurements vs time for $CF_0$=0.18 in both scales 544 and 575 hohlraums, as well as the results of post-shot calculations and the time-varying parameters of the analytical model. Based on simulations, $\theta_i$ = 88° and 80° and $\theta_0$ = 43 and 49° are used in (Eq. [5]) for scales 544 and 575 respectively, which also corrects for a calculated inward wall motion of 0.1 mm. The analytical model requires $\Delta$=0.07 and $C_i$ ~ 0.2 at all shown times for both hohlraum scales to get reasonable agreement with calculations without CBET. The model and calculations also show that, while the CF after CBET is similar at 1.3 and 1.6 ns, P2/P0 still decreases in time due to an increase in the hohlraum x-ray albedo [5]. The model predicts the gain exponents $GP_L$ decrease in time from 1.9 to 0.9, while the gain coefficients G are increasing in time as $P_L$ drops (Table 1) consistent with calculations which show a decrease in plasma Te as $P_L$ and hence inverse Bremsstrahlung heating drops in time. Table 1 also shows that the large discrepancy between the measured $P_2/P_0$ and calculations without CEBT is reduced to ~ -10% when CBET is accounted for in calculations.

Results of the analytical model $P_2/P_0$ vs incident cone fraction tuning curves at the peak of the x-ray drive at the capsule (t=1.6ns) are also summarized in Fig. 4 for both scales 544 and 575 hohlraum geometries. The analytical $P_2/P_0$ agree with both sets of hohlraum data for similar model parameters for all cone fractions, demonstrating that the difference in $P_2/P_0$ between these scales can be explained just by the variations in geometry and beam pointing.

Interpolating on Fig. 4, symmetric drive pickets, i.e. where $P_2/P_0$ = 0, were obtained for $CF_0$ of 0.26 and 0.235 for scale 544 and 575 hohlraums, respectively. Applying the ignition capsule vs re-emit offset (Fig. 1), this translates to symmetric picket $CF_0$ for ignition targets of 0.225 and

0.2, respectively, that correspond to cone fractions of 0.16 and 0.1 at maximum picket power at t=0.5 ns. Recent dual axis shock timing experiments [21] confirmed that using these cone fractions led to ignition hohlraum picket symmetry within ±10% of zero $P_2/P_0$ from the near simultaneous (± 50 ps) break-out times of the first shock at pole and equator.

We have successfully tuned the $P_2/P_0$ mode of the picket radiation symmetry for ignition hohlraums using Re-emit experiments on the NIF. The analytical model used to fit both 544 and 575 scales data confirm that the observed symmetry differences are explained by variation in geometry and beam pointing. The model also predicts significant CBET, resulting in >200% increase in inner cone power that exceeds by about 2x that observed during the final high power part of the laser drive [16]. 3D HYDRA calculations including CBET underestimate the power transfer by 25%. The validity of picket symmetry tuning using the reemit technique was further confirmed by dual axis shock timing experiments [21].

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Table 1 Analytic model parameters, calculations and data for scale 544 and 575 hohlraums with $CF_0$ = 0.17 at t = 0.5 ns.

| Case | | Analytic Parameters | | | | | Instantaneous Cone Fraction | | | Symmetry | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | CBET Off | | CBET On | | |
| | | | | | | | Laser | Calc | Anal | Calc | Anal | Calc | Anal | Data |
| Scale | t ns | $\alpha_{wall}$ | F | $GP_L$ | $P_L$ TW | G /TW | $CF_0$ | CF | CF | $P_2/P_0$ % | $P_2/P_0$ % | $P_2/P_0$ % | $P_2/P_0$ % | $P_2/P_0$ % |
| | 1.0 | .22 | .24 | 1.9 | 11 | .17 | 0.18 | 0.32 | 0.58 | 56 | 54 | 35 | 8 | 7 |
| 544 | 1.3 | .45 | .67 | 1.2 | 7 | .17 | 0.23 | 0.34 | 0.49 | 33 | 32 | 12 | 3 | 4 |
| | 1.6 | .57 | .93 | 0.9 | 4 | .23 | 0.27 | 0.35 | 0.48 | 22 | 23 | 5 | 1 | 1 |
| | 1.0 | .20 | .24 | 1.7 | 10 | .17 | 0.18 | 0.32 | 0.54 | 38 | 26 | 33 | 1 | 1 |
| 575 | 1.3 | .40 | .56 | 1.2 | 6.7 | .18 | 0.22 | 0.33 | 0.48 | 22 | 15 | 10 | -3 | -4 |
| | 1.6 | .47 | .70 | .95 | 4 | .24 | 0.27 | 0.33 | 0.48 | 14 | 10 | 4 | -5 | -5 |

**Figure captions**

Figure1 Calculated incident $P_2/P_0$ for re-emit and ignition targets and imploded core shell density cross-section (hohlraum axis vertical).vs cone fraction offset in the picket.

Figure 2 a) Setup of Re-emit experiments on NIF showing location of outer-to-inner power transfer, b) incident power/beam, cone fraction (black dash) hohlraum x-ray flux measured by Dante (black solid) in scale 544 hohlraum for a minimum cone fraction of 0.17 at 0.5 ns

Figure 3 Re-emit images measured in scale 544 hohlraums at the peak of the x-ray drive (t=1.6 ns, hν=800 eV) for three cone fractions (defined at t=0.5 ns, see Fig.2b) showing radiation symmetry at the capsule changing from pole hot (left image) to waist hot (right image) when increasing the cone fraction.

Figure 4 Incident $P_2/P_0$ vs cone fraction at t=1.6 ns inferred from data (solid circles), calculated with (solid squares) and without (open squares) CBET, and from analytical model with (solid lines) and without CBET (dashed lines) for scale 544 and 575 hohlraums.

Figure 1

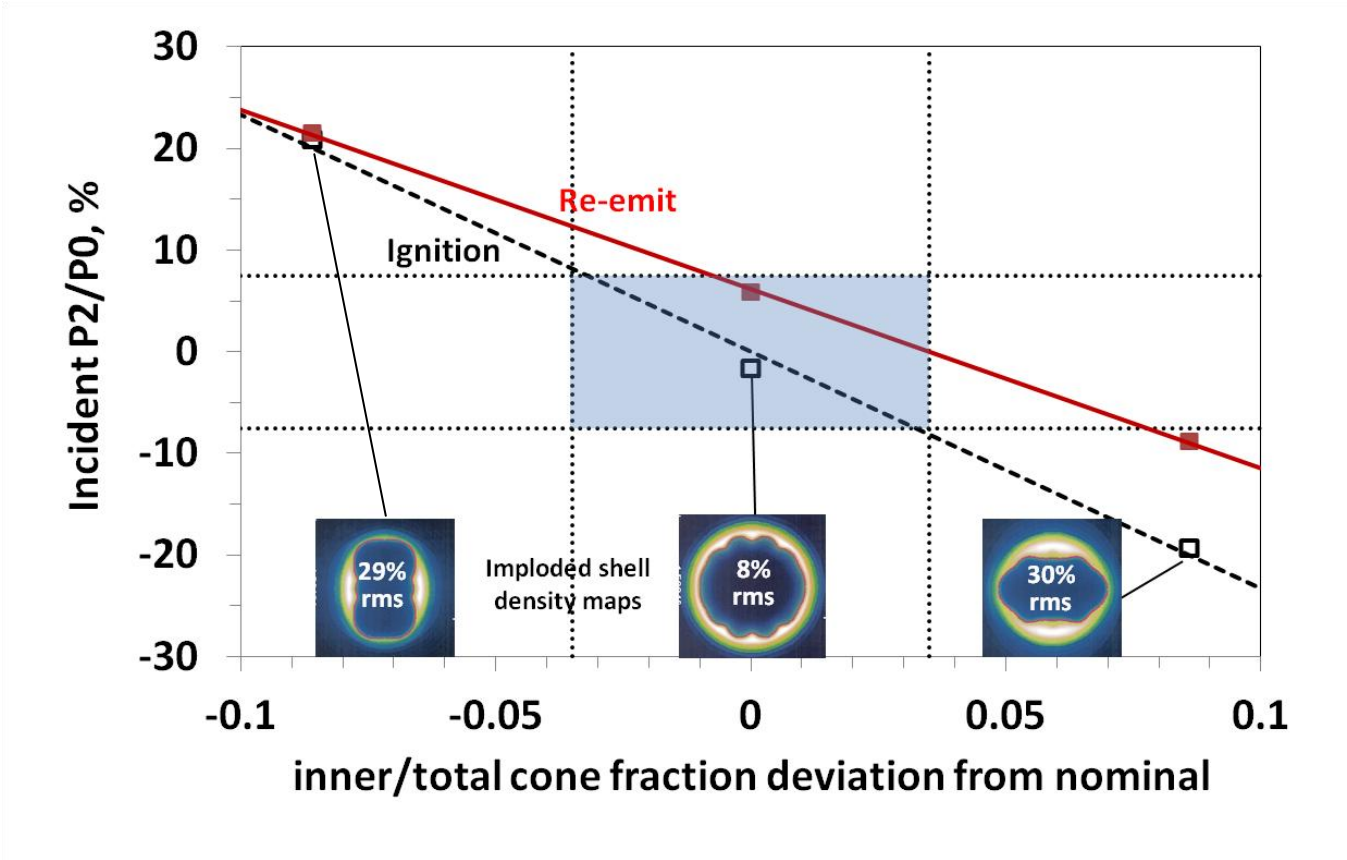

30
20
10
0
-10
-20
-30
Incident P2/P0, %
Re-emit
Ignition
29% rms
Imploded shell density maps
8% rms
30% rms
-0.1
-0.05
0
0.05
0.1
inner/total cone fraction deviation from nominal

Figure 2

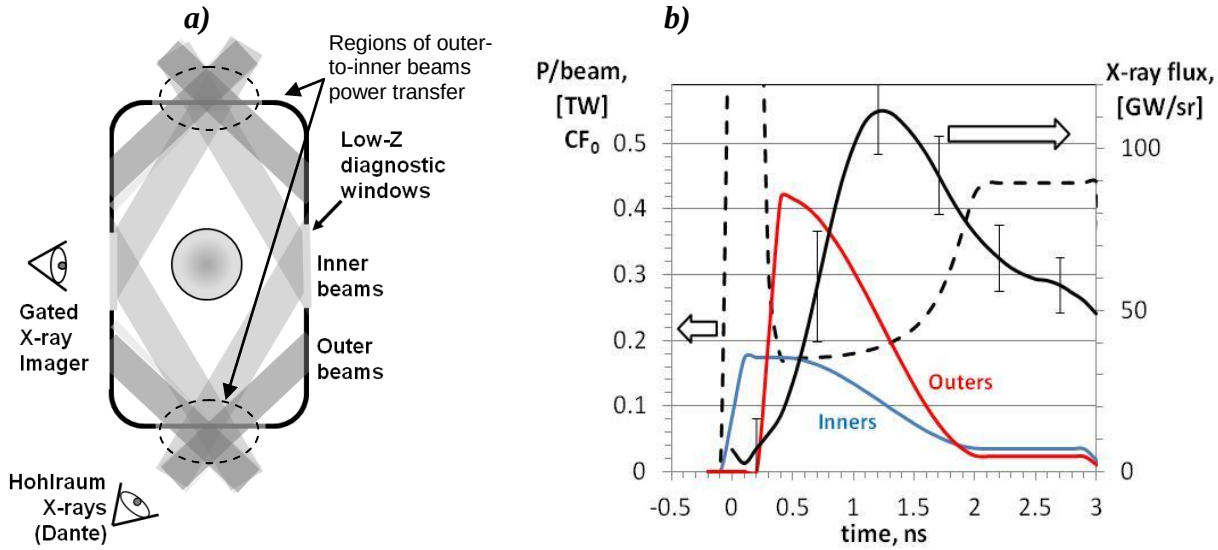

a)
Regions of outer-to-inner beams power transfer
Low-Z diagnostic windows
Inner beams
Outer beams
Gated X-ray Imager
Hohlraum X-rays (Dante)
b)
P/beam, [TW]
CF0
X-ray flux, [GW/sr]
0.5
0.4
0.3
0.2
0.1
0
100
50
0
-0.5
0
0.5
1
1.5
2
2.5
3
time, ns
Outers
Inners

Figure 3

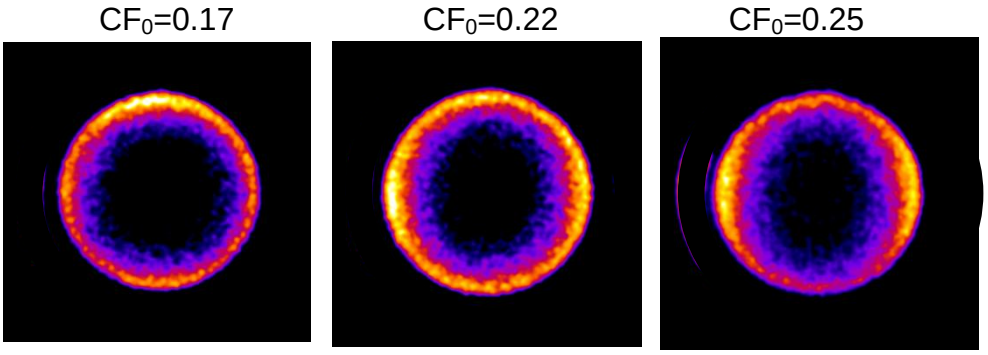
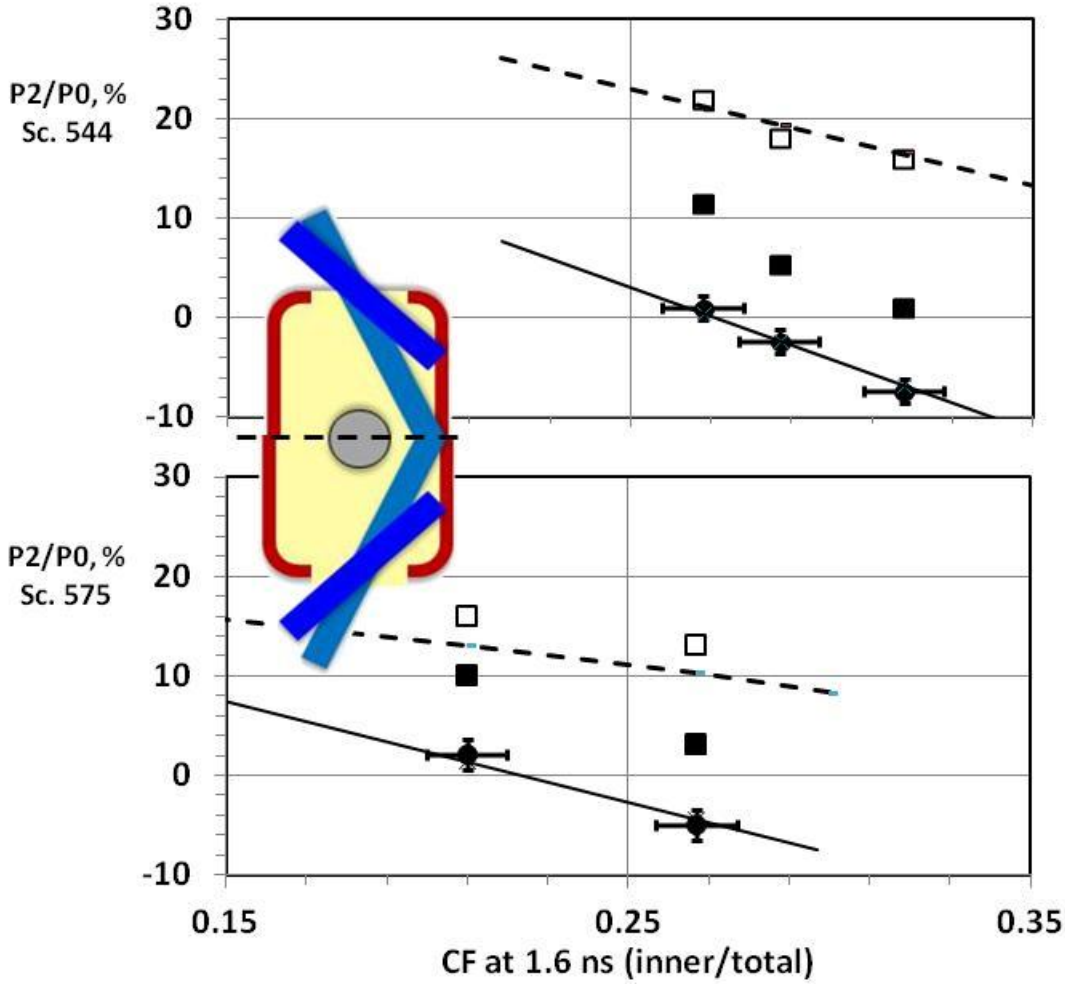


Figure 4


P2/P0, %
Sc. 544
30
20
10
0
-10
P2/P0, %
Sc. 575
30
20
10
0
-10
0.15
0.25
0.35
CF at 1.6 ns (inner/total)