LLNL-PRES-750904

The potential of imposed magnetic fields to enhance ignition probability in indirect (and direct) drive targets

L. John Perkins

with thanks to: B. G. Logan, G. B. Zimmerman, D. D. Ho, D. J. Strozzi, J. D. Moody, M. A. Rhodes,

Meeting on Magnetic Fields in Laser Plasmas, Laboratory for Laser Energetics, University of Rochester, 23 and 24 April 2018

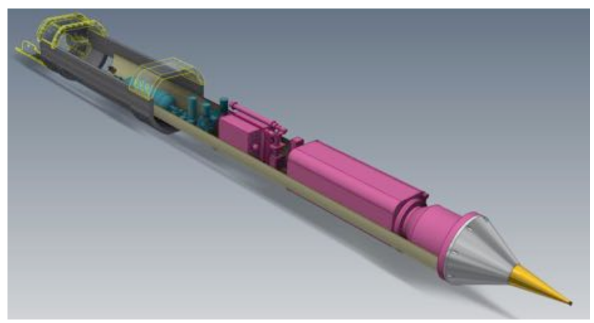
Lawrence Livermore National Laboratory

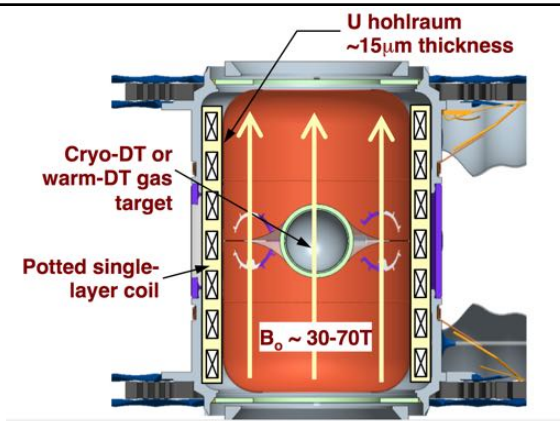
Design Physics Division

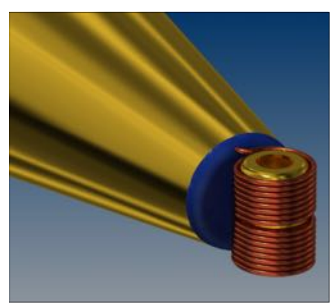
April 24, 2018

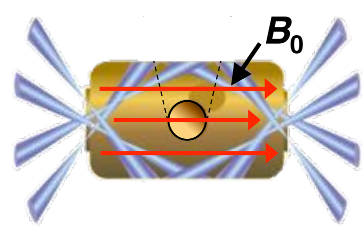
This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract DE-AC52-07NA27344. Lawrence Livermore National Security, LLC

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









Laboratory Directed Research and Development

THE APPLICATION OF IMPOSED MAGNETIC FIELDS TO IGNITION AND THERMONUCLEAR BURN ON THE NATIONAL IGNITION FACILITY

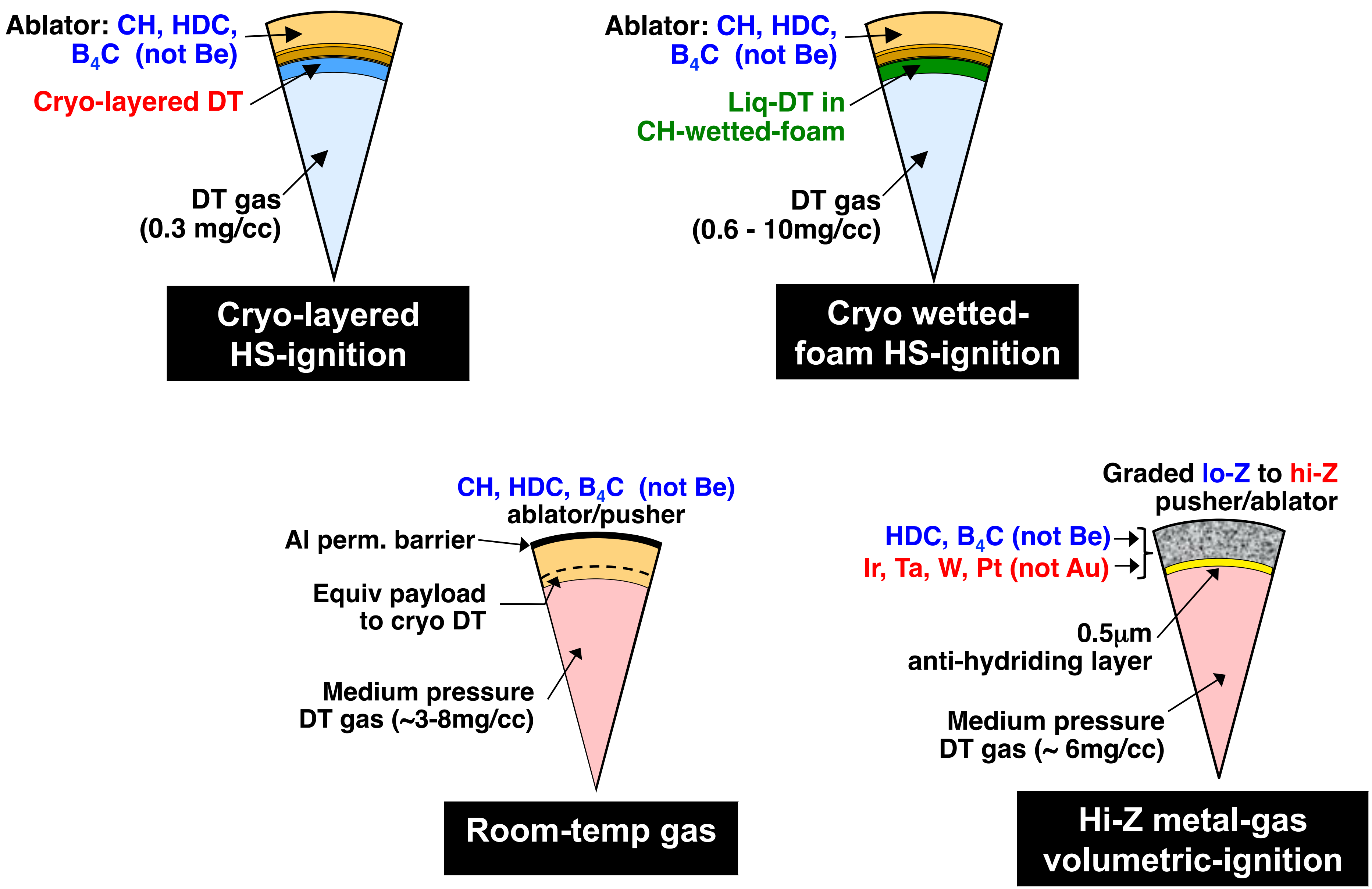
We are studying the impact of highly compressed magnetic fields on the ignition and burn of National Ignition Facility targets. Initial seed fields of 20-50T compressing to greater than 10^4T (100MG) under implosion may reduce hotspot conditions required for ignition and propagating burn through range reduction and magnetic mirror trapping of fusion alpha particles, suppression of electron heat conduction and potential stabilization of hydrodynamic instabilities. This might permit recovery of ignition, or at least significant alpha particle heating, in capsules that would otherwise fail because of adverse hydrodynamic conditions [1]. More generally, it may also permit attainment of ignition in targets redesigned to operate under reduced drive and/or lower convergence ratios.

Our 2-D simulations for NIF indirect-drive ignition platforms suggest that compressed magnetic fields may shift the ignition "cliff" to the right in that capsules might now attain ignition and fusion yield at shell perturbations that would otherwise result in only low yield, non-ignition. In particular, simulations indicate that optimum fields of ~50T might elicit MJ-yields from our current best performing – but, presently submarginal – capsules. We are also studying utility of magnetic fields to enhance volumetric yield in room-temperature DT-gas capsules (likely the first proof-of-principle tests) and metal-gas capsules, and to ameliorate hot electron preheat from hohlraum laser-plasma interactions. However, results thus far are merely code predictions for what, in reality, will be complex 3-D MHD processes. ***Therefore initial proof-of-principle experiments are now essential to gauge the utility of this concept to enhance the ignition probability of NIF capsules***

We have also tested candidate hohlraum magnet coils containing U "hohlraum" sleeves driven by a pulsed power supply that could be later integrated in the NIF TANDM DIM and have achieved axial fields of ~58T with a nominal design goal of 50T

[1] L. J. Perkins, et al, "The potential of imposed magnetic fields for enhancing ignition probability and fusion energy yield in indirect-drive inertial confinement fusion", *Phys. Plasmas* 24, 062708 (2017)

Four classes of NIF magnetized ignition/burn platforms have been studied in indirect drive

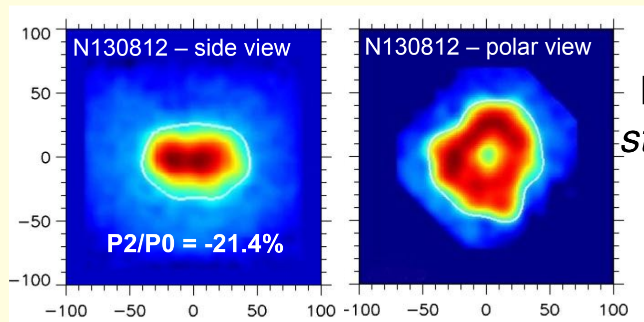


Could imposed magnetic fields enhance the prospects for NIF ignition in the face of our present fundamental issue?

Which is (IMHO): Our cold-fuel piston is not efficiently compressing the hotspot

Piston is not round

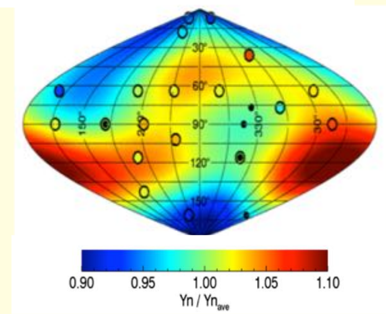
- Larger surface area for hotspot heat loss
- Less ideal 3D spherical compression
- Cold fuel-hotspot penetration/mix (but may be ~modest because higher mode instabilities may be suppressed by adiabatic shaping)



N130812 *x-ray stagnation shape (D.Hinkel)*

Piston is not a good tamper and has thin spots

- Lower tamp ρ-R, less momentum transfer to the hotspot

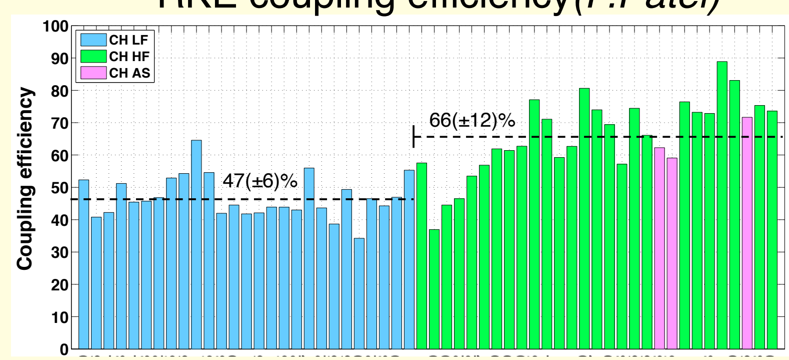


N140520 NAD yields *(R.Bionta)*

Piston is not efficiently converting its kinetic energy to thermal compression at stagnation

- Residual kinetic energy remains at "stagnation" (can be more than 50% of the peak inflight value) $\Rightarrow$low coupling efficiency

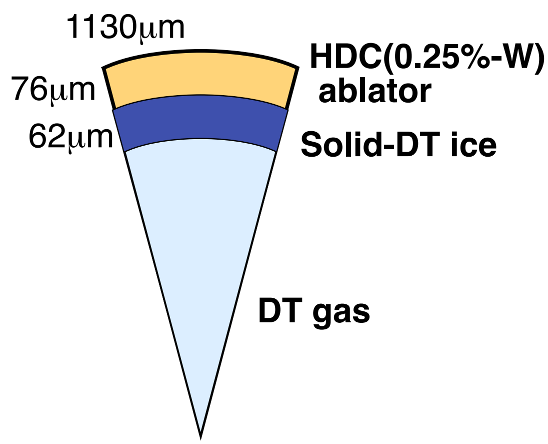
RKE coupling efficiency*(P.Patel)*

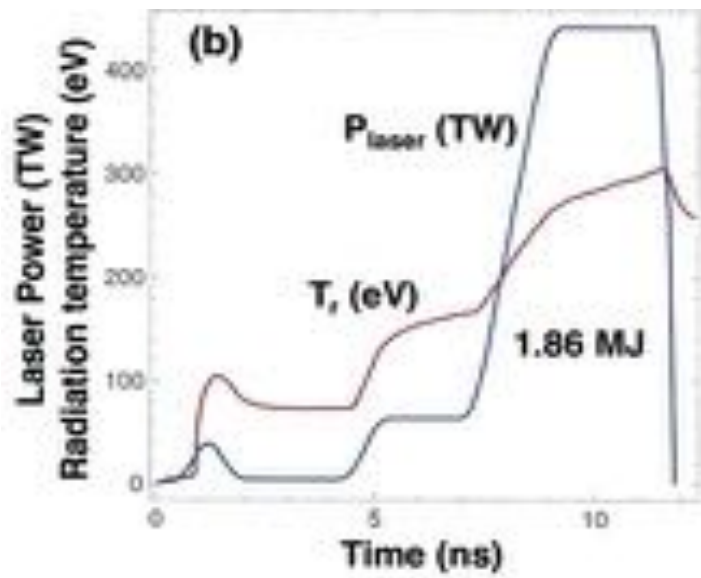


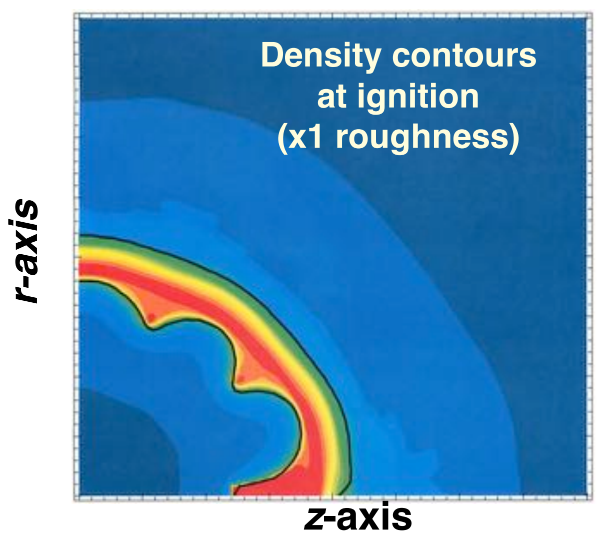
<u>But</u> – our best performing shots to date are on the foot of the alpha-heated ignition cliff!

- This is the regime where compressed magnetic fields offer the most benefit to ICF ignition

Starting point: Cryo-layered-DT capsule with HDC ablator, 672 U-hohlraum, full laser pulse shape, 3-shock, x1 roughness







Yield = 21MJ

E_{KE}^{max} = 13.5kJ (fuel only),

V_{max} = 3.94x10^{7}cm/s

RKE: E_{KE}^{stag} = 3.1kJ (⇒high 2D ideal margin, =23%)

α = 1.85

ρR = 1.1g/cm^3 (rms=21%)

CR = 33

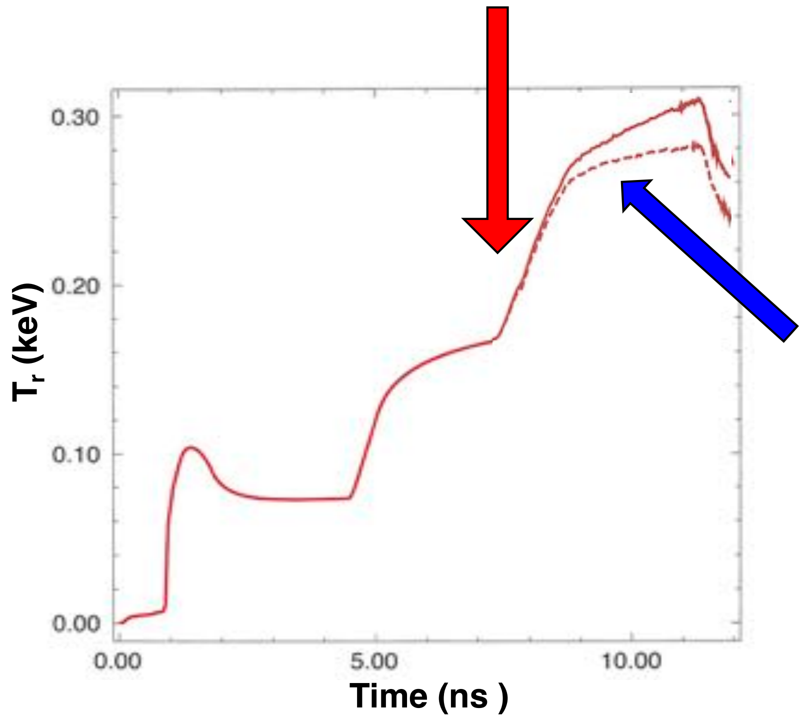
But with only nominal x1 roughness on ablator and ice surfaces, gives full yield of ~20MJ in 2D simulations, i.e., doesn't fail because there's no low mode or RKE perturbations

Now make it fail: Apply low mode shape perturbations and increase residual kinetic energy at stagnation

(1) Apply angle-dep. P4 rad flux perturbation to the 2D simulation

$$\phi_{rad}(\theta) = \phi_0[1 \pm a.Cos(P(\theta + 180 / P)],$$
$$P = 4, a = \pm 0.1$$

Apply angular flux perturbation
from start of main rise



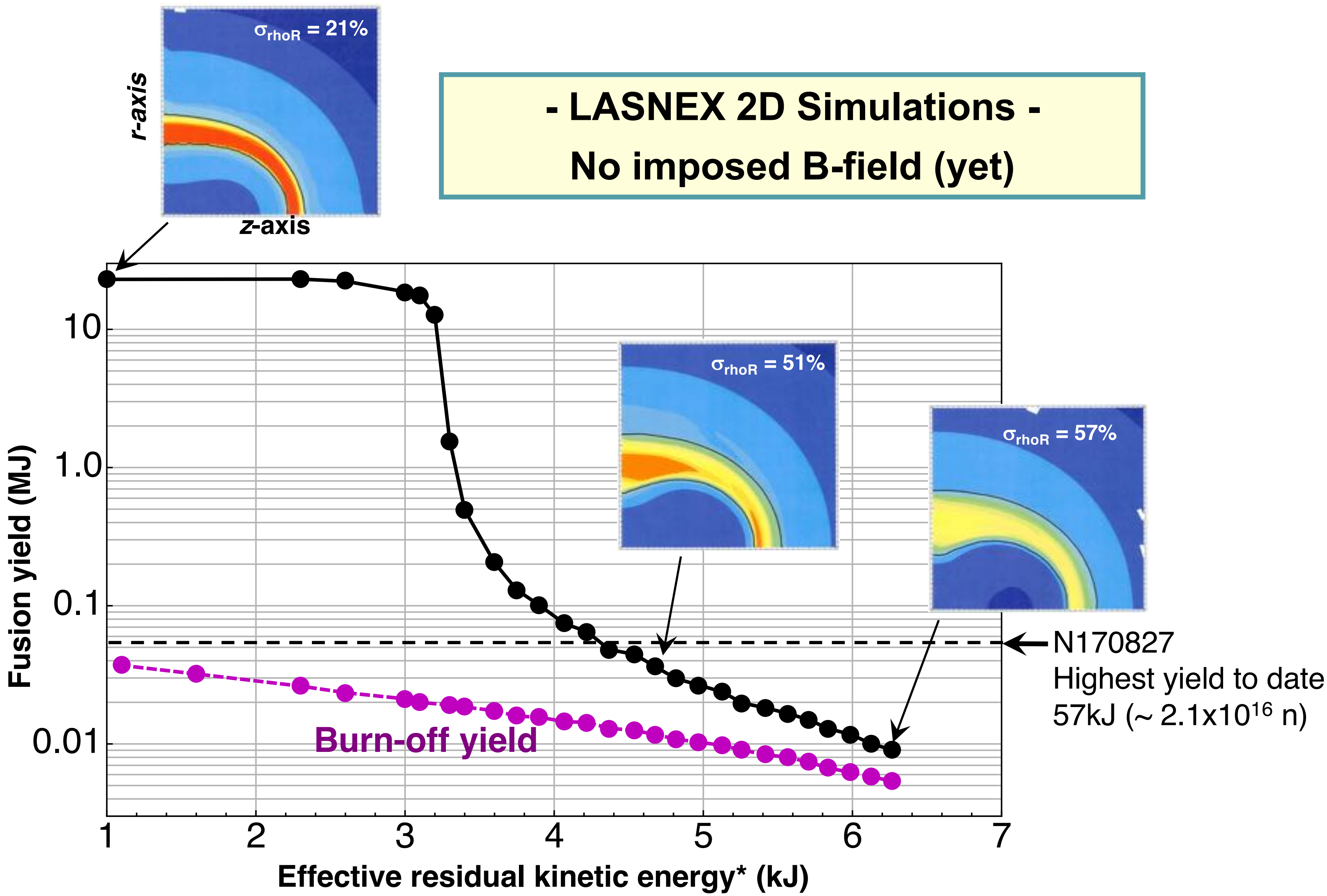
(2) Increase "effective RKE" at stagnation by reducing main drive

RKE ~ E_{KE}^{max} (full drive) – E_{KE}^{max}(reduced drive)

Now make it fail: Apply low mode perturbations and increase residual kinetic energy at stagnation

- LASNEX 2D Simulations -

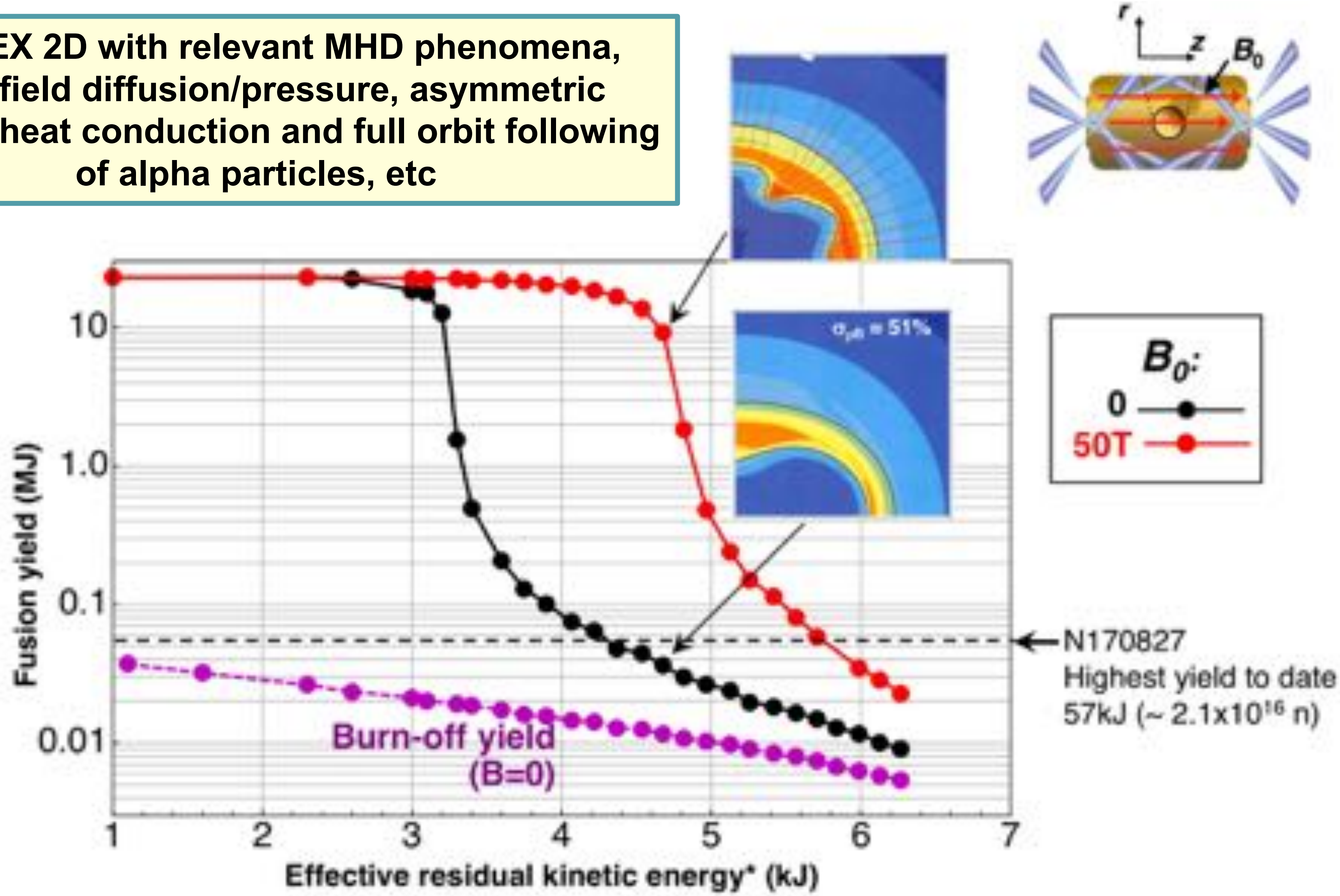
No imposed B-field (yet)



*RKE ~ E_{KE}^{max} (full drive) – E_{KE}^{max}(reduced drive)

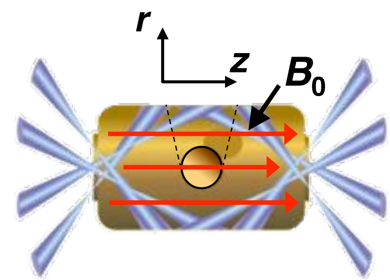
Application of an imposed axial magnetic field of 50T for the <u>same</u> inflight implosions

LASNEX 2D with relevant MHD phenomena, e.g.,: field diffusion/pressure, asymmetric electron heat conduction and full orbit following of alpha particles, etc

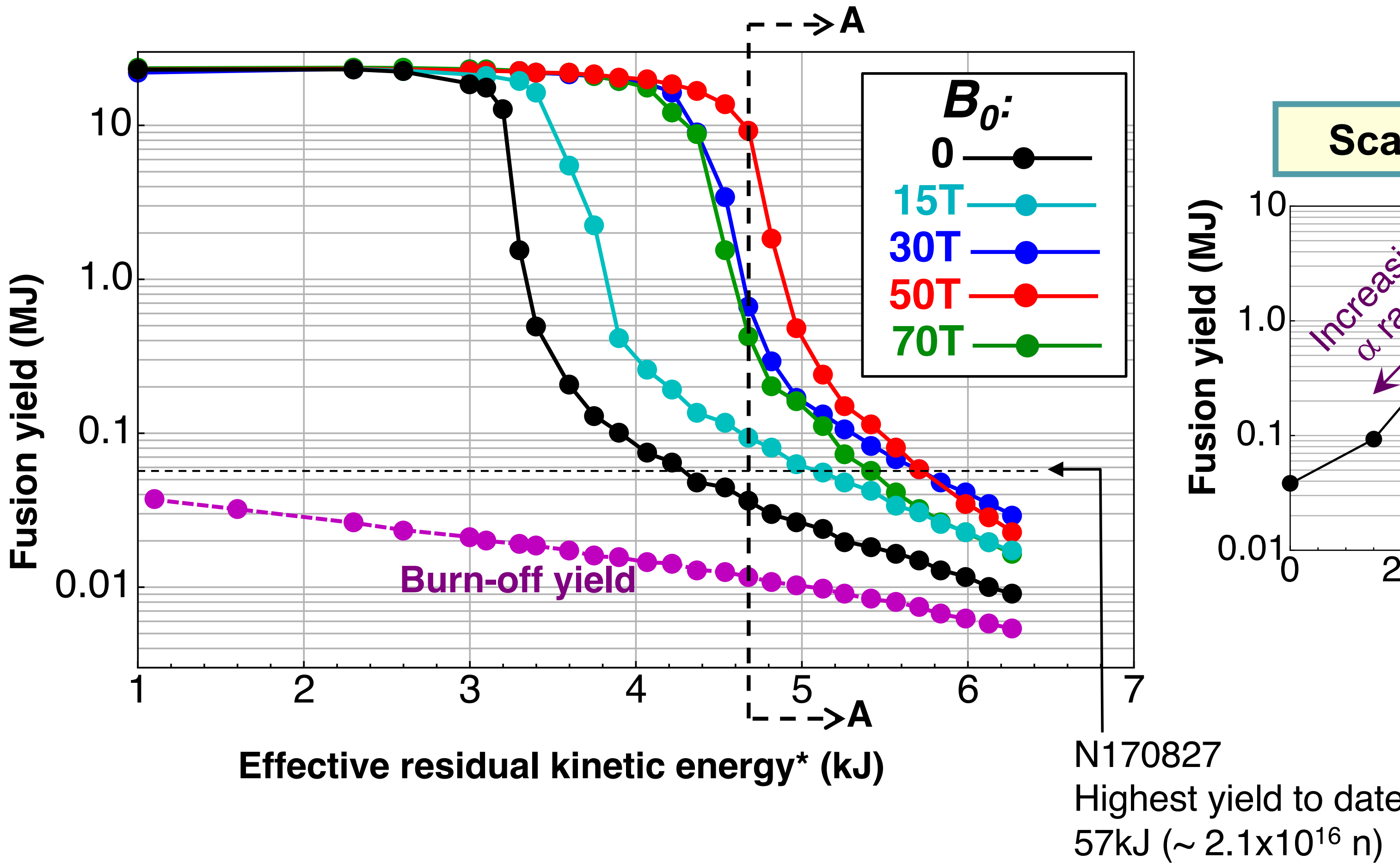


*RKE ~ E_{KE}^{max} (full drive) − E_{KE}^{max}(reduced drive)

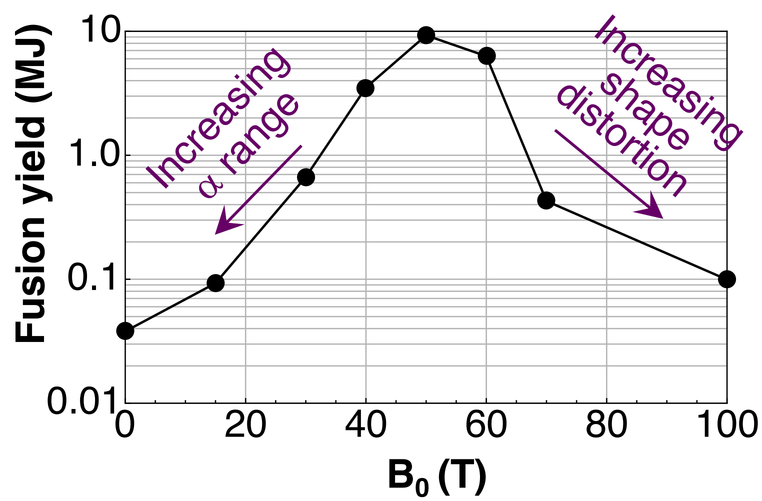
What applied B-fields should we be seeking? Where's the optimum?



The optimum imposed field is around 50T

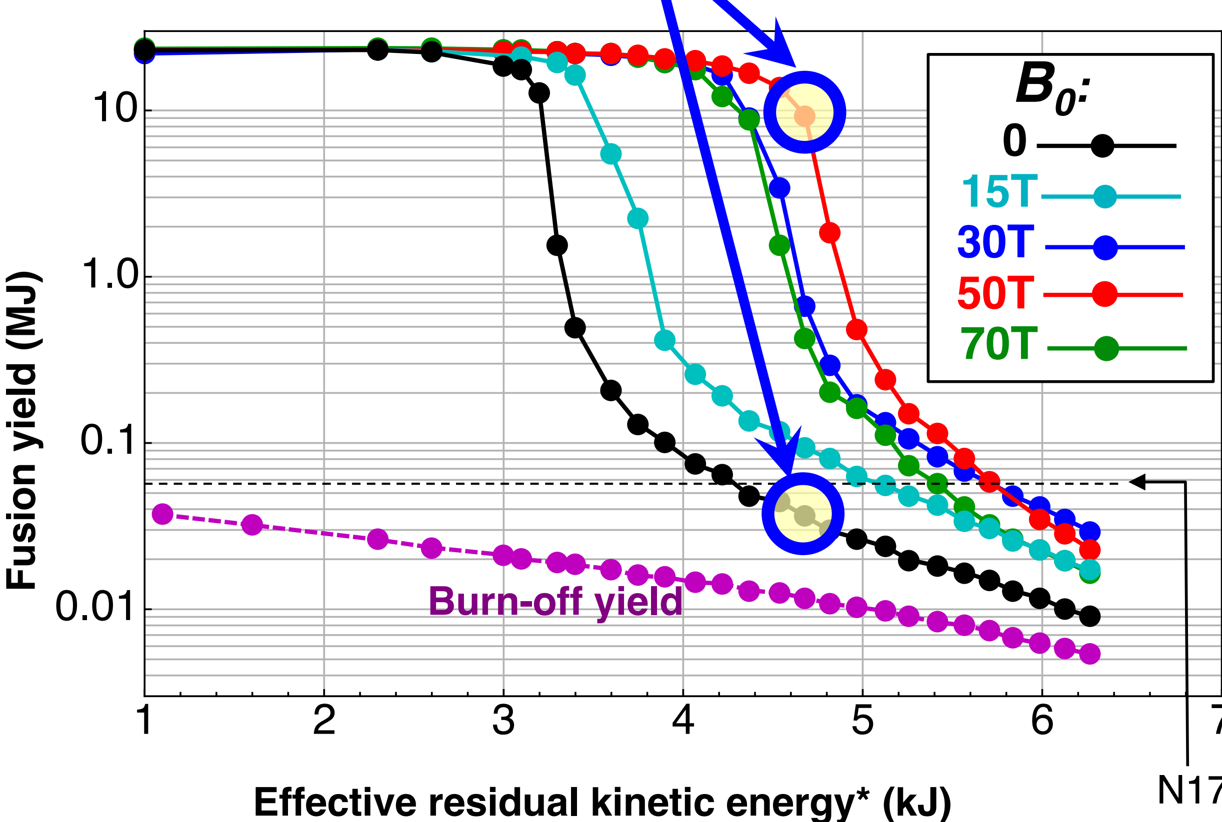


Scan -v- B_0 across A-A

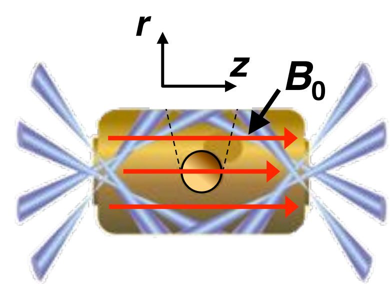


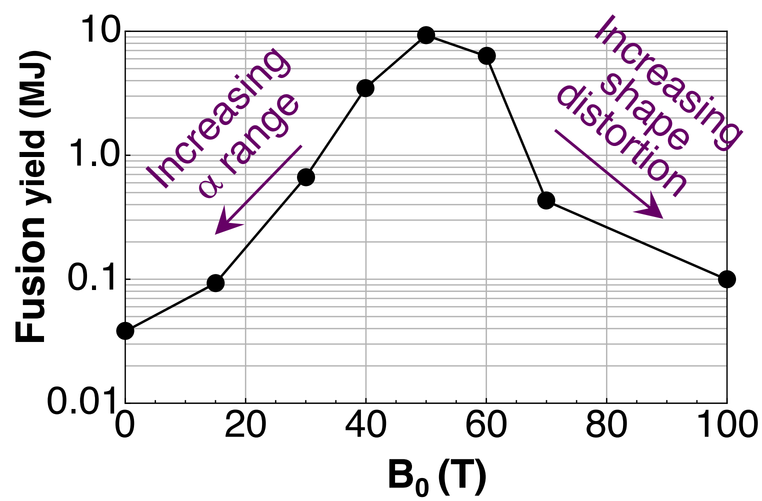
What applied B-fields should we be seeking? Where's the optimum?

Compare these two cases at the bottom and top of the ignition cliff (over)



N170827
Highest yield to date
57kJ (~ 2.1×10^{16} n)

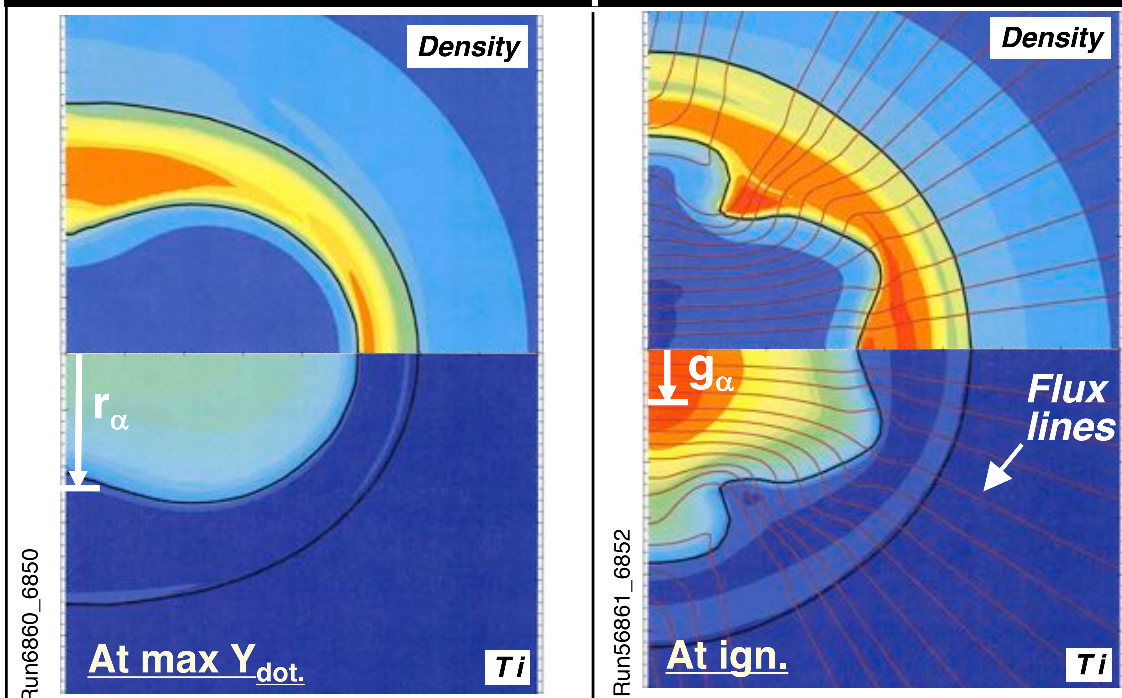




Application of imposed B-field of 50T for a submarginal capsule at the bottom of the ignition cliff – it now ignites!

r_α = 3.5MeV alpha range

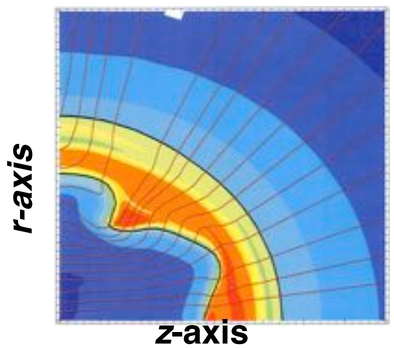
g_α =3.5MeV alpha gyro-orbit radius



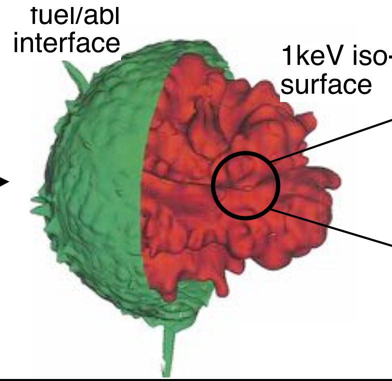
$\langle B_{HS} \rangle$ = 5.2*10^{4}T (530Mgauss)

	2D Perturbed. No B	2D Perturbed. B_0=50T
Fusion yield (MJ)	**0.036** (1.3*10^{16} n)	**9.28** (3.3*10^{18} n)
T_{i_Brysk} (keV)	3.80	17.9
ρR_{shell}	1.38 (σ_{RMS} = ±51%)	1.27(σ_{RMS} = ±26%)
Conv. ratio	33.0	31.6
Burn off:		
Yield (kJ)	11.7	17.3
T_{i_Brysk} (keV)	3.23	3.65
P_{hs} (Gbar) max, burn-av.	221, 164	260, 191

Are toroidal fields formed by asymmetry-driven turbulence and RKE of axial field ⇒closed field lines? If so, maybe even better for ignition

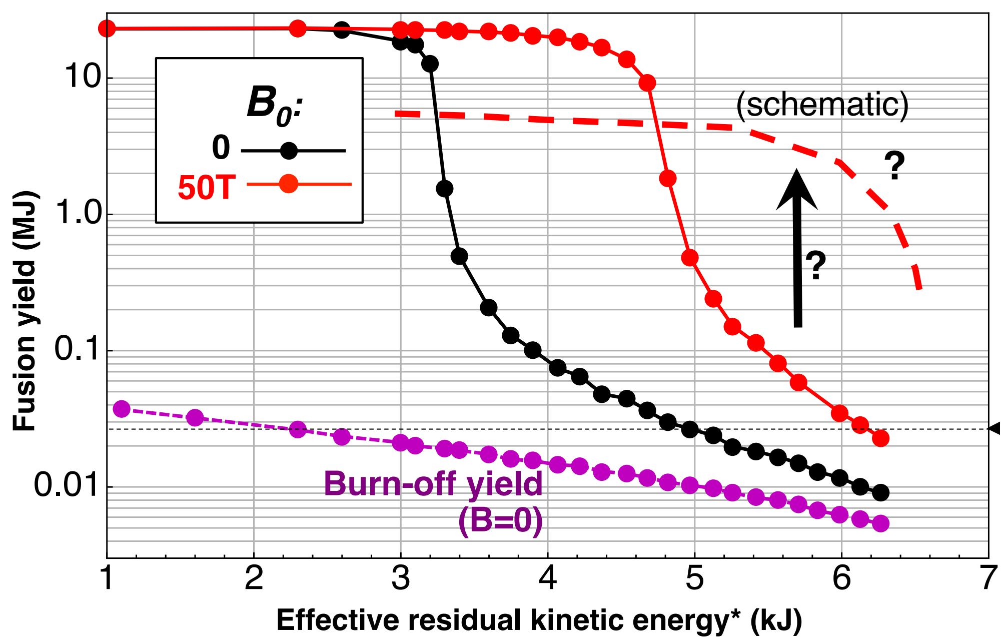


Compression of imposed axial field (2D code)



HS stagnation dynamics are really 3D (D. Clark)

Does tangling (and reconnection?) form quasi-closed field lines?



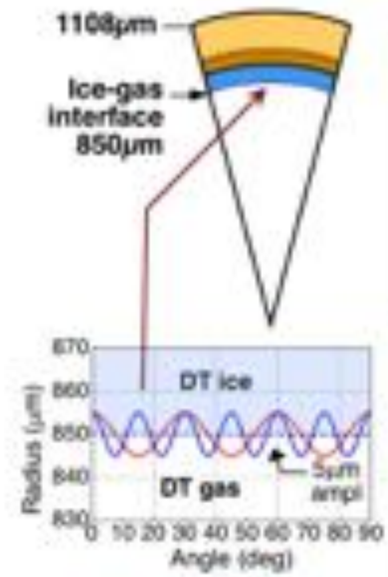
Closed field lines may further improve ignitability of hotspot but may inhibit alpha burn propagation and high yield

In reality, this is complex, resistive 3-D MHD.
So experiments are essential

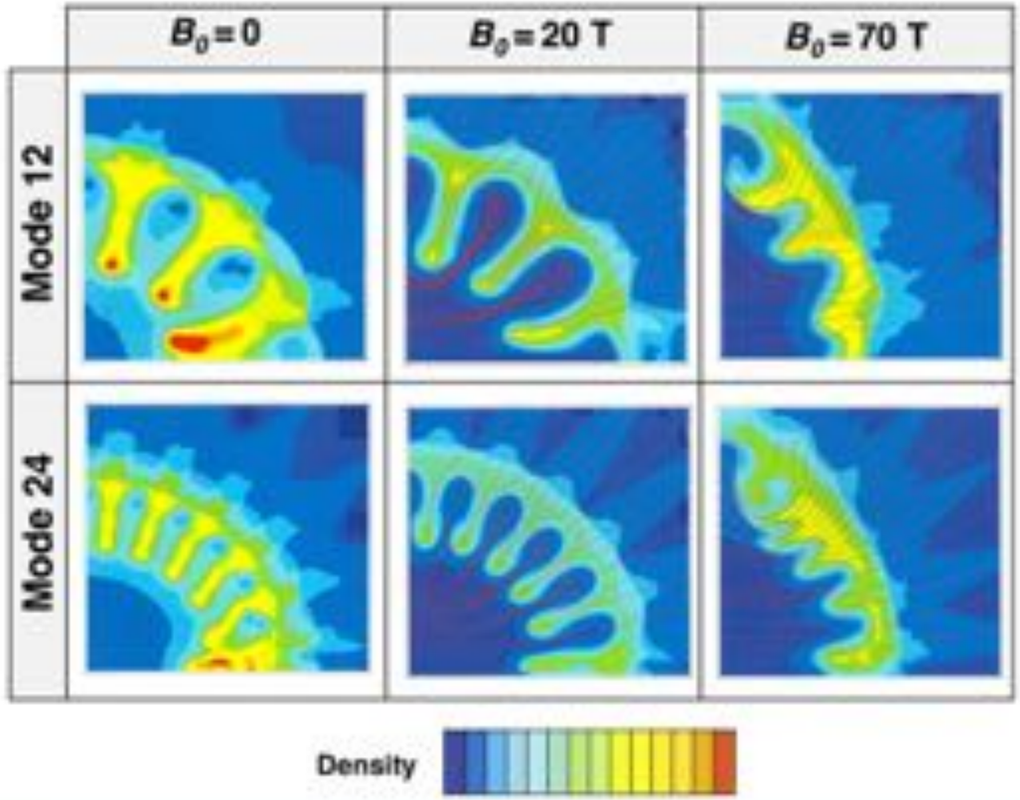
Simulations indicate that RT-growth into the hotspot may be suppressed at higher B-fields (in 2-D at least)

LDRD
Laboratory Directed Research and Development

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



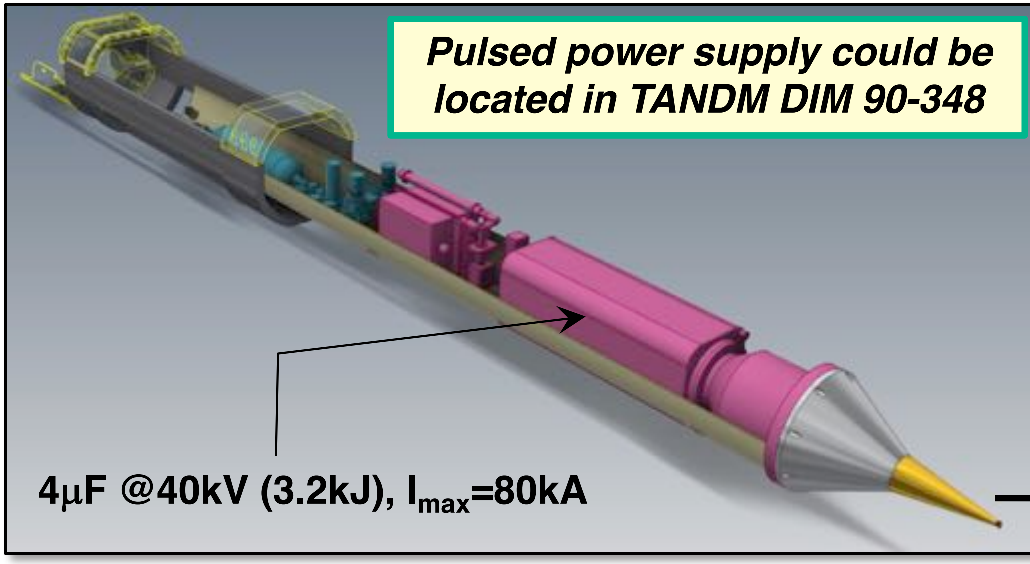
5μm amplitude
ℓ =12 and ℓ =24 cosine initial perturbation on ice-gas interface at t=0



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

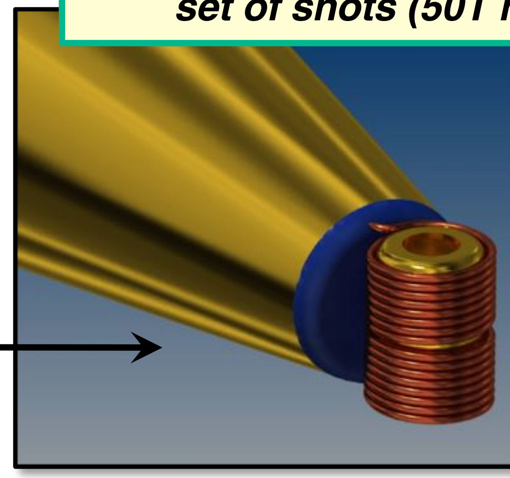
Effect will be enhanced at higher mode numbers (smaller bend radii) but 3-D simulations will be required for full insight

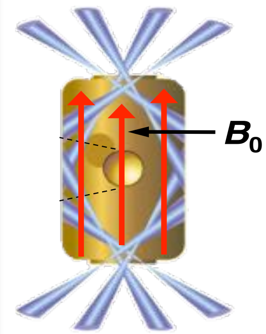
Could an imposed ~50T hohlraum field compressing to 100's MG under implosion recover ignition in otherwise submarginal targets?



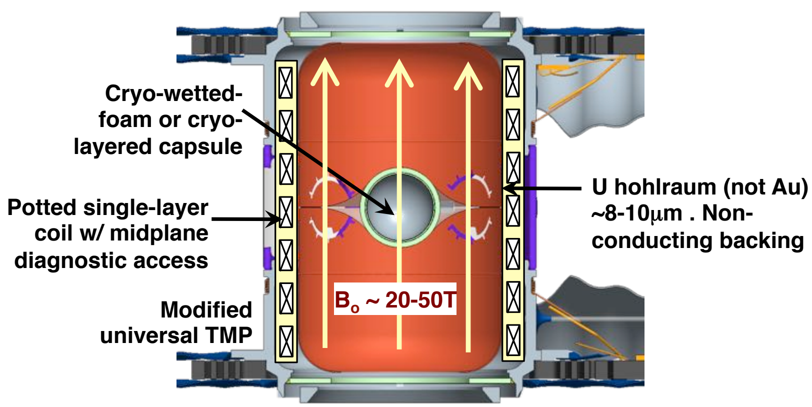
Pulsed power supply could be located in TANDM DIM 90-348

Room-temp hohlraum coil for first set of shots (50T nominal)

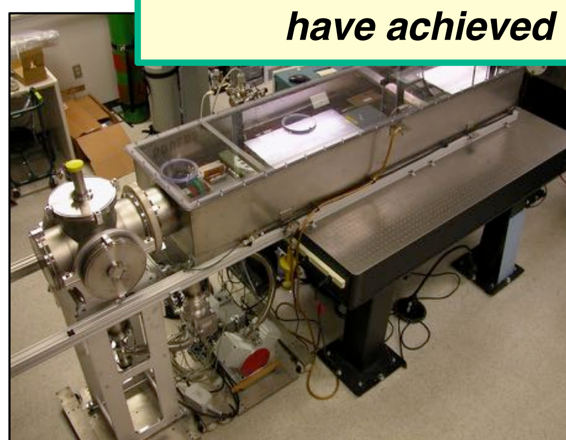


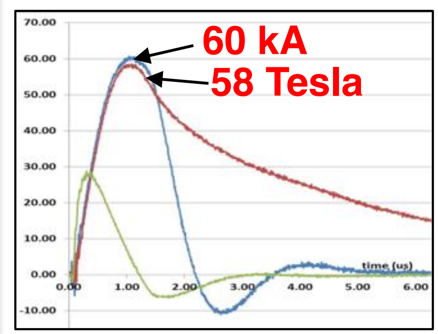


For cryo-targets coupling to a cryo-hohlraum-coil is required

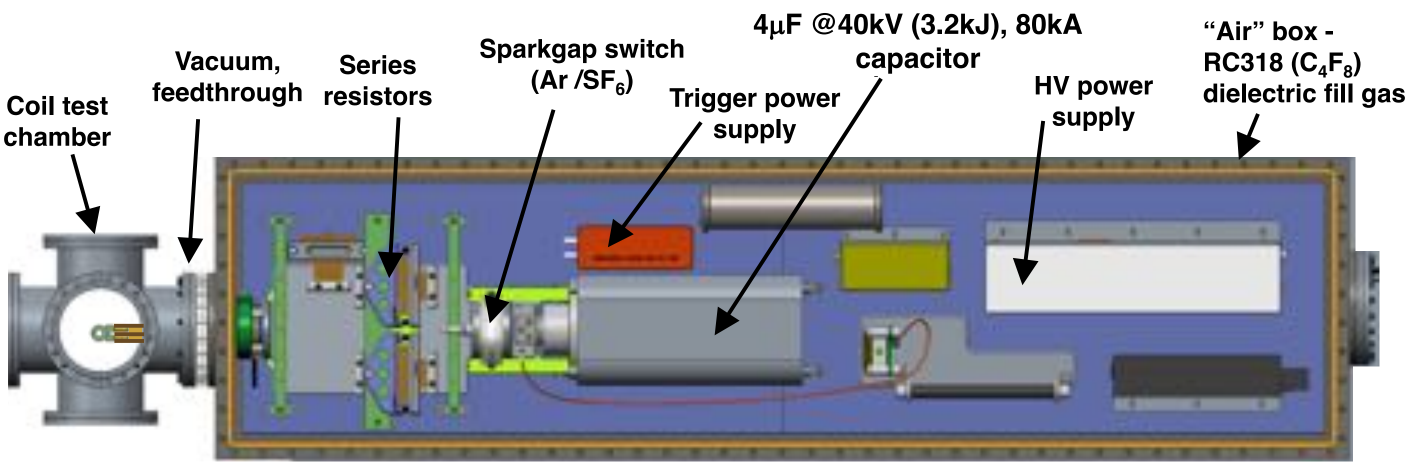


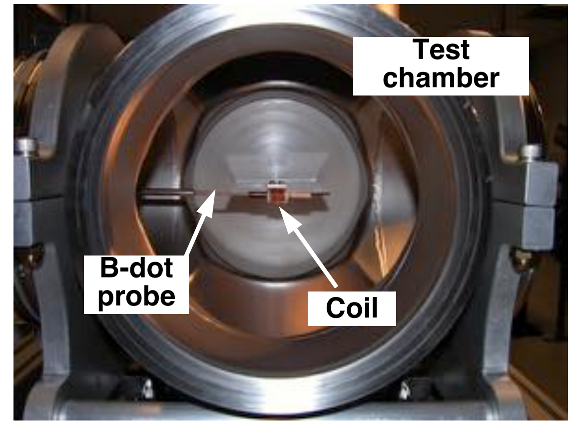
Pulsed-power supply tests of (offline) U-lined hohlraum coils have achieved 58T

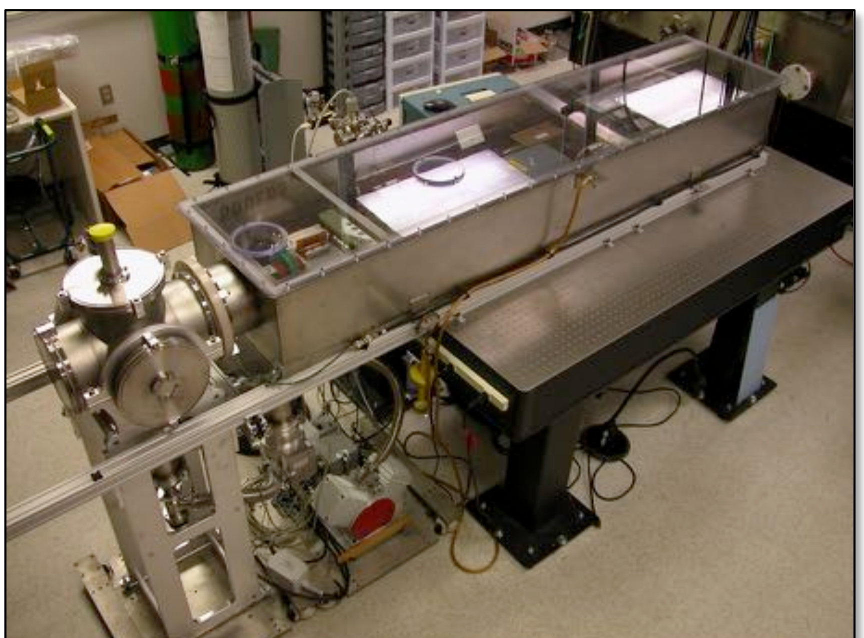




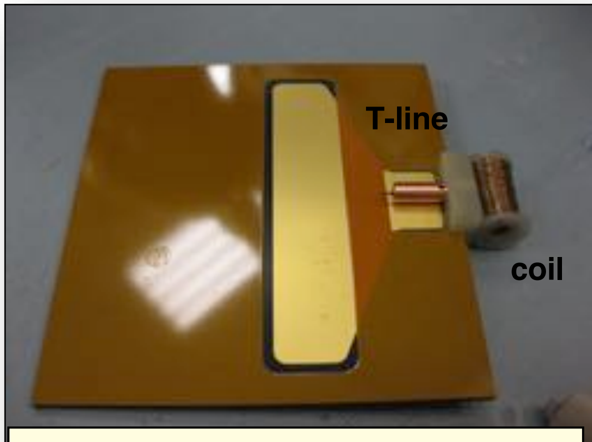
We are testing hohlraum coils in our B490 lab with a candidate NIF-integrable pulsed-power-supply



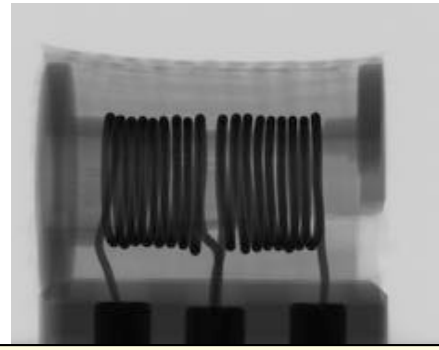




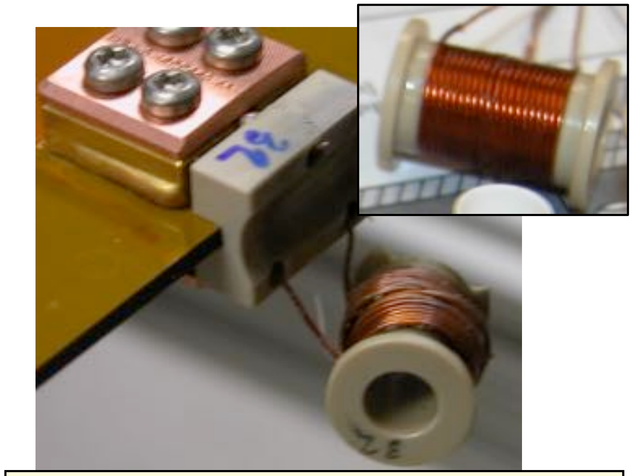
Design field for NIF hohlraums =50T nominal, 70T max.
We have achieved 58T in the lab tests so far



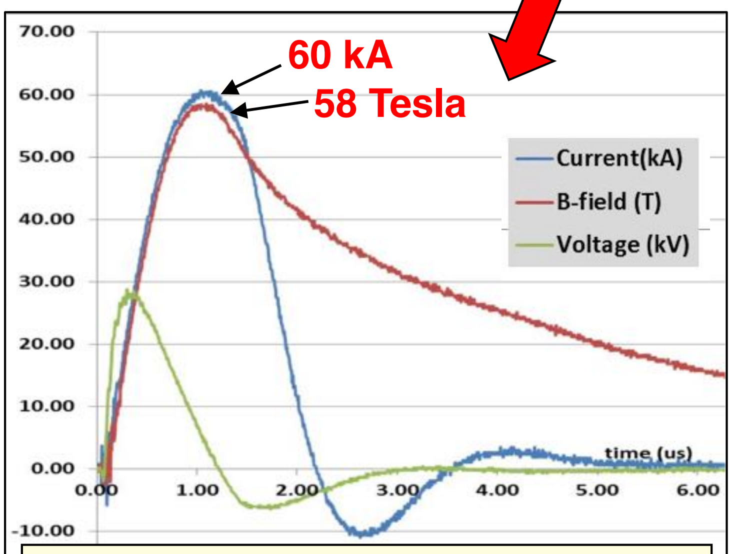
Zylon wrapped coil and T-line



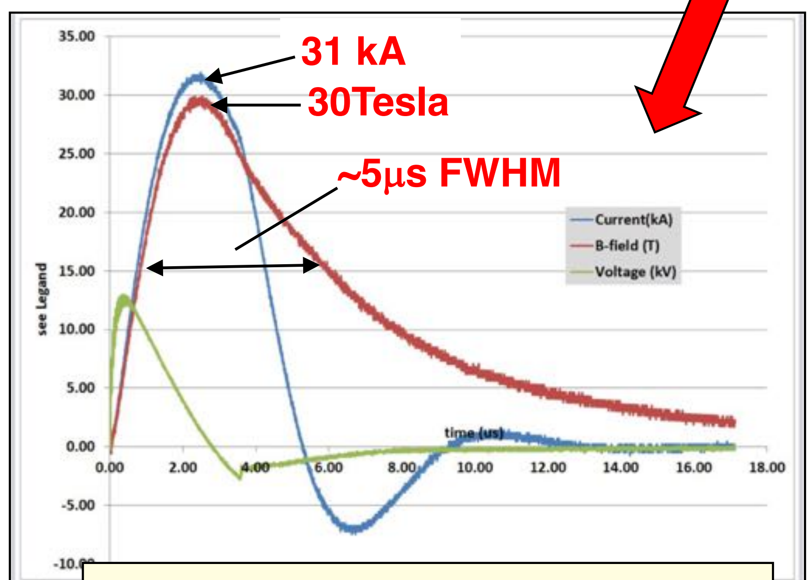
Zylon-wrapped coil is intact after a 31T shot. 58T achieved to date (~70T max)



Bare coils have survived to ~30T

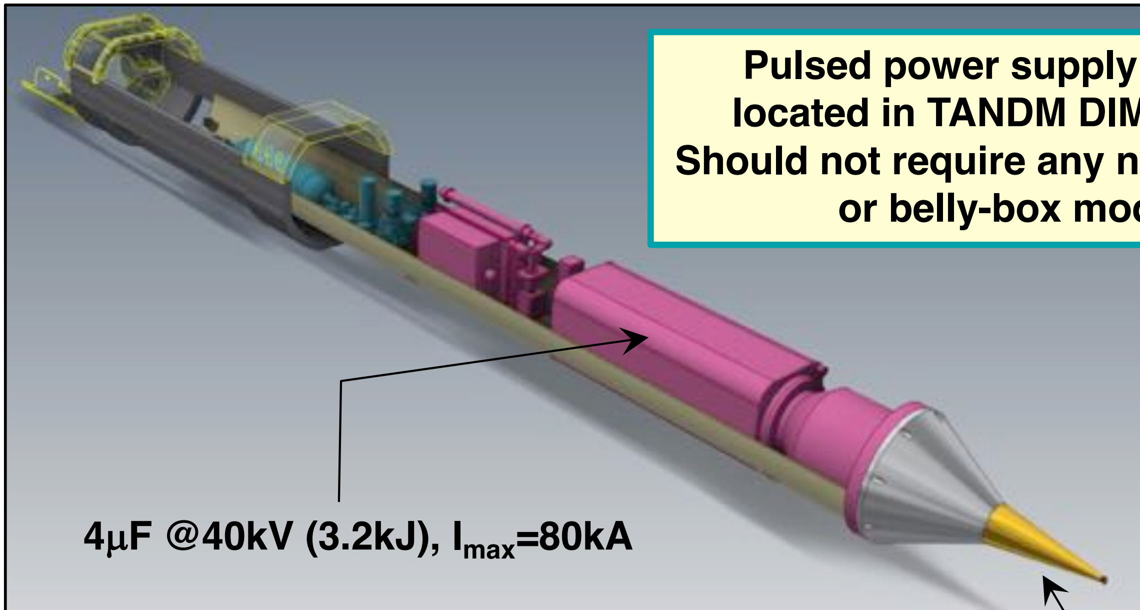


With Zylon wrap 58T attained so far (peak design field =70T)



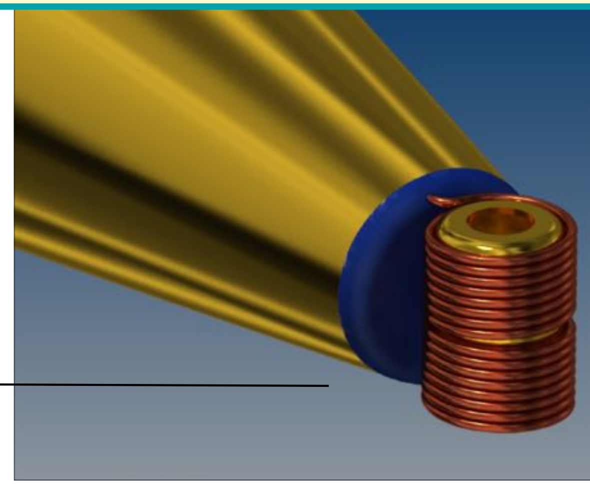
Bare coils survive to ~30T so far

Room temperature gas and metal-gas targets could be fielded from the TANDM DIM. No need for cryo-TARPOS



**Pulsed power supply can be located in TANDM DIM 90-348
Should not require any new utilities or belly-box mods**

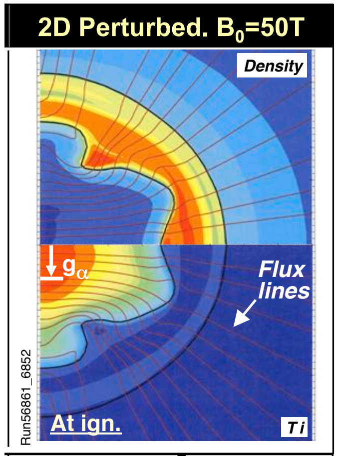
**Room-temp hohlraum coil for first set of gas-taget shots.
(50T nominal, 70T max)**

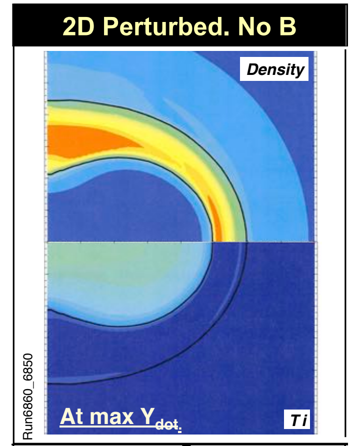


Central goal of the project:

To have magnetized ign. target(s) designed and a pulsed-power-supply/hohlraum-coil constructed and tested offline for integration on NIF for experiments for 2017+

What's the most important phenomenon for B-dependent burn: Reduction of e-heat-conduction or alpha-orbit-confinement?



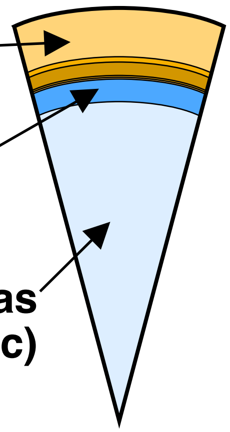


$\omega\,\tau_e$ (B) Alpha-orbits(B)	On On	On Off	Off On	Off Off	No B_0
Yield (MJ)	9.28	0.204	0.041	0.032	0.036
T_{Brysk} (keV)	17.9	5.5	3.9	3.7	3.6
Max $T_i(0)$ (keV)	43	9.0	6.6	6.7	6.2
Burn off yield (MJ)	(0.017)				(0.012)

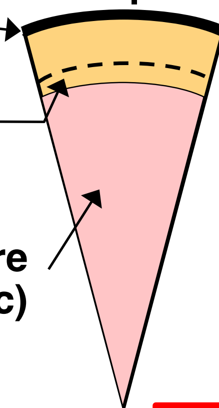
⇒ Both effects are synergistically important. B-dependent reduction of electron heat conduction raises the hotspot temperature to where alpha-orbit-confinement bootstraps the hotspot to ignition

The first set of proof-of-principle experiments would be conducted with room-temperature gas targets

Cryo Ignition

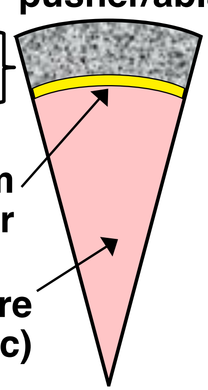


Room-temp Gas

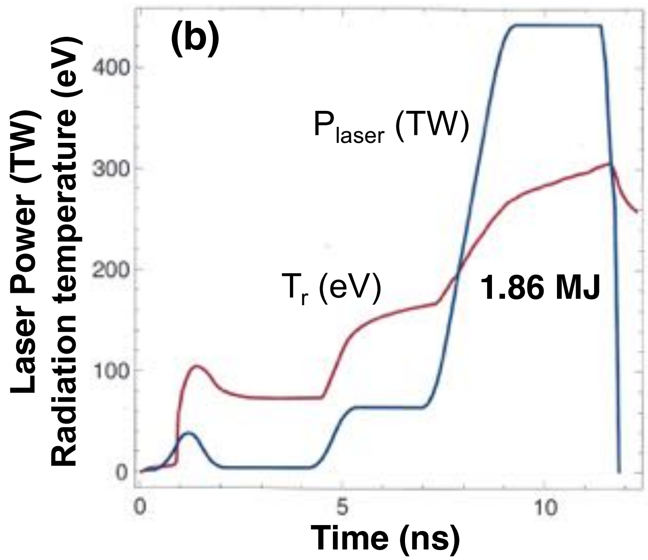


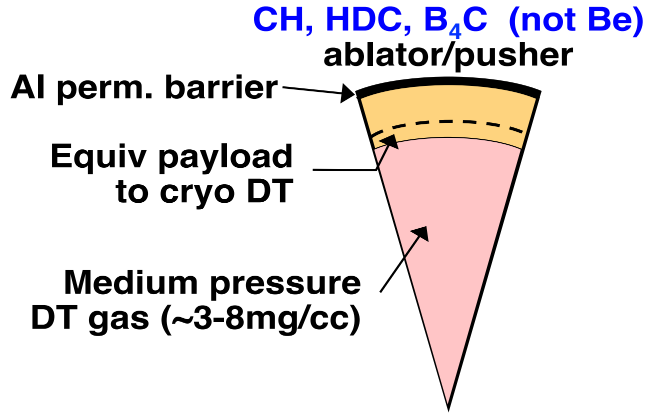
Room-temp gas capsules for proof-of-principle tests

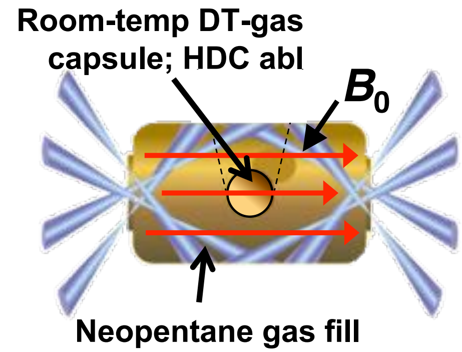
Hi-Z Metal-Gas

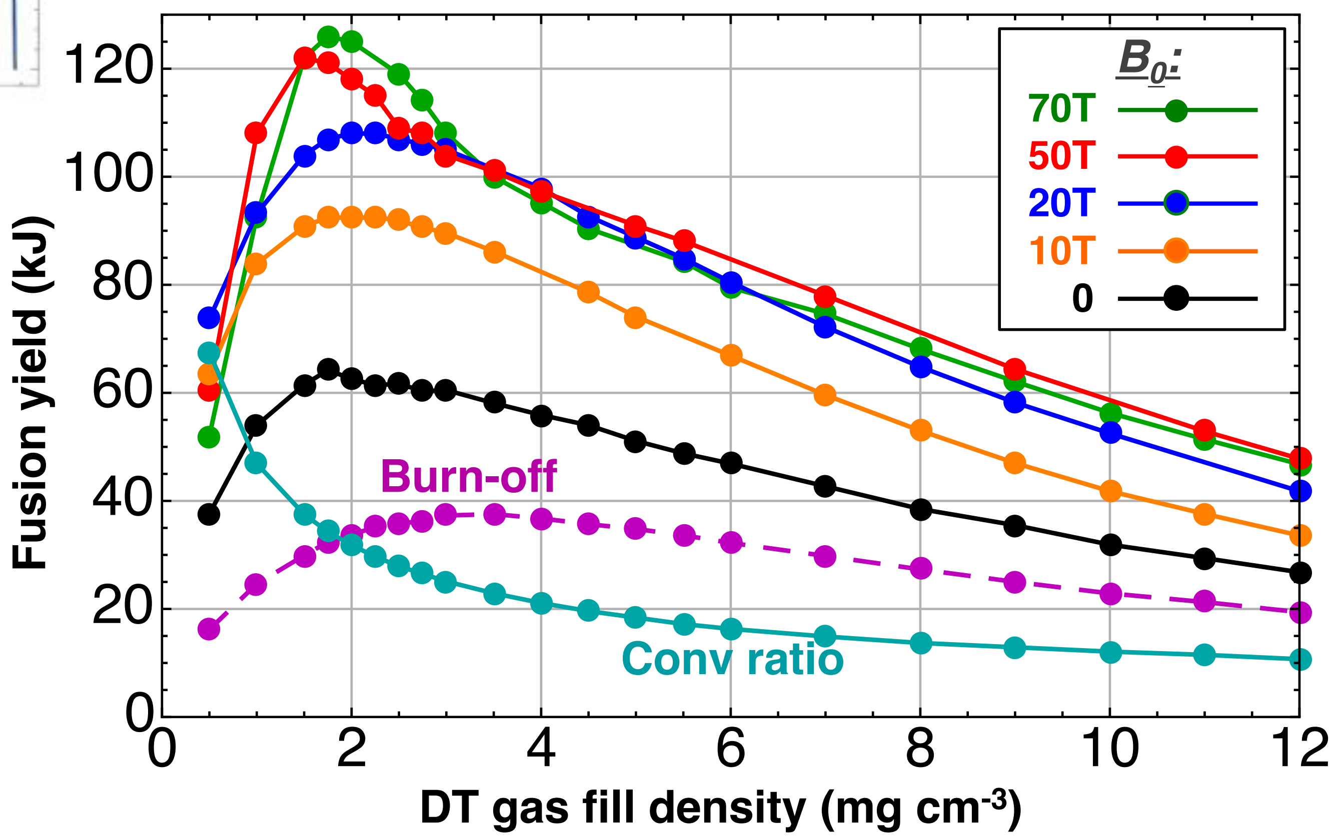


Room-temperature gas target performance, HDC shell – Addition of axial B field gives at best ~80% yield increase



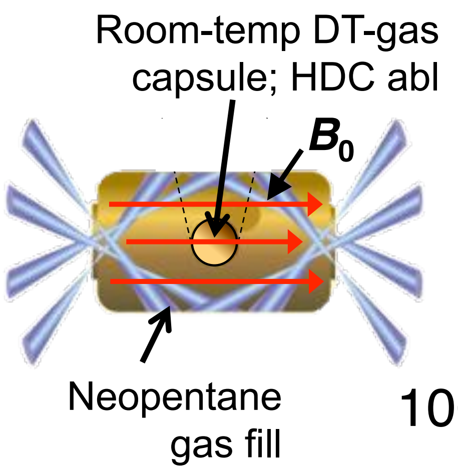




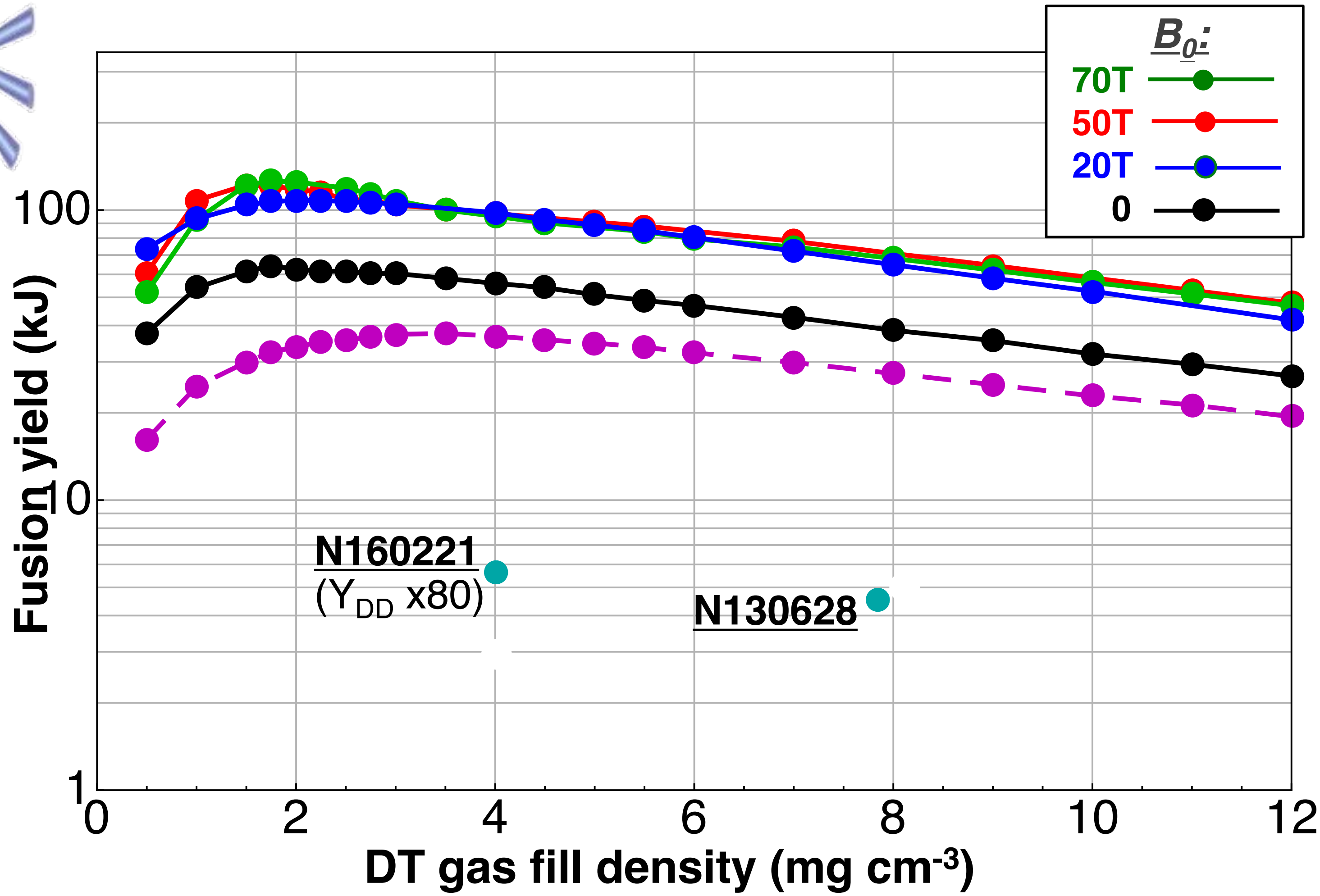


HDC shell with room-temp DT gas
Fusion yields –v- gas fill density. 2D simulations with axial B-field
No asymmetry or instability perturbations

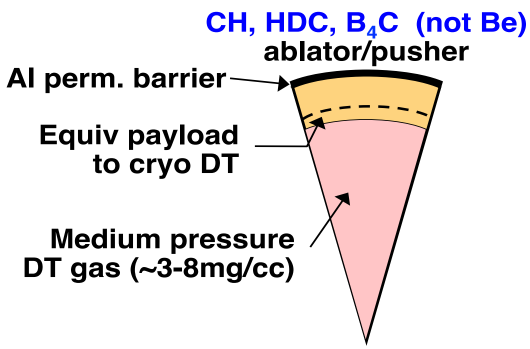
Room-temperature gas target performance, HDC shell – Comparison with experiments

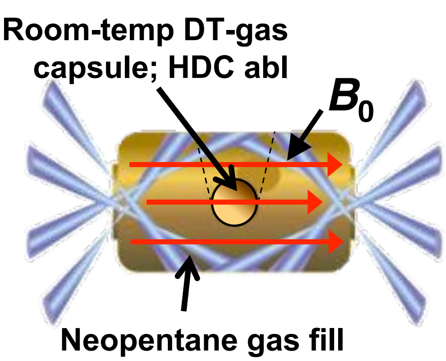


Fusion yields –v- gas fill density. HDC shell Comparison with HDC Symcaps

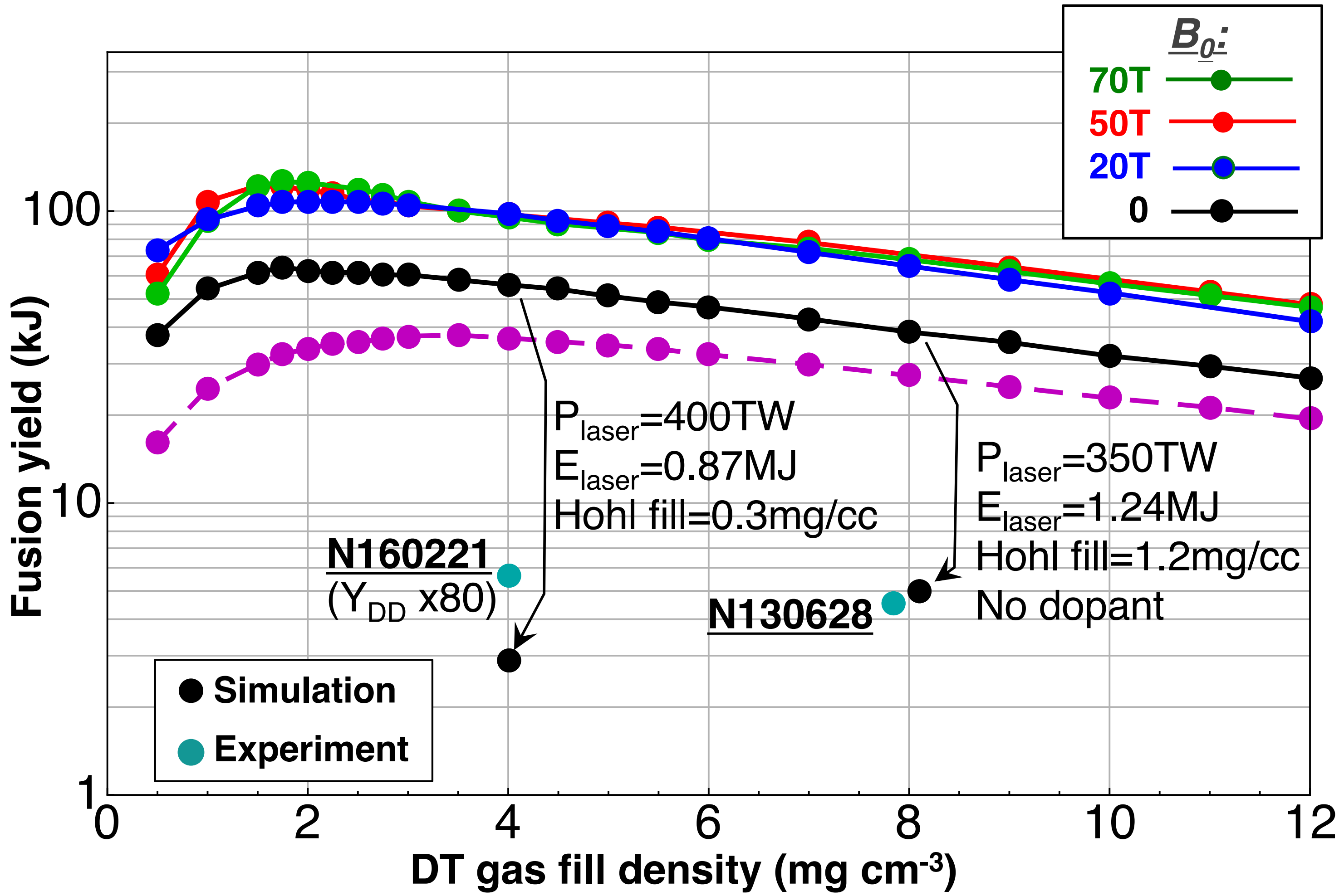


Room-temperature gas target performance, HDC shell – Simulate these experiments using reduced drive

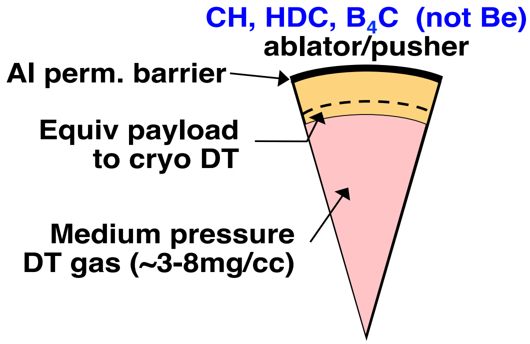


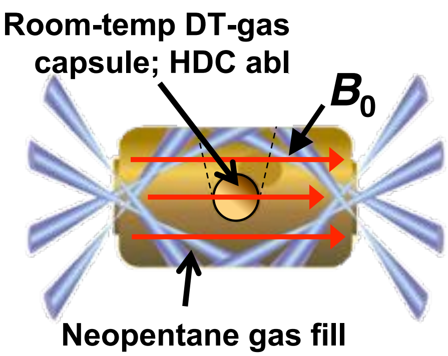


Fusion yields –v- gas fill density. HDC shell
Comparison with HDC Symcaps



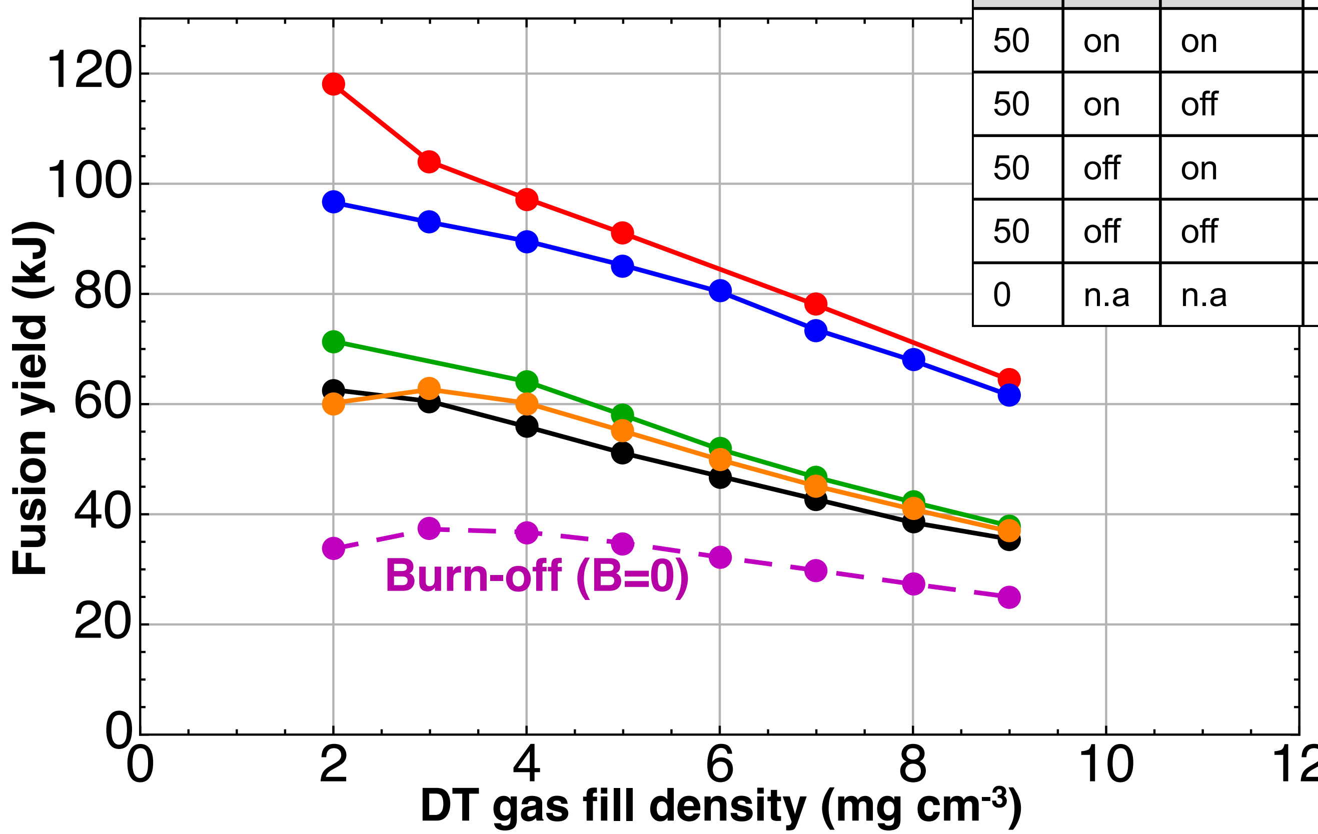
Room-temperature gas target performance, HDC shell – What's the most important role of the B-field?



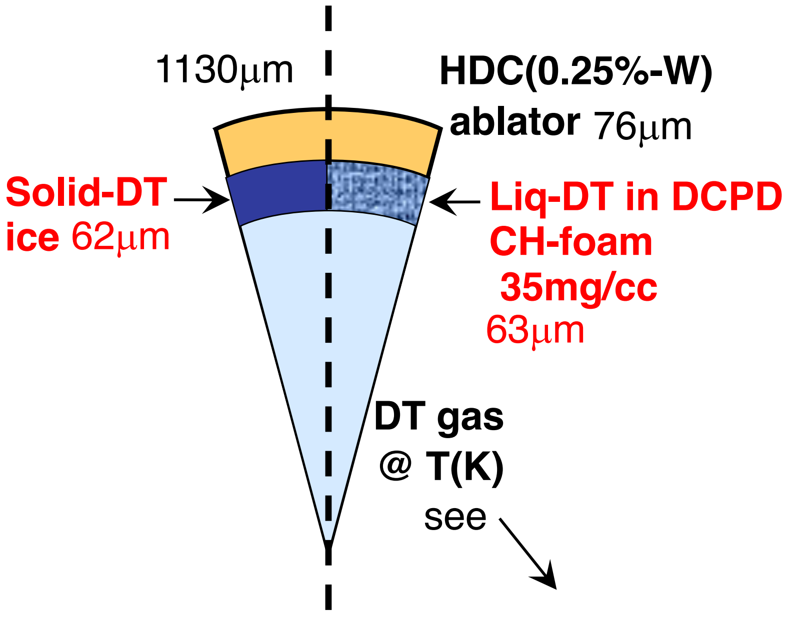


Most important effect of B for (non-metal) gas targets is on electron heat conduction as there's few alphas.
⇒ Can get interesting results at low imposed B-fields (~20T) because $\omega\tau_e$ is still very high

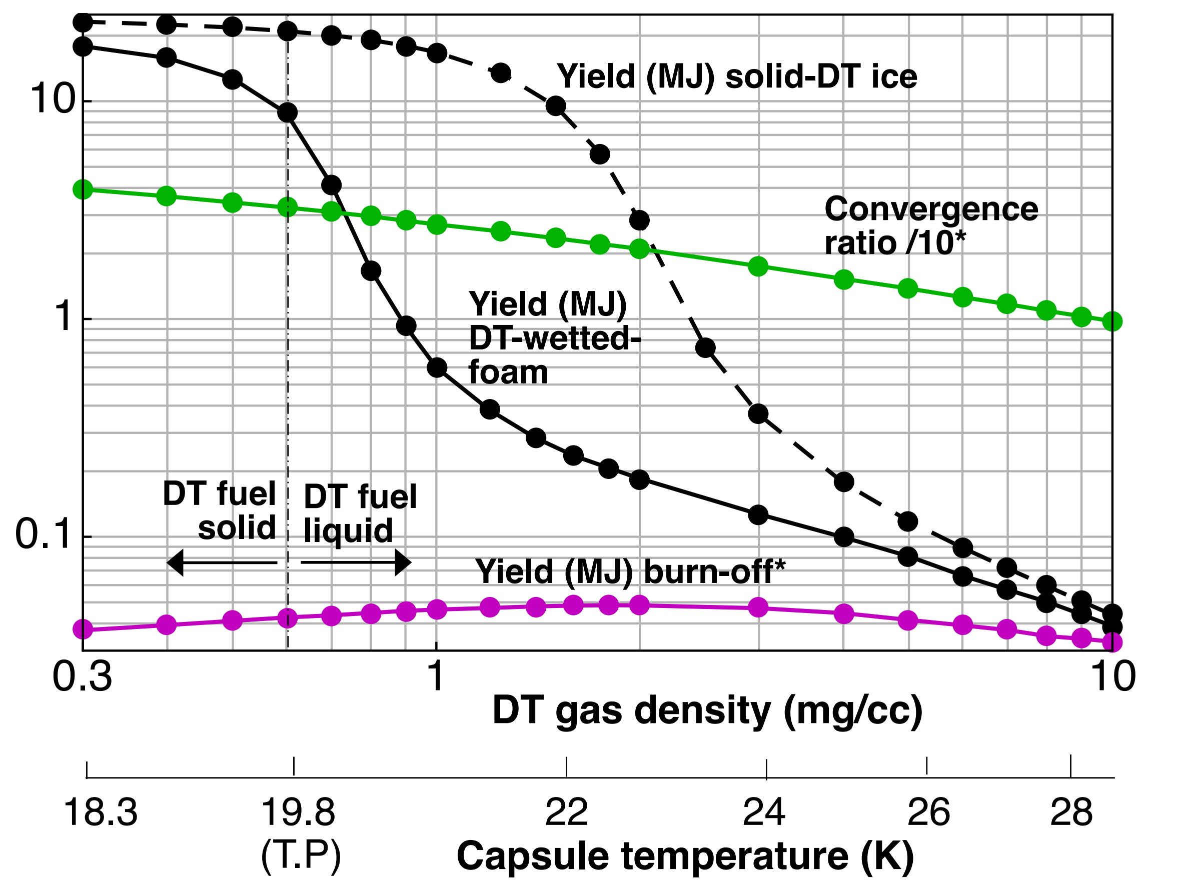
B_0 (T)	$\omega\tau_e$	α-B-orbits	
50	on	on	
50	on	off	
50	off	on	
50	off	off	
0	n.a	n.a	



Comparison of DT-CH wetted foam and solid-DT targets with HDC(W) ablator -v- capsule temperature (= gas density)



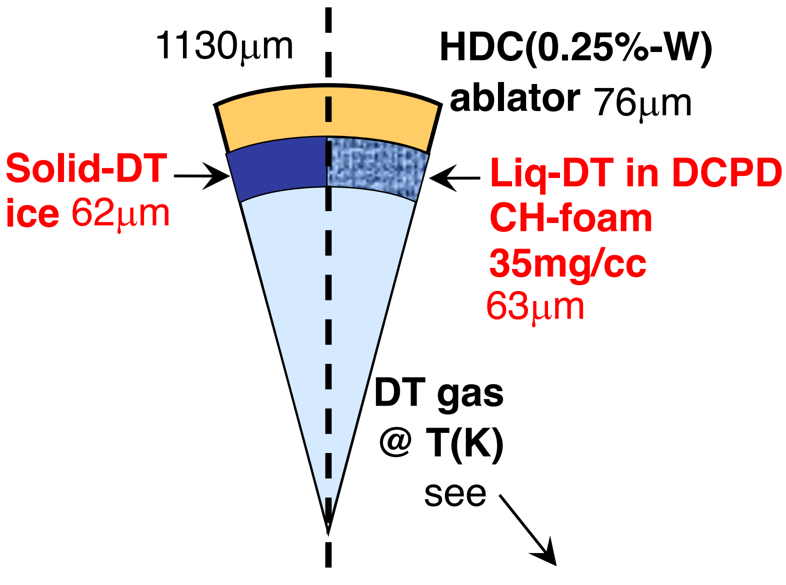
2-D simulations, X1 roughness.
No imposed B-field

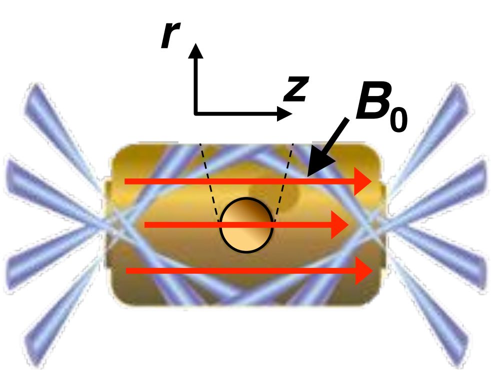


* for wetted-foam

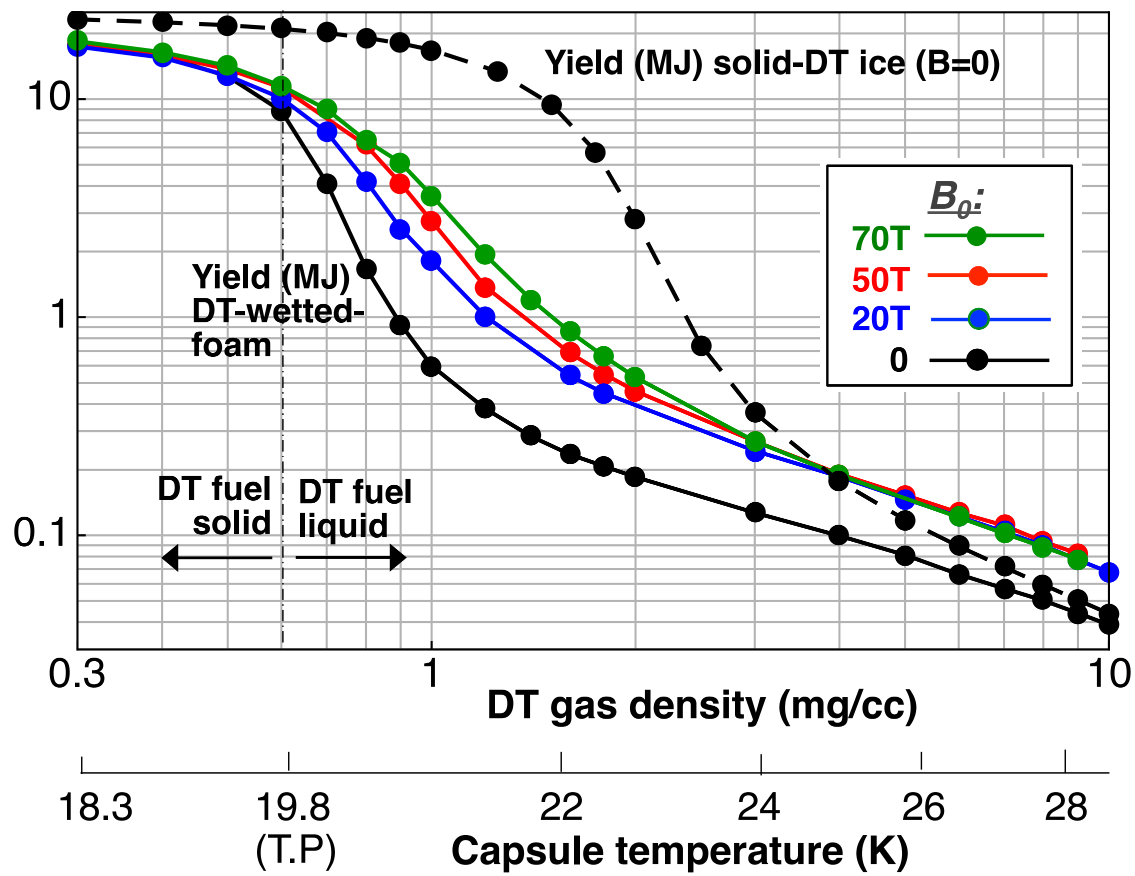
Of course, solid/liquid fuel targets cannot operate above/below 19.8K, respectively, but plot serves to show the loss of margin for wetted foams due to reduced burning with carbon present

Addition of B-field restores some of the wetted-foam margin, permitting ignition around CR ~20





2-D simulations with imposed axial B-field. Includes all relevant MHD phenomena,.. field diffusion/pressure, asymmetric electron heat conduction and full orbit following of alpha particles



Ignition conditions and scalings are modified with imposed B-field

Laboratory Directed Research and Development

Conventional Cryo HS-Ignition Targets

Hotspot energy balance: $dE_{HS}/dt \sim W_\alpha - W_{Brem(DT)} + W_{PdV} - W_{ec} - W_{mix} > 0$

B B non-DT rad B
+ non-DT dilution

Shell/HS momentum balance: $\frac{d}{dt}(\rho R\, V\, r_{HS}^2) \sim P_{HS} r_{HS}^2,$

Fuel burn fraction: $f_{burn} \sim \frac{1}{1+7/\rho R}$

Need $\rho R_{HS} \sim 0.3 - 0.4\text{g/cm}^2$ at $T_{ign} \sim 10\text{keV}$ for α prop. burn into cold fuel

$\Rightarrow, V_{\min} \sim 3.5\text{x}10^7\text{cm/s}, \quad \rho R_{\min} \sim 1.5\text{g/cm}^2, \quad \text{conv. ratio} \sim 35, \qquad f_{burn} \sim 15\%$ if good shell ρR

The rich physics of NIF magnetized ignition targets – Findings to date (from 2-D rad-hydro simulations)….

- Initial fields of 20-50T compressing to $>10^4$ T (100's MG) under implosion may relax stagnation conditions for ignition and thermonuclear burn in *standard* NIF targets
- Trapped alpha particles are localized within hotspot; electron heat conduction loss in hotspot is shut off across the field ($\omega_{ce}\tau_{ei}$>>1):
  - => Can reduce required hotspot ρR*T and pressure for ign around a factor of 2
- Mirror fields in sausage implosions may provide further insulation to electron and alpha conduction loss. As might frozen-in closed field lines spun up by residual-KE
- Compressed field may suppress Rayleigh-Taylor instability ingress into hotspot during stagnation
- Imposed magnetic fields may enable volumetric ignition/burn in room-temperature high-Z metal-gas targets and may enhanced gas yields in room-temperature low-Z platforms (first experiments?)
- Hohlraum field may improve inner beam propagation and may inhibit transport of late-time LPI hot electron preheat to capsule

Might permit the recovery of ignition, or at least significant fusion alpha particle heating and yield, in otherwise sub-marginal NIF capsules

⇒ Validating proof-of-principle experiments are now required

A NIF magnetized target capability would enable a rich portfolio of discovery science and HED applications. Examples…

- **Ignition and TN-burn in magnetized capsules (various types) - enhancement of ign. margins:** *~50T, hohlraum volume, room temp and cryo capsules, ≥1MJ*
- **Validation of laser preheat in magnetized channels for application to Sandia's MagLIF initiative:** *~30T,1cm-length, gas channel, 30kJ*
- **Collisionless shocks in background fields (gamma-ray bursters, supernova remnants):** *~30T+, 1cm, D_2-CH low-density plasma, 1cm-length (0.3cm access) 250kJ*
- **Magnetic stagnation of plasma flows (solar-terrestrial magnetosphere, heliosphere), instabilities and inhibition.** *Need $B^2/2\mu_0 \sim \rho v^2$.*
- **Astrophysical jets (accretion columns, white dwarfs):** *10's-T, 0.25n_{crit} doped neopentane, nozzle-LEH for high Mach-No., ≥1MJ*
- **High T_{rad} hohlraums: high intensity beams in small volume hohlraum with B-suppression of e-transport in hi-Z non-LTE conversion layers:** *~10'sT, 80μm beam spots ~10^{16}W/cm^2 (no phaseplates)*
- **High altitude phenomena:**
  - **- Exploding plasma collisionless shocks**
  - **- EMP E1 (WEMP code benchmarking):** *~20T, $\rho R_{gamma\text{-}absorber}$~1gm/cm^{2,} ⇒100 Compton gyro orbits, e-mfp/gyro orbit ~1/3 (EMP from compressed capsule burn?)*

⇒ Applications require ~10's T in ≲cm^3 volumes, so all are potentially appropriate experiments for our system