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

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Lawrence Livermore National Laboratory

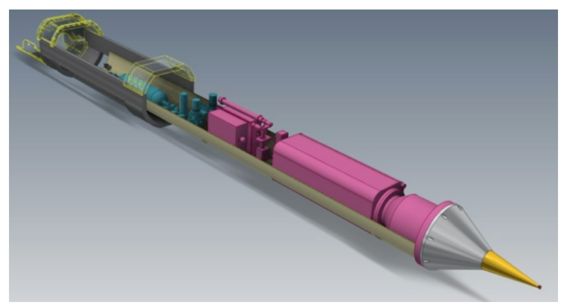
Anomalous Absorption Conference

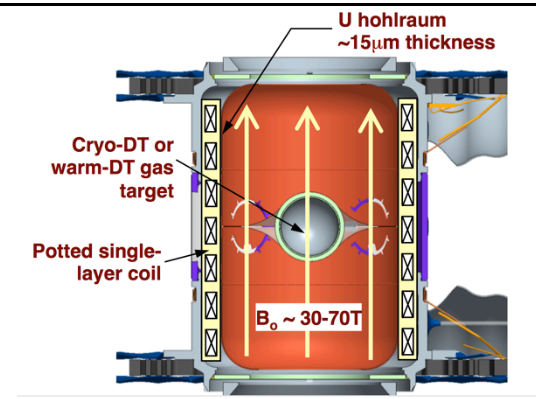
June 16, 2015

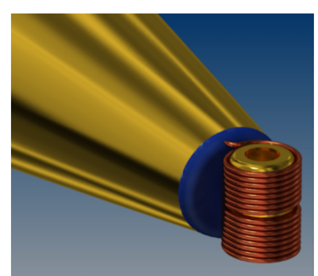
LLNL-CONF-672979

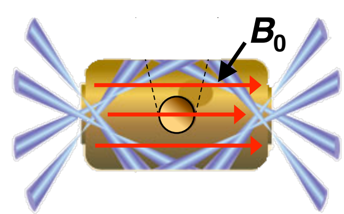
This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract DE-AC52-07NA27344. Lawrence Livermore National Security, LLC

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









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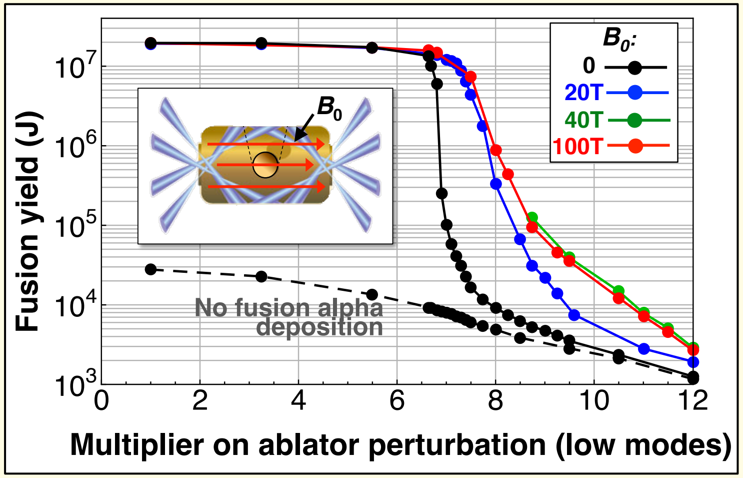
Rich physics of NIF magnetized ignition targets – Findings to date

- Initial fields of 30-70T compressing to >10^4 T (100’s MG) under implosion can relax conditions for ignition and thermonuclear burn in NIF targets (HS- and vol-ignition)
- Trapped alpha particles can be localized within hotspot resulting in reduced hotspot criteria for ignition (reduces required ρR*T and pressure for ign)
- Electron heat conduction loss in hotspot is shut off across the field
- Mirror fields in sausage implosions provide further insulation to electron and alpha conduction loss
- Compressed field may suppress Rayleigh-Taylor instability ingress into hotspot during stagnation



- Imposed magnetic fields for indirect-drive room-temperature metal-gas targets enable nuclear performance only seen previously under direct-drive (first experiments?)
- Hohlraum field can improve inner beam propagation and inhibit transport of late-time LPI hot electron preheat to capsule (but can enhance early-time TPD e- deposition)

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

Our pulsed power supply will be located in DIM 90-315. First magnetized target experiments will likely be shot from the DIM

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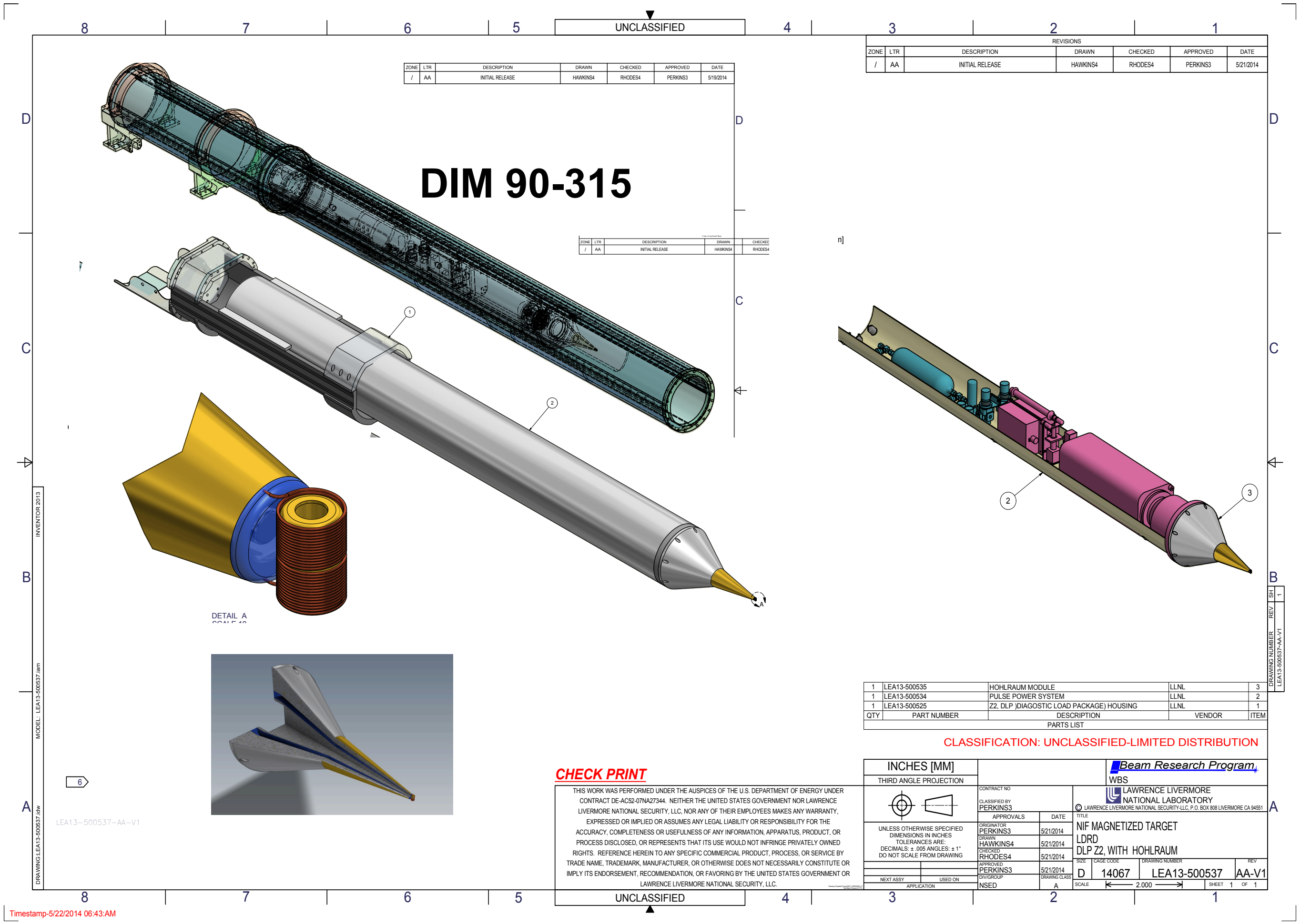
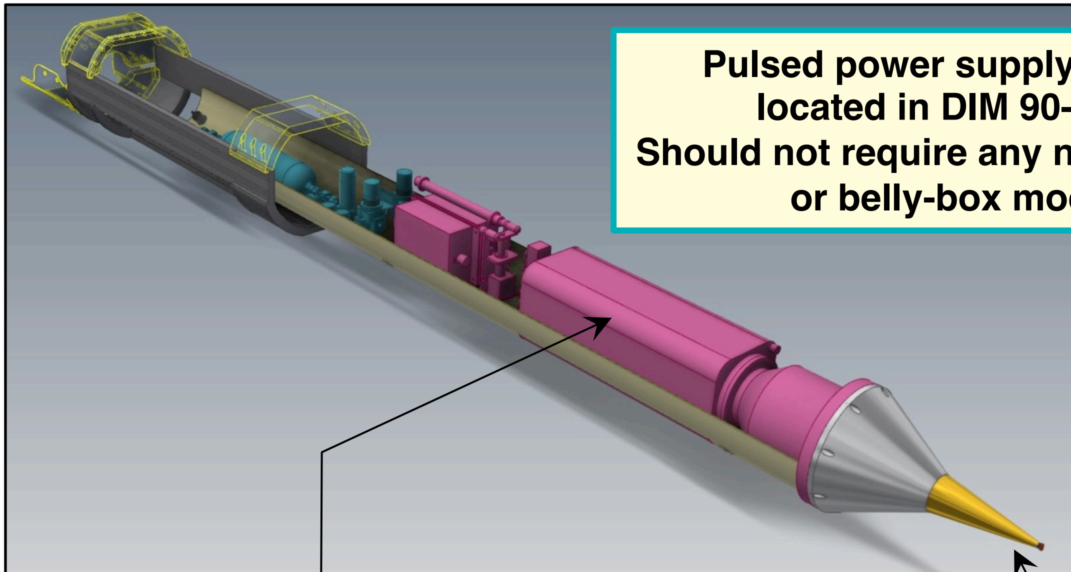


Central goal of the LDRD project:

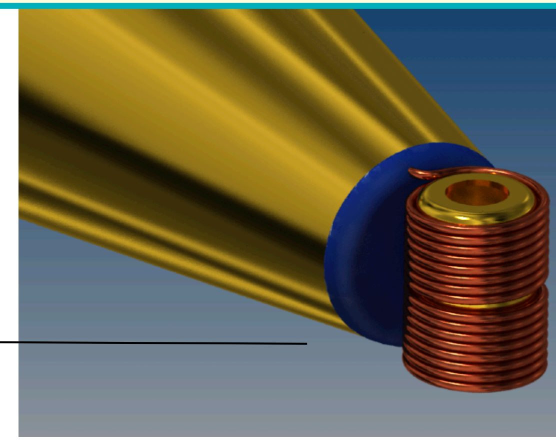
To have magnetized ign. target(s) designed and a pulsed-power-supply/hohlraum-coil constructed and tested offline for integration on NIF for experiments for 2016+

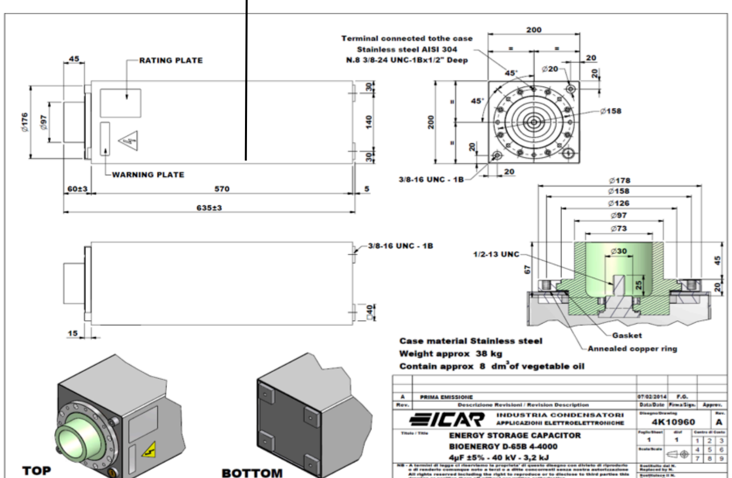
Pulsed power architecture: Maximum hohlraum coil fields are determined by DIM volume for stored energy +coil ampere-turns



Pulsed power supply will be located in DIM 90-315.
Should not require any new utilities or belly-box mods

Room-temp coil hohlraum coil. (50T nominal, 70T max w/ Xylon composite wrap)





We have worked with ICAR to develop the required spark-gap-switched capacitor and taken delivery of five ~4μF @40kV (3.2kJ), I_{max}=70kA

Magnetized capsule types for this project

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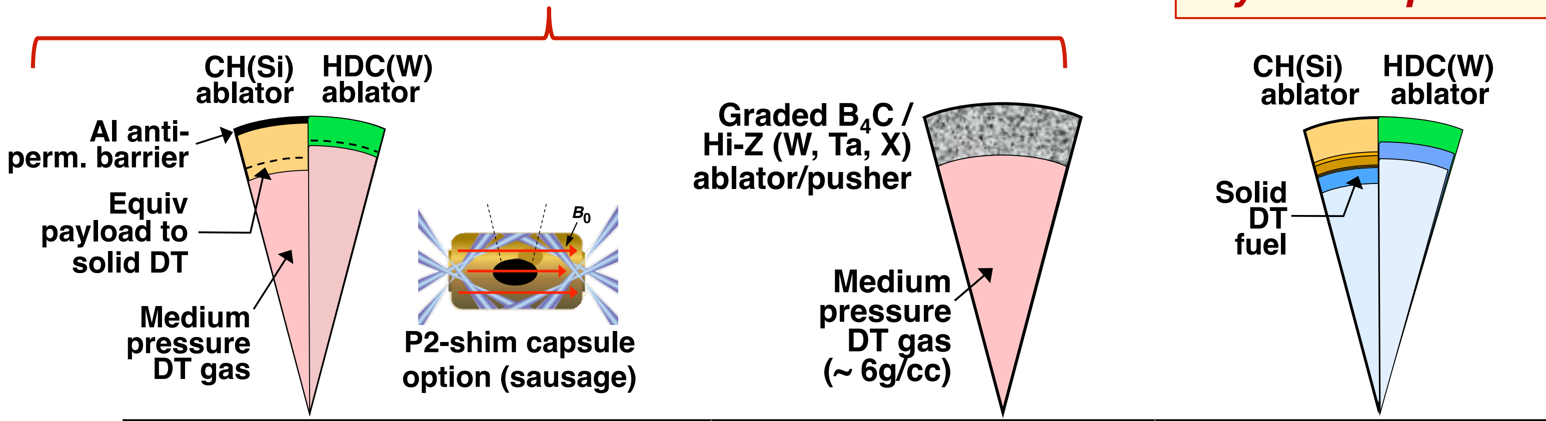
Magnetized room-temp. gas capsules for first experiments

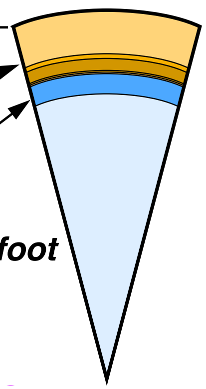
Follow-on cryo-layered capsules



	Room-Temp Gas	Metal-Gas	NIC Cryo Ignition*
Rationale	B-dependent α heating feedback on burn and yield	Volumetric ign at ~5keV and low velocity; other apps	Ignition and propagating burn
Temperature	300K	300K	Cryo, ~18K
DT Fuel	Gas (~25Atm)	Gas (~25Atm)	Solid, cryo-layered
Ignition type	Volumetric heating	Volumetric ignition	Hotspot ignition
T_{i_ign} / T_{i_max}(keV)	Likely only α heat. to <10keV	~5 / 20 (Rad. trapped)	~12 / 100
Max yields (MJ)	~0.1	≳1	~1-20

NIF cryo-CH capsules: What does a compressed B-field do for a 3-shock "N140304 hi-foot-like" implosion?

Apply angle-dep. P4 rad flux perturbation to approx. match N140304 3-shock hi-foot inflight + stagnation params



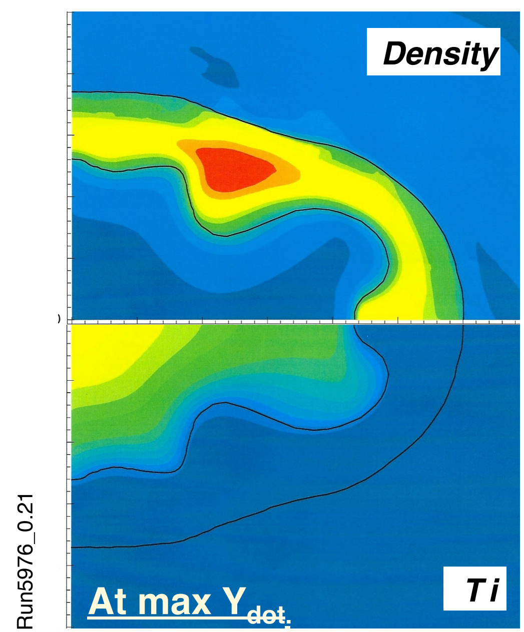
__N140304 Hydro Parms:__

442TW, 1.86MJ, 3-shock hi-foot

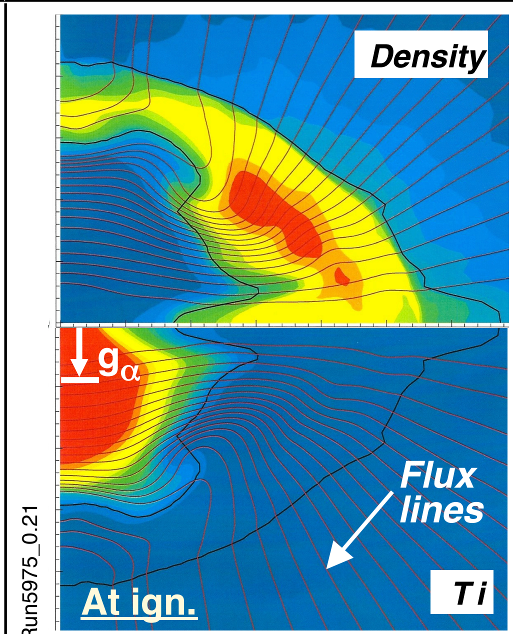
V =3.7e7cm/s, α =2.42

2D clean fusion yield=5.7MJ

2D Perturbed. No B



2D Perturbed. B_0=70T



	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

LASNEX sims indicate that inherent magnetic mirrors further enhance alpha and electron deposition. Can we design for this?

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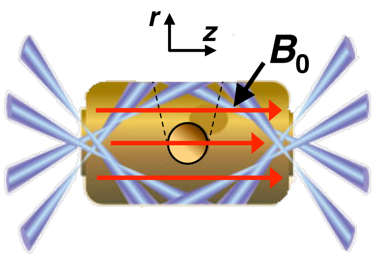
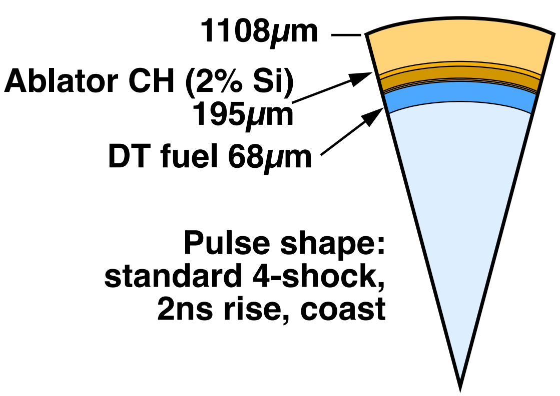
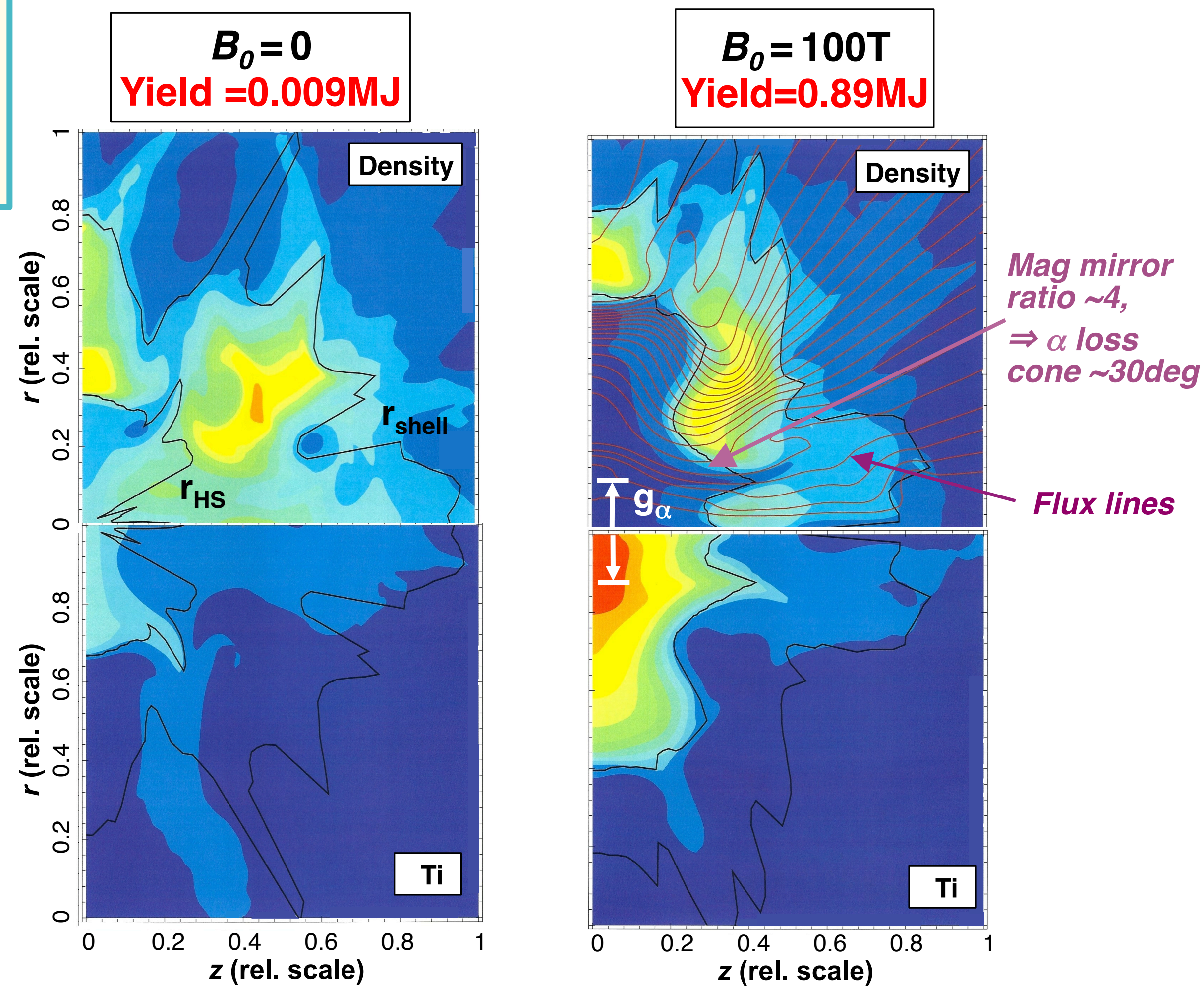
CH cryo capsule, 4-shock. Contours at ign/stagnation for a large outer surface amplitude low-mode perturbation of X8.

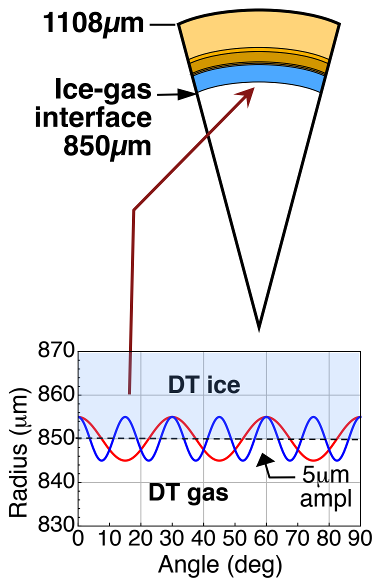




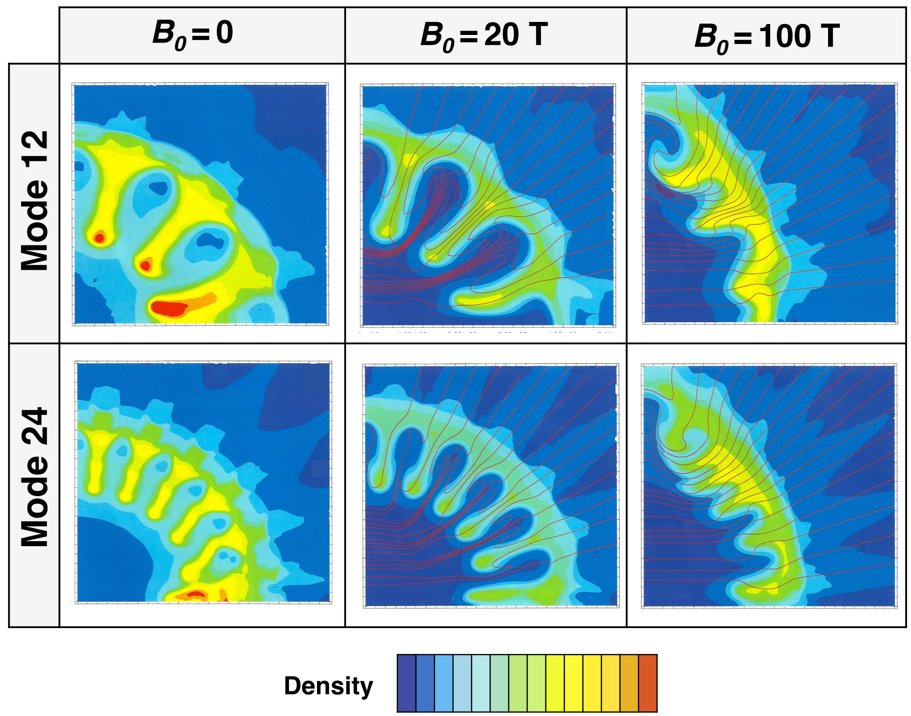


Rayleigh-Taylor instability growth into the hotspot may be suppressed at higher B-fields (in 2-D at least)

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).

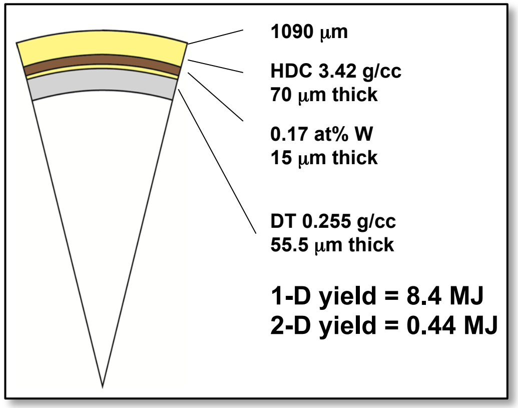
Effect will be enhanced at higher mode numbers (smaller bend radii) but 3-D simulations will be required for full insight

NIF 3-shock cryo-HDC capsules: Application of compressed B-fields

B field (T)	Surface roughness	Yield (MJ)	Hotspot ρR (g/cm²)	Hotspot radius (μm)	Hotspot Ti (keV)	Hotspot density (g/cm³)	Hotspot pressure (Gbar)
0	0	8.4	0.43	36	7.3	116	768
0	Nominal	0.44	0.22	37	3.7	60	180
40	Nominal	5.6	0.2	37	4.9	56	211

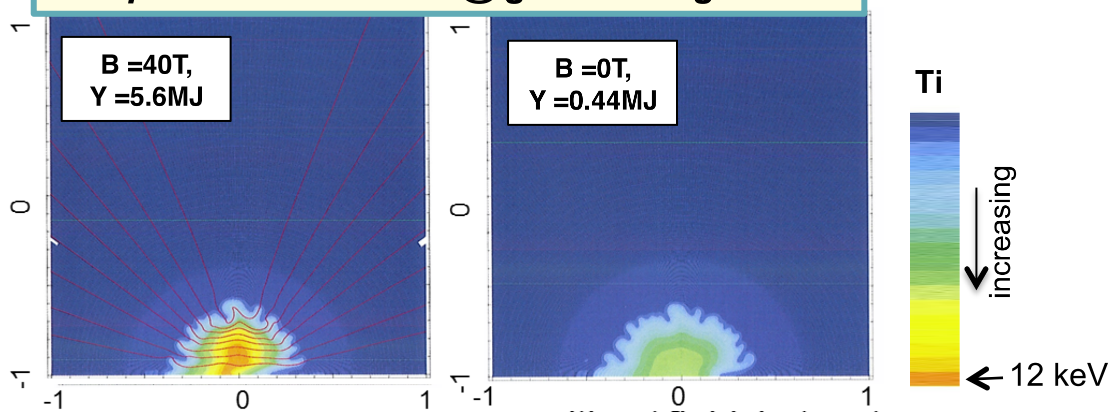
Alpha gyro-radius ~16μm

@ ignition both attain Ti(0) = 12 keV



HDC(W) ablator, 3-shock

Temperature contours @ignition/stagnation



with 40 T seed field, hotspot reaches ignition Ti of 12 keV

without field, hotspot fails to reach 12 keV

Imposing a 40 T initial seed field reduces hotspot areal density ignition requirement by ~50% and obtains ignition in an otherwise marginal capsule

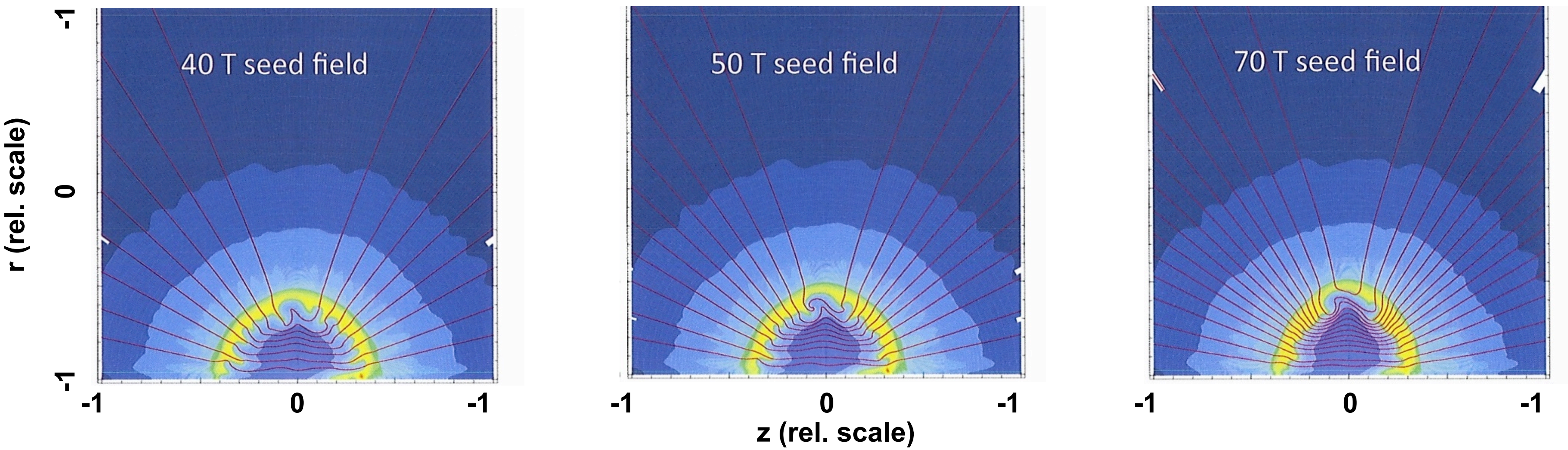
NIF 3-shock cryo-HDC capsules: Summary of roles played by B field in yield enhancement

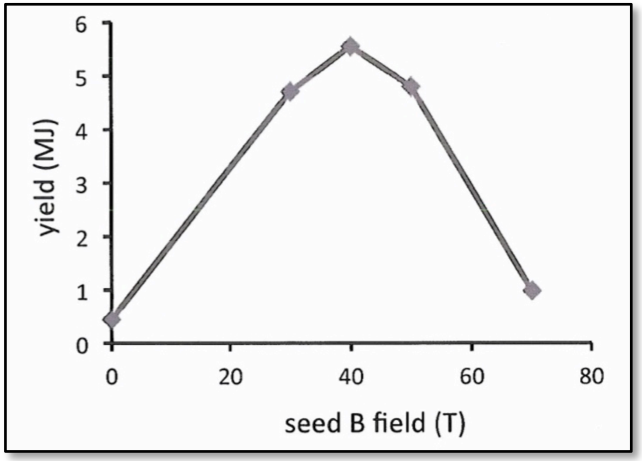
Seed B-field (T)	surface roughness	B-field effect on α-particles	J$\times$B force	yield (MJ)	role played by B-field
0	nominal	N/A	N/A	0.44	N/A
50	nominal	off	off	0.9	magnetize electrons, no shape distortion
50	nominal	off	on	0.65	magnetize electrons, shape distortion
50	nominal	on	on	4.8	magnetize α-particles and electrons, shape distortion

- This table shows the magnetization of α-particle 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.

NIF cryo-HDC capsules: Implosion departs further from sphericity as strength of seed field increases beyond 40 T

Density contours @ignition

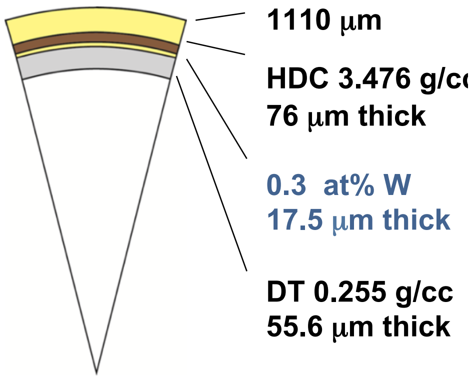


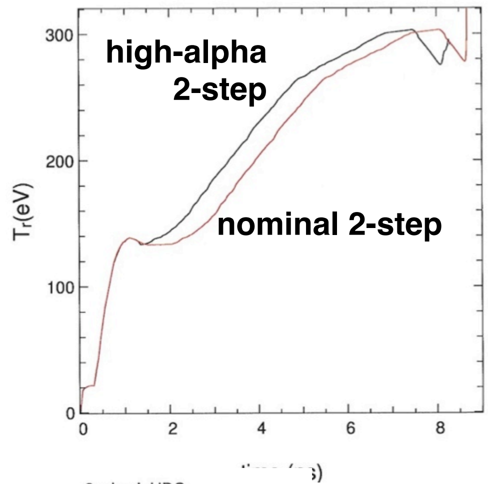


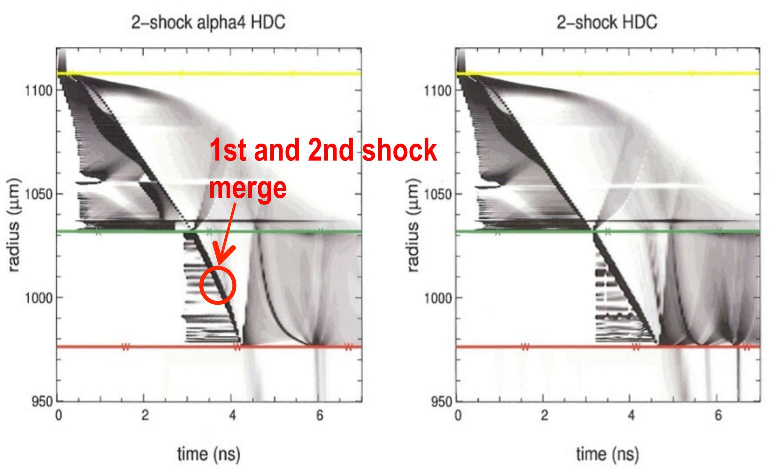
The optimum seed field for the present baseline HDC 3-shock capsule is around 40T

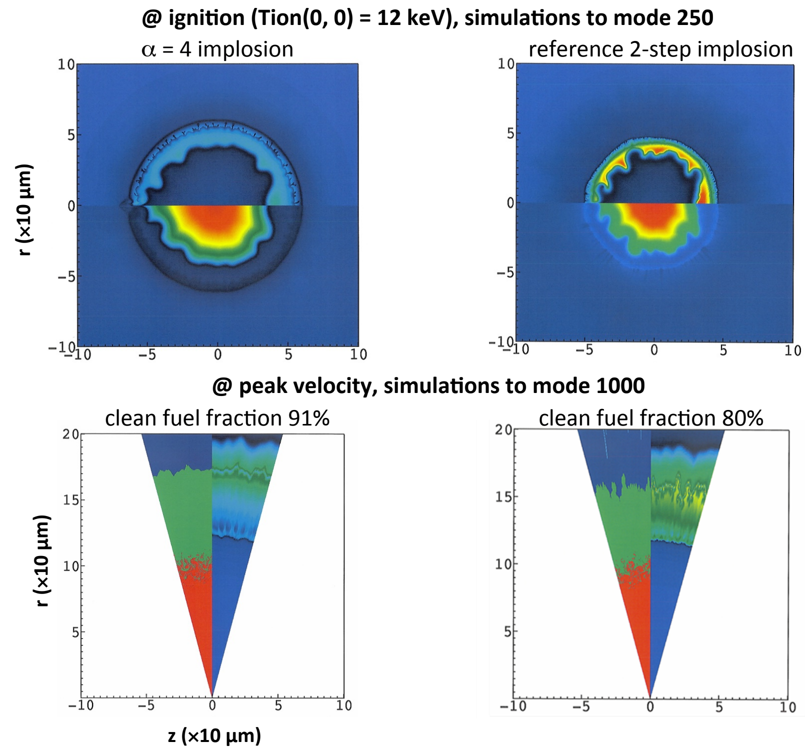
NIF cryo-HDC : High alpha (α = 4) capsules may be good candidates for imposing B field to boost yield

Capsule configuration









Shell is less perturbed and mix is reduced in α = 4 implosions

High alpha capsules are robust to surface perturbations and are good candidates for imposing seed fields to boost their modest yields.

But their lower convergence ratios will require higher initial fields

Magnetized Hohlraum Physics: HYDRA MHD simulations with coupled ZUMA hot electron transport

HYDRA MHD Simulations

- **Modeled NIF low-foot target with and without initial 70 T axial magnetic field**
- **Self-generated ($\nabla n X \nabla T$) fields also assessed: Preliminary results show they may be significant; being examined for numerical accuracy (⇒not included in present results)**
- **Magnetic field is ~ frozen-in to hohlraum plasma flow: good conductor**
- **Axial field significantly reduces electron heat conduction across field, increases hohlraum fill temperature, widens equatorial channel between capsule and wall, improves inner-beam propagation (less inverse-brem. absorption)**

ZUMA Hot Electron Studies

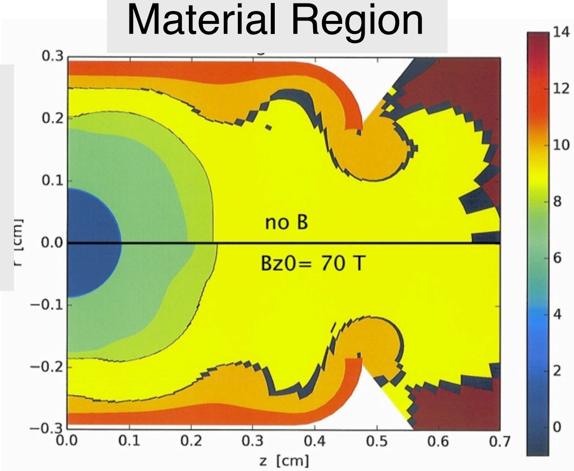
- **Hybrid-PIC code (D. Larson) currently using in "Monte-Carlo" mode: collisions, and *vxB* force in specified B field**
- **At early-time picket:**
  - **- B field magnetizes window TPD hot electrons but directs them toward capsule**
  - **- ~12x more deposition into DT ice with B but still only 20mJ so ~OK (TBD)**
  - **- Picket pulse shaping controls source, so may not be concern (design around?)**
- **At peak power:**
  - **- B field directs hot electrons along field lines in hohlraum fill gas**
  - **- ~35x less deposition in DT ice with B (⇒ ~eliminates late time preheat concerns)**

HYDRA hohlraum simulations without and with imposed 70T axial magnetic field

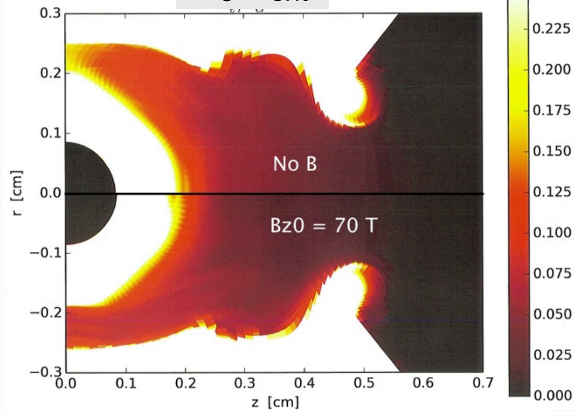
Low-foot NIF shot N120321: Plastic ablator, DT ice layer: Reduced e- heat flow across B ⇒ hotter fill, wider equator channel, better inner beam propagation

18 ns: early peak power

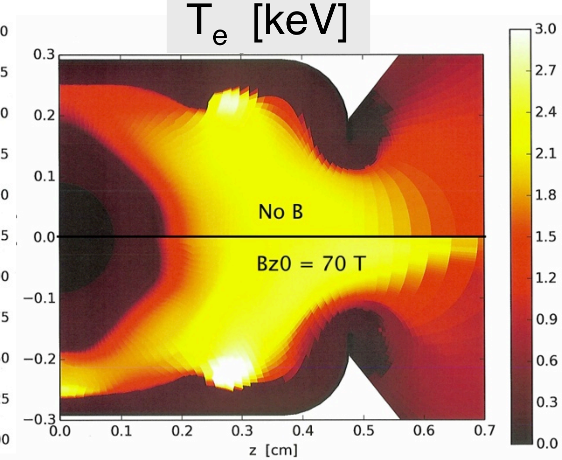
Material Region



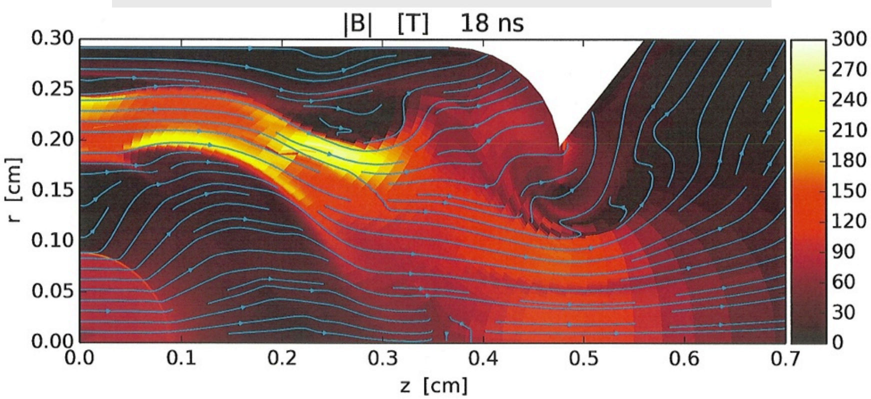
n_e/n_{crit}



T_e [keV]

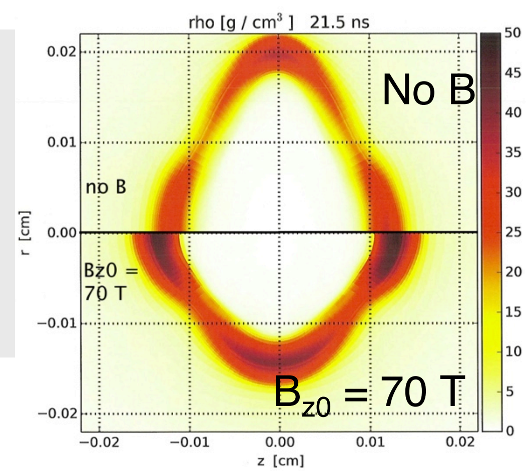


IBI 18 ns: field lines frozen in to plasma flow



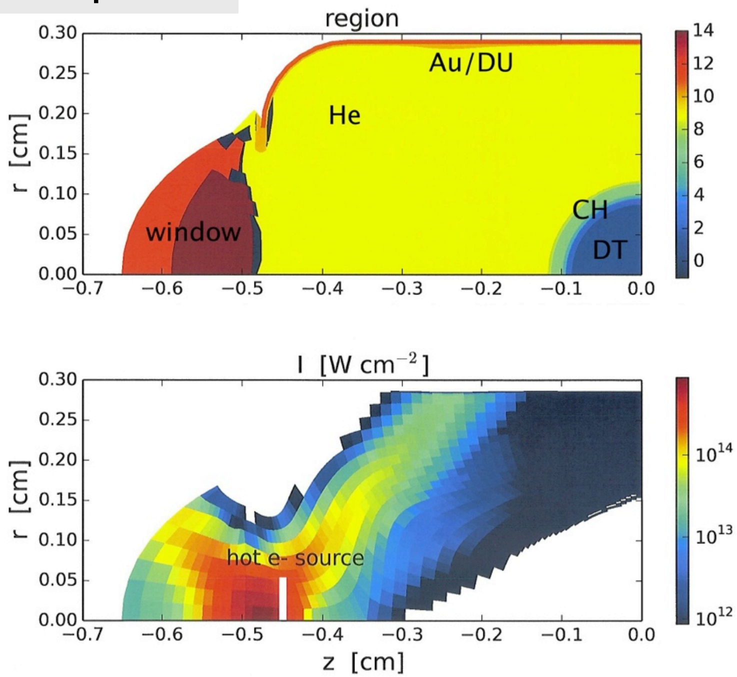
21.5 ns:

- No B: shell oblate (pancaked)
- with B: close to round, better inner-beam propagation

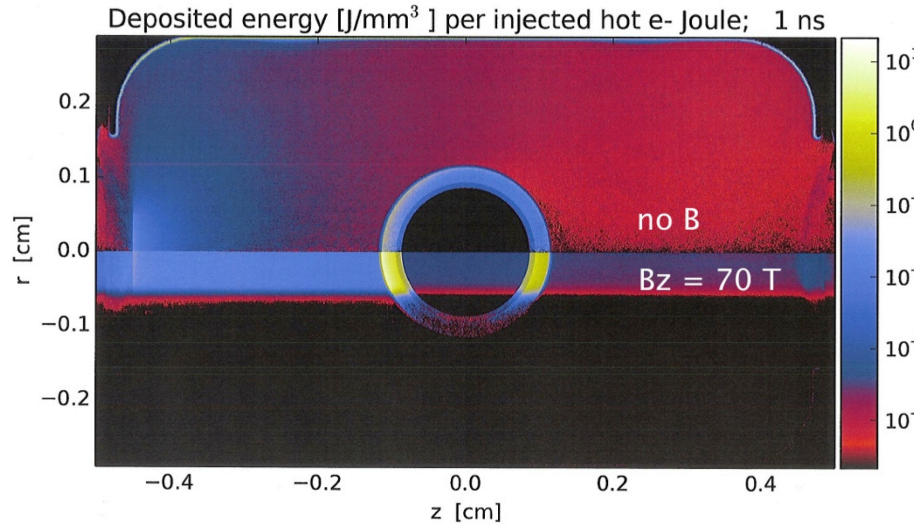


Coupled HYDRA-ZUMA hot electron propagation studies: Early-time picket

1 ns: picket



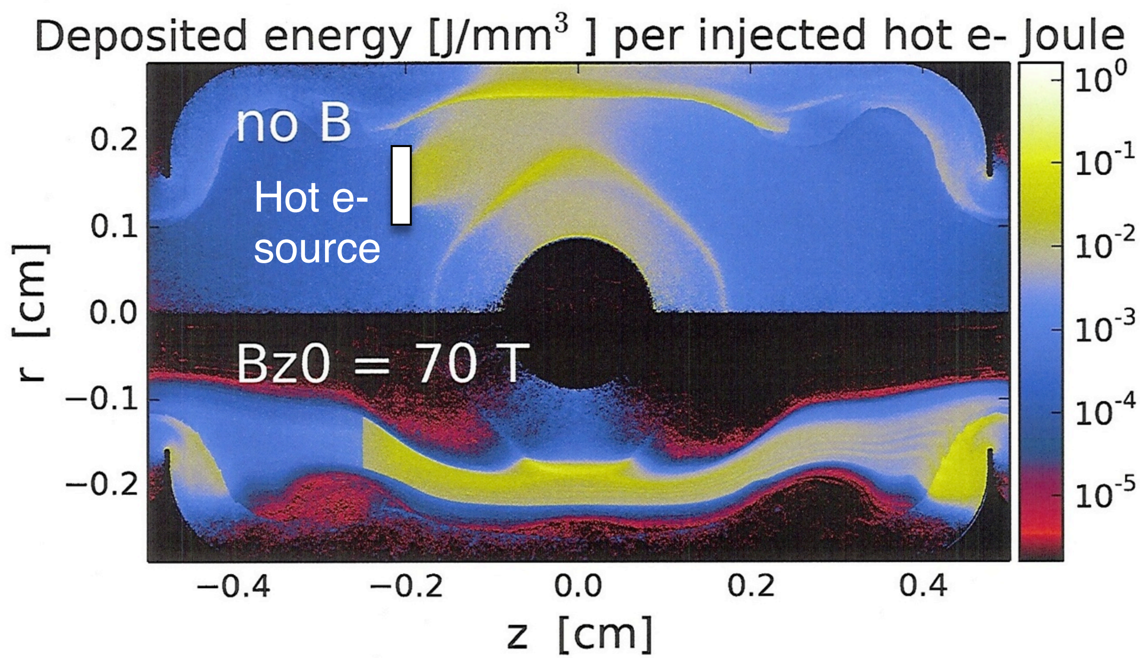
Hot electron energy deposited



- Hot e- source based on two-plasmon decay in window: T_{hot} = 80 keV, R=500um
- B_z = 70 T (uniform) magnetizes hot e-'s in fill gas, transported directly at capsule
- Fraction of hot e- energy deposited in DT ice: no B: 2.2E-3, with B: 2.6% **(12x higher)** but still only ~20mJ so OK? (hi-foot/picket?)
- Pre-heat concentrated along poles – may be shape issue
- Absolute preheat depends on hot e- production, which NIF has shown is controllable by picket pulse shaping (e.g. low-power “toe”). ⇒Design around?

Coupled HYDRA-ZUMA hot electron propagation studies: Late time peak power

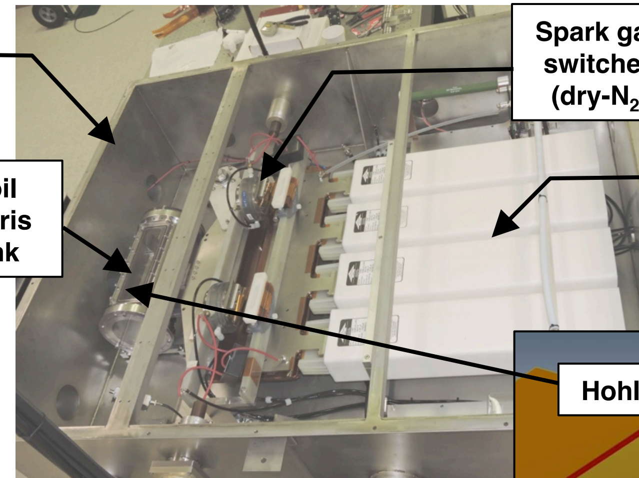
- Time 18 ns: early peak power
- Hot e- source based on inner-beam Raman scattering: T_{hot} = 30 keV, 27° propagation angle
- B field and plasma conditions taken from HYDRA MHD simulation at this time



- Hot e-'s magnetized in fill gas, follow field lines outside of capsule (frozen-in to flow)
- Fraction of hot e- energy deposited in DT ice: no B: 1.2E-4, with B: 3.4E-6 **(35x lower)**

We are performing power supply and hohlraum coil tests in our B490 lab. Coils are wound and potted in B321

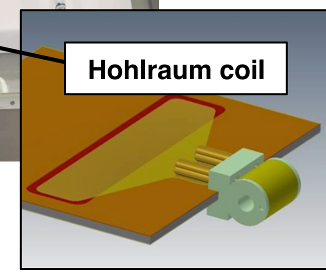
Main tank



Spark gap switches (dry-N_2)

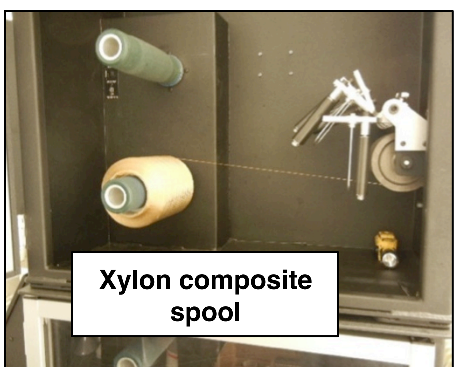
Coil debris tank

Capacitor

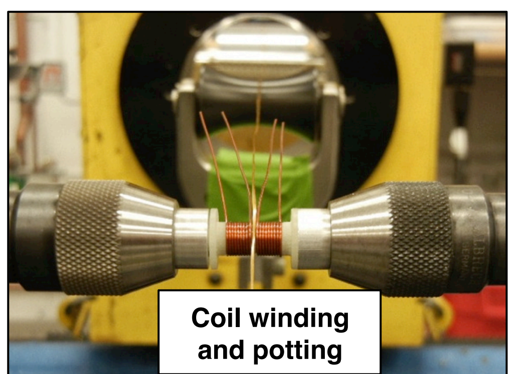


Hohlraum coil

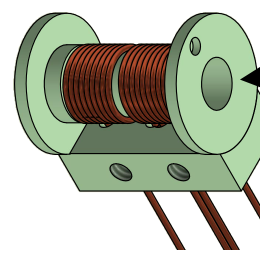
B490 Lab.



Xylon composite spool



Coil winding and potting



Center-fed dual coil 6mm dia hohlraum dimension 50T/70T

B321 Winding Facility

Design field =50T (70- max). Tested 5 prototype coils (18 shots). 31T attained presently limited by sparkgap switches and air box

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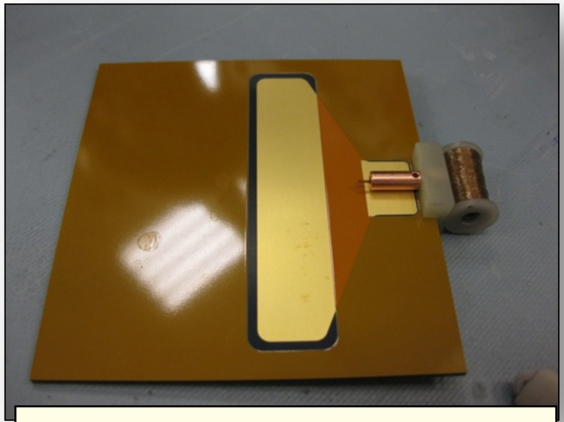
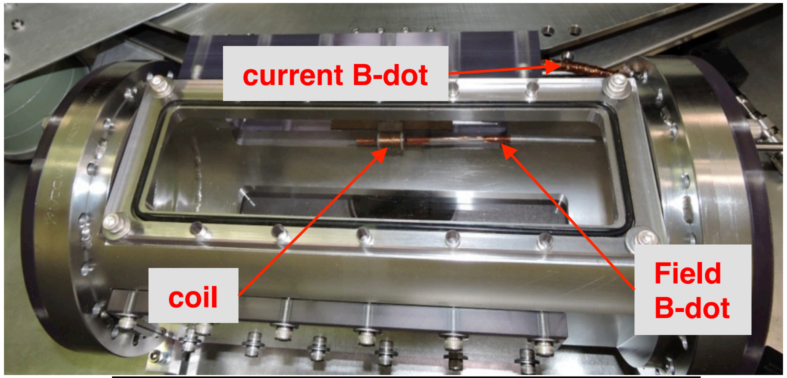
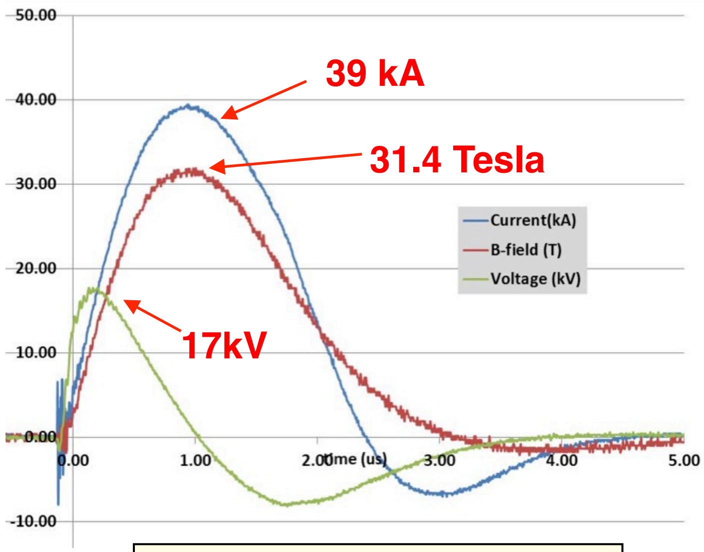


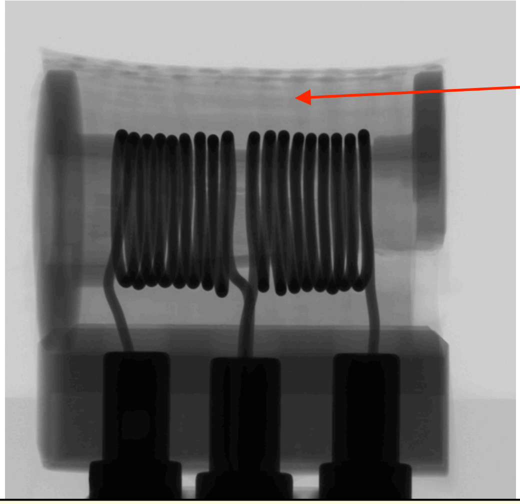
Wound potted coil and T-line



Coil mounted in debris tank



Waveforms – 31T shot



31T coil after shot

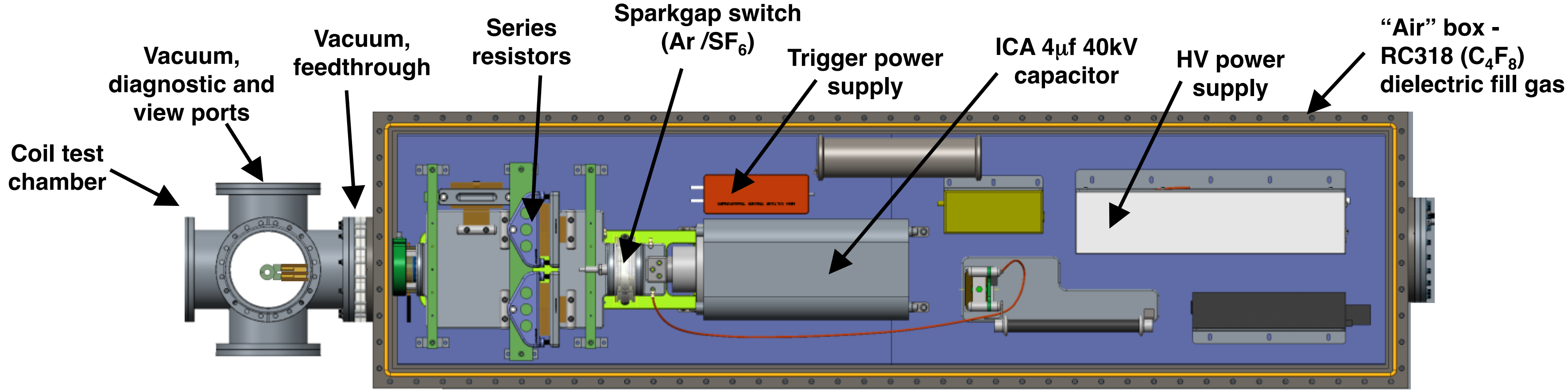
Tensile strength of Xylon composite ~ 5800 MPa.

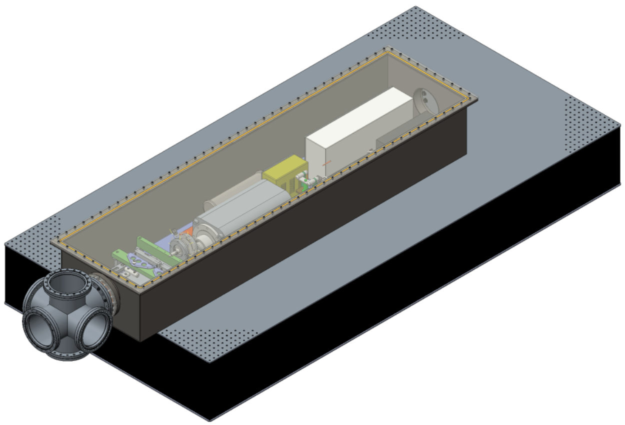
Tube stress at 50T ~1600MPa.

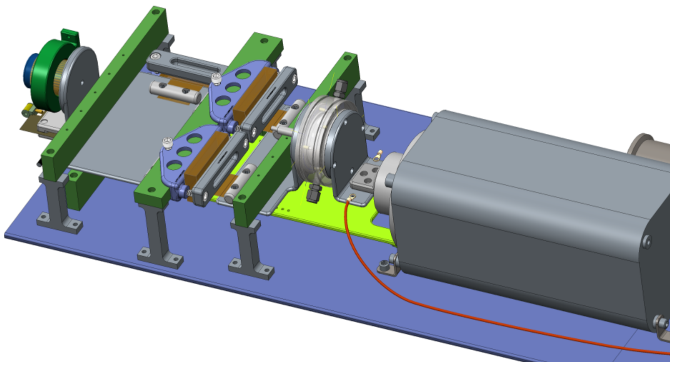
So shouldn't disassemble

(ALE3D suggests no melt at 50T, 70% of melt at 70T but after peak field is reached)

A new test tank with NIF-integrable components is under construction for vacuum coil tests this summer in our B490 lab.





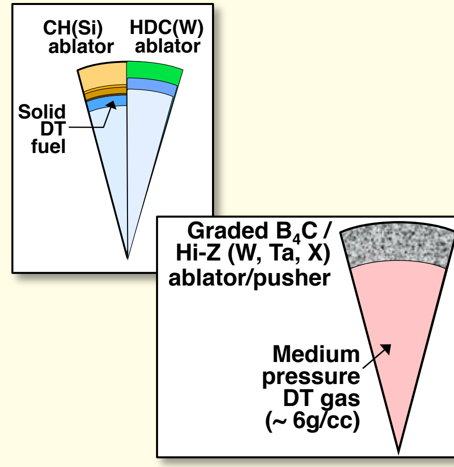


A NIF engineer (Phil Datte) is liaison to the LDRD project to assess 2016 NIF integration. The NIF FY16 new experimental capabilities program contains a line item for this (NNSA MTE 10.3 - NIF Diagnostics, Cryogenics, and Experimental Support)

Where to from here?

Cryo Ignition Targets

- Application of imposed B-field to the high alpha (α=4) “robust hotspot” option to boost yields above 10^{17} neutrons
- Investigation of suppression of hotspot RT instabilities at high mode number
- Determine feasibility of engineered mirror fields by imposed P4’s
- Recommended final design of HDC and CH cryo targets with B-field

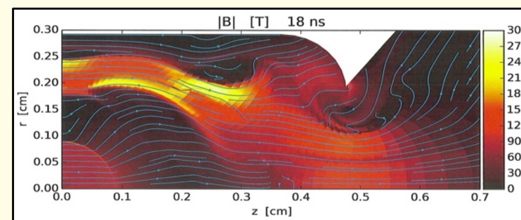


Room-Temperature Metal-Gas Targets (first expts?)

- 2D integrated hohlraum capsule design(s)
- Target fab, experimental planning

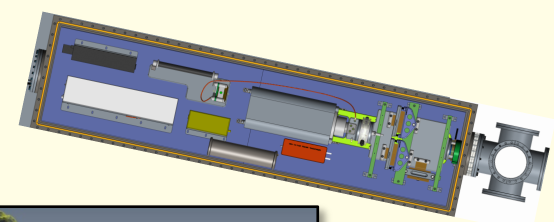
Hohlraum Physics

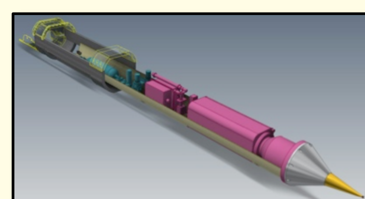
- Final assessment of B-dependent hohlraum conditions (laser and hot-e transport)
- Examination of room-temp fill gases



Power Supply & Hohlraum Coils

- Complete construction of NIF-integratable pulsed power system
- Coil tests to determine final nominal-operating and maximum attainable fields (room-temperature coils)
- Addition of U-hohlraum sleeve and characterization of hohlraum conditions under field
- Design (but not construction) of cryo-capable T-line and coil (??)
- NIF integration liaison





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

LDRD
Laboratory Directed Research and Development

- **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