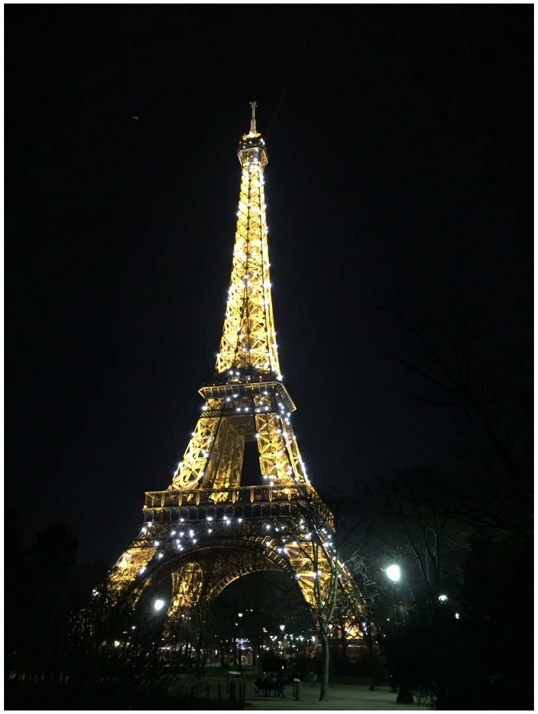
Inertial confinement fusion (ICF) with high magnetic fields

B. Grant Logan
BGLogan Scientific, Inc., Danville, CA, USA
Visiting scientist at U.Orsay-Paris-Sud, CEA-DIF, Ecole Polytechnique
Consultant for Lawrence Livermore National Laboratory
Consultant for Sandia National Laboratory, Albuquerque

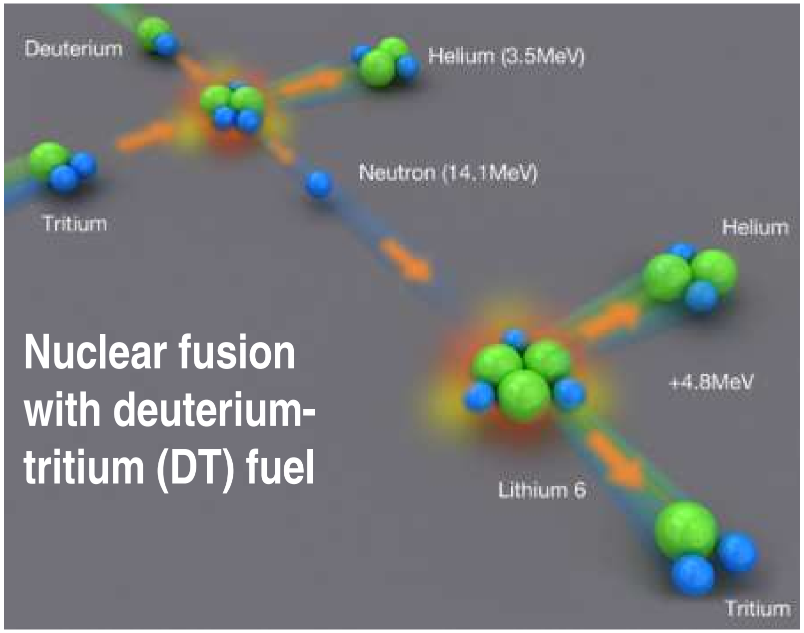


Seminar at CEA-ENS-Cachan 21 Mai, 2015

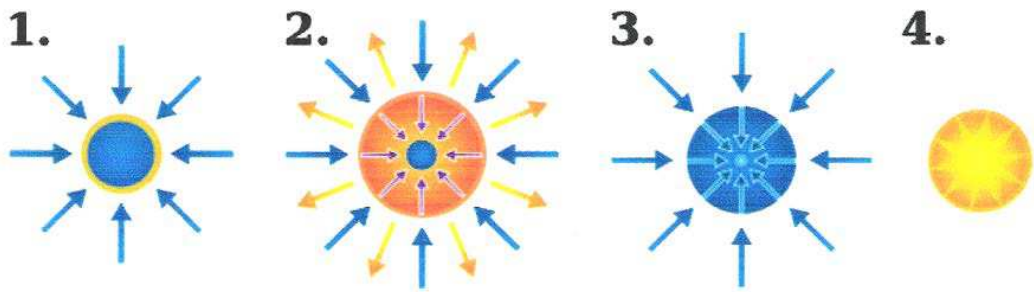
Critics of inertial fusion as well as magnetic fusion say fusion is too far into the future (irrelevant time scale for young scientists), and won't be needed anyway (new technology giving faster, cheaper oil and gas extraction). →My message today: NOW is the best time for international scientific discovery opportunity for fusion physics, *particlularly with the application of high magnetic fields to ICF*.

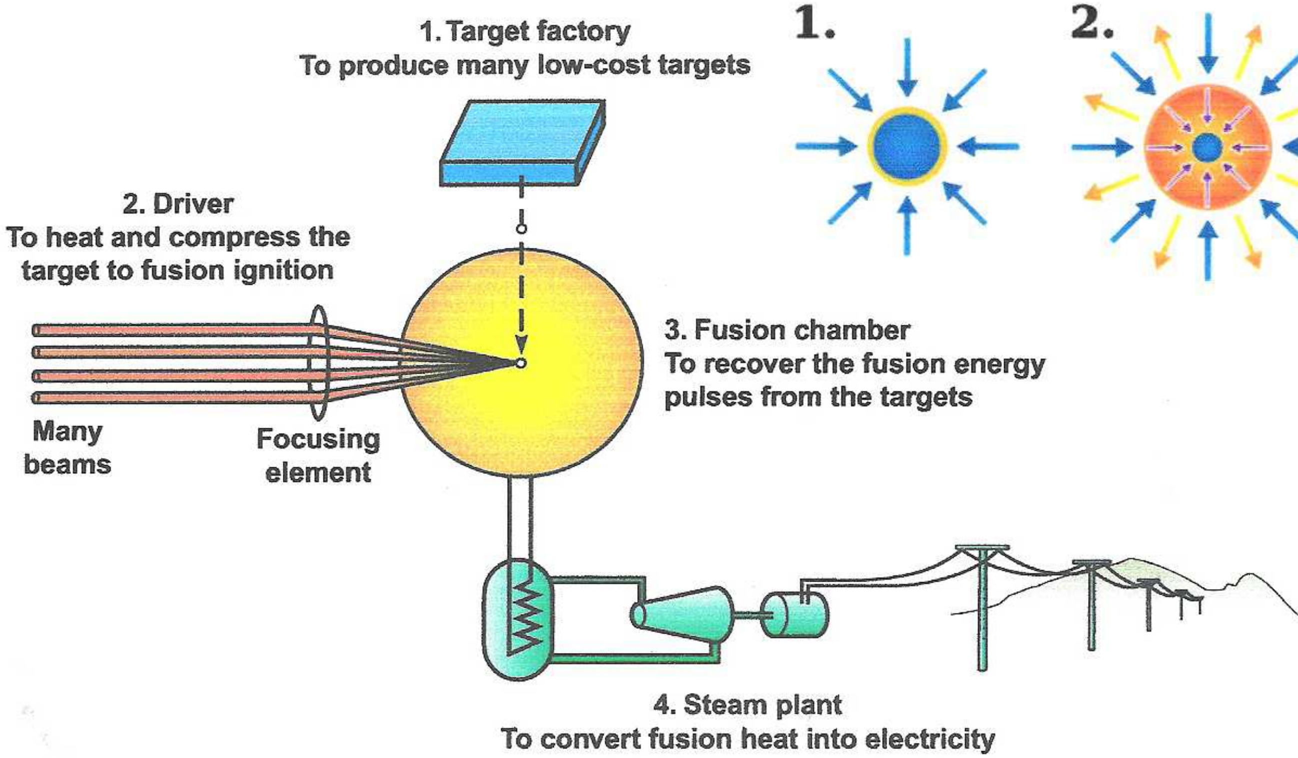
Acknowledgement:
Ce travail a beneficie d'une aide Investissements d'Avenir du LabEx PALM (ANR-10-LABX-0039-PALM)
Funding agency : Investissement d'Avenir LabEx PALM
Grant number : ANR-10-LABX-0039

What is inertial confinement fusion?



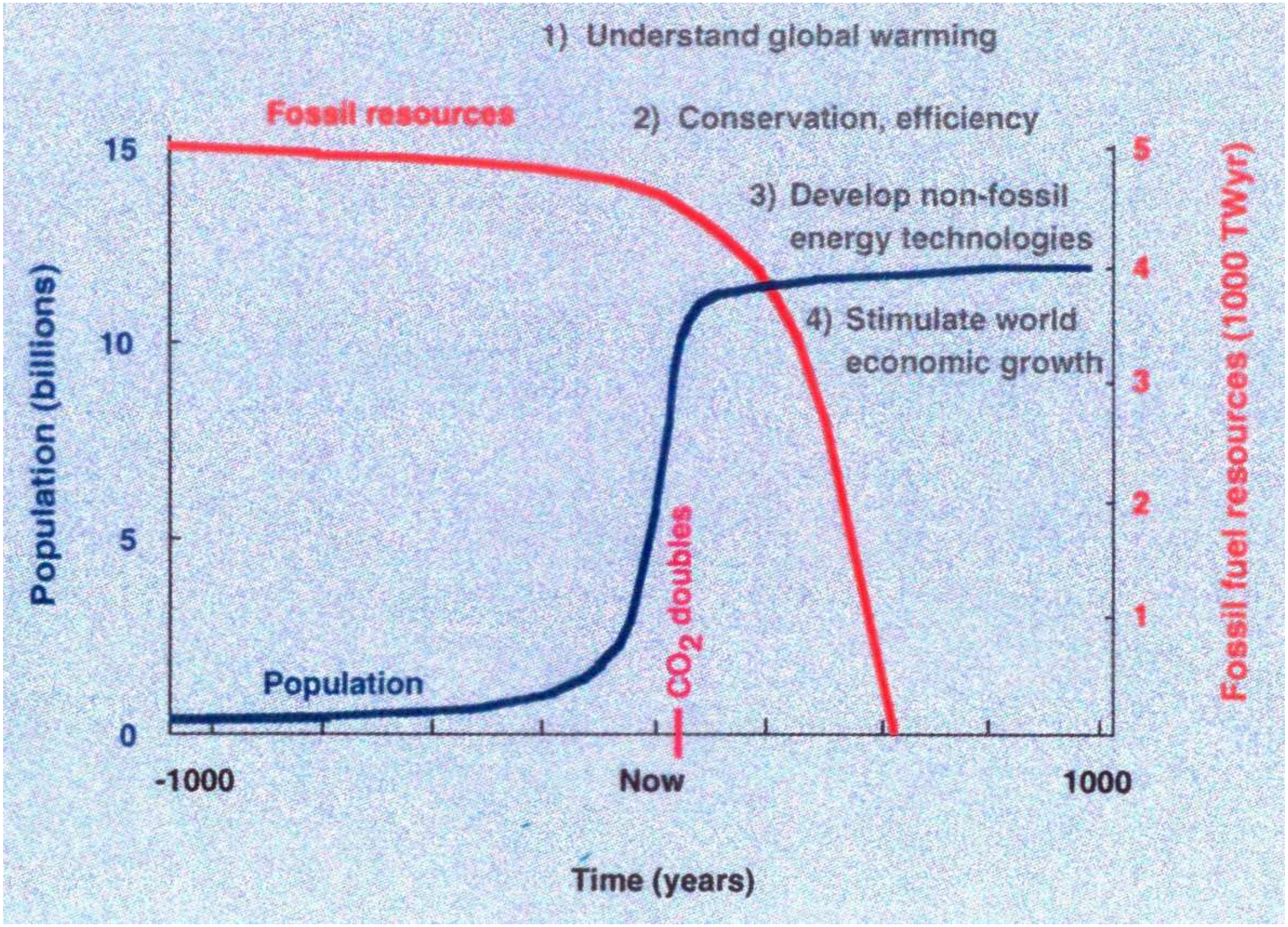
1. Deliver laser or particle beams to a mm-radius capsule shell with DT fuel (~ 1 MJ in 3 ns ~ 300 TW).
2. Outer capsule surface ablates, rocket force implodes DT fuel to pressures > 300 Gigabar.
3. 30X convergent compression heats fuel to ignition temperature (30 keV per D+T+e).
4. DT fuel ignites and burns in 0.1 ns before much expansion, giving 17,600 keV fusion energy/reaction.





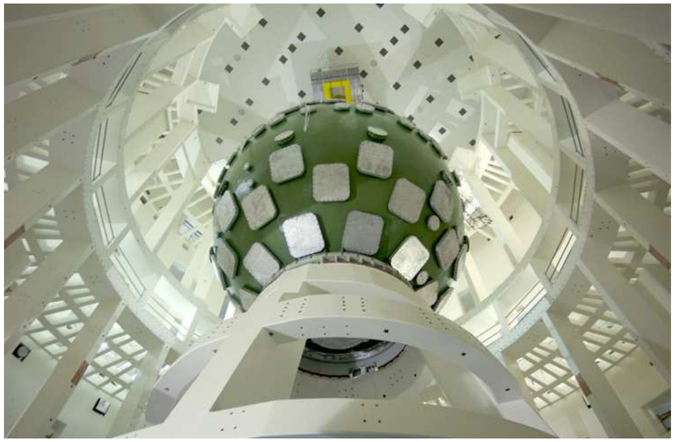
Repetition of fusion microexplosions @ 5 Hz repetition rate can heat fusion chambers for thermal conversion (Also pulsed direct conversion to electricity possible).

It doesn't matter if we can't say if fusion will come in 20 or 50 years more:
We must care for the future of 10^{10} +people forced to live on a hot planet!

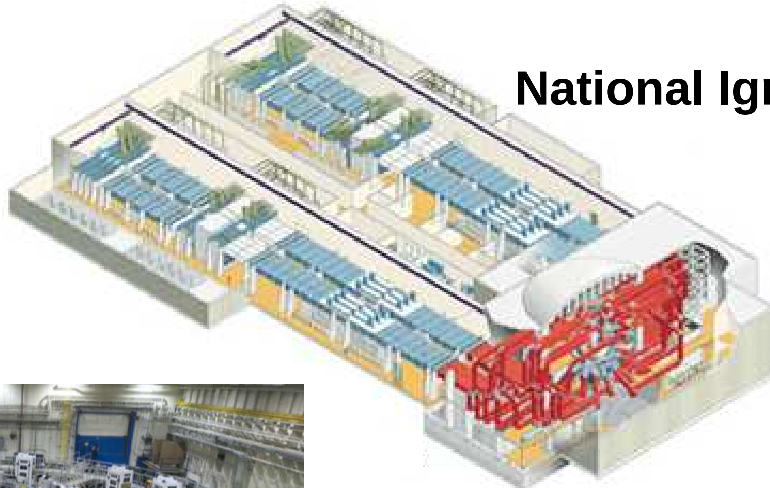


From the CEA website: Le Laser Mégajoule (LMJ) est une installation majeure du programme Simulation. Il sert à étudier, à toute petite échelle, le comportement des matériaux dans des conditions extrêmes similaires à celles atteintes lors du fonctionnement nucléaire des armes. Le LMJ est dimensionné pour délivrer sur une cible de quelques millimètres, en quelques milliardièmes de seconde, une énergie lumineuse supérieure à un million de joules.Le LMJ a été mis en service fin 2014, avec une première campagne de physique des armes.

LMJ : near-term scientific opportunity-example: Recently a call for proposals to use the first groups of beams from LMJ for basic high energy density (HED) plasma science has already attracted interest in an international proposal (submitted) to study the effects of *laser-generated megagauss magnetic fields* to ICF-relevant HED plasma hydrodynamics.

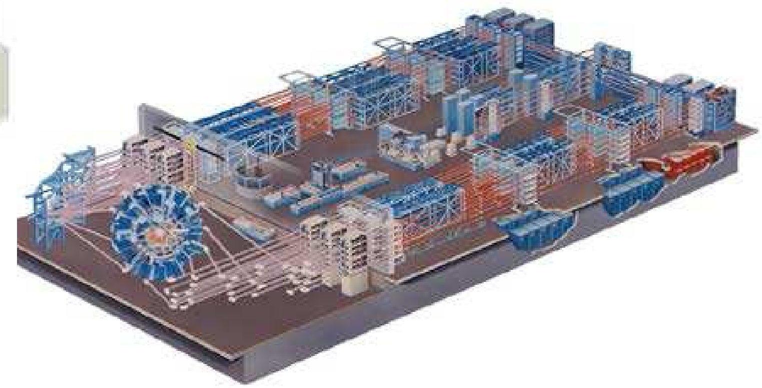


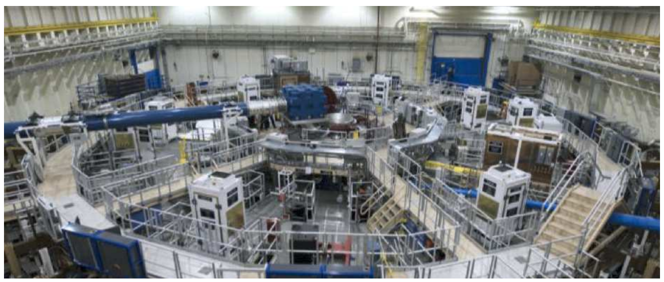
Other existing facilities* are available now for a broad array of experiments to explore the science of inertial fusion.



National Ignition Facility (US)

Omega + EP (US)





ZR MagLIF (US)

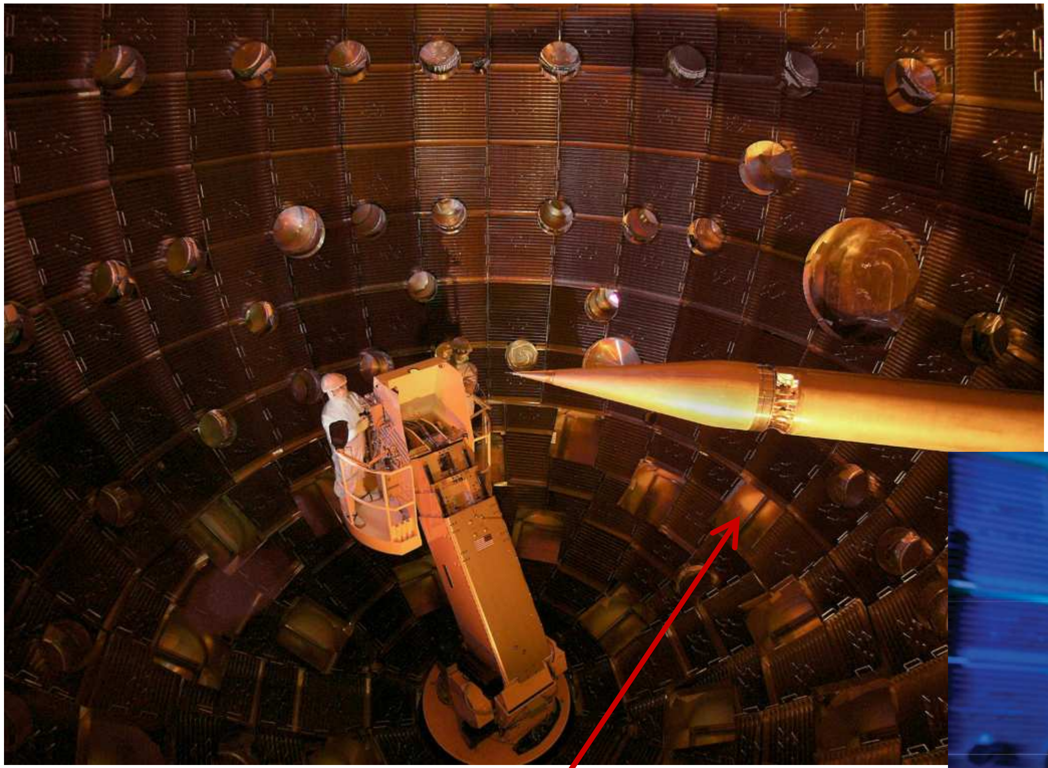
GEKKO XII + FIREX I (Japan)

SG-III (China)

** All are developing capabilities for integrated fuel implosions with high applied magnetic fields.*

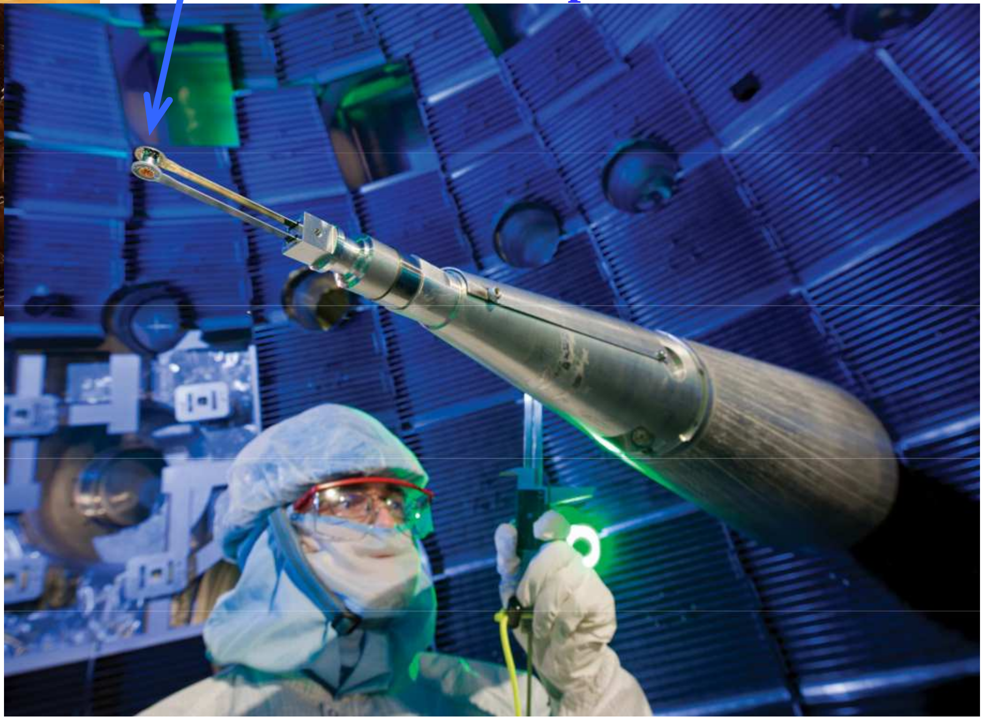
NIF has made much progress, but unfortunately falls short…

..of meeting extreme requirements* on implosion velocity, symmetry, entropy, and mix required for ignition within laser limitations of 1.5 MJ energy and 500 TW peak power.



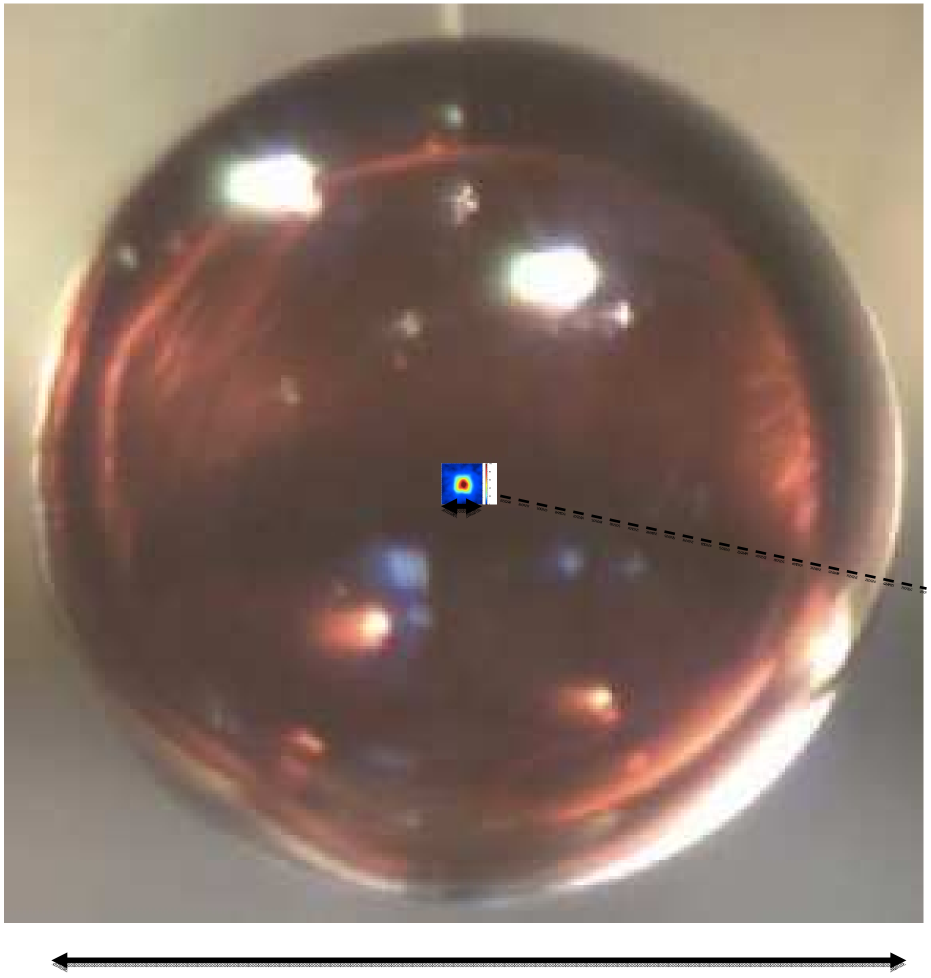
*** 2D-MHD simulations (Perkins, et.al. Phys of Plasmas 20 072708 (2013) show applied B_z of 40 T may relax these requirements!***

NIF hohlraum ~ 1 cm long x 3mm radius contains a ~2 mm dia. plastic DT-filled fuel capsule. Lasers enter thin plastic windows on top and bottom.



96 rectangular beam ports on bottom and 96 on the top of the 4 m radius NIF chamber lead to final focus optics @ 7 m radius from target center

<u>The NIF capsule:</u> (~2 mg of plastic ablator with ~200 μg of cryo DT annulus).
90 % of the plastic is ablated away to drive a spherical rocket which compresses the fuel ~ 30 X in radius, to a final ρr product ~ 1 g/cm^2, pressure > 200 gigabars, 3-5 keV T_{ion} .
Improved diagnostics show the DT hot spot gas (~4μg) still suffers from low mode hydro instabilities, *but 2-D MHD simulations show ignition is enabled at applied B_{zo} ~ 40 T.*

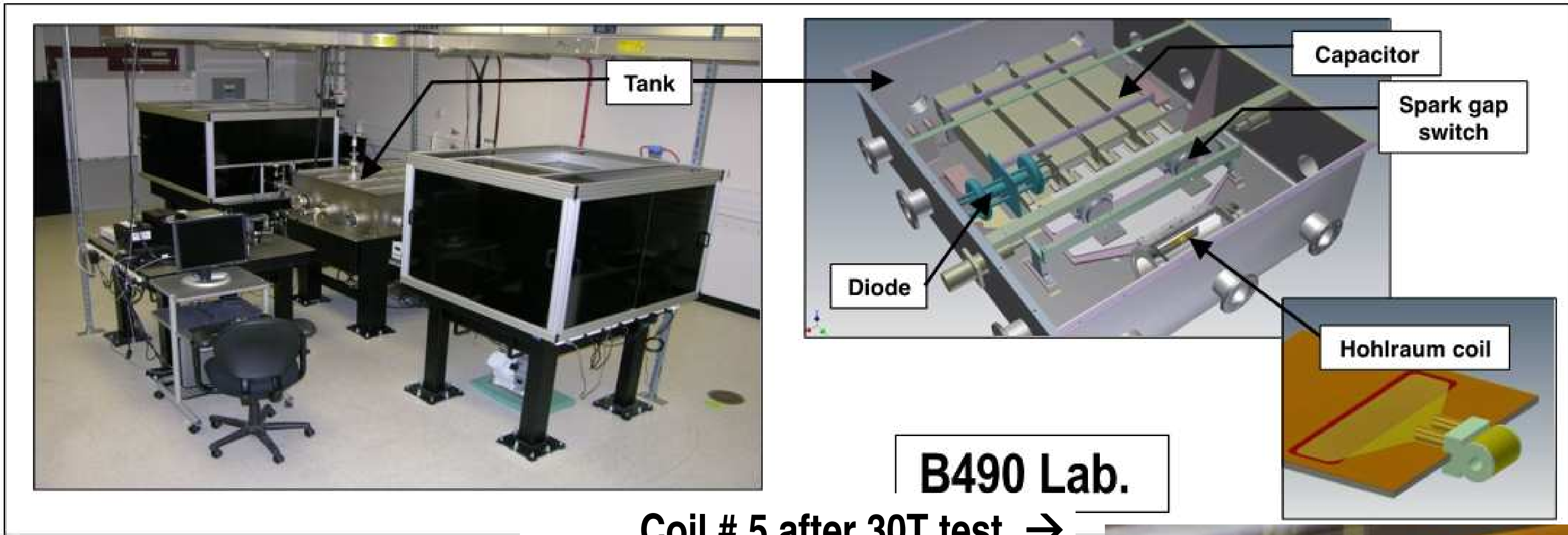


NIF provides an opportunity to study improved targets that may have relaxed ignition requirements (e.g., higher adibats, lower fuel convergence for improved stability with compressed B_z to confine alphas in lower ρr hot spots).

50 μm dia hot spot image

(DT shot N120716 @ Bang time)

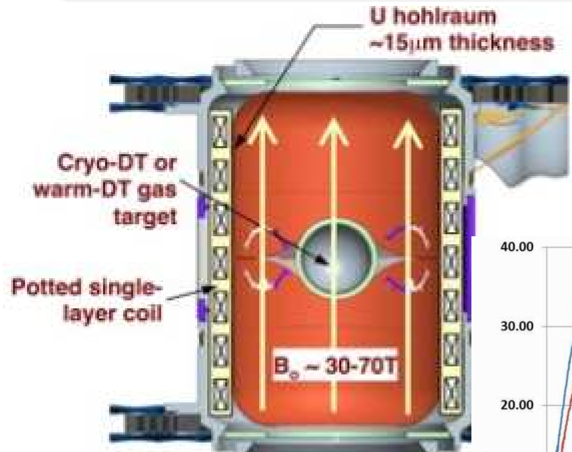
Prototype NIF hohlraum magnet tests reach 32T so far (Mark Rhodes, LLNL). Design expected to reach 50T (limit still TBD).

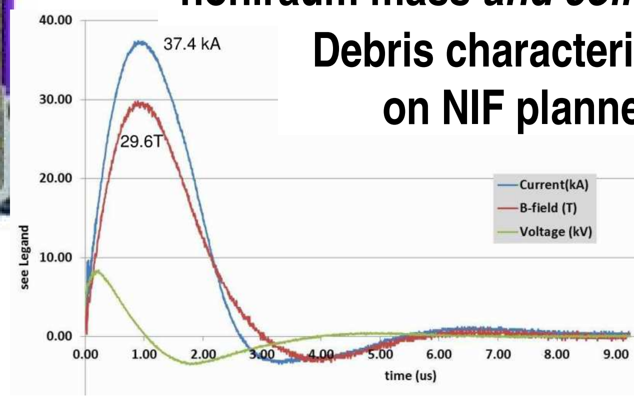


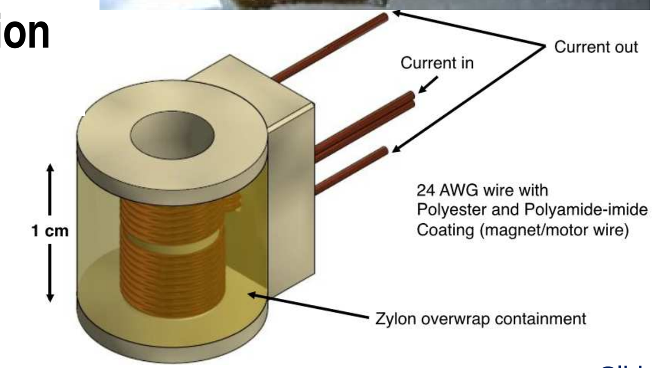
Coil # 5 after 30T test →

Coils designed to disassemble @ >50T. On NIF, 1 MJ of laser deposition inside will vaporize hohlraum mass *and coil mass*.

Debris characterization on NIF planned.







Magnetized targets are an old idea: *why reconsider applied Bz to laser-driven hot spot gas ignition now?*

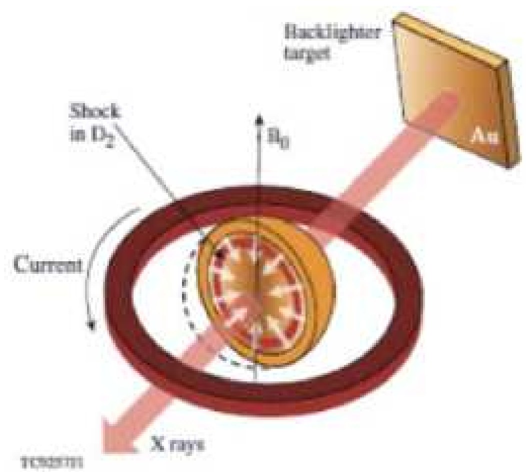
- Recent faster implosions on Omega (2011) and on MagLIF (2014) show that applied seed fields B_{zo} ~ 8 T are **compressed by 1000 X @ convergence 30**, reaching measured fields > 80 MG. Flux compression → $R_{g\alpha} < R_{hs}$ *at ignition-scale.* (Omega has higher T with B_z, but is too small for α coupling).

- Recent "high foot" pulse shapes now largely eliminate ablator carbon mix, (Omar Hurricane) → less radiation loss + less heat conduction+ more alpha deposition → *higher temperatures from present 5 keV T → 10 keV with B?*

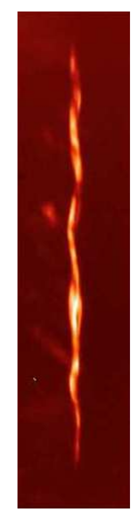
$\omega\tau_{ei} \sim B_z \cdot T_e^{1.5} / \langle Z^2 \rangle n_{ion}$

- Darwin Ho and John Perkins' recent 2-D MHD Lasnex runs using full-helical alpha orbits *show improved deposition more important to NIF ignition than e- heat conduction suppression alone*.

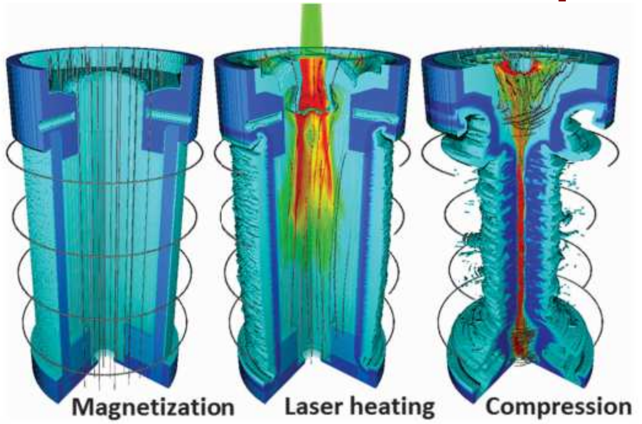
Omega [PRL 107, 035006 (2011)]: 8 T applied B_{zo}, → 80 MG compressed, enough for $\omega\tau_{ei}$ >1



SNL MagLIF (2014): 10T applied B_{zo} → 100 MG compressed, and, *enough $B_z \cdot R_{hs}$ to confine DD tritons.* 2-HYDRA sims (Sefkow) consistent with data.



Applied Bz physics common to MagNIF and MagLIF: reduced transverse heat conduction, improved confinement of charged fusion product ions.



Three critical components of the MagLIF concept: magnetization, laser heating, and compression. An axial current creates a $J_z \times B_\Theta$ force that implodes a gas-filled, premagnetized, cylindrical target. Near start of implosion, fuel is heated by the laser. The liner compresses and further heats fuel to fusion-relevant conditions.

[PRL 113, 155003 (2014)]

Experimental Demonstration of Fusion-Relevant Conditions in Magnetized Liner Inertial Fusion

M. R. Gomez, S. A. Slutz, A. B. Sefkow, D. B. Sinars, K. D. Hahn, S. B. Hansen, E. C. Harding, P. F. Knapp, P. F. Schmit, C. A. Jennings, T. J. Awe, M. Geissel, D. C. Rovang, G. A. Chandler, G. W. Cooper, M. E. Cuneo, A. J. Harvey-Thompson, M. C. Herrmann, M. H. Hess, O. Johns, D. C. Lamppa, M. R. Martin, R. D. McBride, K. J. Peterson, J. L. Porter, G. K. Robertson, G. A. Rochau, C. L. Ruiz, M. E. Savage, I. C. Smith, W. A. Stygar, and R. A. Vesey

Sandia National Laboratories, P.O. Box 5800, Albuquerque, New Mexico 87185, USA

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This Letter presents results from the first fully integrated experiments testing the magnetized liner inertial fusion concept [S. A. Slutz *et al.*, Phys. Plasmas 17, 056303 (2010)], in which a cylinder of deuterium gas with a preimposed 10 T axial magnetic field is heated by *Z* beamlet, a 2.5 kJ, 1 TW laser, and magnetically imploded by a 19 MA, 100 ns rise time current on the *Z* facility. Despite a predicted peak implosion velocity of only 70 km/s, the fuel reaches a stagnation temperature of approximately 3 keV, with $T_e \approx T_i$, and produces up to 2×10^{12} thermonuclear deuterium-deuterium neutrons. X-ray emission indicates a hot fuel region with full width at half maximum ranging from 60 to 120 μm over a 6 mm height and lasting approximately 2 ns. Greater than 10^{10} secondary deuterium-tritium neutrons were observed, indicating significant fuel magnetization given that the estimated radial areal density of the plasma is only 2 mg/cm^2.

Levels of thresholds for applied B_{zo} affecting ICF implosions

In order of increasing applied B_{zo} to affect each physics level: [Compressed B_z~ (CR^2~1000)xB_{zo}]:

(1) <u>Affect hot spot mass and temperature:</u> Level needed~ 10 T. Does the total gas mass created by the heat wave front grow faster or slower when omega-tau ~>1 (when heat flux is non-spherical- less transverse but more parallel flux)?

(2) <u>Affect alpha energy deposition vs hot spot ρR</u>: Level needed ~ 30-40T. How much does the fraction of alpha energy deposition within the gas increase with $R_{\alpha gyro}$ / $R_{hotspot}$ as a function of ρR gas / 0.3 g/cm^2-collisional-alpha-range?

(3) <u>Affect stagnation shape P2 (pancaking):</u> Level needed~ 50 to 100T. How much P2 is induced in the gas adiabat by ohmic heating from paramagnetic currents that flow near the hot spot gas equator to give flux compression during the early implosion phase when the plasma is resistive?

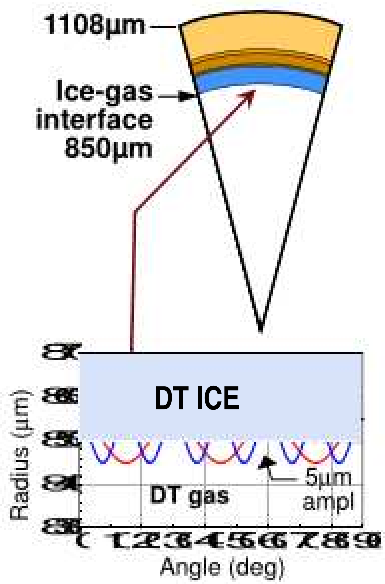
(4) <u>Affect deceleration Rayleigh-Taylor instability growth:</u> Level needed 50 to 300T? Depends on stabilizing line bending energy (k_ϕ)- increases for *short* ϕ-wavelengths. Need to consider 3D growth of maximum growth (high k_θ, finite k_z flute modes) with ballooning and alpha FLR effects.

(5) <u>Affect anisotropy of propagating thermonuclear burn waves</u>. Level unknown, but likely ~level (4)→ Field pressure ~ stagnation pressure! Propagating burn starts by e-heat conduction and alphas, both reduced @ > 100 MG compressed B fields *transverse*. However, burn pressures >> 10 Terabars can propagate across B flux via detonation-level shocks.

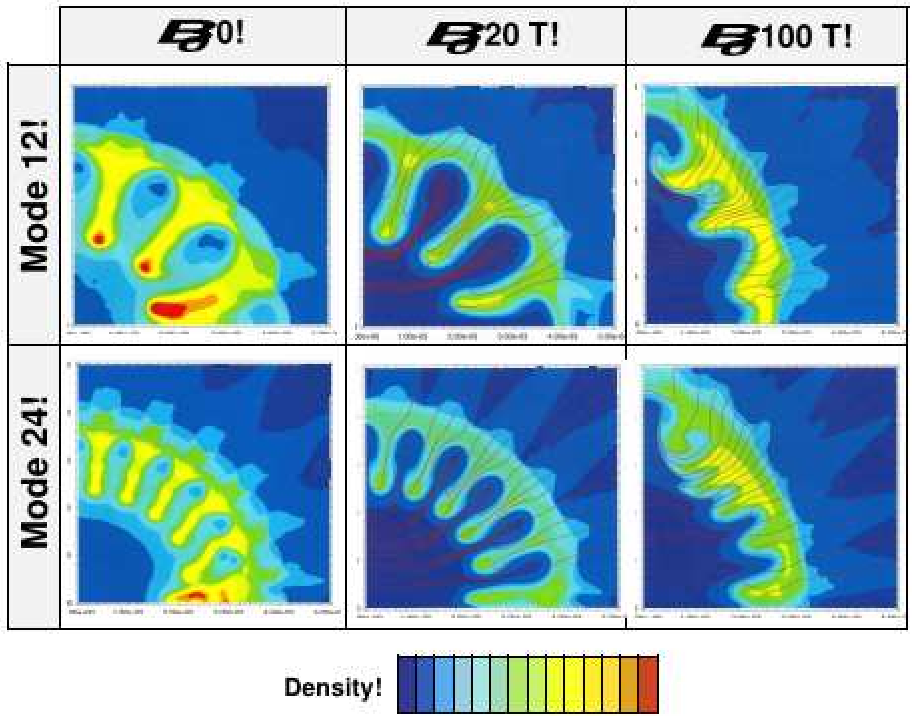
→Each of these scientific questions deserve many 2D and 3D simulations prior to magnetized implosion experiments, and the results would be worth publishing!

Simulations indicate that RT-growth into the hotspot may be suppressed at higher B-fields (in 2-D at least)

Density contours in the r-z plane at ignition (T(0)=12keV) for imposed single-mode perturbation of amplitude 5μm on ice-gas interface at t=0



Impose a 5μm amplitude ℓ=12 and ℓ=24 cosine initial perturbation on ice-gas interface at t=0



Suppression of RT instabilities is due to the field-line bending energy that must be expended (good curvature direction → stabilizing).

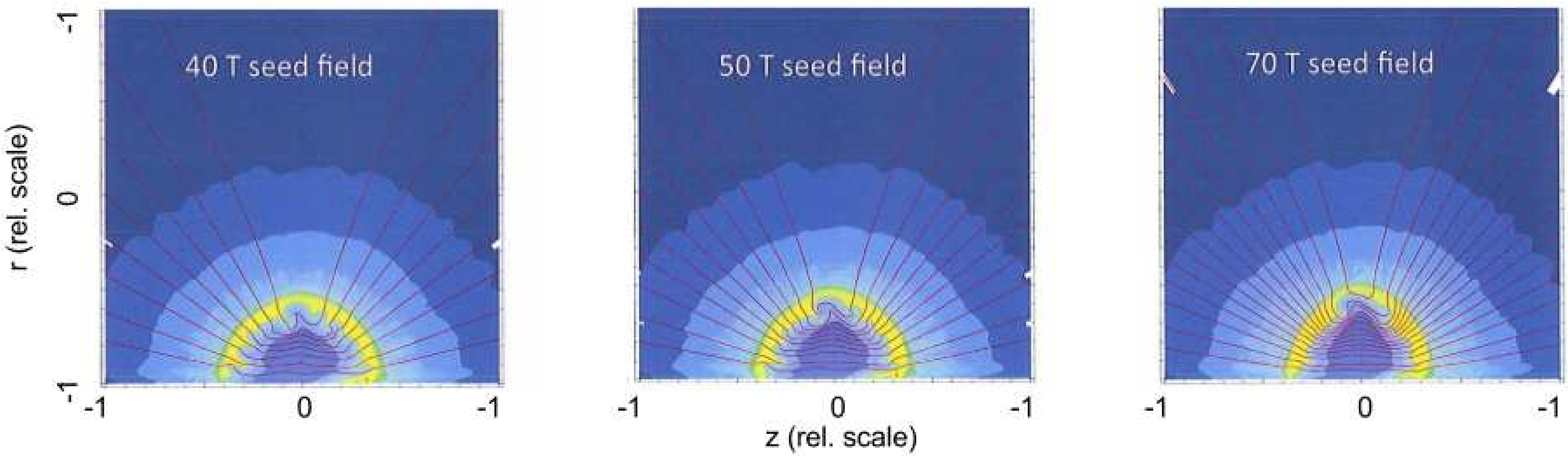
Effect will be enhanced at higher mode numbers (smaller bend radii) but 3-D simulations will be required for full insight

Implosion departs further from sphericity as strength of the seed field increases beyond 40 T

(Darwin Ho, LLNL 6/8/2014)

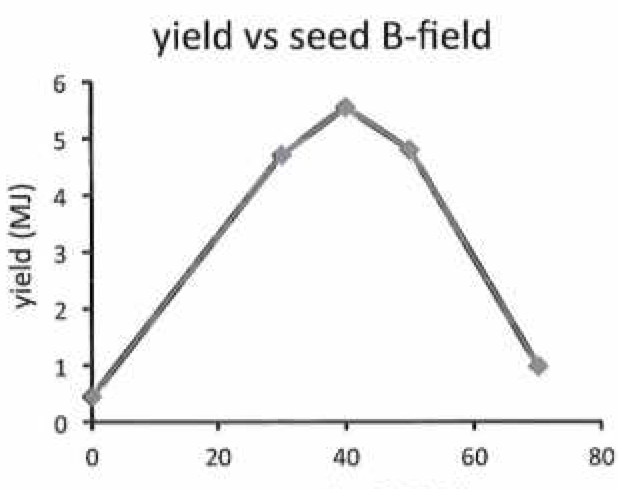
Indirect Drive (NIF)

density contours @ignition Ti(0, 0) = 12 keV

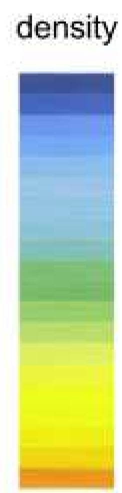


- Yield decreases as the shell departs from sphericity
- Symmetric irradiation in all these simulations

Can retune the drive to recover round, or, achieve ignition at *lower convergence with B_z* with modest "sausage" elongation



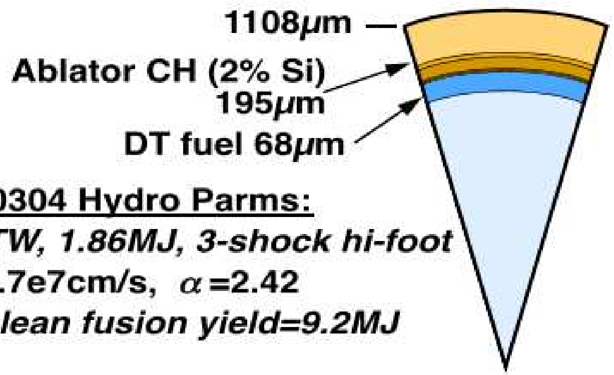
Magnetized direct drive will also show a peak in yield vs. B_{zo}, but the optimum B_{zo} is lower, e.g., 10-20 T, at higher implosion KE.



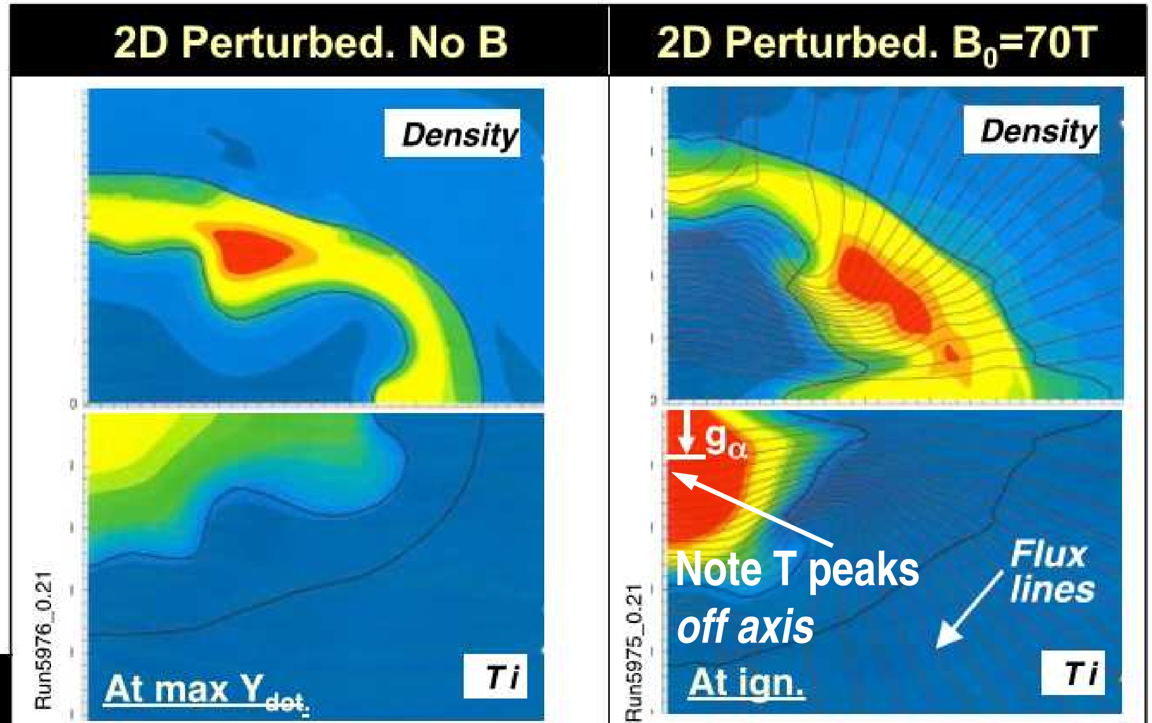
John Perkins (Indirect drive-NIF) compares“high-foot” CH capsule performance with/without applied Bz using 2D-MHD

LLNL-PRES-663377
This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract DE-AC52-07NA27344. Lawrence Livermore National Security, LLC

Apply angle-dep. P4 rad flux perturbation to approx. match N1400304 3-shock hi-foot inflight + stagnation params



N140304 Hydro Parms:
442TW, 1.86MJ, 3-shock hi-foot
V=3.7e7cm/s, α=2.42
2D clean fusion yield=9.2MJ



	N140304 Data	2D Perturbed. No B	2D Perturbed. B_0=70T
Fusion yield	N_n=9.43e15, 26.6kJ	N_n=8.88e15, **25.1kJ**	N_n=8.49e16, **240kJ**
Ti_Brysk (keV)	5.55(Incl Doppler?)	3.62	9.50
Ti(0) max (keV)	–	6.64	15.0
$\rho R_{hs}/\rho R_{shell}$	0.140/0.775	0.338/0.740	0.266/1.13
P_{hs} (Gbar)	173	221	349
Conv. ratio	33.5	33.0	37.1
Yield–no α dep.	12.3kJ	**11.6kJ**	**14.9kJ**

B-field effect on electron heat conduction and alpha deposition

B-field effect on electron heat conduction only

Application of the analytic magnetized implosion model to the CEA low aspect ratio A=3 direct drive design for LMJ [Brandon, Canaud, Temporal, Ramis, Nuclear Fusion 54 (2014) 083016] at *below marginal ignition velocity* 280 km/s, and with and without applied Bz = 10T

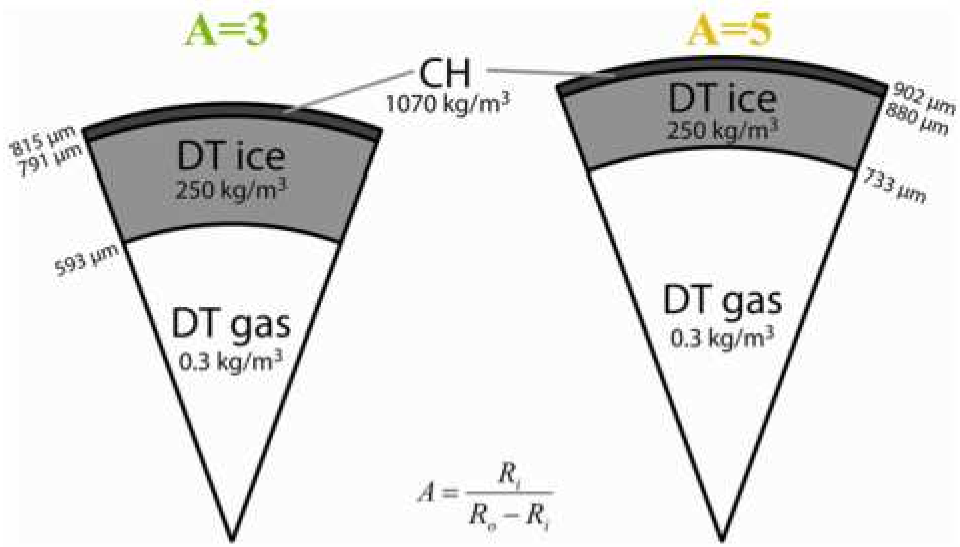


Figure 1. 300 μg-DT Target design with a CH-mass of 208 μg and 235 μg for $A = 3$ (left) and $A = 5$ (right) respectively.

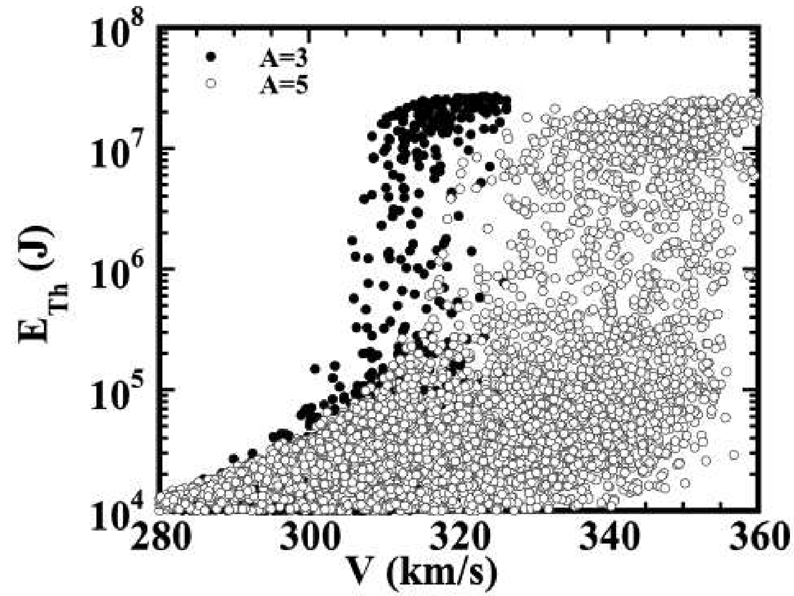
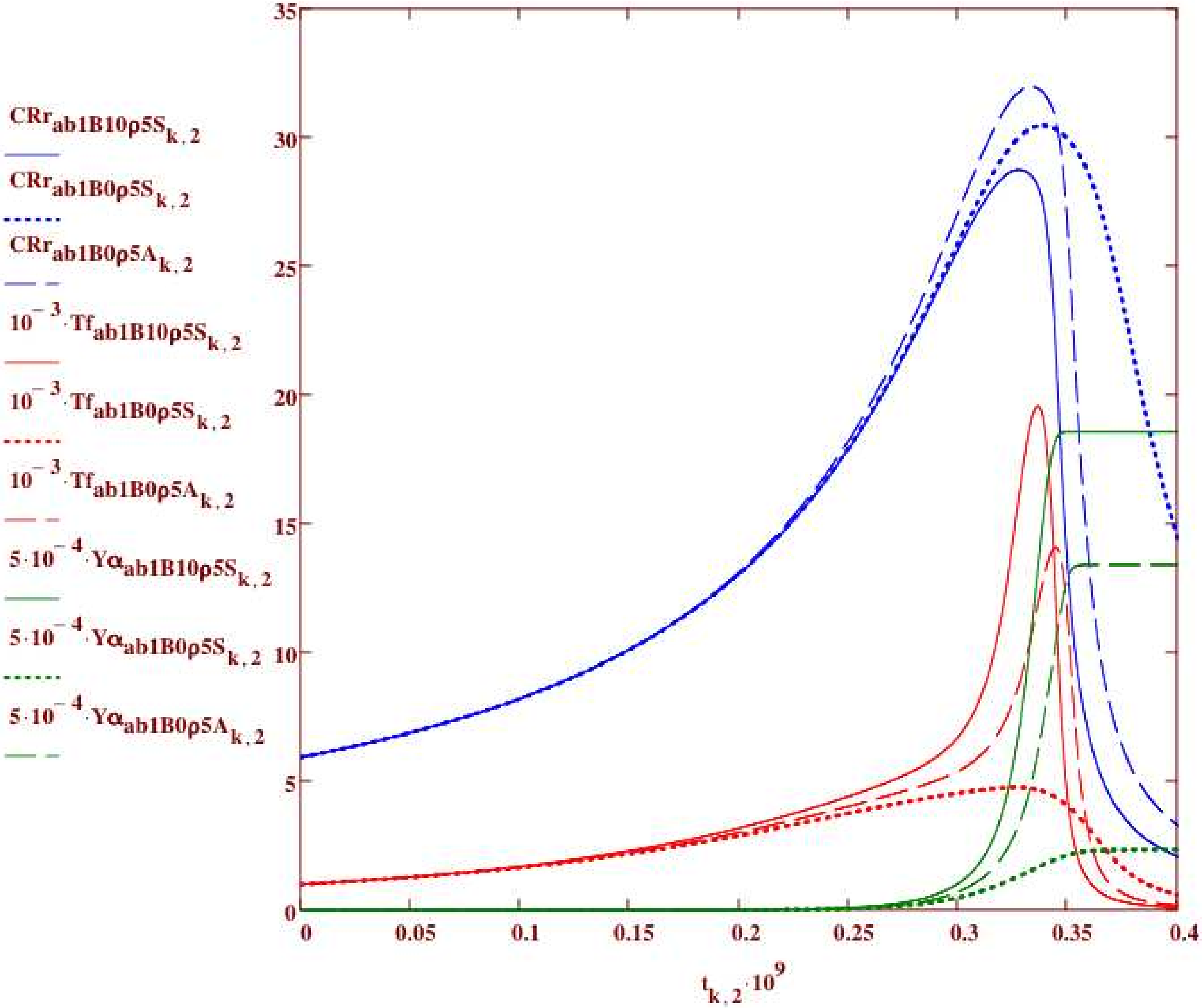


Figure 3. Thermonuclear energy versus implosion velocity for $A = 3$ (filled circles) and $A = 5$ (open circles).

→Model application (next slide): can modest applied B_{zo} ~ 10 T ignite *hot spot gas* at lower implosion velocities v_{imp}= 280 km/s and shell KE = (1/2)(300*10^{-9} kg)(2.8.10^5)^2 = 12 kJ, than otherwise required without Bz? (*Seeking improved robustness to TPD and RTI growth at lower implosion velocity enabled at reduced heat conduction loss rates*).
Caveat: model calculates only gas burn, neglecting fusion from dense DT shell.
2D MHD simulations needed to show propagating burn with Bz, likely if gas yield > ~ 50 kJ.

Results of analytic magnetized implosion model for A=3 Direct Drive: a modest applied B_{zo}=10 T at sub-marginal implosion velocity 280 km/s restores hot spot ignition (>10keV) otherwise lost without B, and produces more fusion yield from gas burn (180 kJ*) and at reduced convergence ratio, compared to hydrodynamic ignition without B at 310 km/s.



** enables propagating burn*

<-Gas convergence ratios
dashed (no B, 310 km/s)
dotted (no B, 280 km/s)
solid (B=10T, 280 km/s)

<-Gas temperature (keV)
solid (B=10T, 280 km/s)
dashed (no B, 310 km/s)
dotted (no B, 280 km/s)

<-Gas fusion yields (10 kJ)
solid (B=10T, 280 km/s)
dashed (no B, 310 km/s)
dotted (no B, 280 km/s)

<-time (ns) after peak velocity, from R_s~100μm

Summary

- 2D MHD simulations of magnetized implosion data from Omega and Z facilties motivate application of magnet fields to enhance prospects for fusion ignition on NIF and LMJ, and for both direct and indirect drive. Engineering development towards higher field magnetized targets on NIF and on Z (MagLIF) has started, and likely to enable implosion experiments pre-magnetized to 30T within 2 more years or less.

- The availability of several major laser and pulsed power facilities capable of imploding fuel capsules with compression of high applied magnetic fields is a unprecedented near term opportunity for young scientists to explore novel fusion ignition physics.

- The CEA needs 2D and 3D radiation-magnetohydrodynamic codes to design and evaluate data for future magnetized experiments in laser driven HED and ICF using LMJ and other international facilities.The full set of magnetized plasma transport (MHD) equations [S. Braginskii, "Transport processes in a plasma" Reviews of Plasma Physics **1**, (1965)] need a numerically robust solver for parameters (density, temperature and field) that must vary over a wide range of temporal and spatial scales.

The speaker would like to thank the LabEX PALM sponsors for the opportunity and support to work with LPGP, CEA-DIF, and Ecole Polytechnique collaborators on these technical studies for future experiments.

Backup slides

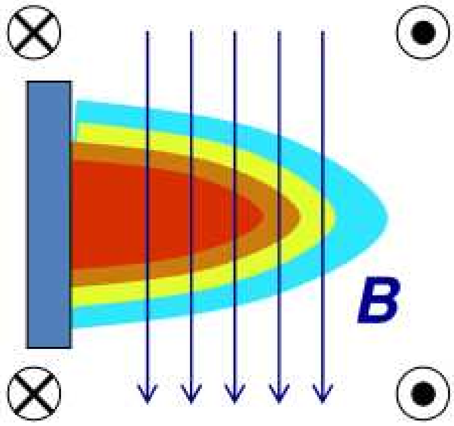
Hydrodynamics in strong B-field

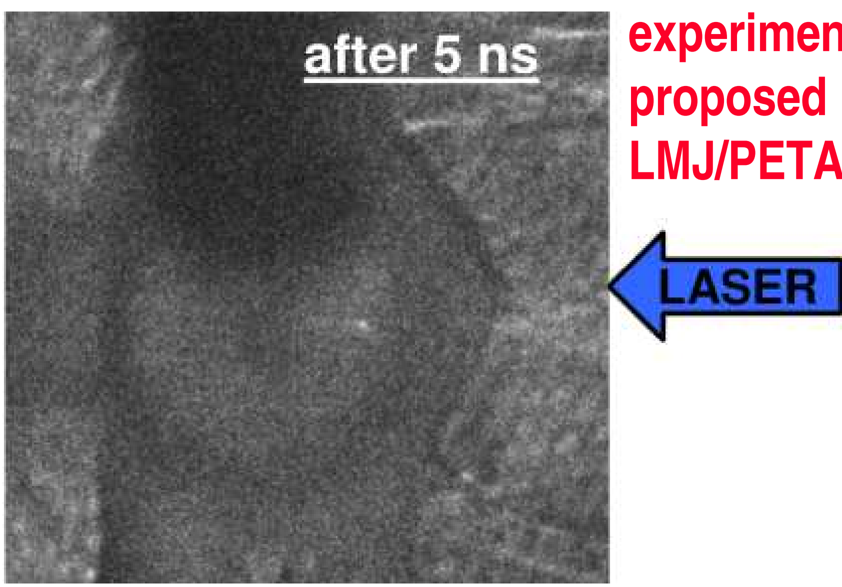
(From S. Fujioka, ILE Osaka)

ILE, Osaka

B-field changes shape of ablated plasmas by B-field.
Ablating plasma may be magnetized!

Ablating plasma image (Perpendicular B-field)

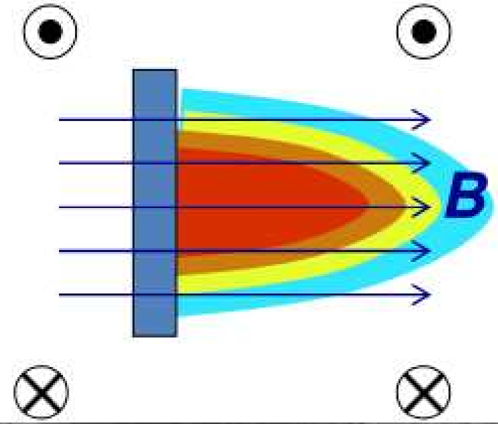


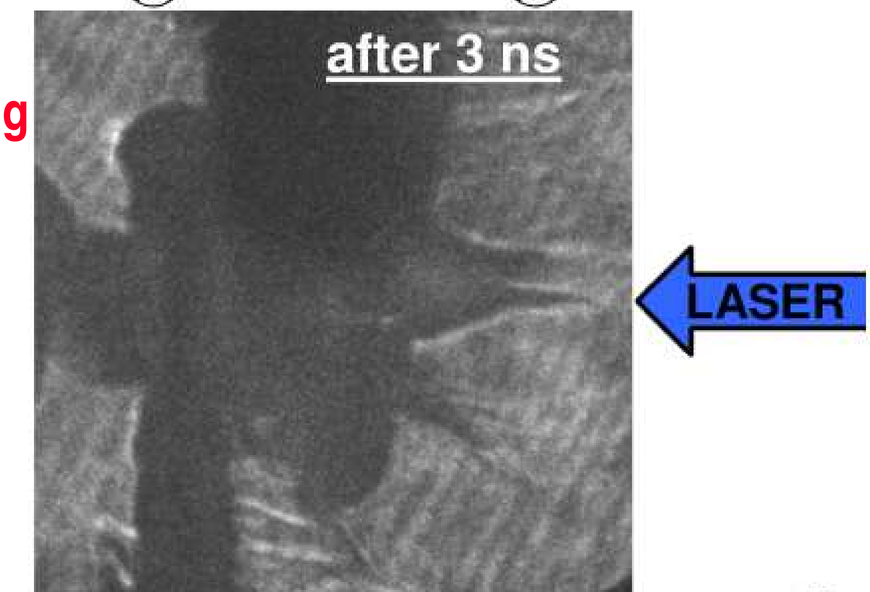


Recent Gekko experiments magnetized by two Helmholtz loops/ laser coils

This kind of experiment is proposed using LMJ/PETAL

Ablating plasma image (Parallel B-field)





The Application of Imposed Magnetic Fields to Ignition and Thermonuclear Burn on the National Ignition Facility

For details contact the Principle Investigator John Perkins perkins3@llnl.gov →

L. J. Perkins, D. J. Strozzi, M. A. Rhodes, B. G. Logan, D. D. Ho, S. A. Hawkins

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Lawrence Livermore National Laboratory

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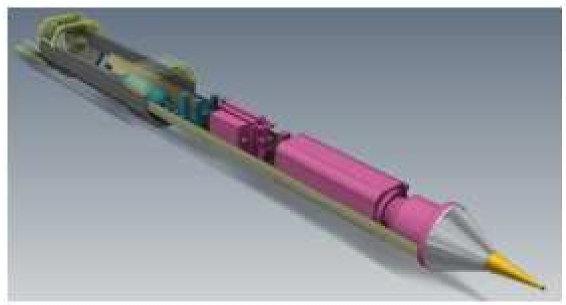
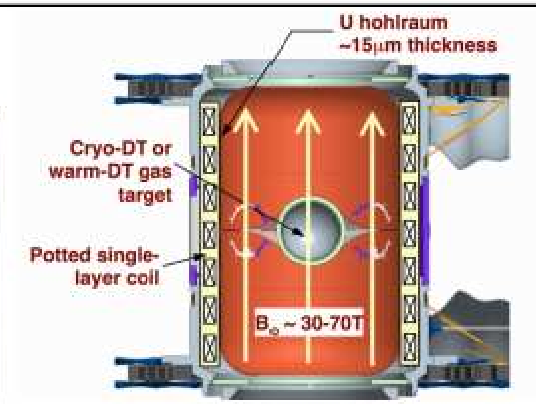
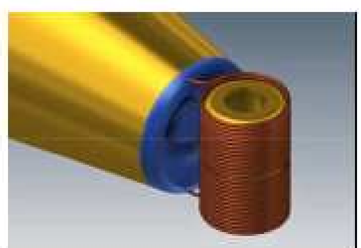
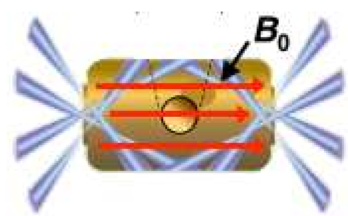
This work supported by LLNL Laboratory Directed Research and Development : LDRD 14-ER-028



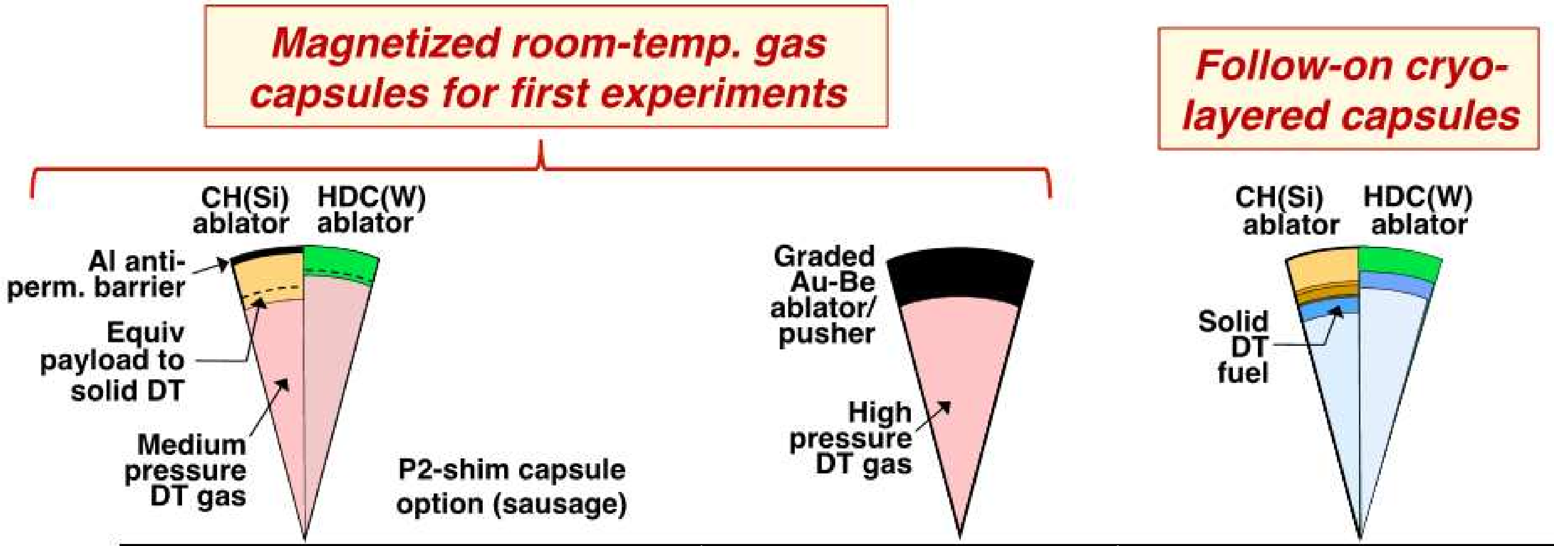






LDRD
Laboratory Directed Research and Development

Magnetized capsule types for this project (John Perkins, LLNL)



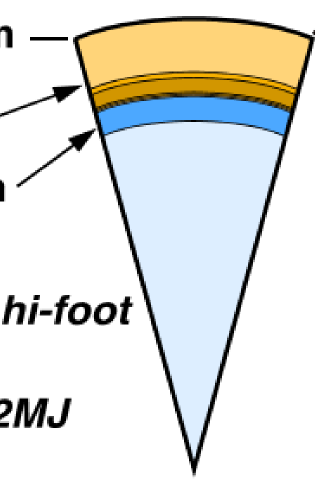
	Room-Temp Gas	Metal-Gas	NIC Cryo Ignition*
Rationale	B-dependent α heating feedback on burn and yield	Volumetric ign at ~4keV; other apps	Ignition and propagating burn
Temperature	300K	300K	Cryo, ~18K
DT Fuel	Gas (~25Atm)	Gas (~60Atm)	Solid layered
Ignition type	Volumetric heating	Volumetric ignition	Hotspot ignition
T_{i_ign} / T_{i_max}(keV)	Likely only α heat. to ≤10keV	~4 / 20 (Rad. trapped)	~12 / 100
Max yields (MJ)	~0.1	~1	~1-19**

*NIC designs reoptimized for B-field **Depending on mag of applied perturbations

John Perkins (LLNL) has compared "high-foot" CH capsule performance with/without applied Bz in 2D-MHD simulations

LLNL-PRES-663377
This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract DE-AC52-07NA27344. Lawrence Livermore National Security, LLC

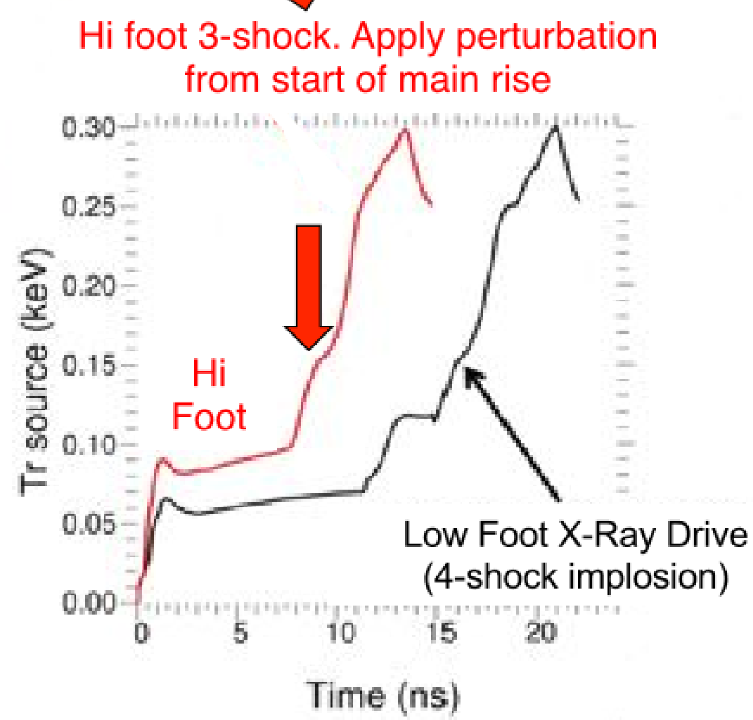
First, apply angle-dep. P4 rad flux perturbation to a clean-2D calc with no B-field to approx. match the inflight + stagnation parameters for N1400304 3-shock hi-foot



$$\phi(\theta) = \phi_0[1 \pm a.Cos(P(\theta + 180/P)],$$
$$P = 4, a = 0.21$$

N140304 Hydro Parms:

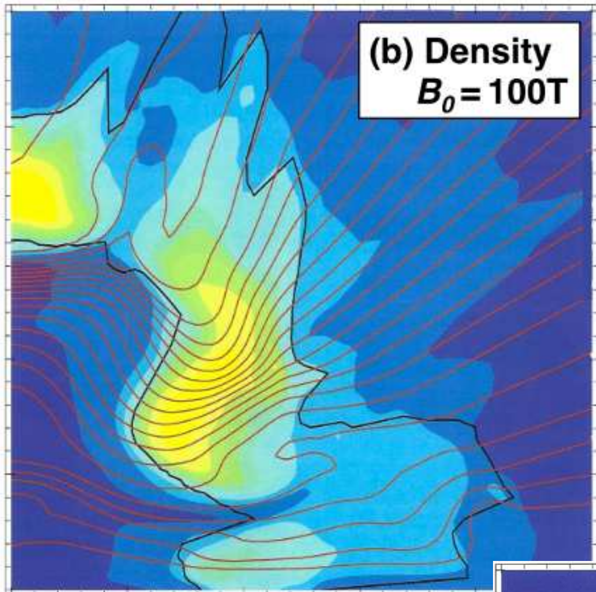
442TW, 1.86MJ, 3-shock hi-foot
V=3.7e7cm/s, α=2.42
2D clean fusion yield=9.2MJ



	N140304 Data
Fusion yield	N_n=9.43e15, 26.6kJ
Ti_Brysk (keV)	5.55 (Incl Doppler?)
Ti(0) max (keV)	–
$\rho R_{hs}/\rho R_{shell}$	0.140/0.775
P_{hs} (Gbar)	173
Conv. ratio	33.5
Yield–no α dep.	12.3kJ

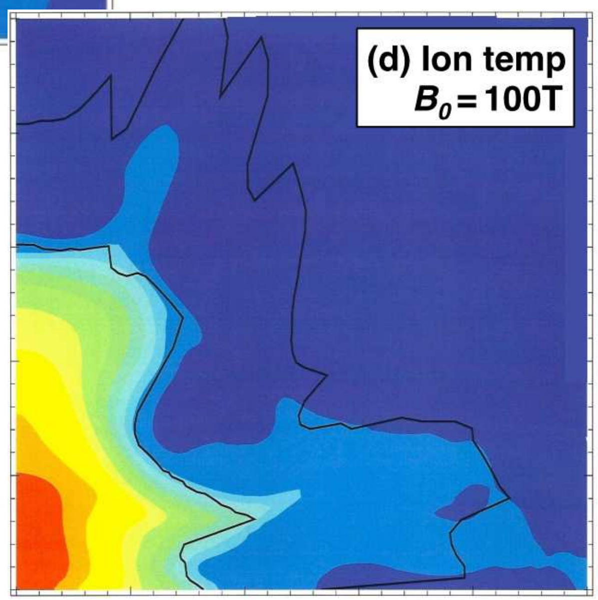
Beauty in Ugliness: Magnetized targets can reach ICF ignition *even with ugly low mode hot spot distortions and spikes!*

From Fig. 4b,d in Perkins, Logan, Zimmerman and Werner PoP 20, 072708 July, 2013



Flux is well conserved in fast ICF implosions, enabling compressed flux lines to bend around spikes and jets from low modes, fill tubes, LEH holes, etc. Thus, electron-heat conduction suppression and improved alpha energy deposition in gas

-can still be expected to work…

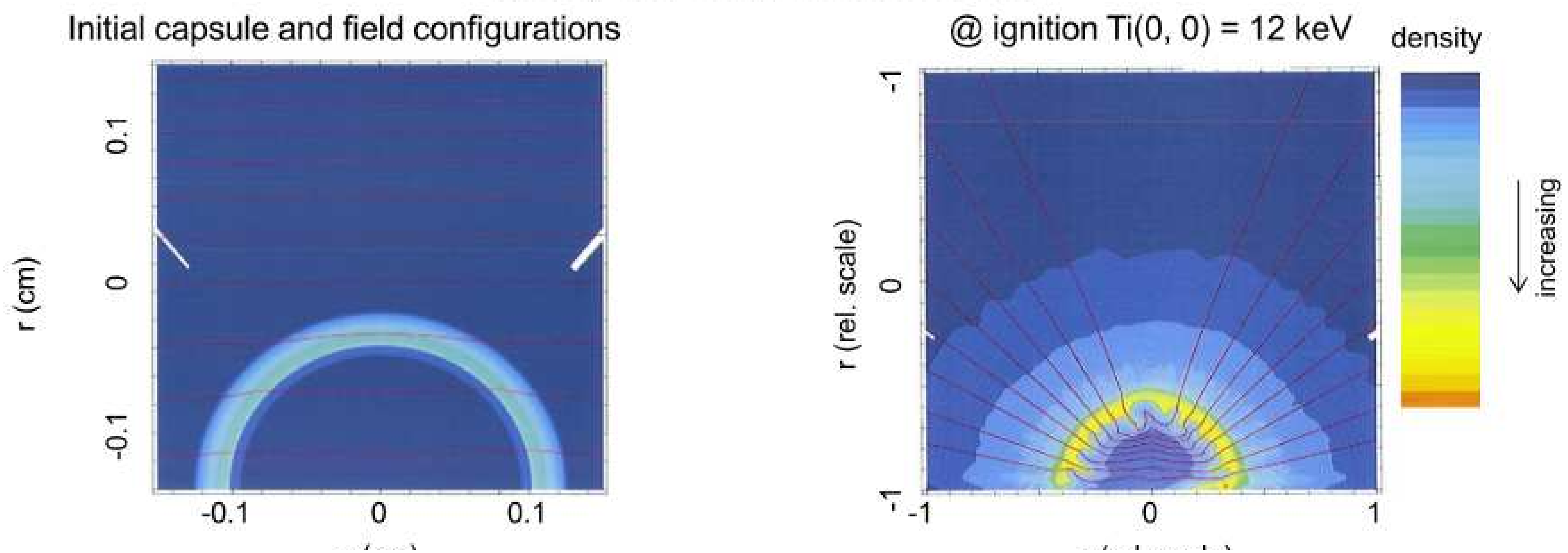


…provided ablator mix and "missing" shell kinetic energy (that which is not converted to pdV) are both managed to moderate levels.

Imposing an initial 40 T B-field turns a 3-shock low-yield capsule into an igniting capsule **(Darwin Ho, LLNL 6/8/2014)**

B field (T)	surface roughness	yield (MJ)	hotspot ρR (g/cm^2)	Hotspot radius (μm)	α-particle range/ (radius) (μm)	vol. ave. hotspot Ti (keV)	mass wt. hotspot density (g/cm^3)	vol. ave. hotspot pressure (Gbar)
			@ ignition: Ti(0, 0) = 12 keV					
0	0	8.4	0.43	37	152	7.3	116	768
0	1x	0.44	0.22	37	152	3.7	60	180
40	1x	5.6	0.2	37	(18)	4.9	56	211

density and magnetic flux contours



Summary of roles played by B-field in yield enhancement (Slide kindly supplied by Darwin Ho, LLNL 6/8/2014)

- To study the various effects with the presence of B-field, we systematically turn on the switches in LASNEX for α-particle trapping and J×B force.

Seed B-field (T)	surface roughness	B-field effect on α-particles	J×B force	yield (MJ)	role played by B-field
0	nominal	N/A	N/A	0.44	N/A
50	nominal	off	off	0.9	electron trapping
50	nominal	off	on	0.65	Electron trapping, shape distortion
50	nominal	on	on	4.8	α-particle and electron trapping, shape distortion

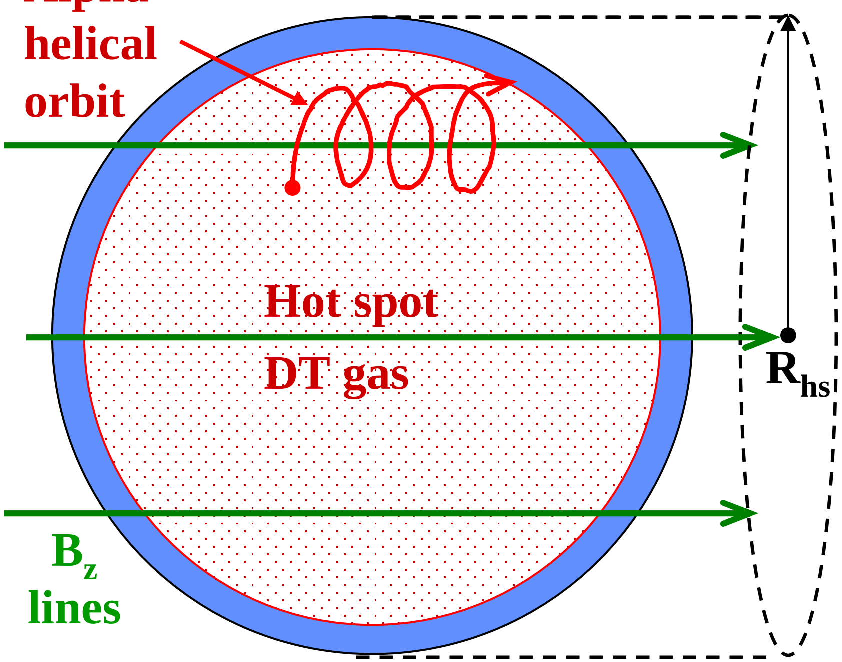
● positive effect ● negative effect

- This table shows the α-particle trapping is the dominant contribution to yield enhancement.
- If we turn off burn beyond the hotspot, the yield enhancement by B-field is only 2.4, i.e. from 0.1 to 0.24 MJ (central Ti from 7.5 to > 12 keV). Increased hotspot Ti then triggers the propagated burn into the fuel and gives the > 10x in total yield enhancement.

Several 2-D MHD simulations over the last 18 months at LLNL confirm the expectations of simple models that applied Bz ~ 40 T should benefit gas capsule alpha-heating via improved alpha-deposition as well as suppression of transverse heat conduction.

Strong fields improve coupling shell KE into hot spot energy

Magnetized hot spot model @ 12 keV, 5 μg DT_{gas}, (11 kJ) vs. R_{hs} = 960μm / gas convergence ratio

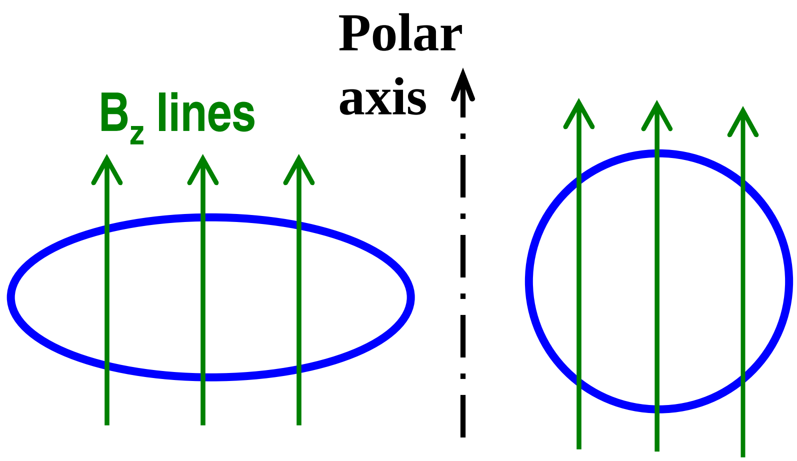


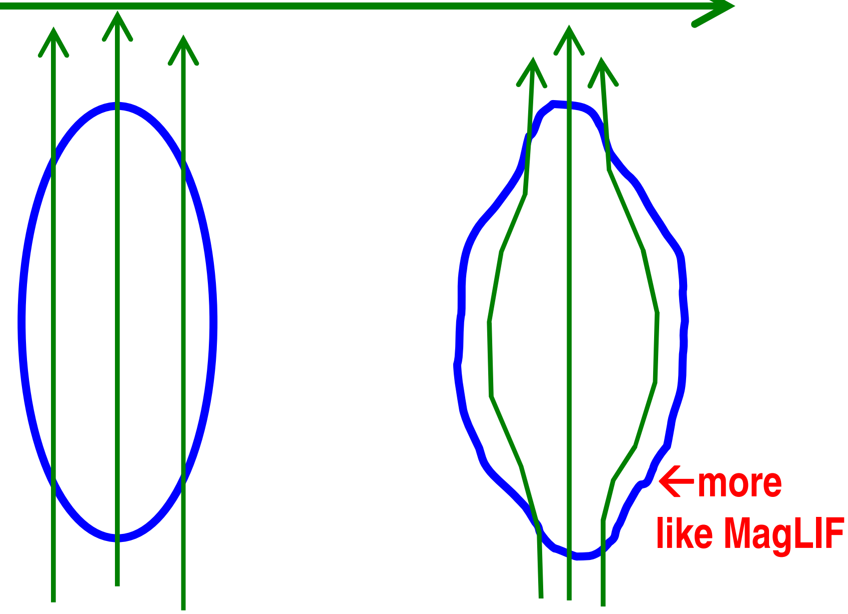
CR*	20	25	30	35	40
R_{hs}(μm)	48	38	32	28	24
ρ_{hs} (g/cm^3)	11	21	37	58	86
ρR_{hs} (g/cm^2)	0.05	0.08	0.12	0.16	0.21
B_{stag} (MG)**	280	360	420	490	560
B_{zo} (T)	70	57	47	40	35
p_{stag} (Gb)	100	190	340	530	780
β_{stag}(p/B^2)	32	38	48	55	63
$\omega\tau_{ei}$	150	100	70	50	40

*** CR = gas convergence ratio;**
$\rho_{hs} \sim CR^3$; **B_{stag} for α gyro = $R_{hs}/5$;
→ B_{zo} needed = B_{stag} / CR^2

Shape with B_z: for sufficient B_{zo} and CR such that $\omega\tau_{ei}$ >>1, the fraction of otherwise 4π heat conduction loss scales as ~ transverse hs area fraction (with no transverse loss) / area of B_z lines intercepting both polar caps

Progressively greater overall reductions of heat conduction with Bz by shape →





Pancake→smallest reduction (~1.5 X) of heat conduction by applied B_z (*because equatorial transverse area perp. to B lines < polar caps area*)

Round→~ 2 X reduction of heat conduction by applied B_z (equatorial transverse area ~ polar caps area)

2:1 Sausage →~ 4 X reduction of heat conduction by applied B_z (equatorial transverse area > polar caps area)

Sausage +P4 →~ 8 X reduction of heat conduction by applied B_z (polar caps area reduced further by P4 "magnetic mirrors")

A simple analytic model for magnetized gas capule implosions (Logan) *closely matches 2D-MHD gas capsule sims (Mar 2014) by reducing effective shell KE (CR) to account for 2D perturbations.*

Analytic model parameters adjusted to give ***same inputs*** *as used in 2D MHD simulations:* nominal round shape, HDC ablator outer/inner 1080/992 μm, HDC mass initial/final 4.7/0.61 mg, v_{imp} 312 km/s, peak shell KE 29 kJ, 4.5 mg/cc DT fill (18.4 μg), T_{DTgas} 0.78 keV @ peak KE @ radius R_{DTgas}= 235 μm

Outputs*	2D sim, B_z=0	Analytic model, B_z=0	2D sim, 70 T	Analytic model, 70T
Fusion yield (kJ)	**64**	**47**	**119**	**121**
$T_{DTgas-ave}$ (keV)	**4.6**	**4.9**	**6.8**	**7.3**
$\rho_{DTgas-ave}$(g/cm^3)	**47**	**42**	**36**	**33**
hs pressure(Gb)	**161**	**156**	**175**	**184**
R_{DTgas} (μm)	**45**	**47**	**46**	**51**
ρR_{DTgas} (g/cm^2)	**0.18**	**0.20**	**0.13**	**0.17**
ρR_{shell} (g/cm^2)	**0.95**	**0.97**	**0.88**	**0.91**
CR=$R_{s-outer}$/R_{gas}	**24.3**	**22.9**	**23.7**	**21.1**

*At time of peak ρRT near stagnation

→ results apply equally to direct and indirect drive!

PHYSICS OF PLASMAS **21**, 072711 (2014)

Design of magnetized liner inertial fusion experiments using the Z facility

A. B. Sefkow,[1,b)] S. A. Slutz,[1] J. M. Koning,[2] M. M. Marinak,[2] K. J. Peterson,[1] D. B. Sinars,[1] and R. A. Vesey[1]
[1]*Sandia National Laboratories, Albuquerque, New Mexico 87185, USA*
[2]*Lawrence Livermore National Laboratory, Livermore, California 94550, USA*

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The magnetized liner inertial fusion concept has been presented as a path toward obtaining substantial thermonuclear fusion yields using the Z accelerator [S. A. Slutz *et al.*, Phys. Plasmas **17**, 056303 (2010)]. We present the first integrated magnetohydrodynamic simulations of the inertial fusion targets, which self-consistently include laser preheating of the fuel, the presence of electrodes, and end loss effects. These numerical simulations provided the design for the first thermonuclear fusion neutron-producing experiments on Z using capabilities that presently exist: peak currents of $I_{max} = 18–20$ MA, pre-seeded axial magnetic fields of $B_z^0 = 10$ T, laser preheat energies of about $E_{las} = 2$ kJ delivered in 2 ns, *DD* fuel, and an aspect ratio 6 solid *Be* liner imploded to 70 km/s. Specific design details and observables for both near-term and future experiments are discussed, including sensitivity to laser timing and absorbed preheat energy. The initial experiments measured stagnation radii $r_{stag} < 75\ \mu$m, temperatures around 3 keV, and isotropic neutron yields up to $Y_n^{DD} = 2 \times 10^{12}$, with inferred alpha-particle magnetization parameters around $r_{stag}/r_L^{\alpha} = 1.7$

[Gomez, et.al. PRL 113, 155003 (2014)]

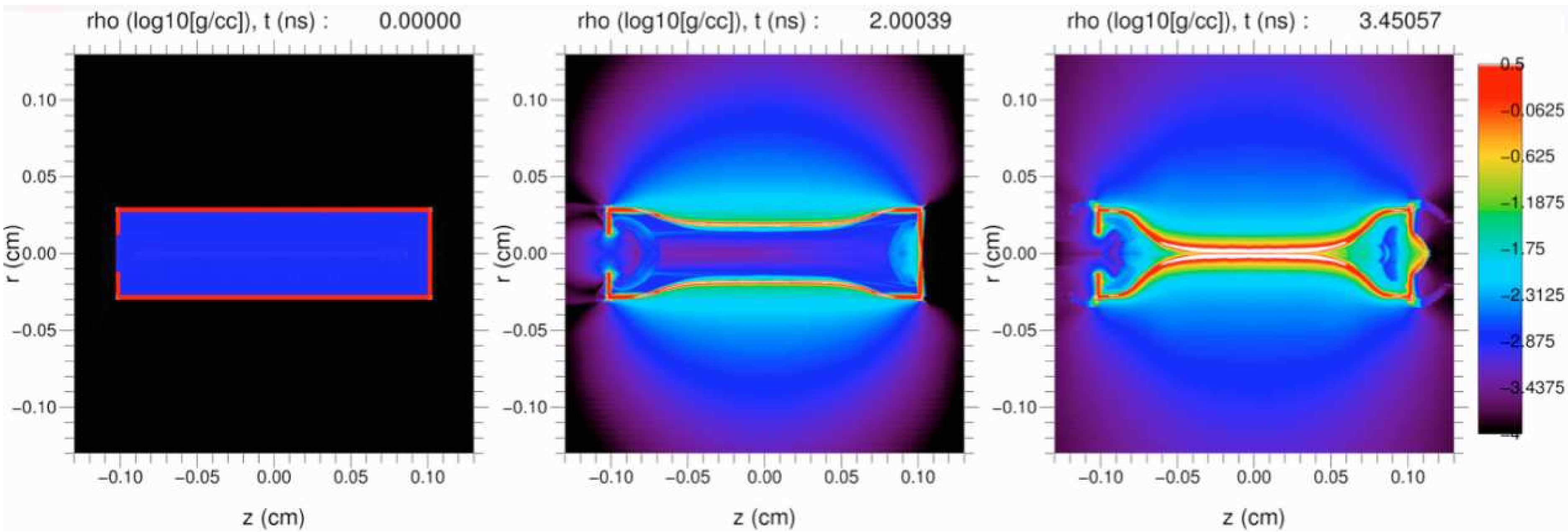
Initial integrated HYDRA simulations for mini-MagLIF on OMEGA

Sandia National Laboratories

First experiments planned on Omega in April 2015 (Riccardo Betti)

A. B. Sefkow, J. R. C. Davies, P.-Y. Chang, S. A. Slutz, and the mini-MagLIF@LLE team

Thursday, December 11th, 2014



These initial runs were about establishing a robust model (zoning, ALE prescription, etc.), and *not* about being representative of a final design, modeling choice, prediction, etc.

- Cylindrical target shell: L = 2 mm, OD = 600 μm, Δ_{shell} = 30 μm (CH)
- Gas: D_{LEH} = 240 μm, δz_{win} = 1.5 μm, ρ_{gas} = 1.5 mg/cc (DD)
- B_z^0 = 15 T, QLMD (DD) and EHLM (CH) resistivities, anisotropic conduction, no Nernst term yet
- Compression: ~10 kJ of 3ω in 2.5 ns (0.2 ns rise/fall) at f/6.65 with supergaussian FWHM~1.2 mm
  - ➢ single representative beam at 90° for now, can use cones and eventually go 3D
- Coupling: ~8 kJ total, ~1 kJ final $K.E._{shell}$
- Heater beam: ~80 J of 4ω also in 2.5 ns with gaussian FWHM~60 μm, **delayed Δt = 1.2 ns**

Material for this slide provided by Adam Sefkow, SNL