Shock-Ignition on the National Ignition Facility

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with contributions from: R. Betti[2], G. Schurtz[3], R. S. Craxton[2], A. Casner[6], A.Mackinnon[1], R.McCrory[2], D.Meyerhofer[2], A.Comley[8], K. LaFortune[1], A. Schmitt[5], P.McKenty[2], D Bailey[1], M.Lambert[1], J.Marozas[2], X.Ribeyre[3], K. Anderson[2], G.Erbert[1], D.Harding[2], D.Blackfield[1], M.Terry[1], B.Koziozemski[1], W.Theobald[2], A.Hamza[1], W.Garbett[1], M.Murakami[7], R.Cook[1], E.Le Bel[3], S.Atzeni[9], A.Schiavi[9], R Stephens[10]

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International Workshop on Shock Ignition
Laboratory for Laser Energetics, U. Rochester, Rochester NY
March 8, 2011

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

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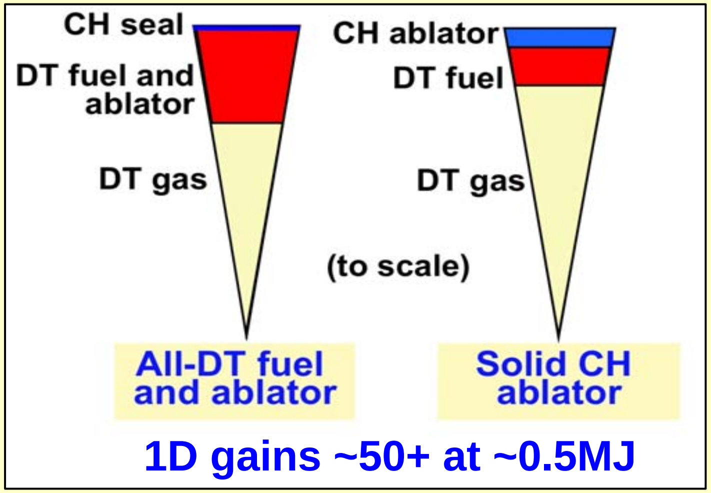
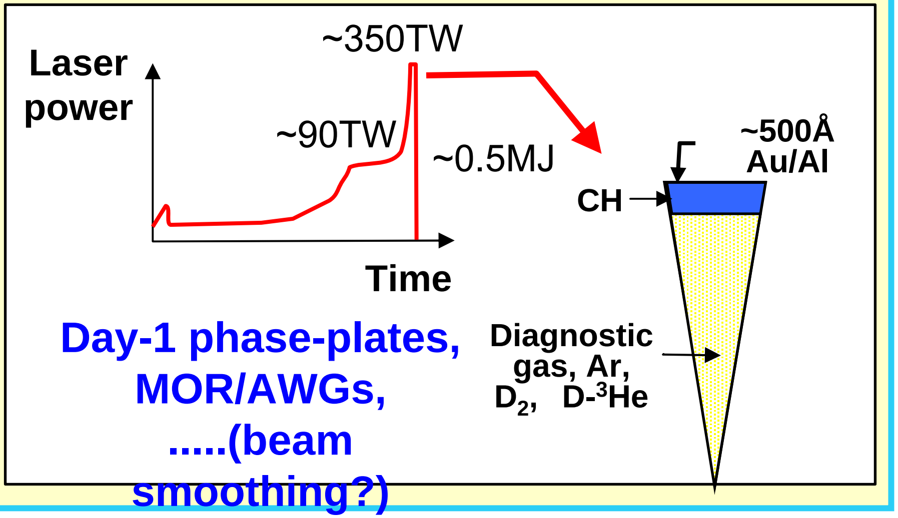
Summary: Two central points to take away.......

Shock ignition offers the potential for high gain* cryo targets on NIF at ~0.5MJ drive energy in the near(ish)-term

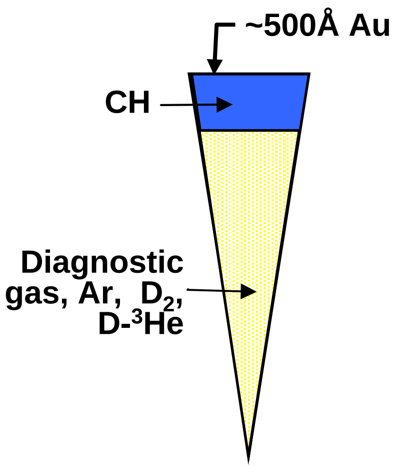
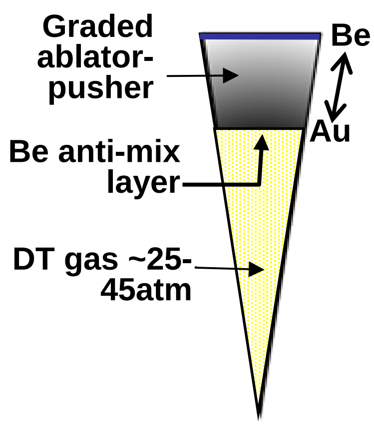
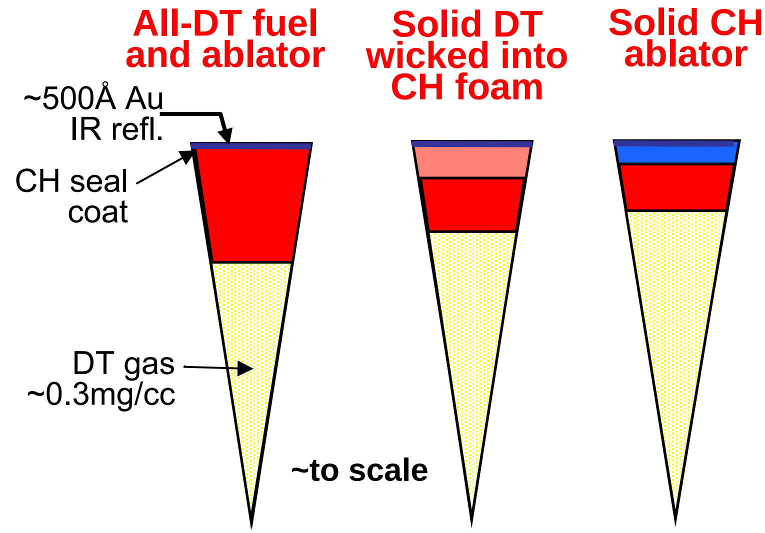
(*And modest gains ~1 in non-cryo metal/gas targets?)



Proof-of-principal experiments of polar drive symmetry, shock drive efficiency and LPI at medium-high convergence ratio may be fieldable *in the immediate term* with cryo-equivalent, room-temp CH targets and present laser hardware



Candidate NIF shock ignition targets

<table>
<tr><th>Non-Cryo
Hydro-Equiv. CH</th><th>Non-Cryo
Pushered Single Shell</th><th colspan="2">High Gain Cryo</th></tr>
<tr><td>
</td><td>
</td><td colspan="2">
</td></tr>
<tr><td>• Immediate term (~1-3yr) tests of polar drive symmetry, shock coupling, late-time LPI with day-1 hardware
• Diagnostic yields only at ~0.5MJ drive</td><td>• Near term (~3yr) tests of room-temp volumetric ignition at ~4keV
• Gain/yield ~1/1MJ @ ~1.5MJ drive
• Req'd NIF hardware?</td><td>• Medium term (~4+yr) tests of high gain shock ignition @ <1MJ
• Gain/yield ~60/30MJ @ 0.5MJ drive
• Req'd NIF hardware?</td><td>• Longer term (≥6yr) tests of high yield shock ignition
• Gain/yield ≥100/100MJ @ ≥1MJ drive</td></tr>
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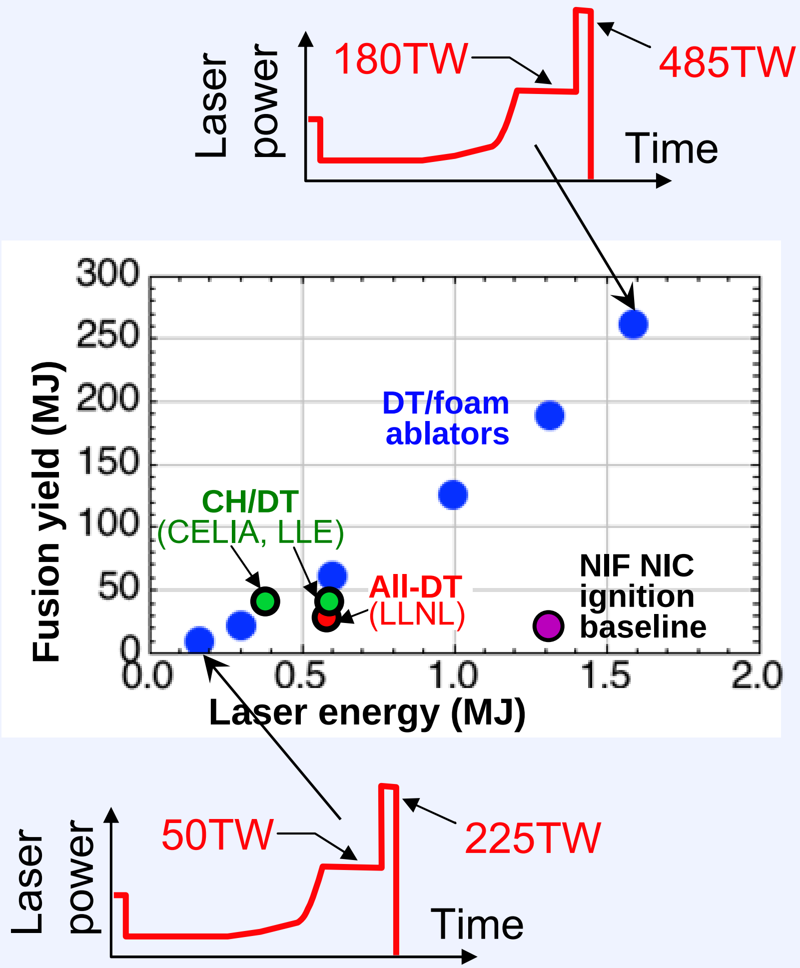
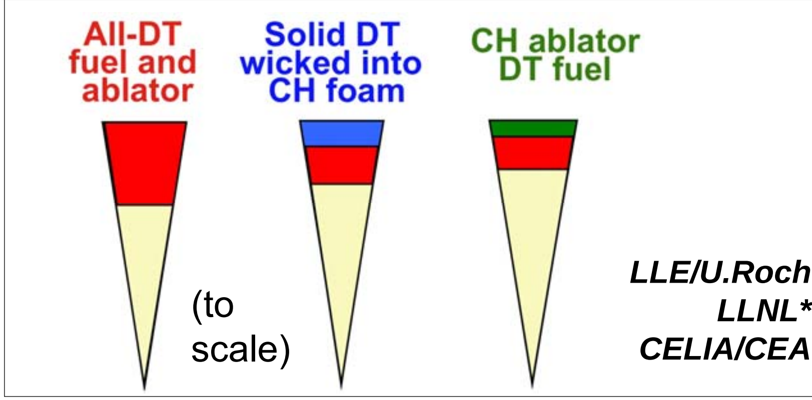
Shock Ignition: Preliminary yield and gain curves for NIF

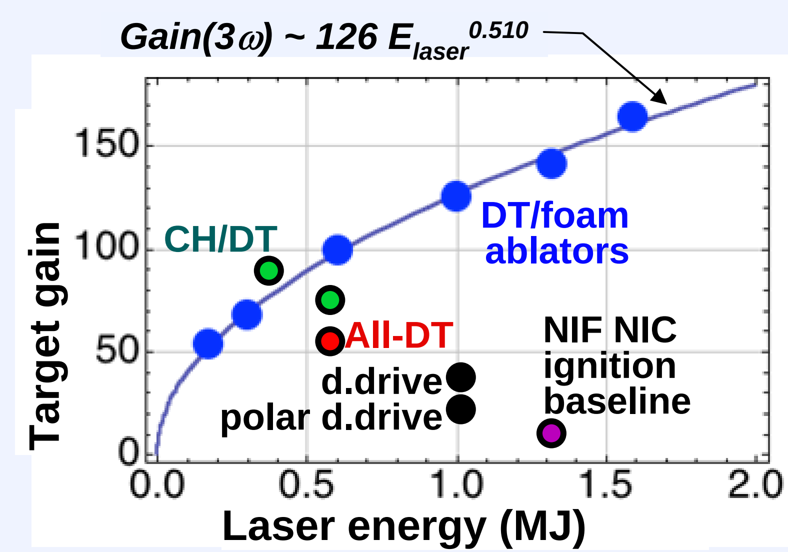
NIF Shock Ignition Yield Curve



NIF Shock Ignition Targets are Simple

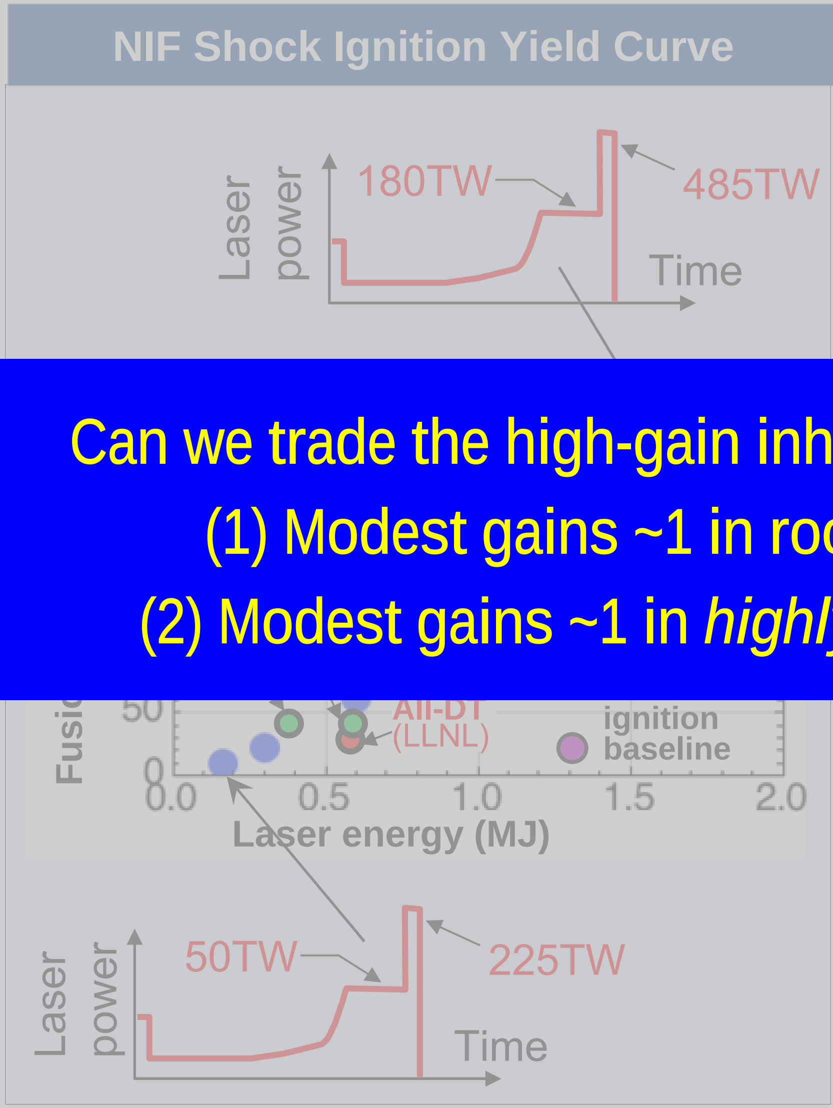


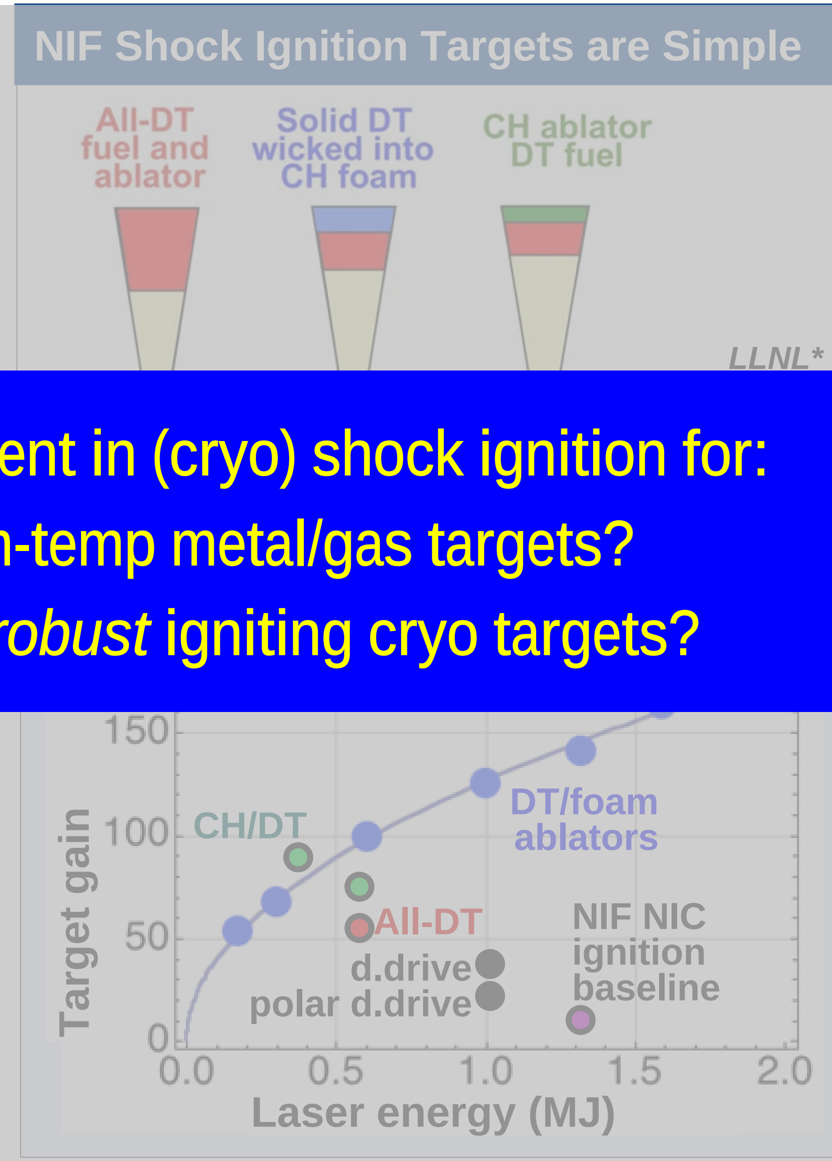
NIF Shock Ignition Gain Curve



* L.J.Perkins,et al., *Phys. Rev. Lett.*, 103, 045004 (2009)

Shock Ignition: Preliminary yield and gain curves for NIF





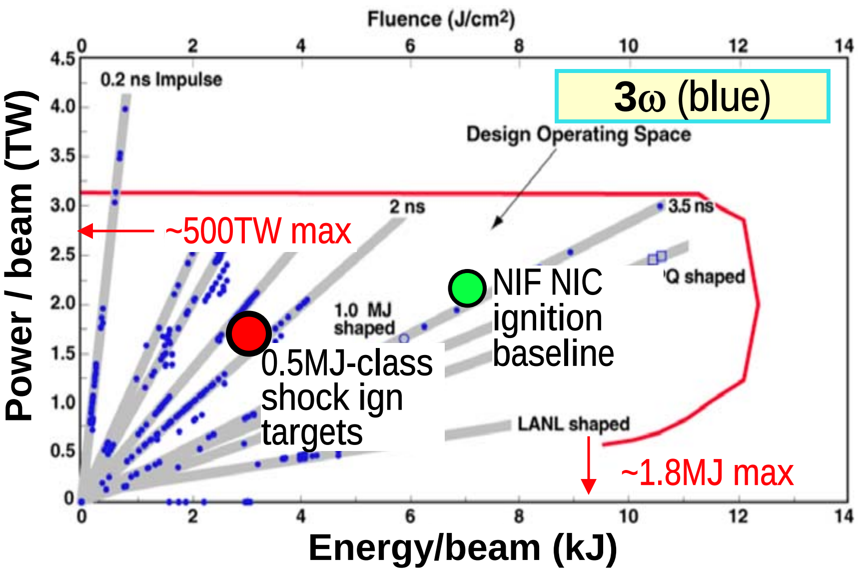
Can we trade the high-gain inherent in (cryo) shock ignition for:

(1) Modest gains ~1 in room-temp metal/gas targets?

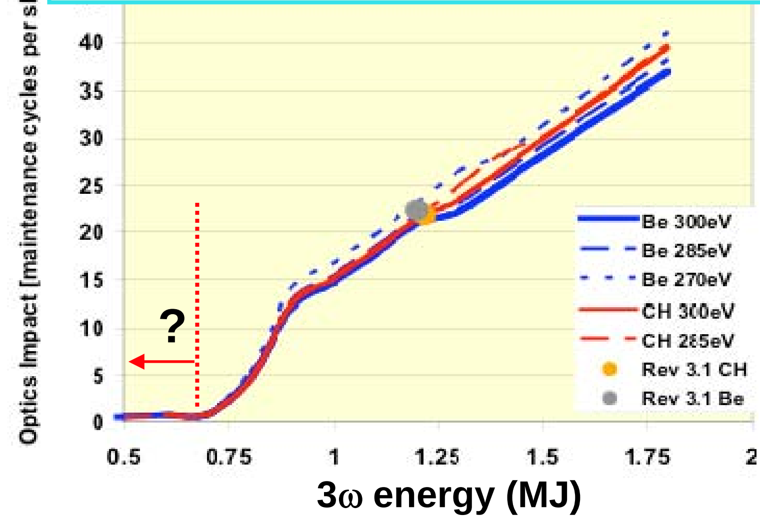
(2) Modest gains ~1 in *highly robust* igniting cryo targets?

* L.J.Perkins,et al., *Phys. Rev. Lett.*, 103, 045004 (2009)

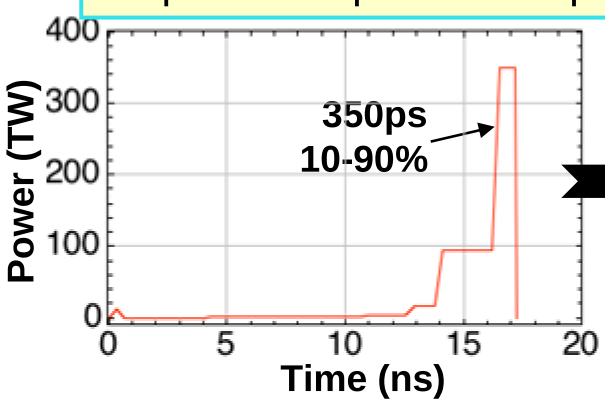
NIF laser operational space and performance limits



Optics Impact Metric: Number of high value optics that are "touched" per shot for maintenance purposes at 3ω



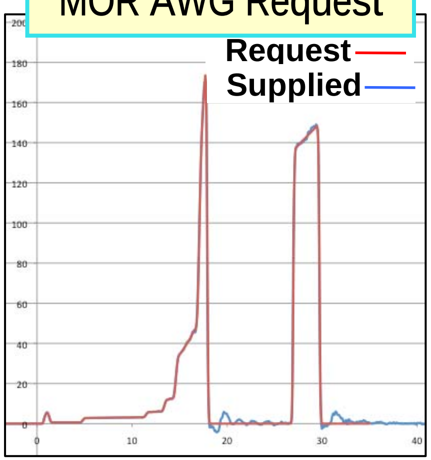
Requested Output Pulseshape



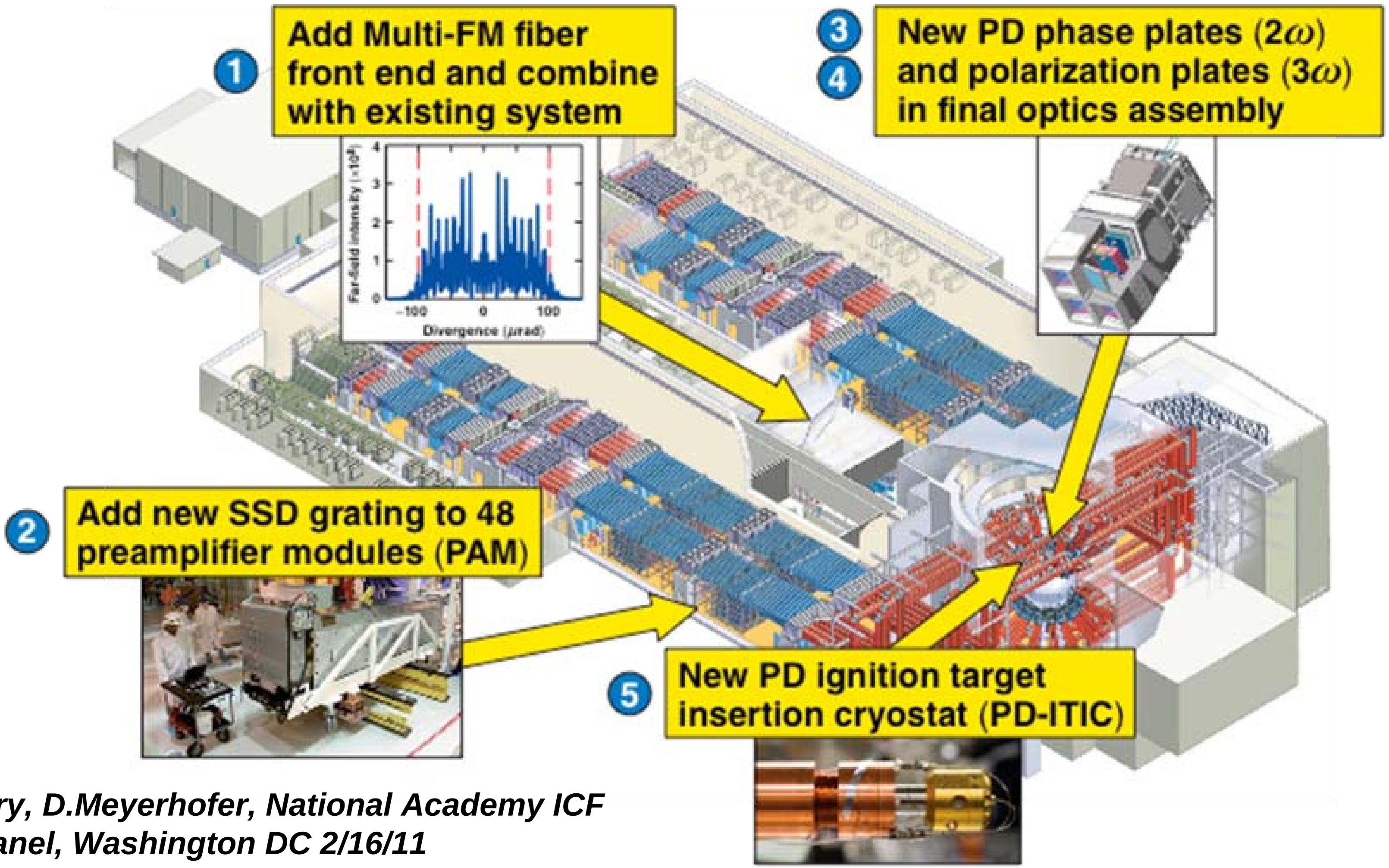
NIF Laser Performance and Operation Code (LPOM)

- ➔Temporal contrasts achievable in main amplifiers
- ➔No equipment protection issues for proposed pulse shape
- ➔Spike pulse achievable with present MOR-AWG

MOR AWG Request



Full implementation of NIF polar drive will require five hardware upgrades for a (cryo) ignition demonstration



R.McCrory, D.Meyerhofer, National Academy ICF Target Panel, Washington DC 2/16/11

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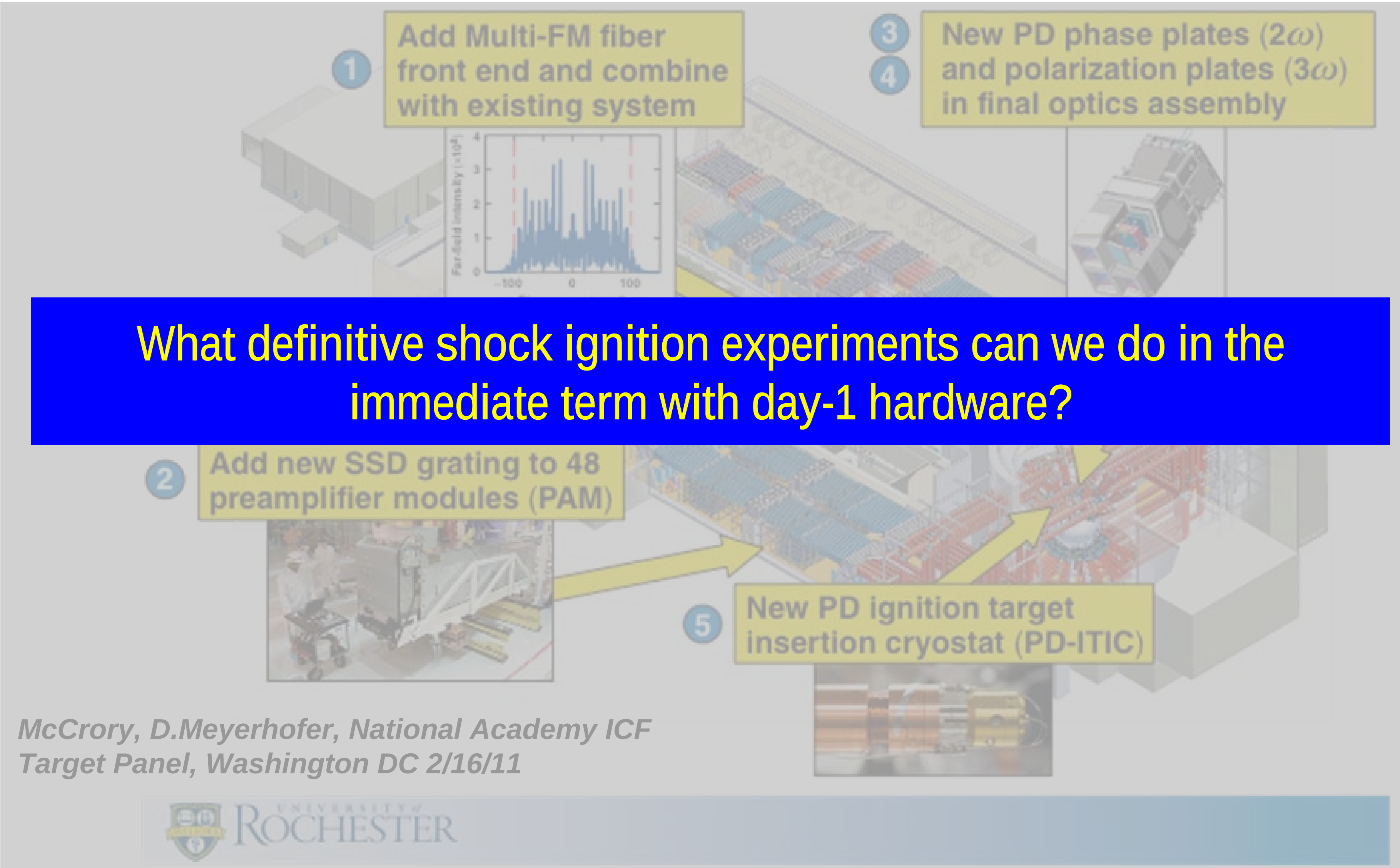
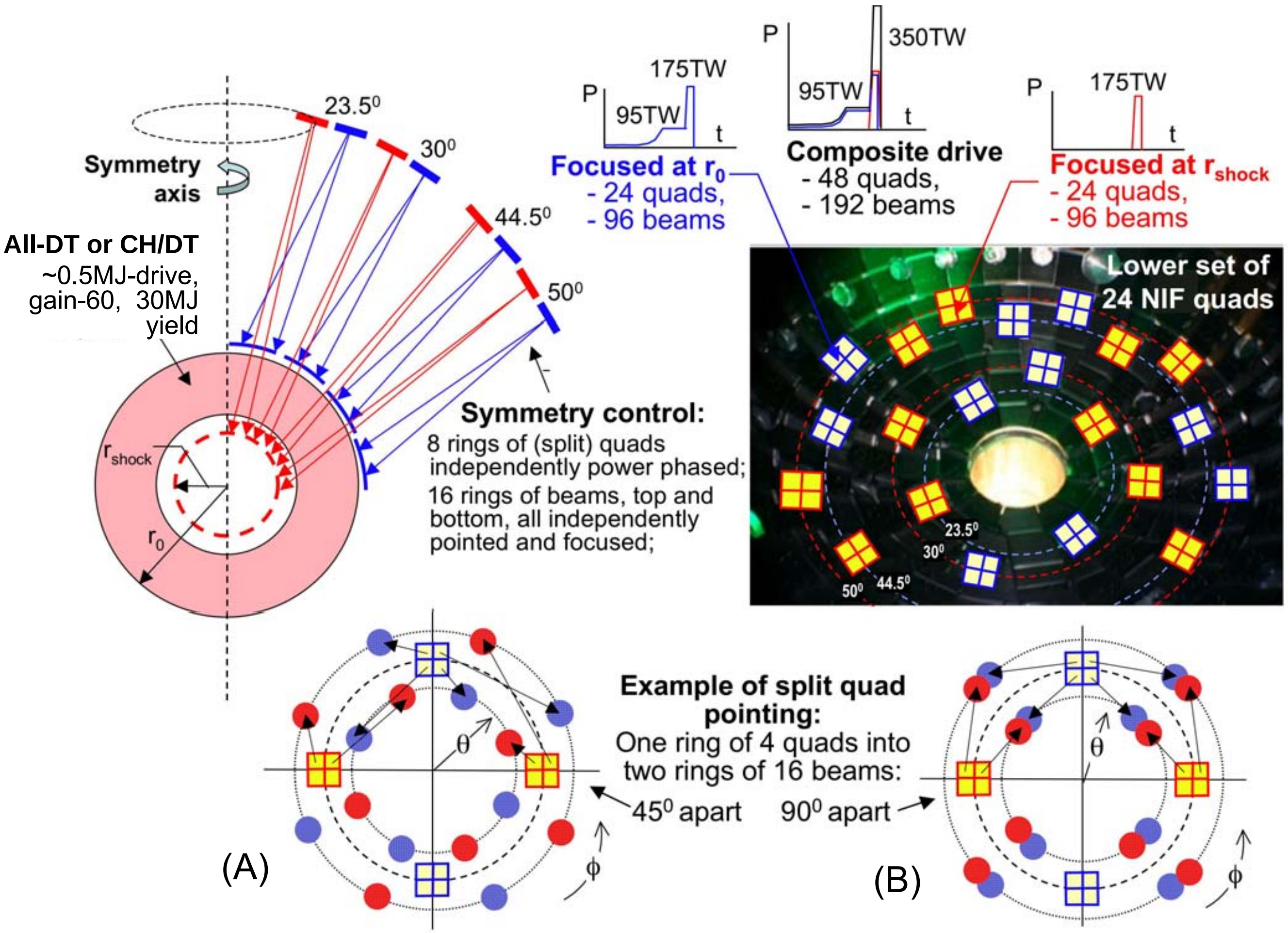


What definitive shock ignition experiments can we do in the immediate term with day-1 hardware?

A paramount issue: Optimization of NIF polar drive symmetry and shock coupling efficiency at high convergence ratio

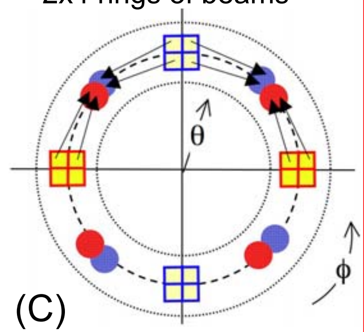
- 96-beams (main+shock) at r_0 at $t = 0$;   96-beams (shock) zoomed at r_{shock} at $t = t_{shock}$
- Optimize pointing, focal spots and power phasing on each of 2x4/8 sets of quad/beam rings



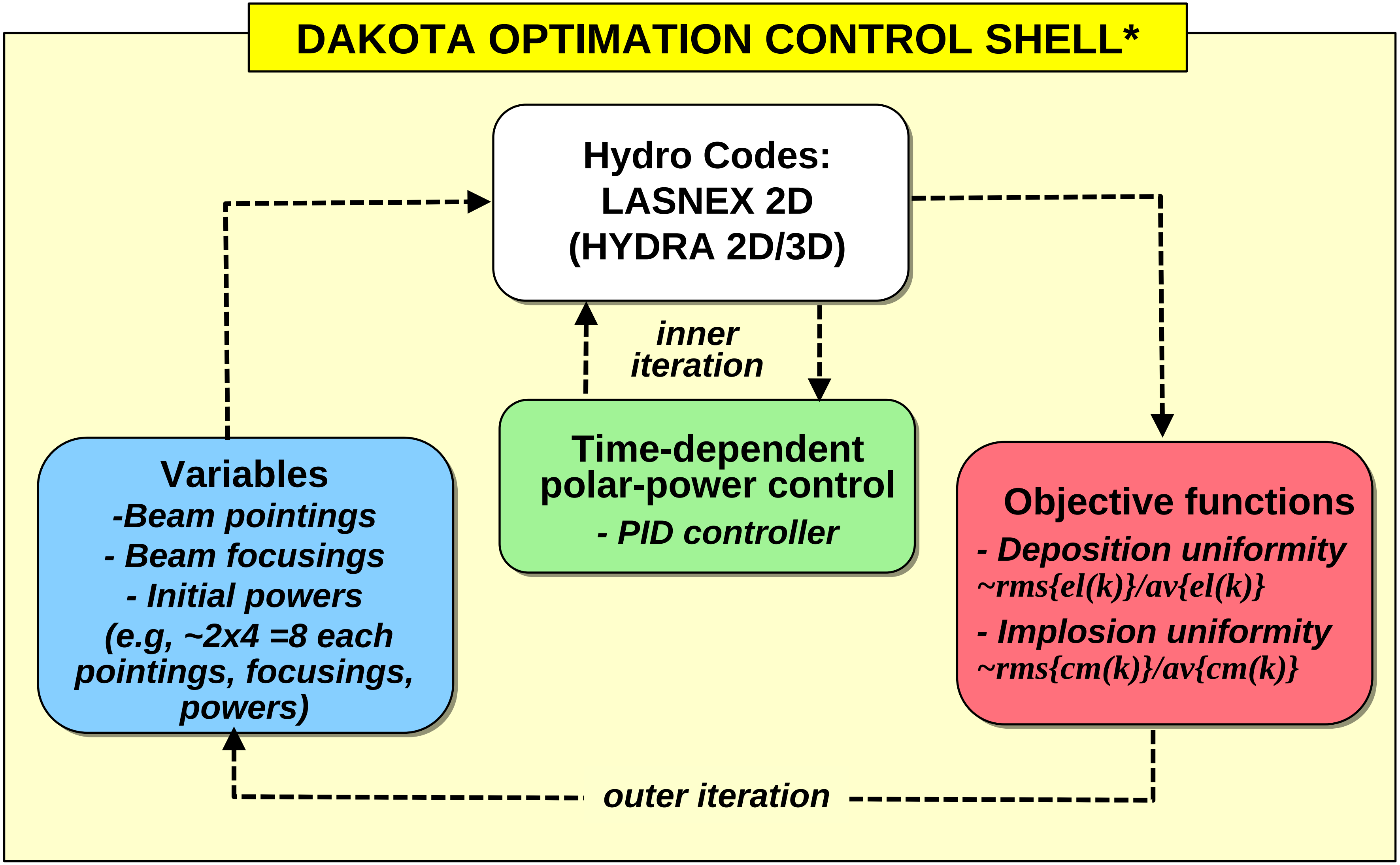
Necessary for beam uniformity?

Example of split quad pointing for optimum beam uniformity

4 rings of quads split into 2x4 rings of beams

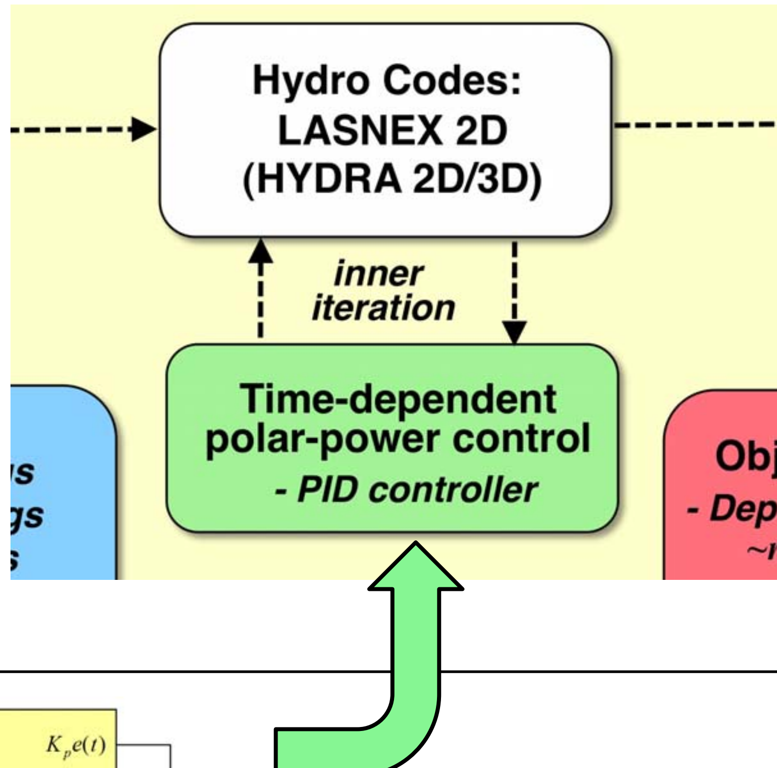


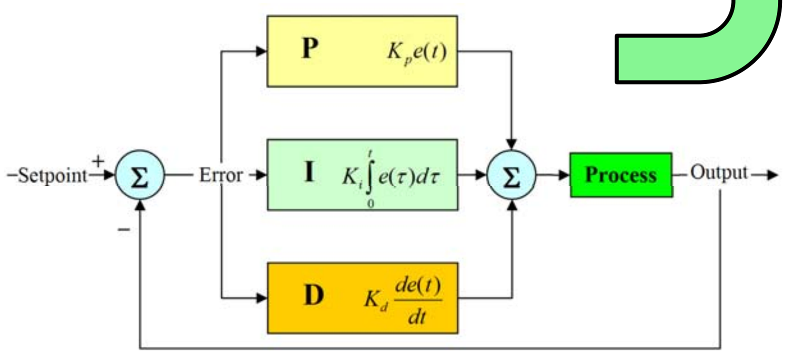
NIF Polar Drive: With ~24 independent variables, optimization formalism will exercise LLNL computation facilities to their limit



* DAKOTA – Sandia National Laboratory, http://www.cs.sandia.gov/DAKOTA/index.html (= "*UQ Pipeline*" at LLNL)

Can we achieve time-dependent polar power optimization via an on-the-fly PID controller in one forward run of the hydro code?



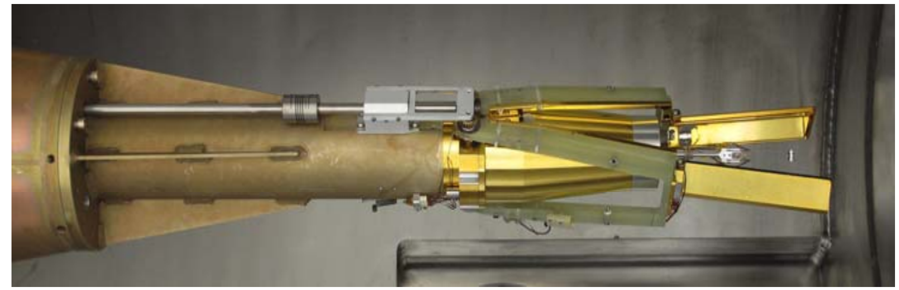


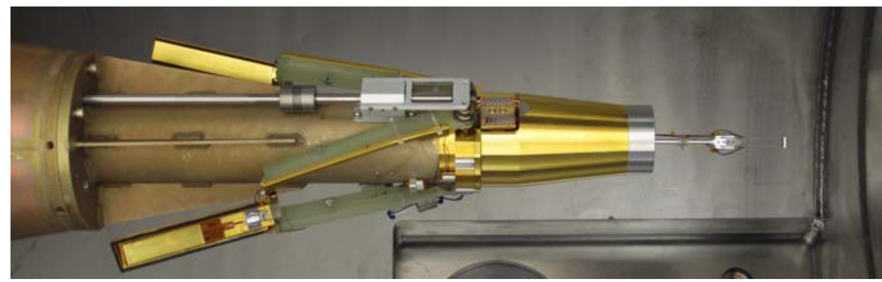
$$Error = K_1 e(\theta) + K_2 de(\theta)/dt + K_3 \int e(\theta)dt$$

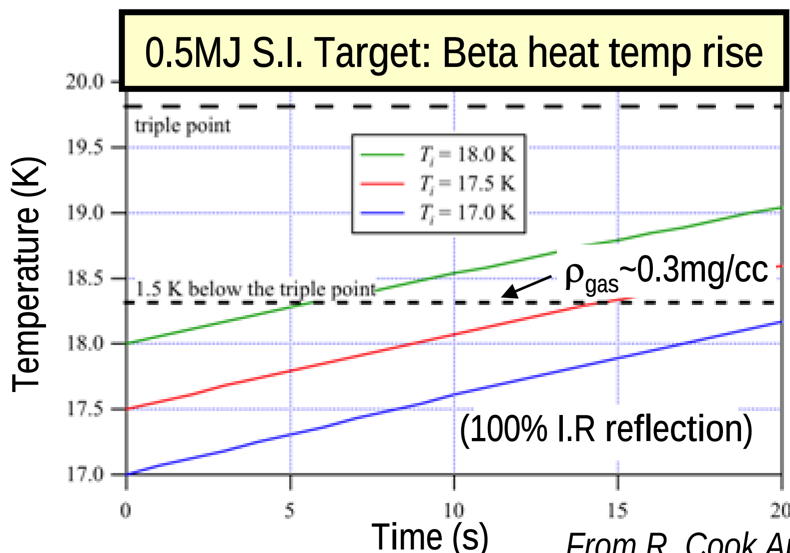
$$e(\theta) \sim f[datum\ r_{1D}(t) - r(t,\theta)]......$$

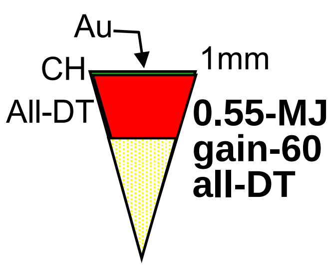
Minimize *Error* through control of 2x4 ring powers at time step t+Δt

The simple target mounts to the modified cryoTARPOS cold plate via its fill tube. A new He gas-tight cryoshroud will be required







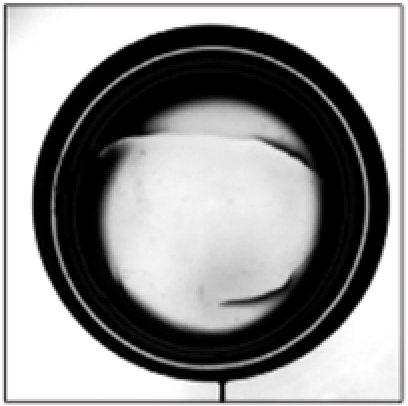


From R. Cook April 2010

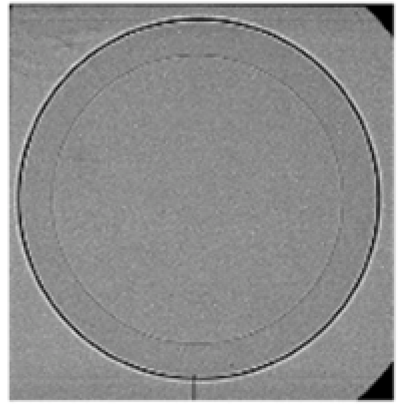
Arm ringdown time is ~3-5s.
Can we get by without an opposed-port cryoshroud?

A NIF fill-tube target has been demonstrated at LLE that will be optimized to meet polar-drive ice specifications

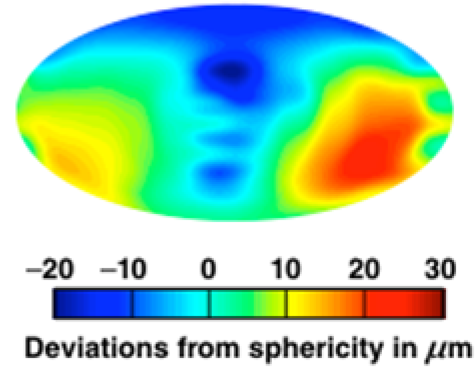
Shadowgraph



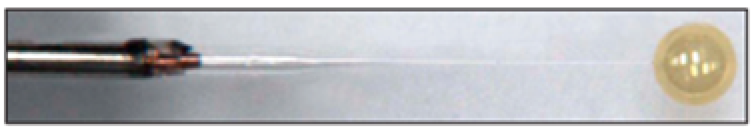
X-ray phase contrast



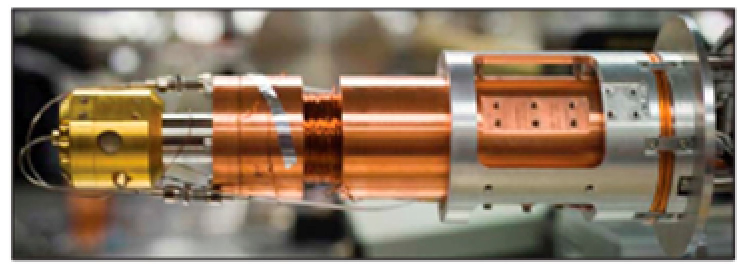
Inner ice layer surface



D_2 layer (297 μm) with mid-IR laser layering



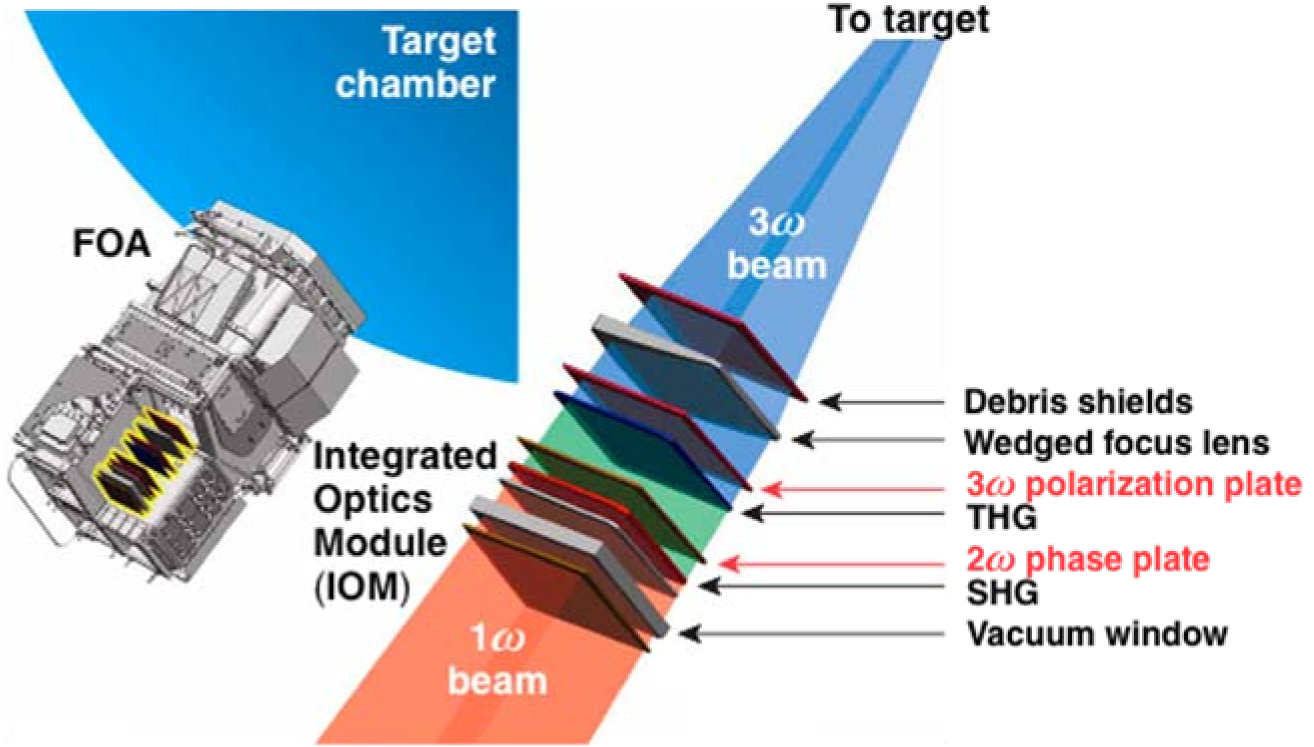
Target: 2.95-mm OD, 20-μm wall
Fill tube: 30-μm OD at shell wall



Cryogenic layering sphere

Facility renovations and equipment upgrades are underway at LLE to demonstrate NIF PD cryogenic layering with DT targets.

The focal-spot conditioning strategy for polar-drive ignition includes phase and polarization plates



The NIF final optics assembly (FOA) will include:

- Phase plate between the frequency conversion crystals (2ω)
- Polarization plate (3ω)

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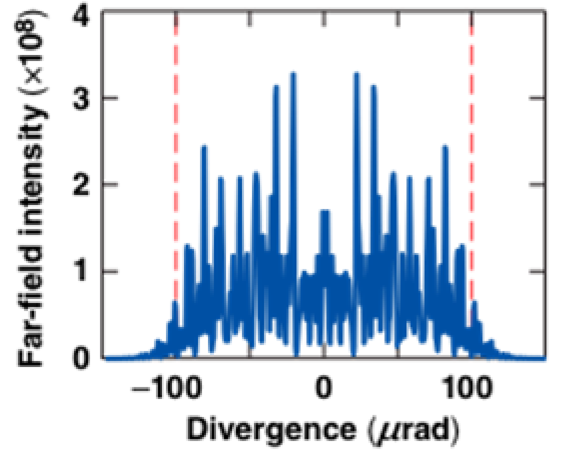
A Multi-FM SSD beam smoothing demo on OMEGA EP will validate laser imprint performance

Integrate NIF PAM into OMEGA EP

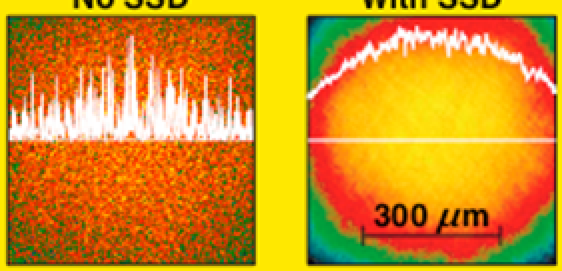
In progress

Early FY12

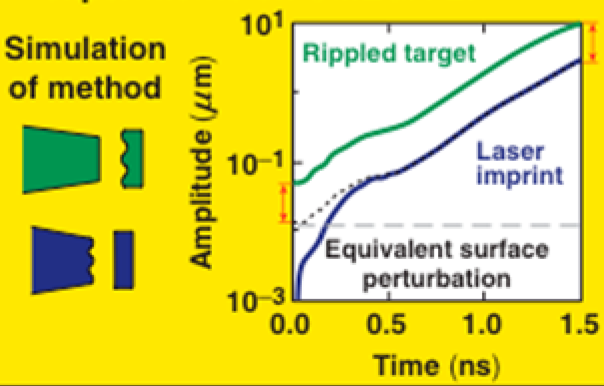
Demonstrate Multi-FM Seed Source



Verify smoothing with equivalent target plane measurements*



Verify laser imprint with foil-target experiments on OMEGA EP**



*S. P. Regan *et al.*, J. Opt. Soc. Am. B 17, 1483 (2000).

**T. R. Boehly *et al.*, Laser Part. Beams 18, 11 (2000).

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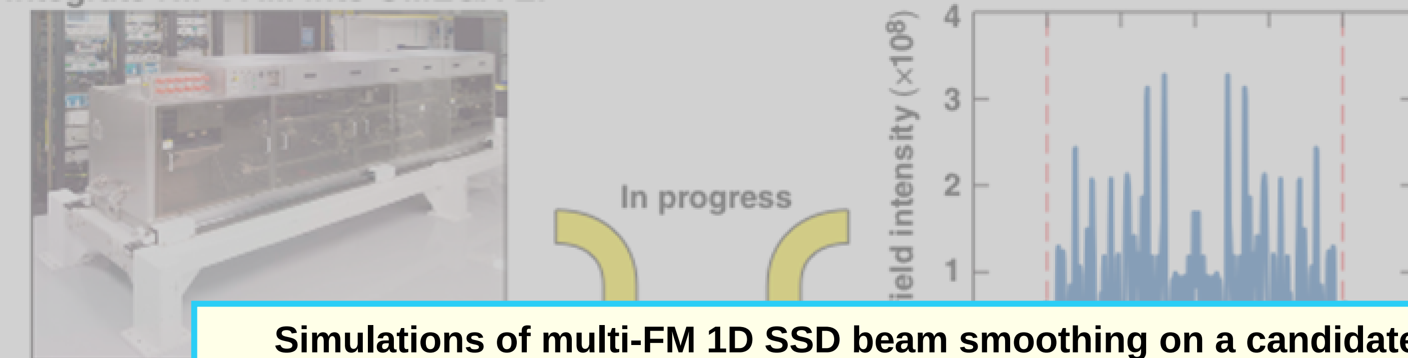
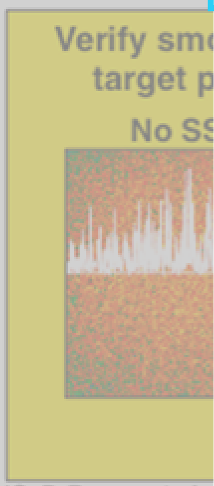
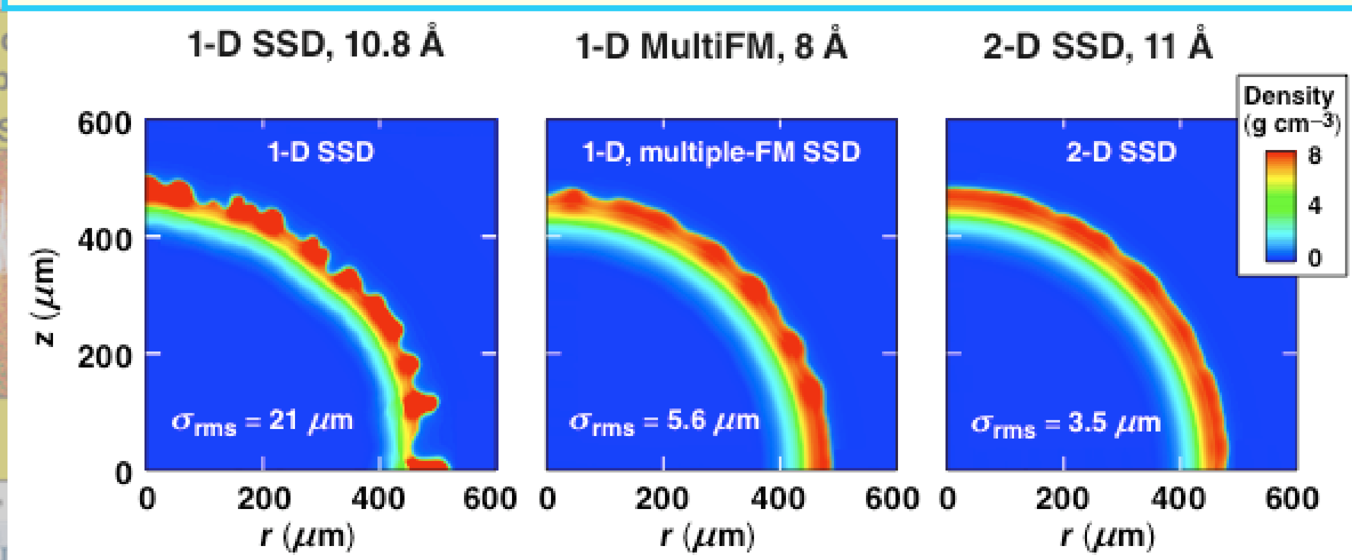
A Multi-FM SSD beam smoothing demo on OMEGA EP will validate laser imprint performance





Simulations of multi-FM 1D SSD beam smoothing on a candidate NIF 1.5MJ-drive CH foam/DT target *(J. Marozas Bull. APS 2008)*
Late time imprint at end of acceleration phase reduces to ~2D SSD levels



*S. P. Regan et al.,

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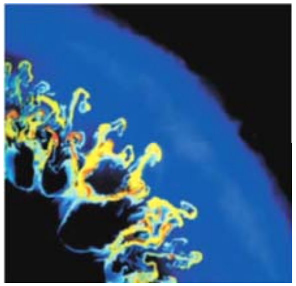
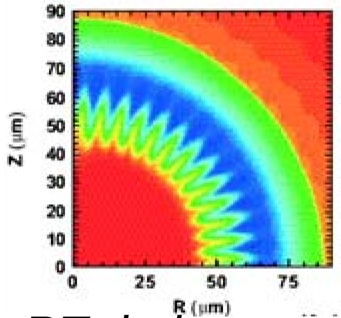
A central question for shock ignition: Is stability more forgiving relative to conventional (fast compression) hotspot ignition?

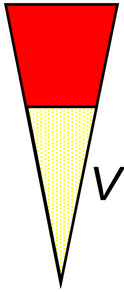
Conventional PdV hotspot ignition with high velocity thin shells:



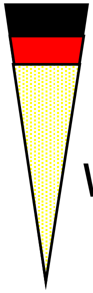
RT during acceleration:
- Inflight breakup



RT during stagnation:
- Ignition quench by mix



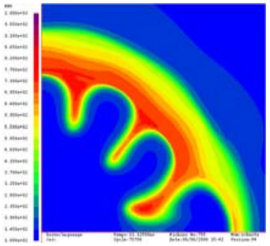
NIF SI
V~2.9e7cm/s



NIF NIC
V~3.9e7cm/s

Shock ignition has low velocity thick shells – more robust to inflight breakup

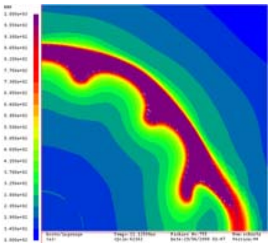
Does the late-time shock mitigate RT growth and HS mix?



Compression only

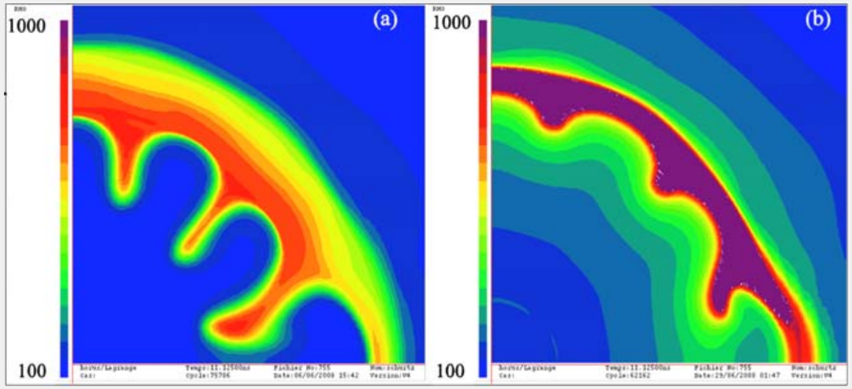
RT instability at stagnation

R.Betti,
G. Schurtz ,
S.Atzeni et al.



Compression plus shock

HiPER all-DT shock ignition target suggests shock mitigation of hotspot R-T growth. Has OMEGA observed this experimentally?



Compression only

At stagnation

YOC ~0

Compression + shock

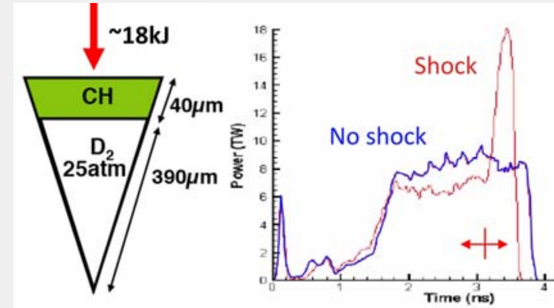
At ignition

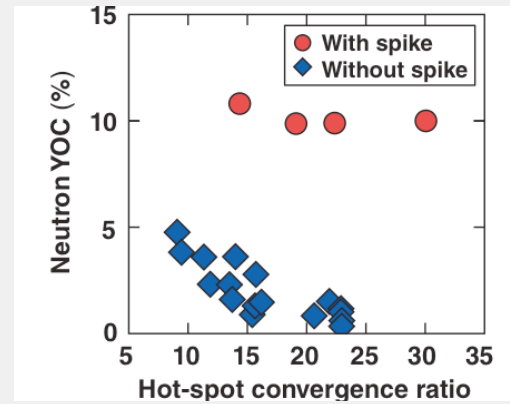
YOC ~80%

HiPER all-DT target

- Compression beams: radial rays with multimode perturbation. Shock beams: symmetric radial rays
- RT mitigation from: (a) shock R-M reversal of compression RT (b) ablation stabliz. of igniting HS

G. Schurtz , S.Atzeni et al.





Is this experimental evidence of shock RT mitigation?

- OMEGA shock driven target
- D2 gas with CH shell
- Same total energy: shock, no shock

W. Theobald et al. et al.

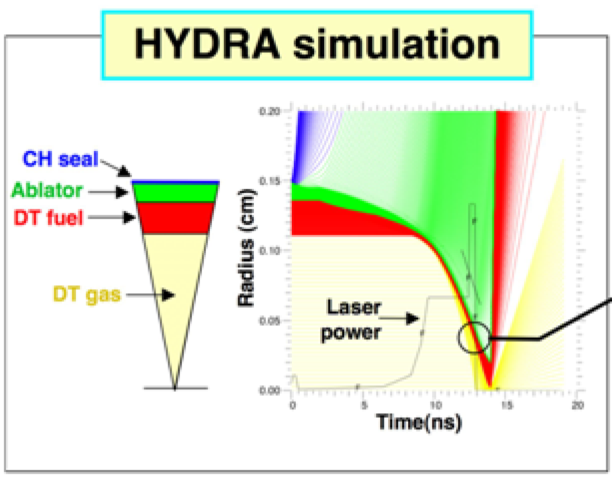
Laser Plasma Interactions: Late time SRS generated by the shock is probably benign and may be beneficial to the shock drive

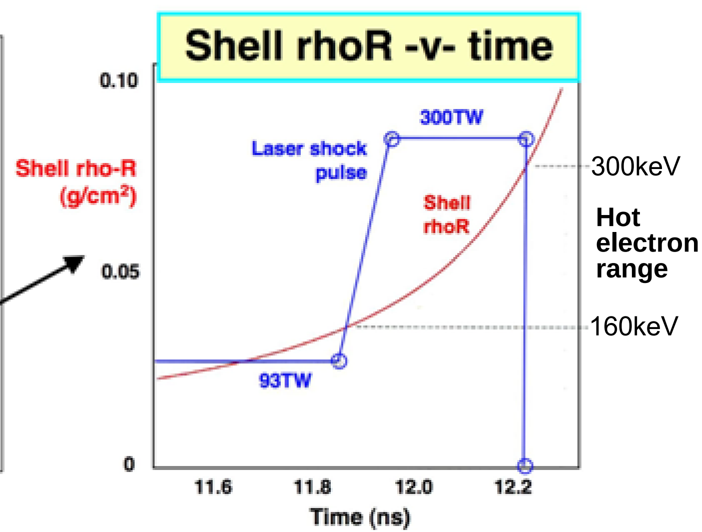
- Early time 2ωp hot electrons are main concern (near-term experiments?)

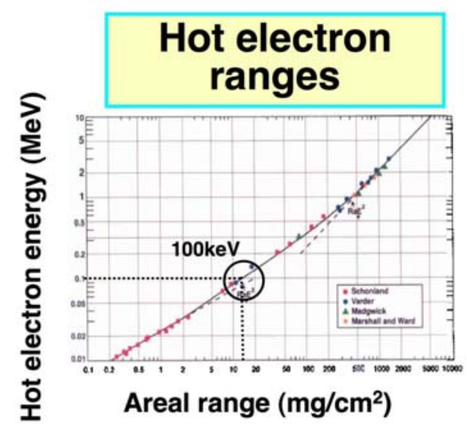
- SRS/2ωp hot electrons generated by high intensity shock may:

- (will) be absorbed in outside of dense converging shell
- improve the ablation process?
- provide good ablative stabilization ?
- contribute to symmetric shock drive by long mfp smoothing?
- permit effective drive at 2□ (green)?

- Efficiency, symmetry and stability of shock coupling is a paramount research issue (near-term experiments?)

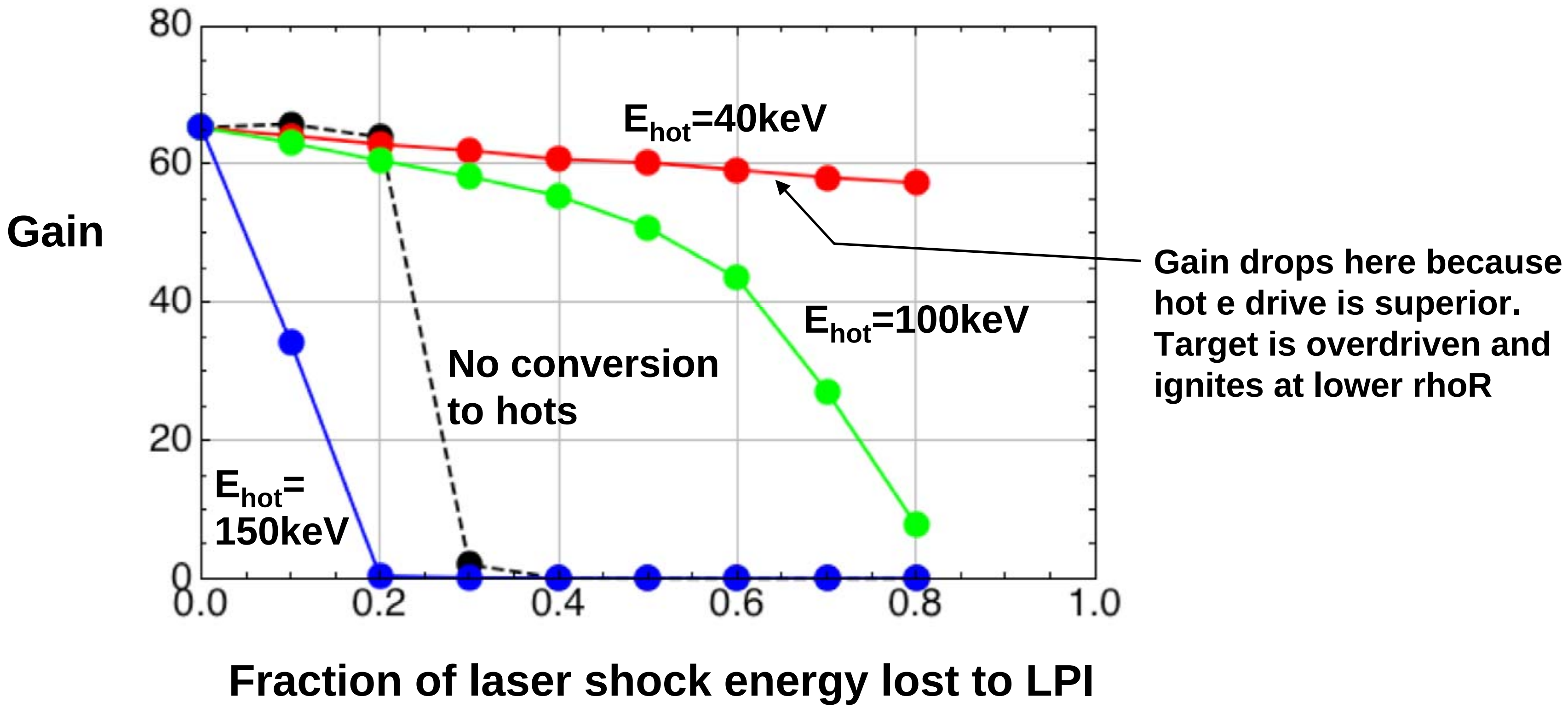






The small, 0.5MJ-class target can withstand shock-laser-induced hot electrons up to ~100keV

- Take 0 to 80% fraction of shock laser energy as converted into LPI and parameterize as a function of hot electron energy
- Transport hot electron population by LASNEX suprathermal electron package



Shock ignition on NIF: Where to from here in the near term?

- **Integrated 0.5MJ-Class Target Designs in Polar Drive Geometry**
  - 2/3D simulations; optimize polar drive symmetry
  - Robustness of ignition window to shock coupling symmetry and stability
- **Laser Plasma Instabilities**
  - TPD(early time)…. SRS, SBS(later time) - beneficial for shock coupling and smoothing? Near term experiments
- **Target Fabrication and Fielding**
  - Targets: ***Non-cryo:*** CH, Au/Be; ***Cryo:*** all-DT, CH/DT, fill-tube, Au/Al IR layer…
  - Cryostat and cryoshield design and fab (horizontally opposed cryoshield?)
- **NIF Laser Hardware**
  - Optimized polar drive geometries with beam balance
  - Phase plates and polarization smoothing
  - 1-D multi-FM SSD
- **Immediate-near term tests of polar drive symmetry on NIF**
  - AWG pulse shape programming – Shoot the desired pulse shape!
  - PDD symmetry and shock coupling efficiency at high CR with characterization of LPI (room-temp hydro-equiv. CH targets with diagnostic fill gases)

  (-Immediate term precursor shock-”ignition” shots on OMEGA in PDD)

Shock-Ignition*: Implode at low velocity and ignite separately

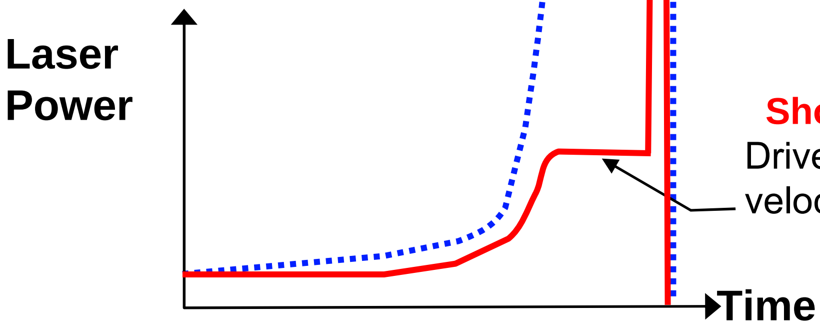
Conventional hotspot (fast compression) drive

Does double duty: fuel assembly and high velocity(≥3.5e7cm/s) for ignition

Shock ignition - shock pulse

Spike launches late-time shock timed to reach fuel at stagnation

⇒ Ignition



Shock ignition – Compression

Drive pulse assembles fuel at low velocity (≤2e7cm/s)

⇒ No ignition

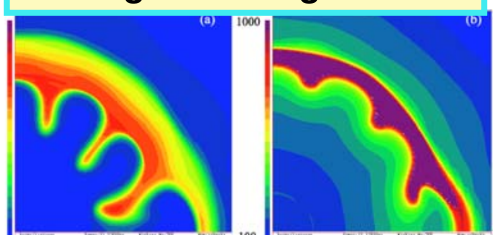
$E_{laser} \rightarrow E_{fuel,\ max\ KE}$

$\sim 1/2\ m_{fuel} V^2$

high   low

- **Higher gain/yield for a given laser drive energy in a more robust capsule**
- **Relative to "fast-ignition" :**
  - Time/spatial requirements less stringent (~ x10)
  - Uses same laser (no separate short pulse laser req'd)
  - Process modeling is (more or less) standard hydro
  - ***But*** conventional symmetry/stability constraints apply

RT instability at stagnation / ignition



Compression only   *Compression plus shock*

Are these more forgiving relative to a conventional hotspot ignition target?

Schurtz, Atzeni, et al

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* R. Betti , C.D. Zhou , K.S. Anderson , L.J Perkins, A.A. Solodov, *Phys. Rev. Lett.*, 98, 155001 (2007)

From a regulatory view, NIF should be able to accommodate yields of >200MJ

LLNL Site-Wide EIS 2005
• Shot budget = 1200MJ/yr
• 1.3MJ Indr-drive ign target, nom.yield = 20MJ
• Indr-drive ign target, max cred. yield = 45MJ
• 0.5rem/yr LLNL limit*

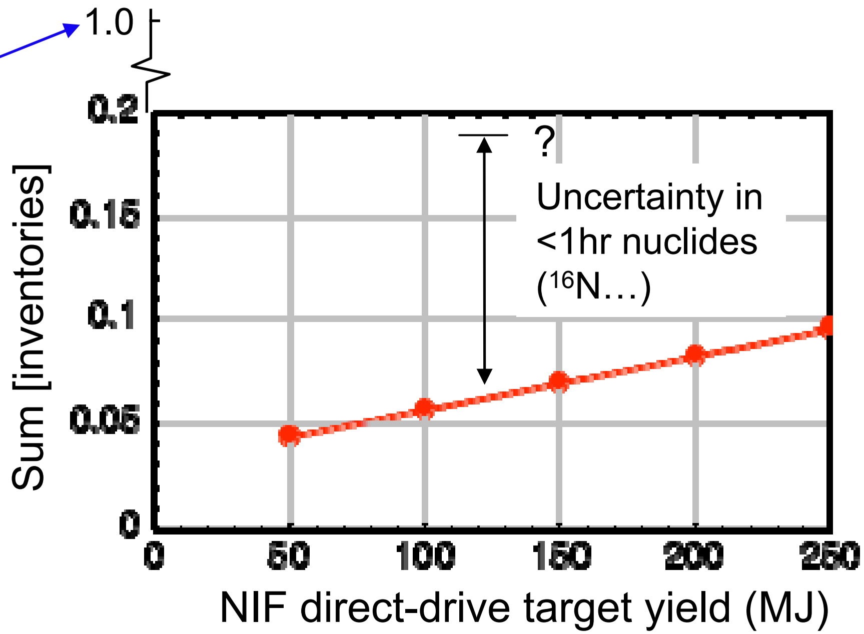
Equivalent NIF Dose Limits
• ~19 person-rems/yr over all personnel**
• 30mrem/yr individual av. (⇒ ~600 people)
• 0.5rem/yr LLNL limit* (⇒ target bay workers)
(*NRC worker limit = 5rem/yr; DOE limit = 1rem/yr)

⇒ Changes to EIS to increase yield limits are probably just "paperwork" until we cross the threshold to a 'Category-3 Nuclear Facility' :

Limit for *"less than Cat-3"* is 1.0

"Less than Category-3" Facility requires:
Sum **[**partial *releasable* inventories**]** < 1.0
(⇒ <10rem@30m)

Category	Example
1	Nuclear reactor,Hanford tanks
2	LLNL Pu bldg,
3	LLNL tritium bldg (≤30g T_2)
<3	Radiological facility (e.g NIF)



Recent references and reports

PRL 98, 155001 (2007) PHYSICAL REVIEW LETTERS week ending 13 APRIL 2007

Shock Ignition of Thermonuclear Fuel with High Areal Density

R. Betti,[1,2] C. D. Zhou,[1] K. S. Anderson,[1] L. J. Perkins,[3] W. Theobald,[1] and A. A. Solodov[1]

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(Received 6 December 2006; published 12 April 2007)

A novel method by C. Zhou and R. Betti [Bull. Am. Phys. Soc. **50**, 140 (2005)] to assemble and ignite thermonuclear fuel is presented. Massive cryogenic shells are first imploded by direct laser light with a low implosion velocity and on a low adiabat leading to fuel assemblies with large areal densities. The assembled fuel is ignited from a central hot spot heated by the collision of a spherically convergent *ignitor* shock and the return shock. The resulting fuel assembly features a hot-spot pressure greater than the surrounding dense fuel pressure. Such a nonisobaric assembly requires a lower energy threshold for ignition than the conventional isobaric one. The ignitor shock can be launched by a spike in the laser power or by particle beams. The thermonuclear gain can be significantly larger than in conventional isobaric ignition for equal driver energy.

DOI: 10.1103/PhysRevLett.98.155001 PACS numbers: 52.57.−z

In direct-drive inertial confinement fusion [1,2] (ICF), a shell of cryogenic deuterium and tritium (DT) thermonuclear fuel is accelerated inward by direct laser irradiation. As the shell stagnates, the compressed fuel is ignited from a low-density central hot spot surrounded by an ultradense

$$G \approx \frac{73}{I_{15}^{0.25}}\left(\frac{3\times 10^7}{V_I}\right)^{1.25}\frac{\theta(\rho R)}{0.2}, \quad (2)$$

where V_I is the implosion velocity in cm/s and the laser intensity I_{15} is in units of 10^{15} W/cm^2. In deriving Eq. (2),

PRL 103, 045004 (2009) PHYSICAL REVIEW LETTERS week ending 24 JULY 2009

Shock Ignition: A New Approach to High Gain Inertial Confinement Fusion on the National Ignition Facility

L. J. Perkins,[1] R. Betti,[2] K. N. LaFortune,[1] and W. H. Williams[1]

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(Received 12 March 2009; published 23 July 2009)

Shock ignition, an alternative concept for igniting thermonuclear fuel, is explored as a new approach to high gain, inertial confinement fusion targets for the National Ignition Facility (NIF). Results indicate thermonuclear yields of ~120–250 MJ may be possible with laser drive energies of 1–1.6 MJ, while gains of ~50 may still be achievable at only ~0.2 MJ drive energy. The scaling of NIF energy gain with laser energy is found to be $G \sim 126E\,(\mathrm{MJ})^{0.510}$. This offers the potential for high-gain targets that may lead to smaller, more economic fusion power reactors and a cheaper fusion energy development path.

DOI: 10.1103/PhysRevLett.103.045004 PACS numbers: 52.57.−z, 28.52.Cx

In inertial confinement fusion (ICF), a driver—i.e., a laser, heavy-ion beam or pulse power—delivers an intense energy pulse to a target containing around a milligram of deuterium-tritium (DT) fusion fuel. The fuel is rapidly compressed to high densities and temperatures sufficient for thermonuclear fusion to commence. The goal of present ICF research is to obtain ignition and fusion energy gain economic fusion power reactors and a cheaper fusion energy development path. The purpose of this Letter is to explore the scaling of fusion yield and energy gain for candidate shock-ignited target designs.

A typical ICF laser target consists of a spherical shell of cryogenic solid DT fuel surrounded by an outer ablator of mass comparable to that of the fuel. Driver energy is

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UCRL-TR-428513

On the Fielding of a High Gain, Shock-Ignited Target on the National Ignition Facility in the Near Term

L. J. Perkins, R. Betti, G. P. Schurtz, R. S. Craxton, A. M. Dunne, A. J. Mackinnon, K. N. LaFortune, A. J. Schmitt, P. W. McKenty, D. S. Bailey, M. A. Lambert, X. Ribeyre, W. R. Theobald, D. J. Strozzi, D. R. Harding, A. Casner, G. V. Erbert, K. S. Andersen, M. Murakami, A. J. Comley, S. Atzeni, R. C. Cook, R. B. Stephens

Revision 0

April 23, 2010

LAWRENCE LIVERMORE NATIONAL LABORATORY

UCRL-TR-432811

Development of a Polar Drive Shock Ignition Platform on the National Ignition Facility

L.J. Perkins, G P. Schurtz, R. Betti, R.S. Craxton, K.N. LaFortune, A. Casner, A.V.Hamza, A.J. Comley, X. Ribeyre, A.J. MacKinnon, P.W. McKenty, D.J. Strozzi, D.T. Blackfield, T.Ma, D.S. Bailey, M.A. Lambert, S.Atzeni, K.S. Anderson, R.C. Cook, G.V. Erbert

Revision 0

May 20, 2010

LLNL LC Closed Side Machines for LASNEX Optimization

Machine	Available Nodes per Job	Processors/ Node	Comments
Inca	25 (per user)	12	200hr job limit
Rhea	64	8	Extendable to ~128 on my request (max machine=512) (Same arch as Minos)
Minos	128	8	500 total nodes
Juno	128	16	1000 total nodes; DAT 500 job limit* (Same arch. as Eos)
Eos	32	16	12/24hr(?) job limit

* DAT = Dedicated Application Time; with permission, can schedule 500 jobs over, say, a weekend or at other slack(er) time