Progress in Simulations of High Gain Direct-Drive ICF targets

Andy Schmitt, Sasha Velikovich, Steve Zalesak
Plasma Physics Division
Naval Research Laboratory

John Gardner, Dave Fyfe
Laboratory for Computational Physics & Fluid Dynamics
Naval Research Laboratory

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Introduction

Performing high-resolution simulations of directly-driven ICF pellets is challenging yet achievable:

- large range of modes must be considered (ℓ=0–256)
- very small initial perturbation levels (~10 Å / mode)
- nonlinear final state

-> requires massively parallel, very low noise, minimally diffusive code

We have improved our FAST radiation-hydrodynamics code:

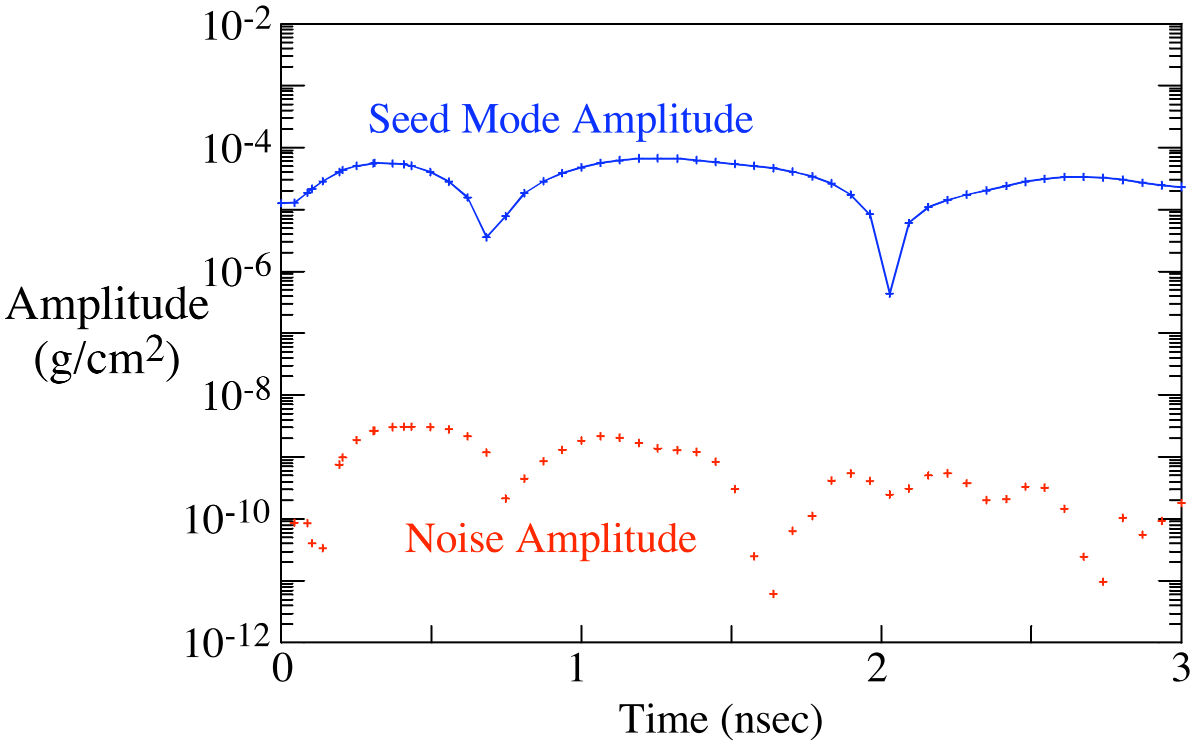
- *Low-noise hydrodynamic and laser raytracing algorithms*
- *New low-noise beam-tracing model incorporates time-dependent beam geometry effects*
  (beam pointing/alignment; energy/power imbalance)

This new capability will allow us to develop specifications for the beam pointing accuracy, power/energy imbalance, and other beam geometry effects.

Algorithm improvements for the FAST simulation code

We have developed numerical methods that preserve the "differentiability" and linearity of small perturbations in the simulation codes, and allow accurate multimode simulation of tiny perturbations.

We have been able to achieve signal-to-noise ratios of ~10^5 for 0.05Å(!) perturbations.

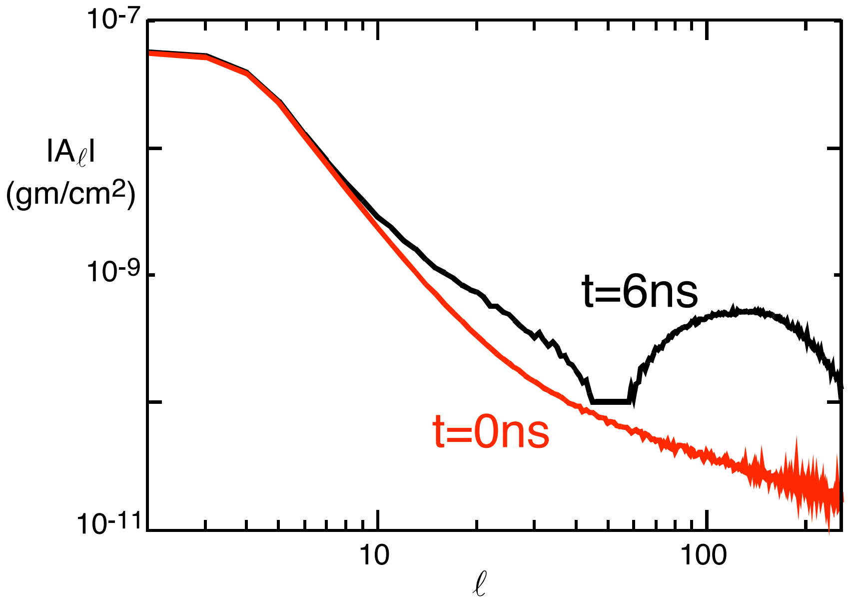


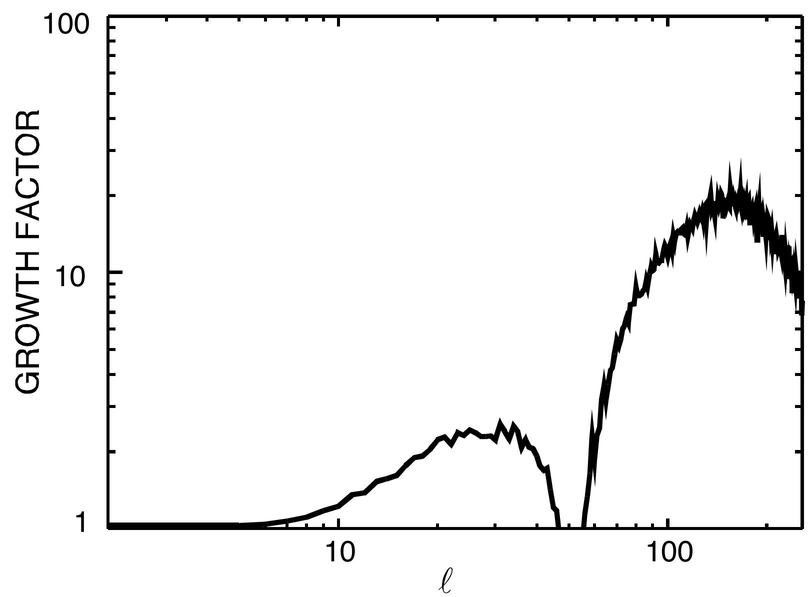
Ablative-RM simulation of single 24μm wavelength mode during initial pellet compression using a mixed first-order Godunov / Lax-Wendroff hydrodynamic algorithm

Variants of these algorithms have been incorporated into FAST

New: compression-phase small-amplitude perturbation growth can now be directly calculated in our code via low-noise algorithms

Perturbation growth during the initial compression of the pellet, before acceleration and exponential growth.

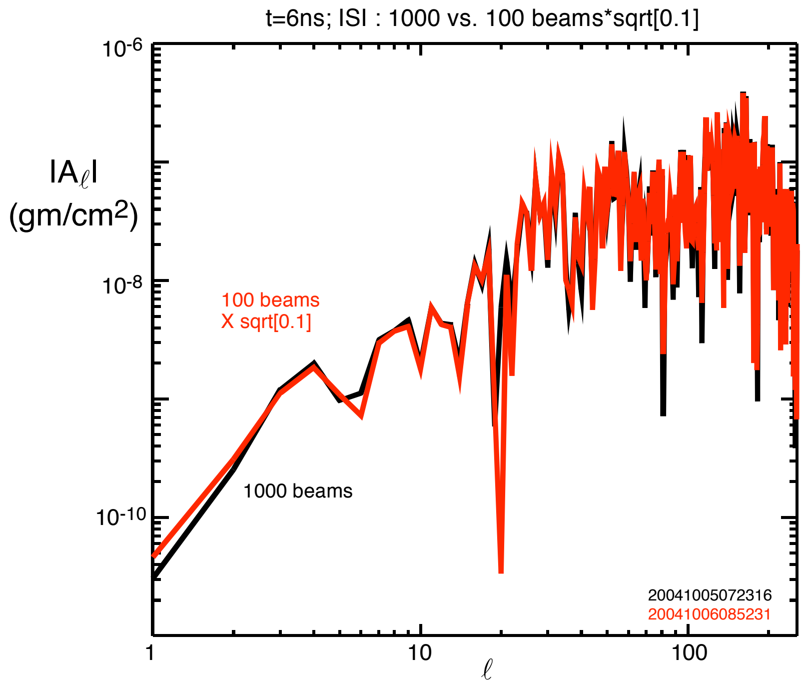




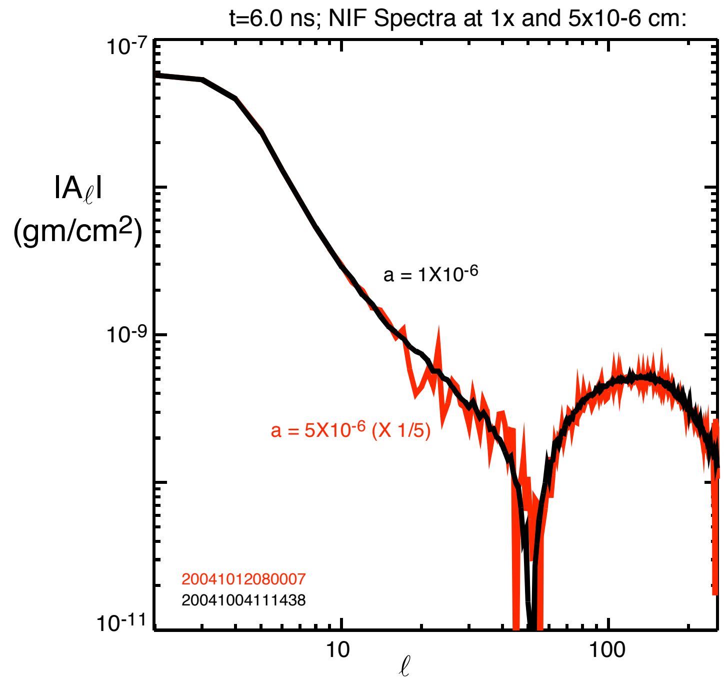
Large multimode tests with very small initial surface amplitudes show growth factors that compare well with benchmarks

New: compression-phase small-amplitude perturbation growth can now be directly calculated in our code via low-noise algorithms

large multimode simulations of laser imprint during pellet compression show excellent linearity for small initial perturbations



scaling with $\sqrt{N_{beams}}$



scaling with amplitude of initial surface perturbation

Historically, the raytracing in the multidimensional hydrocode is based on a quasi-one-dimensional model.

Normal ray tracing in multidimensional codes is quite noisy,
noise scales as $\sim N_{rays}^{-1/2}$.

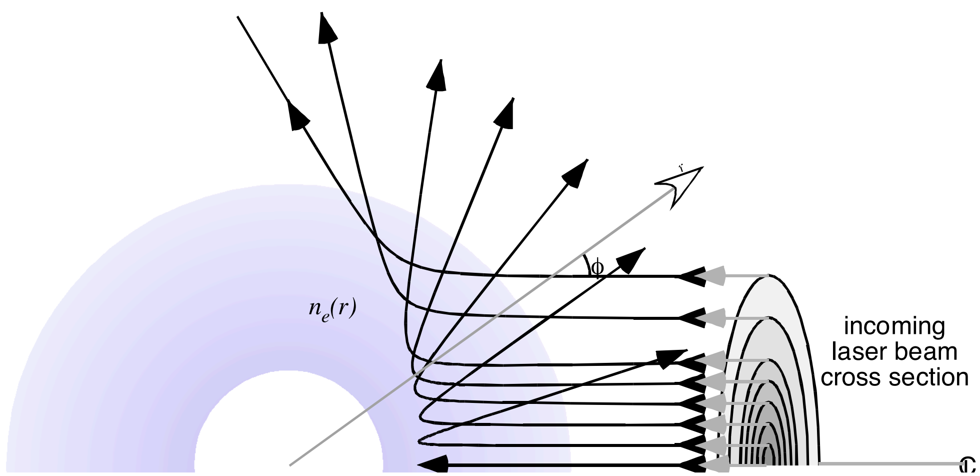
The following approach minimizes the noise:

1. Given that the pellet conditions are usually very symmetric (spherical) to 0^{th} order.
(E.g., very uniform pellets and illumination conditions).

Approximation: Each transverse slice (e.g. y/z or θ/ϕ coordinate) of the target is taken to be independent of each other, and ray-tracing is done in the local profile (ignore transverse gradients).
-> The general 2D/3D raytracing is a combination of independent 1D projections.

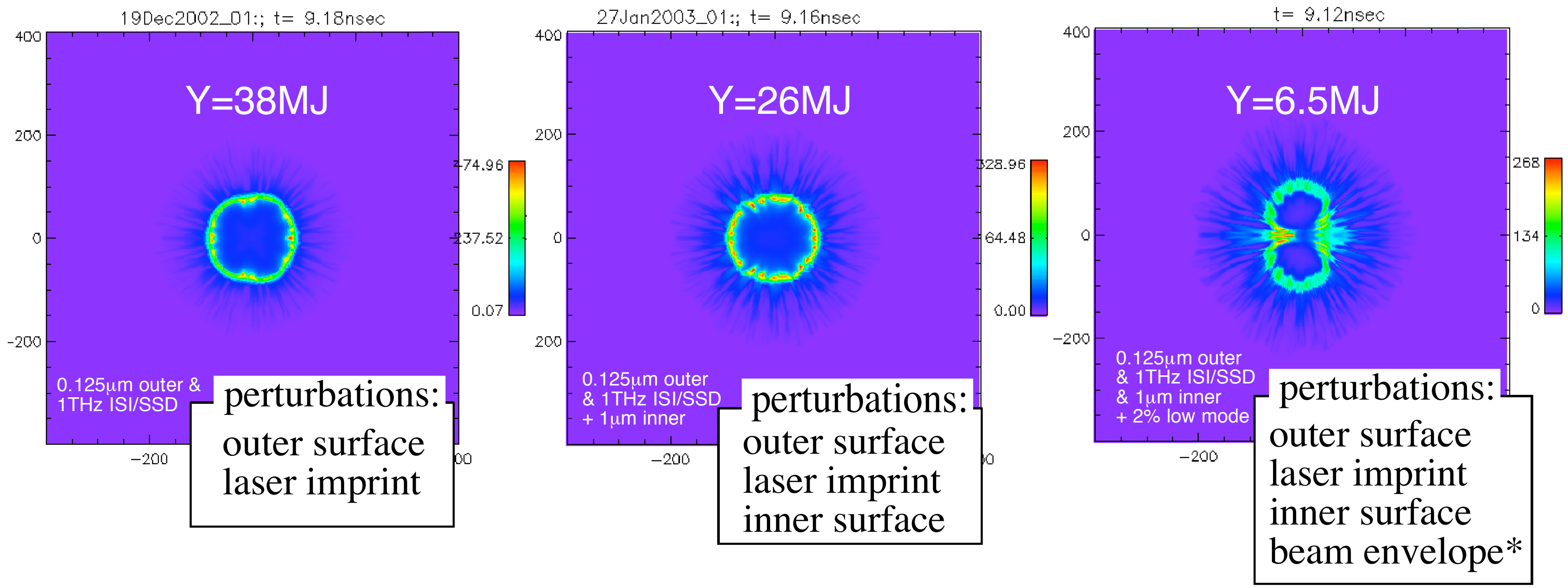
2. Instead of point-like rays, ***we use "fat rays"***, rays that have a finite width. The boundaries of these ray sections are traced, and the power within is distributed continuously between the ray boundaries.

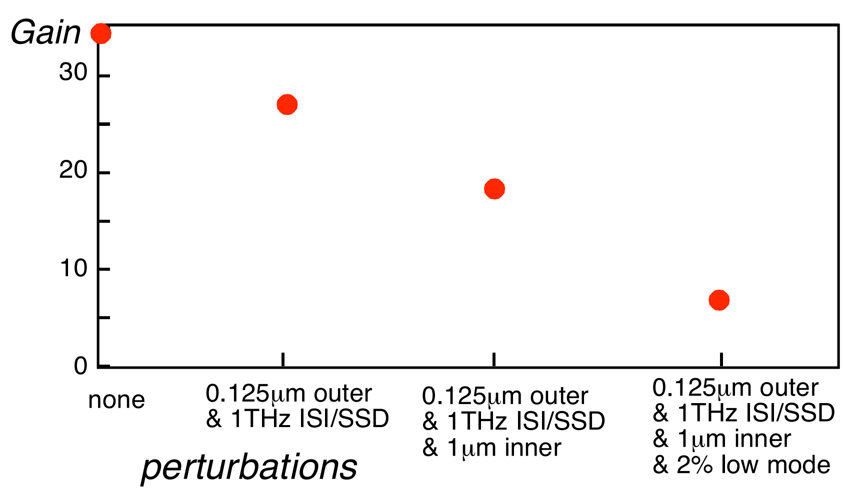
3. Laser imprint and beam geometry is superposed as a spatial envelope of the incident intensity:
   - Short spatial wavelength:
     Optical smoothing effects
     Local intensity variation on times of order $\Delta\nu^{-1}$,
     spatial scales > $F\lambda_0$.
   - Long spatial wavelengths:
     beam geometry/alignment/power balance
     Previously ad-hoc, are handled by the
     new beam tracing module.



The all-DT NIF target: with renormalization, the pellet ignites with degraded but significant gain

Renormalization of perturbations at the end of compression appears to give reasonable results



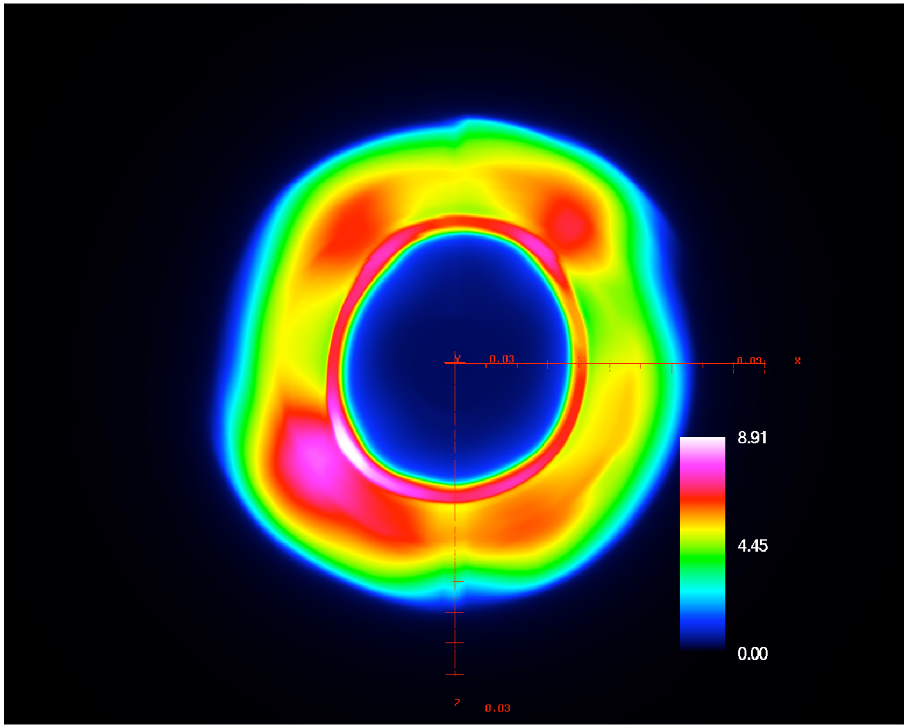


** constant-in-time model by Weber et al., Phys. Plasmas* ***4****, 1978 (1997)*

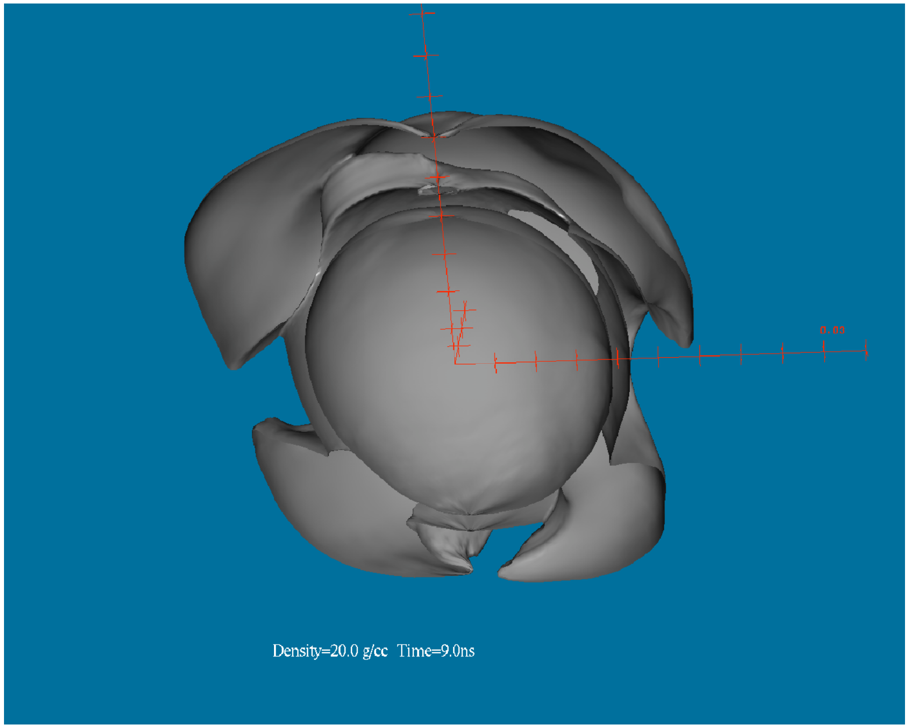
3D Simulation Case: 2% Nonuniform Laser Intensity: Gain 5

Pellet density near burn time

density cross section T=9.0ns

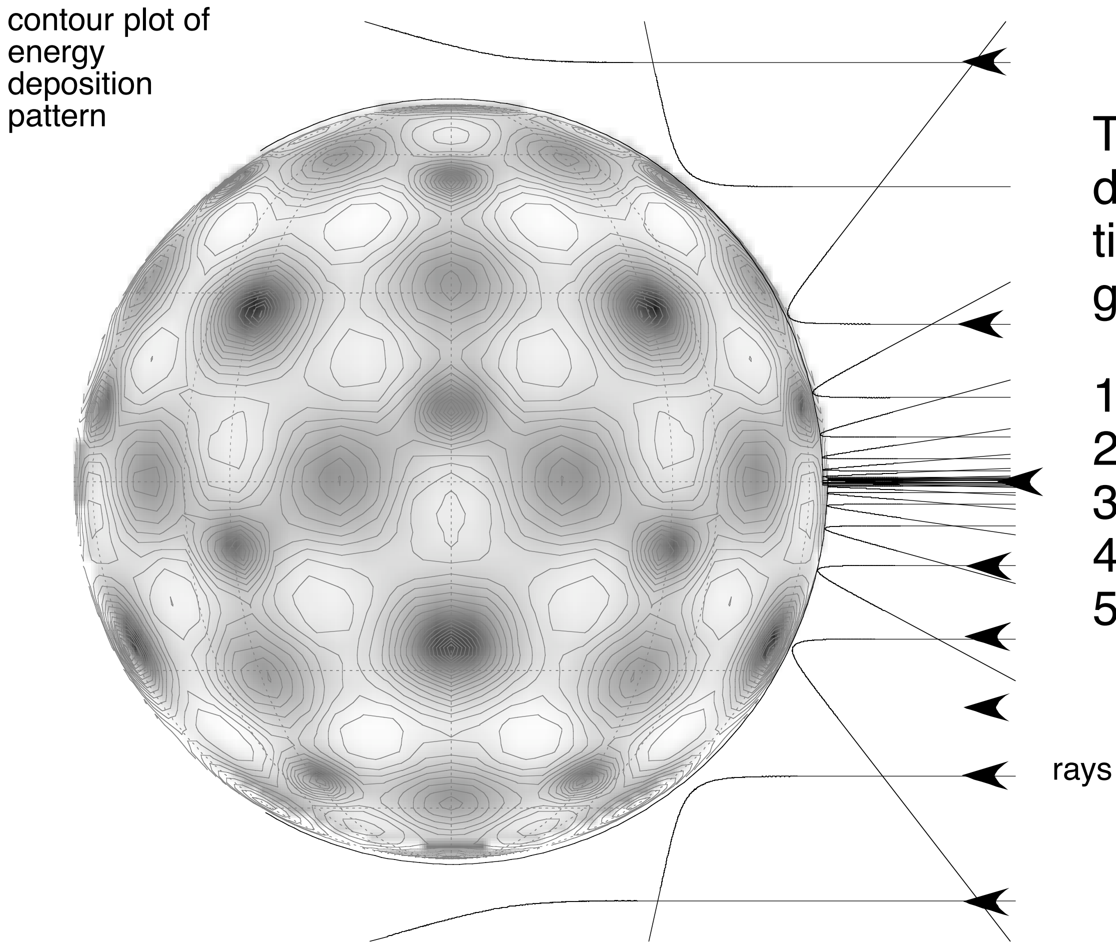


Iso-surface of ρ=20 gm/cm^3 at 9.0 ns



The new beam tracing module adds the dynamic effects of beam aiming and geometry

We're improving the raytracing in the FAST code to dynamically calculate the (low-ℓ mode) 2D or 3D illumination patterns/uniformity in the spherical plasma corona.



This will give us the capability to produce (low-ℓ mode) energy deposition distribution as function of (θ, ϕ), given:

1. Coronal plasma distribution
2. Individual beam intensity profiles
3. Beam aiming configuration
4. Energy/Power imbalance specs.
5. Beam misalignment specifications
   (or pellet misplacement)

The beam tracing module is being used in variety of ways:

(1) 1D or (averaged) *multi*-D simulations are postprocessed:

- vary the laser parameters (e.g., a beam spot size and shape -- which can change discontinuously during "zooms")
- use weighting functions $w_a(t)$ and $w_u(t)$ that describe the relative importance of absorption and uniformity during the implosion

> Optimize the parameters to give the "best" uniformity and absorption.

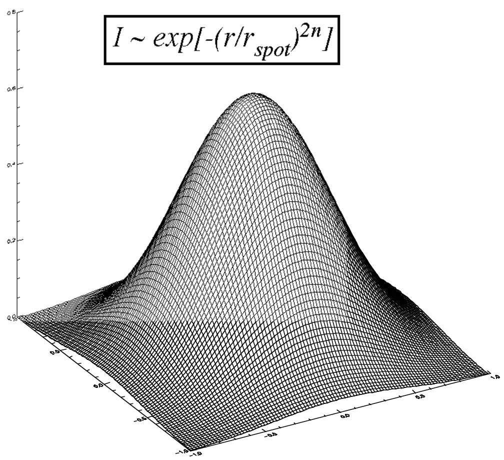
(2) Postprocessing: the beam misalignment &/or power balance can be varied, producing new $Absorption(r_{spot},n)$ and $Uniform(r_{spot},n)$ distributions, different optimizations

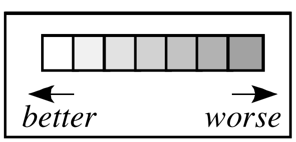
(3) Postprocessing: results (1) and (2) give beam envelope functions E(θ,ϕ,t) that can drive the 2-/3-d hydrocode simulations to determine gain sensitivity to beam misalignment.

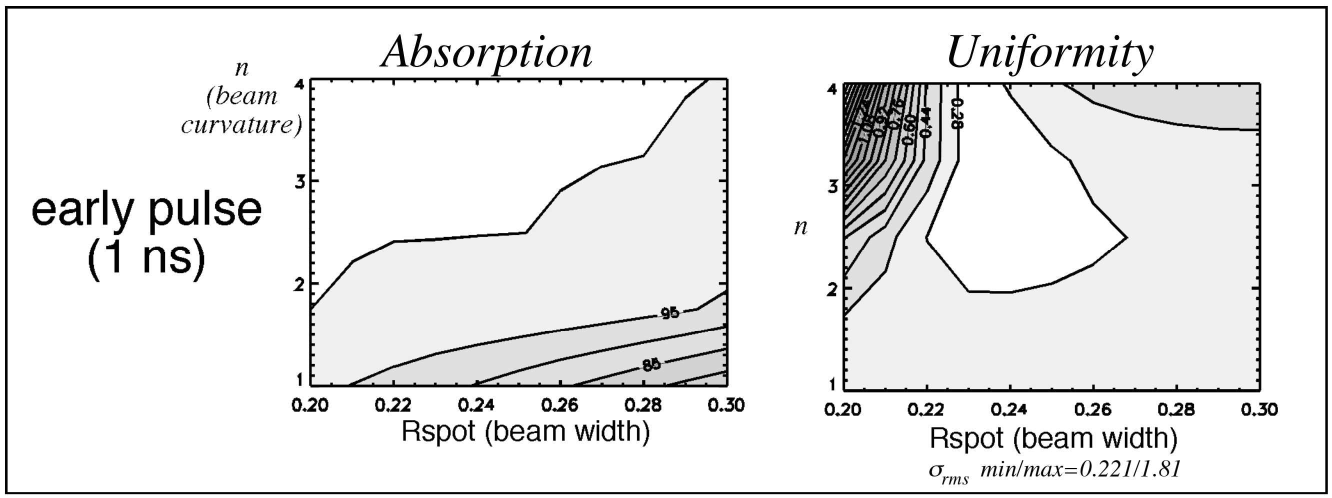
(4) The module is being integrated into the FAST hydrocode to compute the beam envelope distributions on the fly.

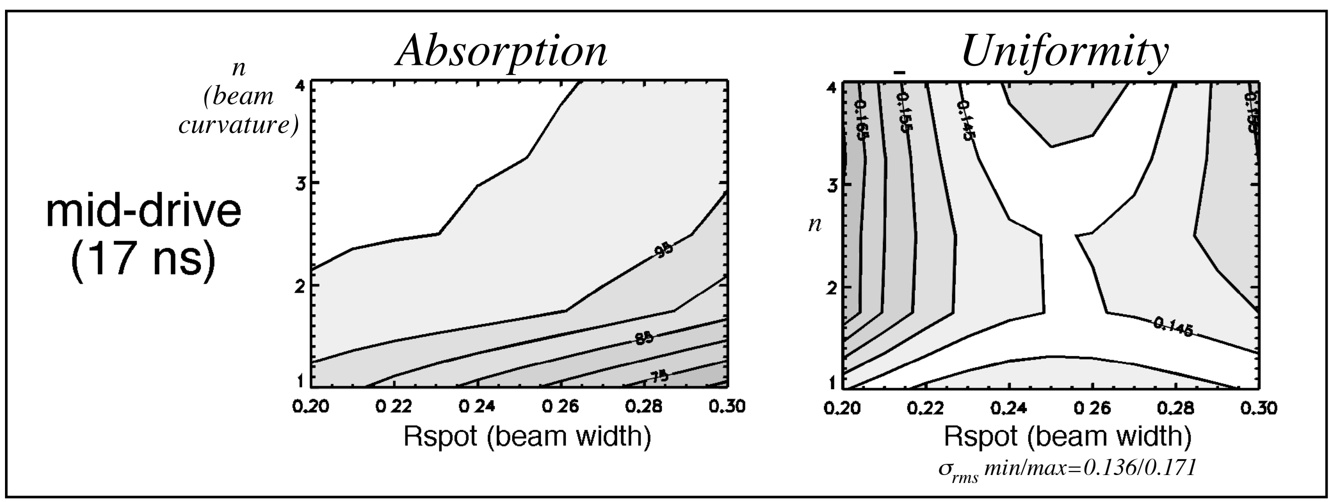
Uniformity and absorption vary with beam shape as well as time.

The beam alignment code can be used to determine optimal beam parameters by postprocessing 1d (averaged) plasma distributions from previous high-gain simulations. This shows to first order how much absorption and uniformity are available at different times in the simulation, depending upon the spot size and shape of the laser profile.

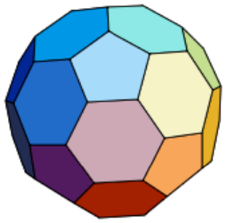




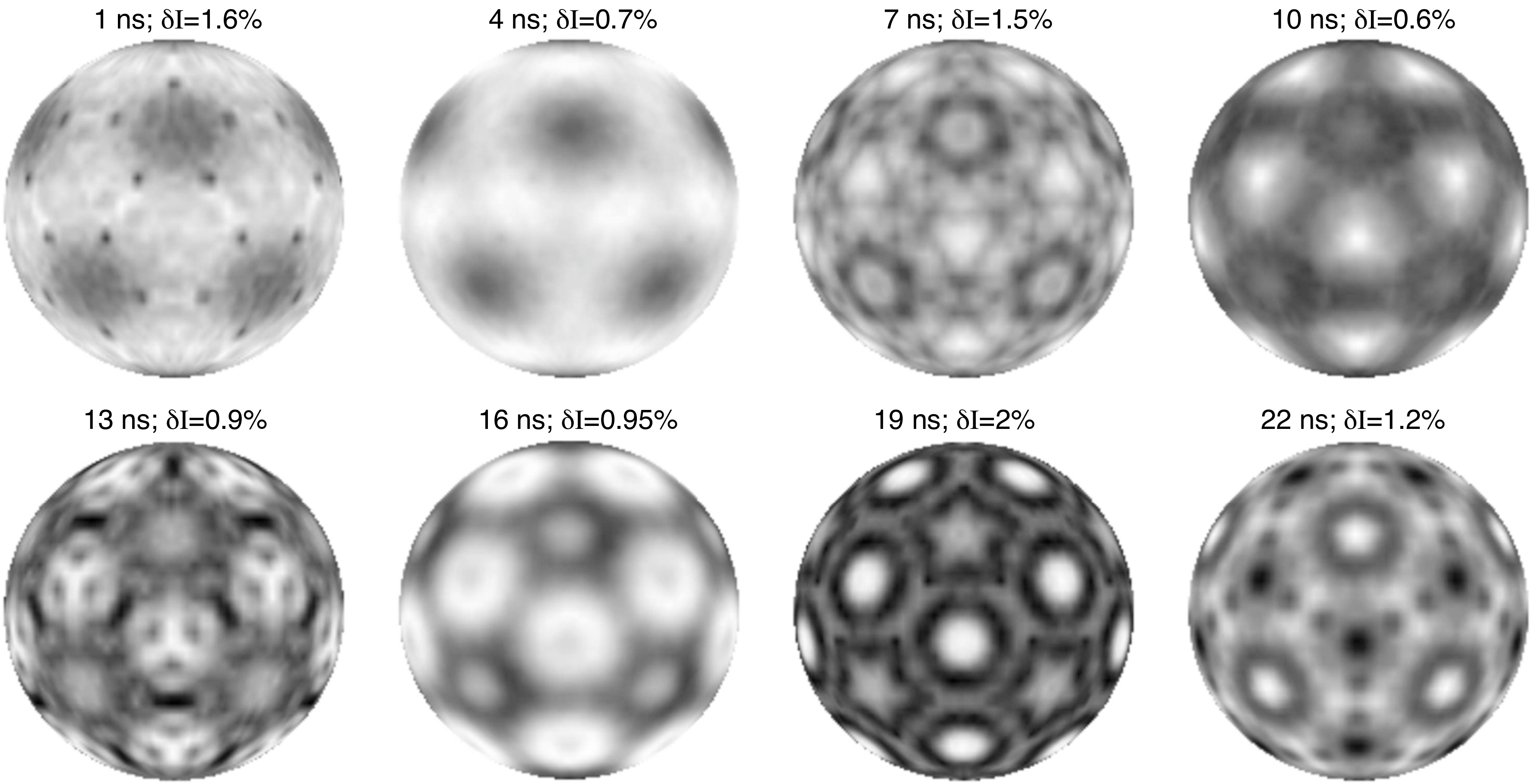




Examples of illumination patterns for the high gain target.



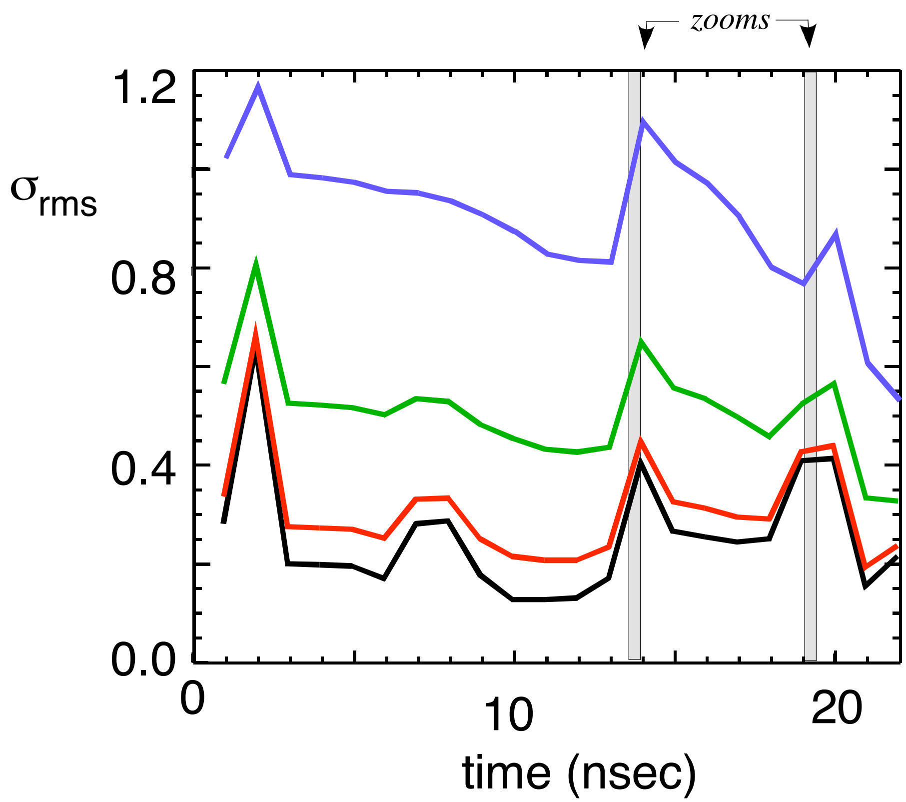
Time increases left-to-right, top-to-bottom.
60 beam (truncated icosahedron [soccer ball]) aiming geometry



δI values quoted above are peak-to-valley

Pellet uniformity decreases with beam misalignment

For 60 beam geometry, typical results indicate pointing accuracy should be less than ~100μm in order to keep σ_{rms} below a percent.



Uniformity vs. time, including zooms

0 % misalignment
1% misalignment (24 μm)
2.5% misalignment (60 μm)
5% misalignment (119 μm)

(misalignment measured as $\langle \delta r/r_0 \rangle_{rms}$; r_0=0.238cm)

Summary

The FAST hydrocode is being used to simulate, with high resolution, the compression, acceleration, implosion, and gain of direct-drive ICF pellets.

Low-noise algorithms have been developed and implemented in the hydrocode.

A low-noise beam tracing module has been developed to:

- postprocess simulations & determine optimum beam parameters
- integrate into the hydrocode to determine gain sensitivity to misalignments.

Future:
A full 3D beam raytracing module is being developed [*D. Eimerl, et al.*], and will be used to provide consistency and validity checks of the low-noise method.

These improvements are being used in new simulations and analysis of high-gain KrF driven pellets, which are still in progress.