Workshop and User Meeting on Fundamental Science using Pulsed Power and High Power Lasers
Santa Fe, NM, July 29, 2011

Magnetized HED breakout session outbrief

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Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

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Topics discussed

- Discussion of new ideas and how to grow the community
- Experimental possibilities for scaled ionization expts
- Measuring magnetic fields in HED expts on Z
- Cluster fusion & related laser expts
- Magnetized plasmas and jets
- Infrastructure & Diagnostic needs

Discussions on how to grow the community

- A major challenge of magnetized HED experiments is that almost by definition they are not "ride-along" or "beamline" experiments—they are driven by the facility itself
- Community sees value in "scaling" experiments up to Z
  - University-scale pulsed power is generally 1 MA, up to 2 MA
  - Big step to go from ~1 MA to ~25 MA (>600x increase in pressure!)
  - SATURN would seem to be ideal (5-6 MA) as intermediate facility, but
    - …SATURN is on standby unless a paying customer exists
    - …cost of doing SATURN shots is high for universities
    - …almost no permanent diagnostics & diagnostic access is poor
  - Alternate option could be "low-current Z" to take advantage of existing diagnostic infrastructure, but has not been demonstrated
- Professors see value in sending students to the lab for extended times
  - Local technical mentors essential, builds interest from students in labs
- Mark Koepke discussed "Distinguished Lecturer" program (as a potential "missionary" effort)
- Interest in having a "MagLIF workshop" to look for opportunities for both fundamental and applied science within the community

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Discussion of new ideas focused on the output of the ReNeW report for the magnetized HED area

- What is the maximum magnetic pressure we can achieve in the laboratory?
- For sufficiently strong magnetic fields, can we study new frontiers of atomic physics?
- Can we understand how magnetic fields affect laser absorption and plasma transport processes?

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What is the maximum magnetic field we can achieve?

Pulsars have fields ~ 10^{12} G and Magnetars have fields > 10^{14}G (P~ $4*10^{20}$Bar)!

Above ~ 10^9 G the magnetic field is large enough to significantly change atomic structure

What can we reach? By applying a large current at small radius:

$$B_\theta(G) \sim \frac{I(\mathrm{A})}{5R(\mathrm{cm})}$$

25 MA at 100 μm -> 500 Megagauss!

We can also do flux compression in cylindrical geometry by doing an implosion

$$B_f \sim B_0\left(\frac{R_0}{R_f}\right)^2$$

For B_0=500kG (50T) at CR ~45 with little loss leads to B_f= 1 Gigagauss

These conditions are well beyond the state of the art, but could provide a long term challenge

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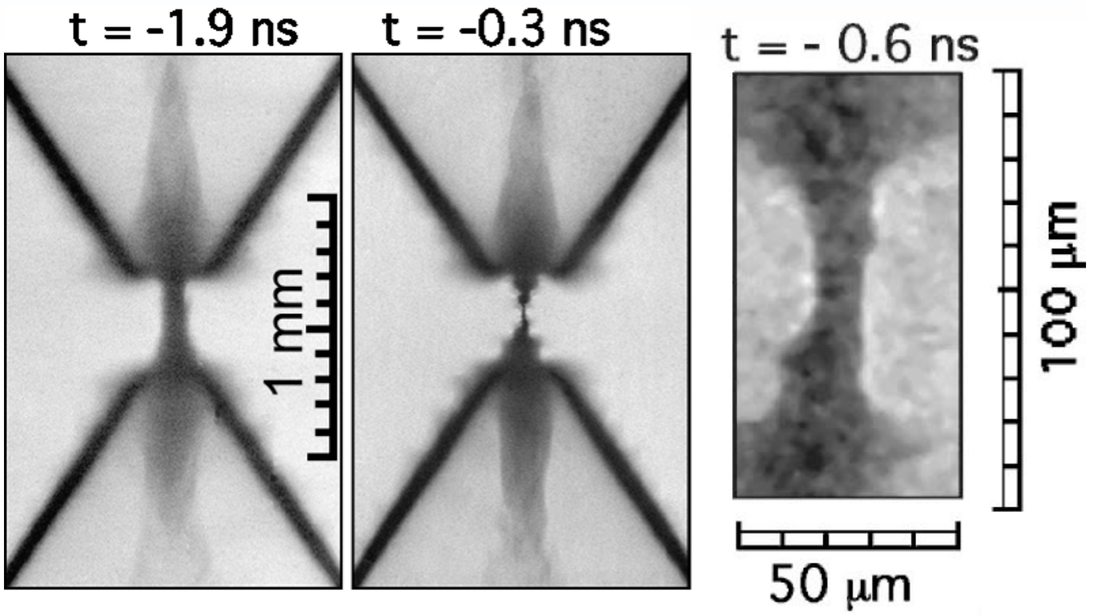
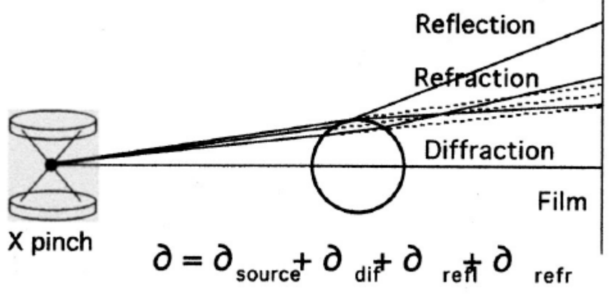
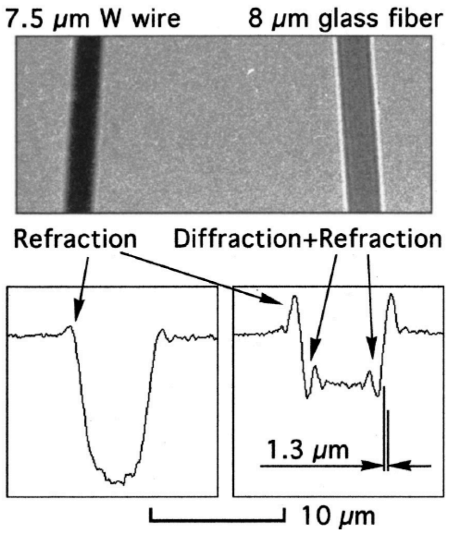
X pinches driven by 200 kA currents are an extreme example of current reaching small radius

- **Diameter: 1.2±0.5 μm**
- **Duration: 10-100 ps**
- **T_e: ~1 keV (Ti, Mo)**
- **n_i: ≥0.1 * Solid density**
- **Matter pressure at ~1 g/cc and 1 keV is ~1 Gbar**
- **200 kA at 1 micron radius has magnetic pressure ~ few Gbar!**







How much current gets to 1 μm?
Why does it stop at 1 μm?

T.A. Shelkovenko *et al.*, RSI 72, 667 (2001).

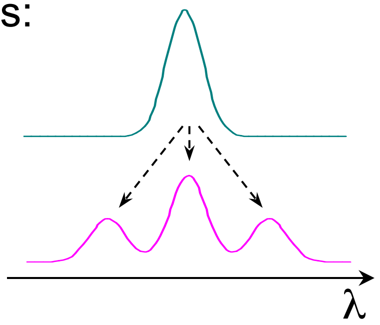
Very large magnetic fields can significantly affect atomic orbits

Magnetic effects are determined by the relative contributions of Coulomb, spin-orbit, and magnetic field interactions to the Hamiltonian:

$E^C \sim Z^2/n^2$ Ry $\quad E^{SO} \sim \alpha^2 Z^4/n^3$ Ry $\quad E^B \sim B/B_0$ Ry + $O(B^2)$

Ry =13.6 eV, $B_0 = 2.35\times10^9$ G

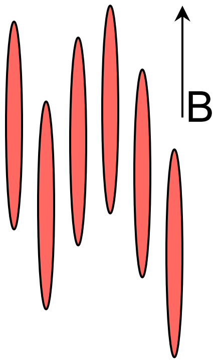
For near-neutrals (Z~1), magnetic fields can give the following effects:



$E^C >> E^{SO} >> E^B$ → Zeeman splitting for B ~ 10^4 Gauss (1T)

$E^C >> E^B >> E^{SO}$ → Paschen-Back effects for B ~ 10^6 Gauss

$E^B >> E^C >> E^{SO}$ → Landau effects for B ~ 10^9 Gauss:



- electrons are confined in Landau orbits ⊥ to B, compressing atoms to one-dimensional "needles" aligned with B in the high-field limit

$$B/4B_0 >> Z^3$$

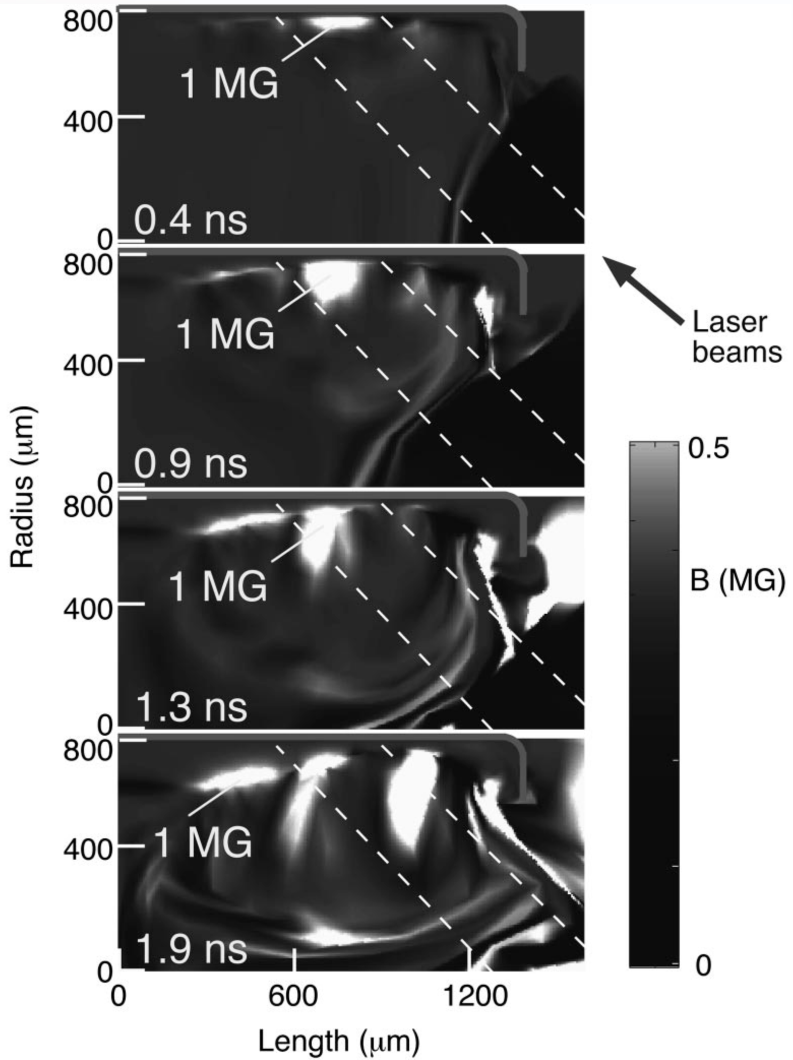
- binding energies increase from ~Z^2/n^2 to ~ $Z(B/2nB_0)^{1/2}$; highly charged negative ions with 4/3 Z bound electrons might exist in the high-field limit

High fields in HED plasmas enables investigations of Zeeman & Paschen-Back effects for Z>>1. Accessing the more exotic effects requires fields that scale as ~ B_0Z^3 and challenges us to limit ionization in or near the extreme environments that can generate B ~ B_0.

Garstang, Rep. Prog. Phys. 40, 105 (1977)

Lieb et al. Comm. on Pure and Applied Mathematics XLVII, 513 (1994)

Magnetic Fields can be spontaneously generated from plasma gradients in HED plasmas



Magnetic field generation is ubiquitous in HED plasmas:

$$\frac{\partial \mathbf{B}}{\partial t} = \frac{\nabla T_e \times \nabla n_e}{e\, n_e}$$

These fields do not affect the plasma motion ($\beta \sim P/B^2 >> 1$)

The fields can significantly change electron heat transport since $\Omega\tau > 1$. This in turn can lead to changes in deposition.

Simulations suggest this field can have 10-20% effects on the electron temperature in laser hot spots

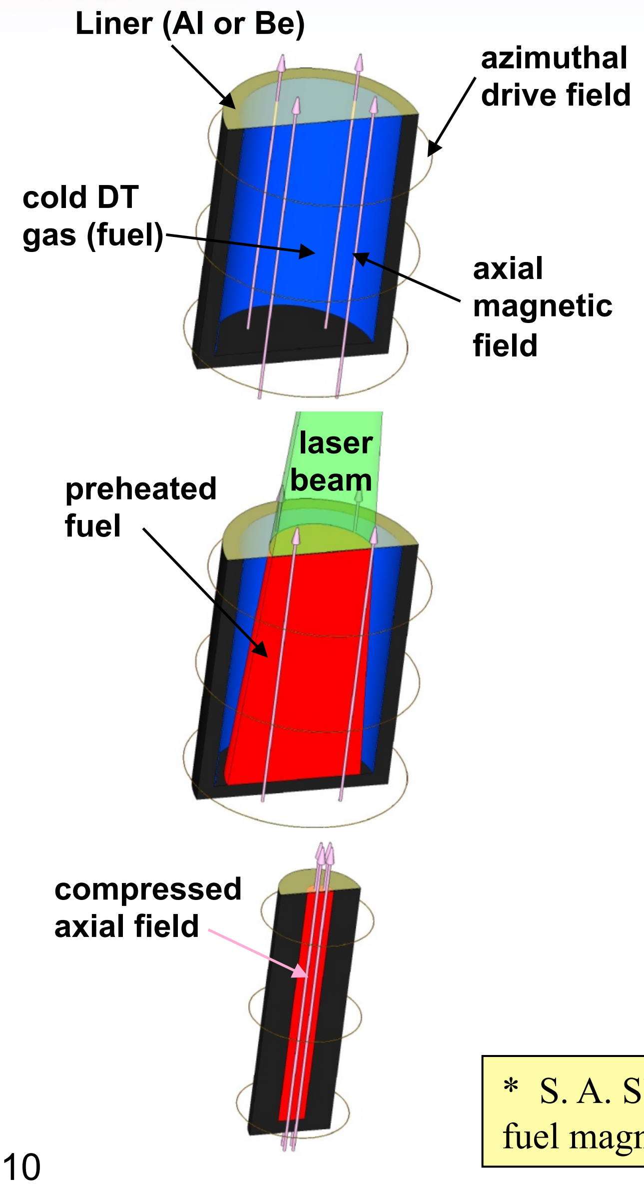
This will need to be validated to have a complete understanding of hohlraums

R. P. J. Town, UCRL PRES-216240

Experimental possibilities for scaled ionization experiments

- **Discussed the MagLIF platform and whether similar or scaled conditions can be achieved in university laboratory experiments that are relevant to MagLIF**
- **Important to find “fundamental” physics items for study that while they may be motivated by applications, still stand on their own right as scientifically interesting**
- **An example could be plasma/energy transport in the presence of a strong magnetic field**

The ICF program on Z is working toward an evaluation of a new Magnetized Liner Inertial Fusion (MagLIF)* concept



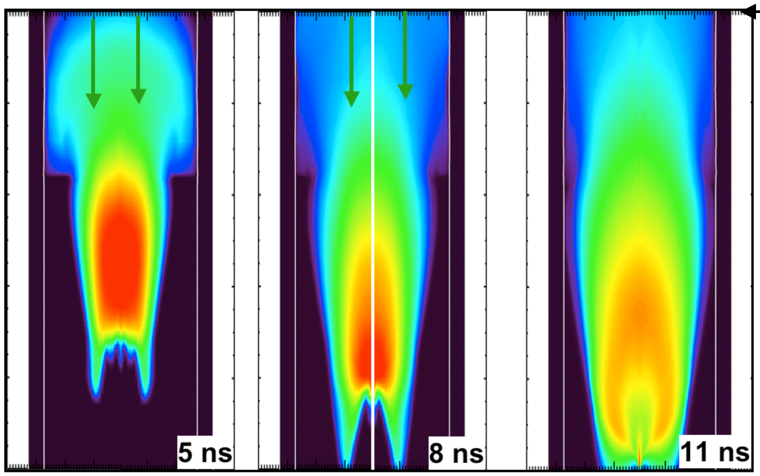
- **Idea: Directly drive solid liner containing fusion fuel**
- **An initial ~10 T axial magnetic field is applied**
    - **Inhibits thermal conduction losses**
    - **Enhances alpha particle energy deposition**
    - **May help stabilize implosion at late times**
- **During implosion, the fuel is heated using the Z-Beamlet laser (<10 kJ needed)**
    - **Preheating reduces the compression needed to obtain ignition temperatures to 20-30 on Z**
    - **Preheating reduces the implosion velocity needed to "only" 100 km/s (slow for ICF)**
- **Simulations suggest scientific breakeven may be possible on Z (fusion yield = energy into fusion fuel); something not yet been achieved in any laboratory**

* S. A. Slutz *et al*., "Pulsed-power-driven cylindrical liner implosions of laser preheated fuel magnetized with an axial field," Physics of Plasmas 17, 056303 (2010).

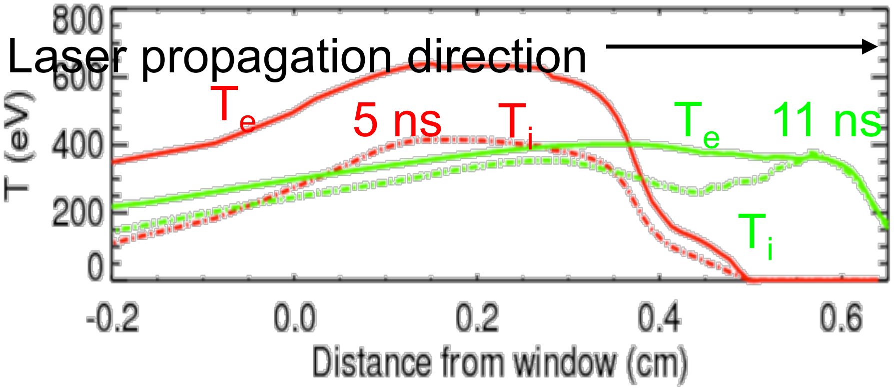
Simulations indicate the Z-Backlighter Laser could preheat fuel for experiments on Z

0.8 TW, 10 ns pulse, 1 mm spot radius, 2.5×10^{13} W/cm^2

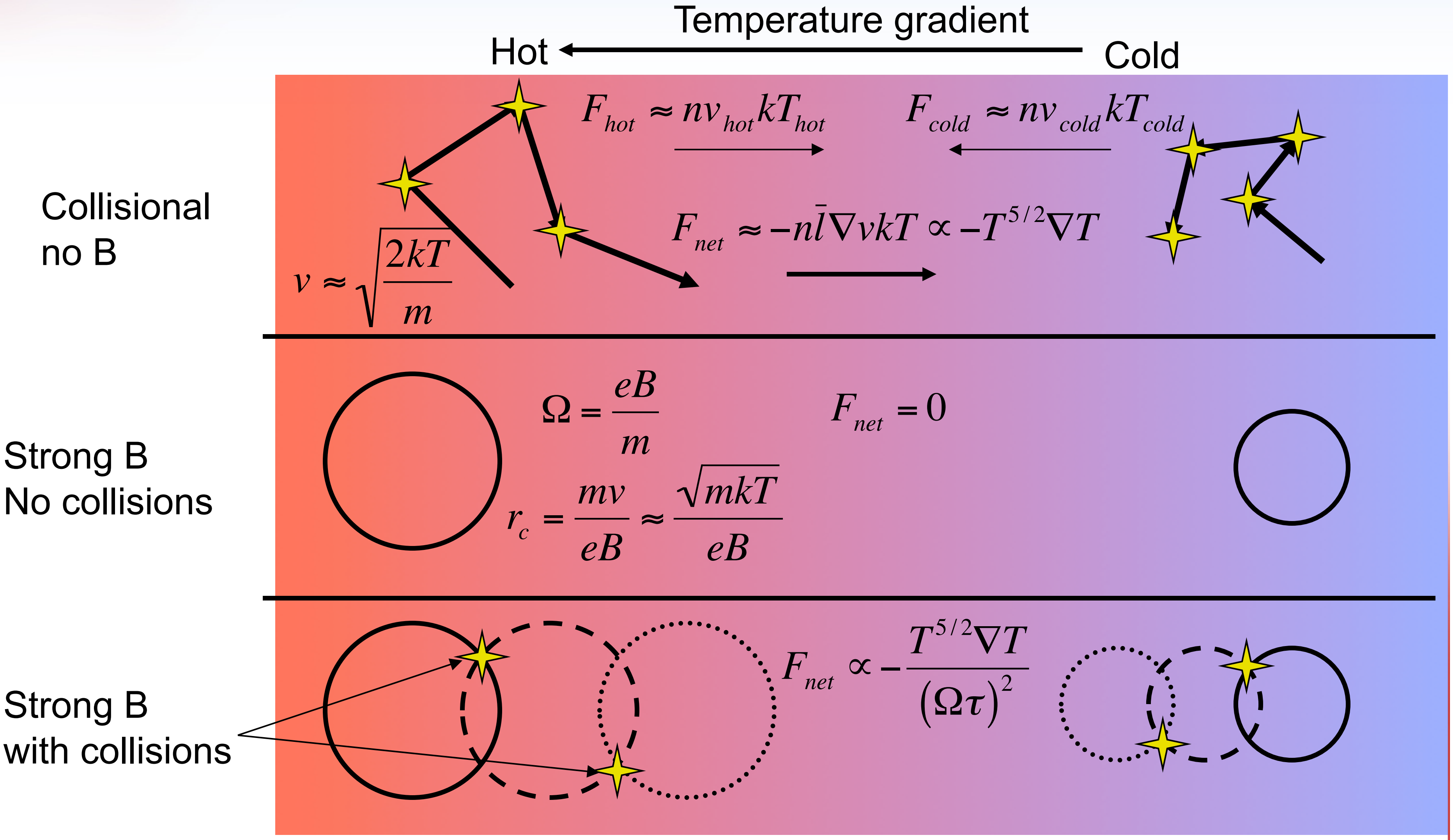
Electron Temperature contours (r,z)



- The gas can be held in place by a 1 μ plastic foil
- The critical density for green light is 4-7 x initial fuel density absorption by inverse bremsstrahlung
- The total laser energy needed <10 kJ
- analytic solution shows that the laser must bleach through the fuel



The presence of a magnetic field can strongly affect transport properties, e.g. heat conduction



Collisional
no B

$$F_{hot} \approx n v_{hot} k T_{hot} \qquad F_{cold} \approx n v_{cold} k T_{cold}$$

$$F_{net} \approx -n\bar{l}\nabla v kT \propto -T^{5/2}\nabla T$$

$$v \approx \sqrt{\frac{2kT}{m}}$$

Strong B
No collisions

$$\Omega = \frac{eB}{m}$$

$$r_c = \frac{mv}{eB} \approx \frac{\sqrt{mkT}}{eB}$$

$$F_{net} = 0$$

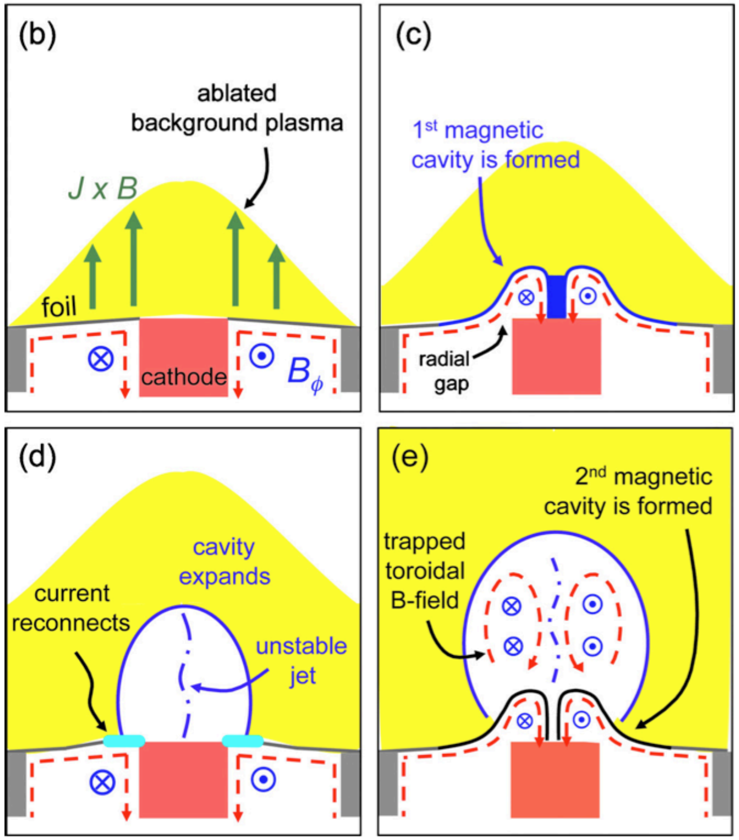
Strong B
with collisions

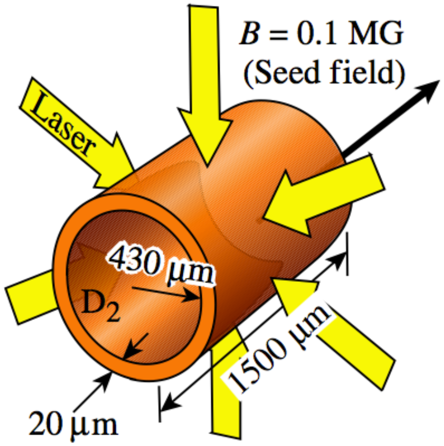
$$F_{net} \propto -\frac{T^{5/2}\nabla T}{(\Omega\tau)^2}$$

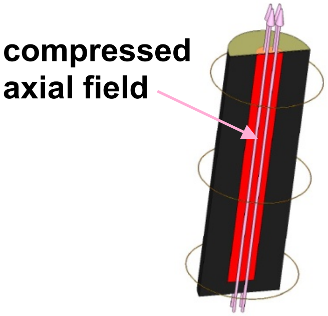
Energetic particles can also be strongly affected by magnetic fields

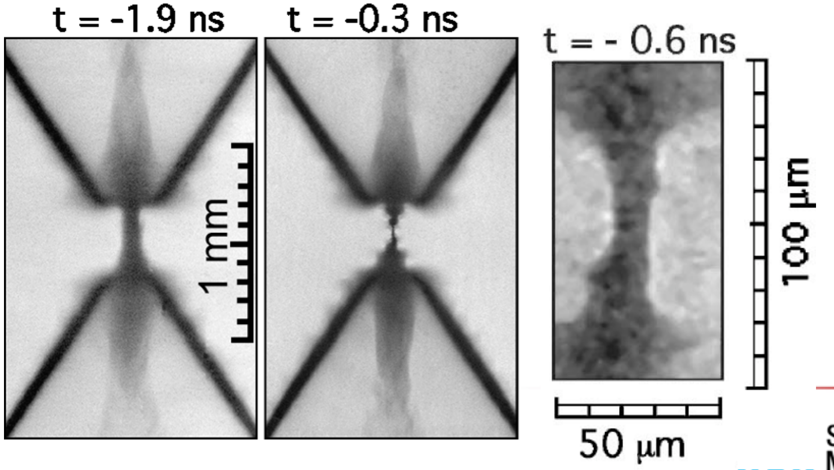
Measuring magnetic fields in HED expts on Z

- **Measuring magnetic fields in compressed, magnetized plasmas, is a major challenge common to all magnetized HED systems**
- **Challenges in spatial scale, time scale, densities, & velocities**



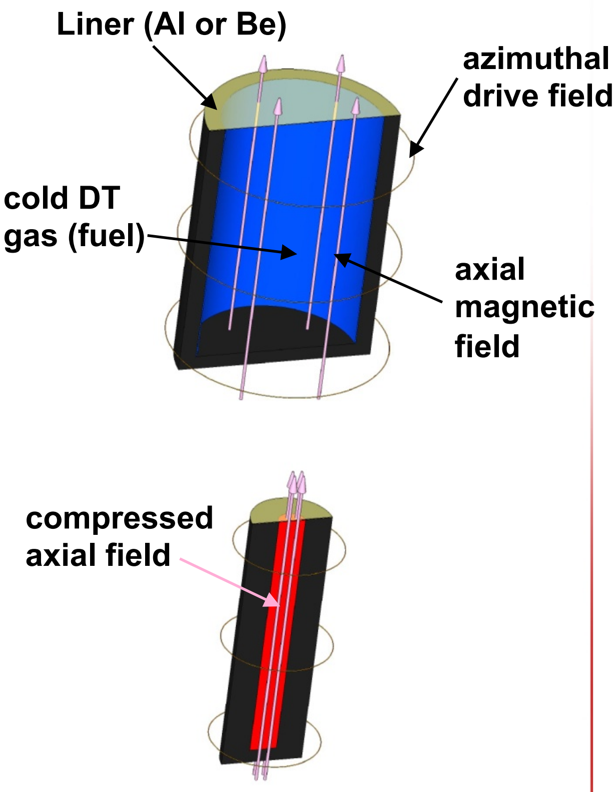




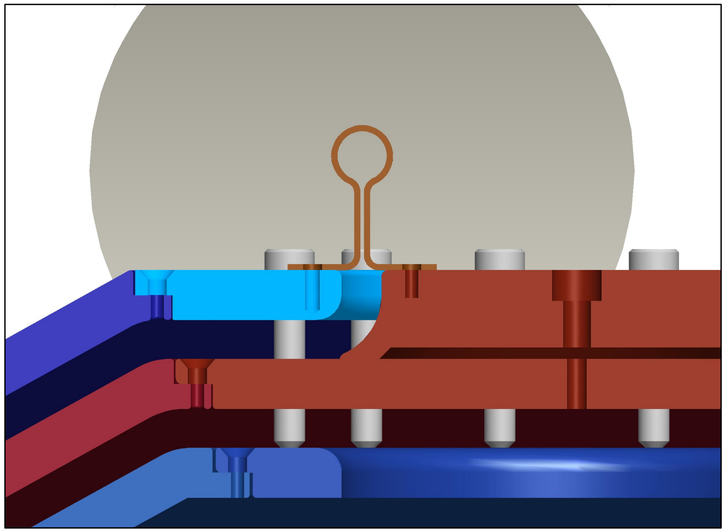


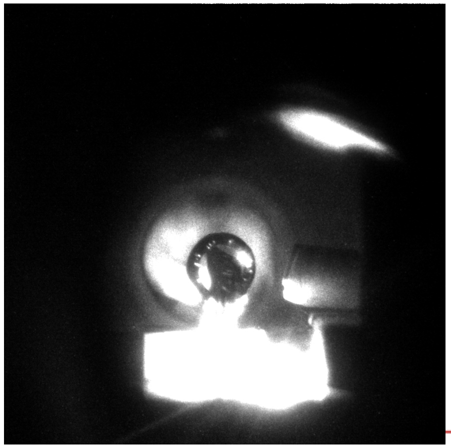
Many measurement techniques don't scale well to Z conditions—MagLIF example

- Spent a great deal of time discussing MagLIF conditions as an example:
  - Bdot probes would require a very small loop area, only work well in non-plasma situations
  - Proton deflectometry (used very well on Omega) difficult due to higher Bfield and larger spatial scale of Z experiments
  - Zeeman splitting complicated by high opacity of plasma (need multi-keV photons), high velocities (Doppler broadening), high densities (Stark broadening), and small magnitude of Zeeman
  - May be possible to use Faraday rotation with fibers on axis of liner, but only under non-plasma conditions?
- I owe Alan a list of conditions in MagLIF for further contemplation by others…



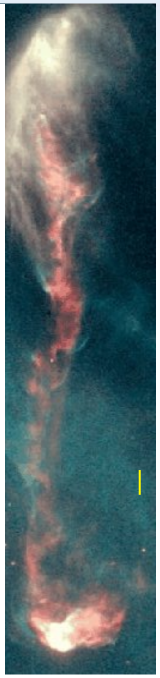
Magnetized cluster fusion experiments on Texas Petawatt are making progress





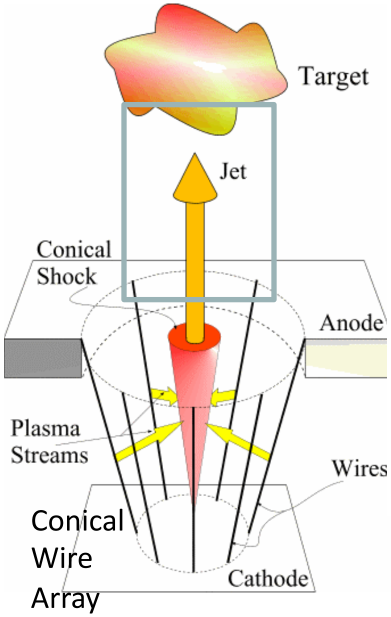
- Motivated by trying to achieve higher fusion neutron yields from clusters by using magnetic confinement
- Sandia-designed coils arrived at UT, being assembled
- System tested to 400 kA, 50 T fields
- Issues being worked on:
  - Paschen breakdown
  - Enough clusters in high-field region?
  - Design of the coil mount
  - Coil debris
  - Funding
- Expect shots in Summer 2012 on Texas Petawatt

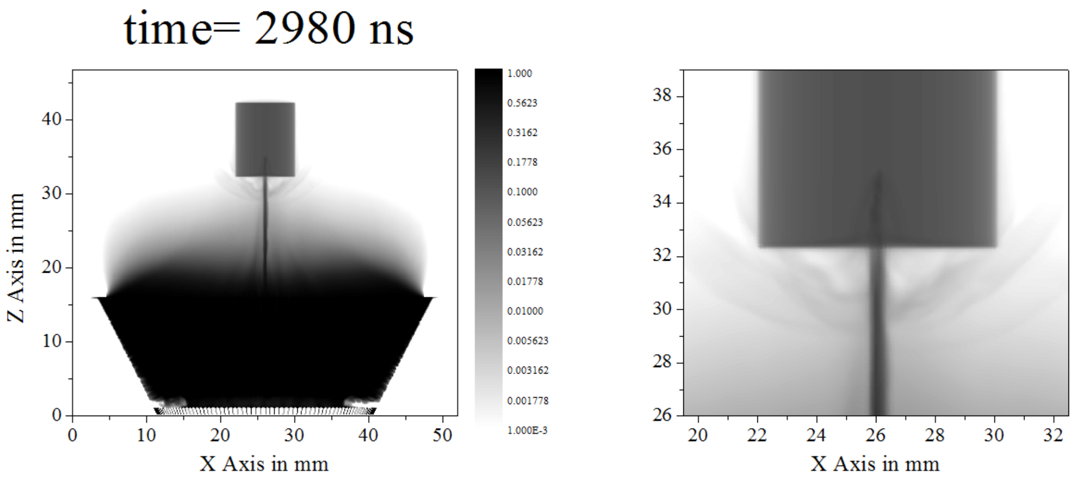
Magnetized plasma jet discussion



HH-47 (Credit: NASA, HST, WFPC 2, J. Morse)

- Simulations of turbulent jets are limited by numerical Reynolds Number
  - Experiments can test validity of simulations in similar regime
  - To be good test of simulations, experiments should have
    - High Reynolds number (to allow turbulence)
    - High radiative cooling (properly capture energy loss across shocks)
    - High mach number flows





3 experiments in Jan. 2011 showed jets could be made, but returned little quantitative data
2 experiments in Oct. 2011 will study jet interaction with a foam using 6.151 keV backlighting

Infrastructure & Diagnostic needs

- **Interest in optical shadowgraphy & interferometry**
  - **Can observe plasma dynamics “easily and cheaply” on most shots**
  - **Sensitive to low-density plasmas that radiography can’t see**

- **Again long discussions on how to measure magnetic fields**
  - **(Can ultra-high harmonic sources be used?)**

- **May be some interest in using the 10-30 T axial B-field coils in future fundamental science experiments**
  - **Magnetized plasma jets**
  - **Opacity measurements in presence of strong fields**

Extra slides

Actual Agenda

8:30-9:30	Discussion of new ideas
9:30-10:15	Experimental possibilities for scaled ionization expts
10:15-10:45	Measuring magnetic fields in HED expts on Z
10:45-11:45	Cluster fusion & related laser expts
1:30-2:30	Magnetized plasmas and jets
2:30-3:00	Infrastructure & Diagnostic needs

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What are Magnetized High Energy Density Plasmas and what is interesting about them?

A working definition of Magnetized High Energy Density Plasmas :

HED Plasmas with fields magnetic fields > 5 Megagauss (Magnetic Pressure > 1 MB)

and/or

HED Plasmas whose transport processes are significantly affected by the presence of a magnetic field

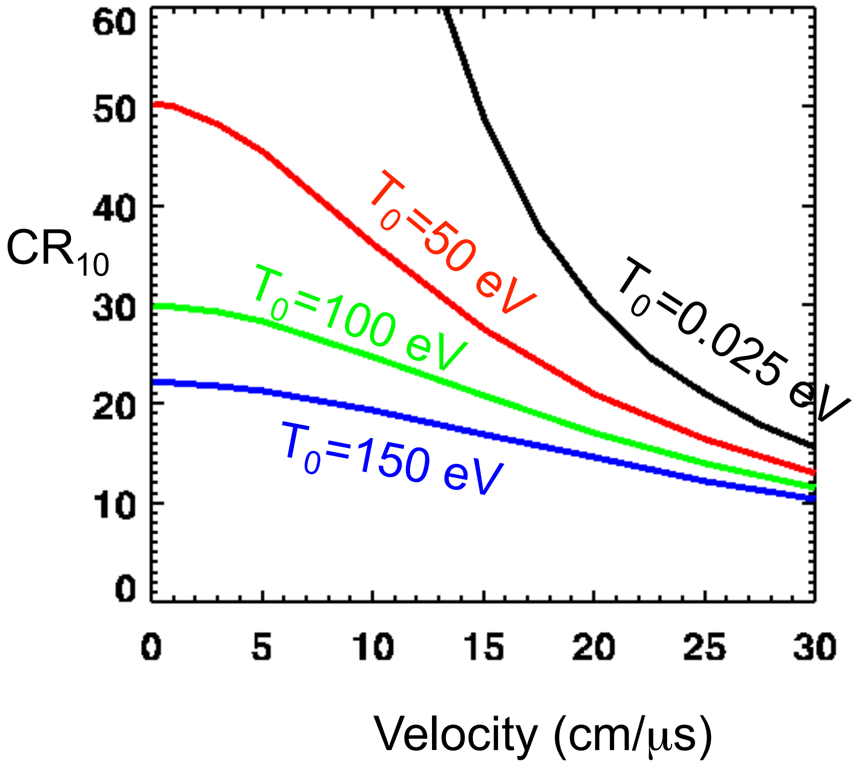
If strong enough Magnetic Fields fundamentally alter the behavior of HED plasmas:

- Magnetic fields and currents can push on plasmas in unique ways
- Magnetic fields can be spontaneously generated and amplified
- Magnetic fields change the way particles and energy are transported in a plasma

Preheat is necessary for liner implosions, which are slow

CR_{10} = Convergence Ratio (R_0/R_f) needed to obtain 10 keV (ignition) with no radiation losses or conductivity

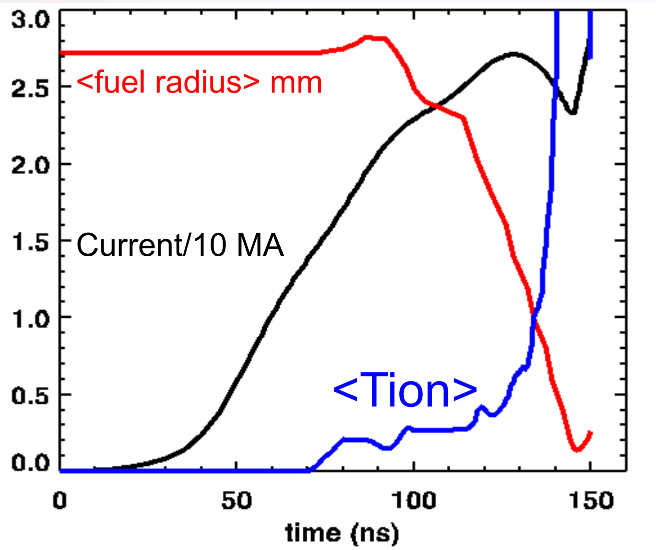
Lasnex simulation with constant velocity

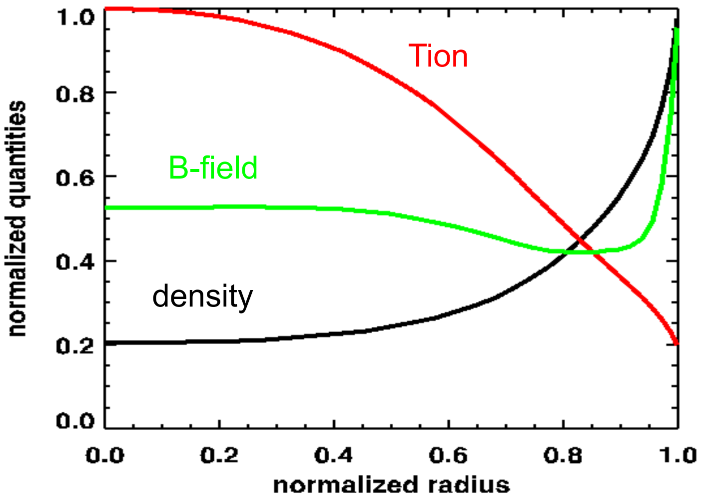


Fuel can be heated to ignition temperature with modest Convergence Ratio when the initial adiabat is large

- adiabat set by implosion velocity (shock) or
- alternatively by fuel preheat plus shock

We are working toward a MagLIF point design for Z





We are using Lasnex to simulate MagLIF

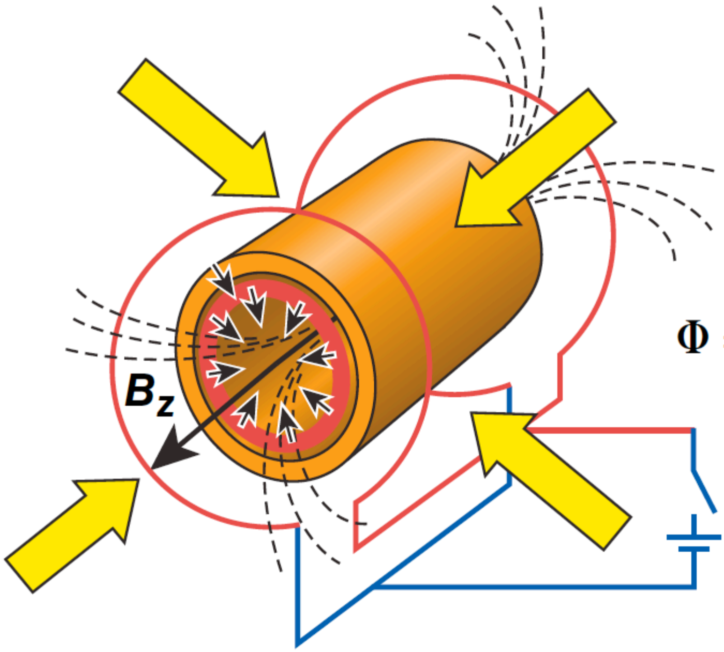
- Well benchmarked
- Radiation hydrodynamics
- Includes the effect of B on alphas

Preliminary point design parameters

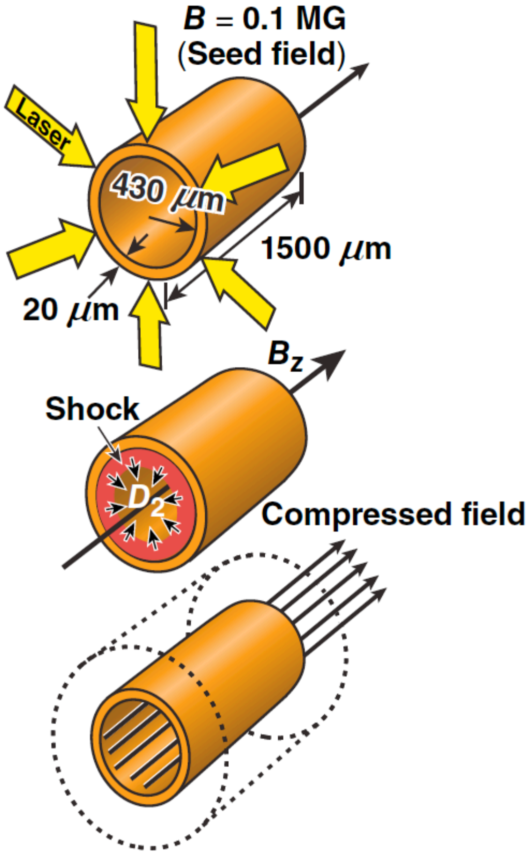
•Beryllium liner R_0	2.7	mm
•Liner length	5.0	mm
•Aspect Ratio $R_0/\Delta R$	6	
•Initial fuel density	0.003	g/cc
•Final fuel density <on axis>	0.5	g/cc
•Preheat temperature	250	eV
•Peak central averaged Tion	8	keV
•Initial B-field	30	Tesla
•Final peak B-field	13500	Tesla
•Peak current	27	MA
•1D Yield	500	kJ
•Convergence Ratio	23	
•Peak Pressure	3	Gbars
•EFUEL	120	KJ

The UR/LLE approach uses lasers to directly drive a cylinder with a preimposed magnetic field

- In a cylindrical target, an axial field can be generated using two Helmholtz-like coils; the target is imploded by a laser to amplify the field



$$\Phi = \pi B_z R^2 \approx \text{const}$$



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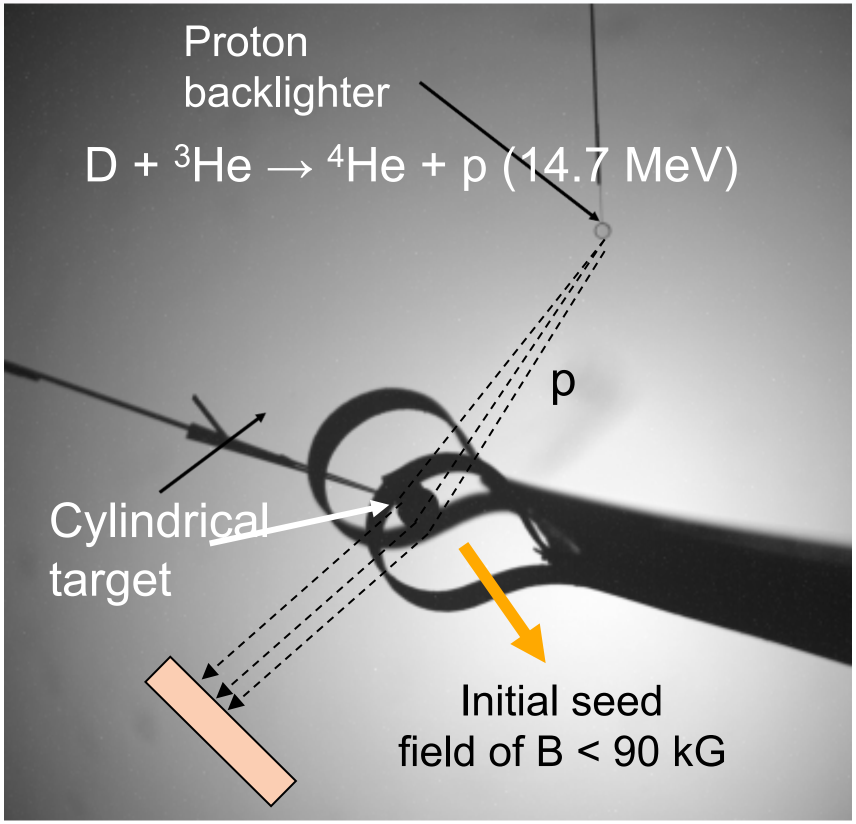
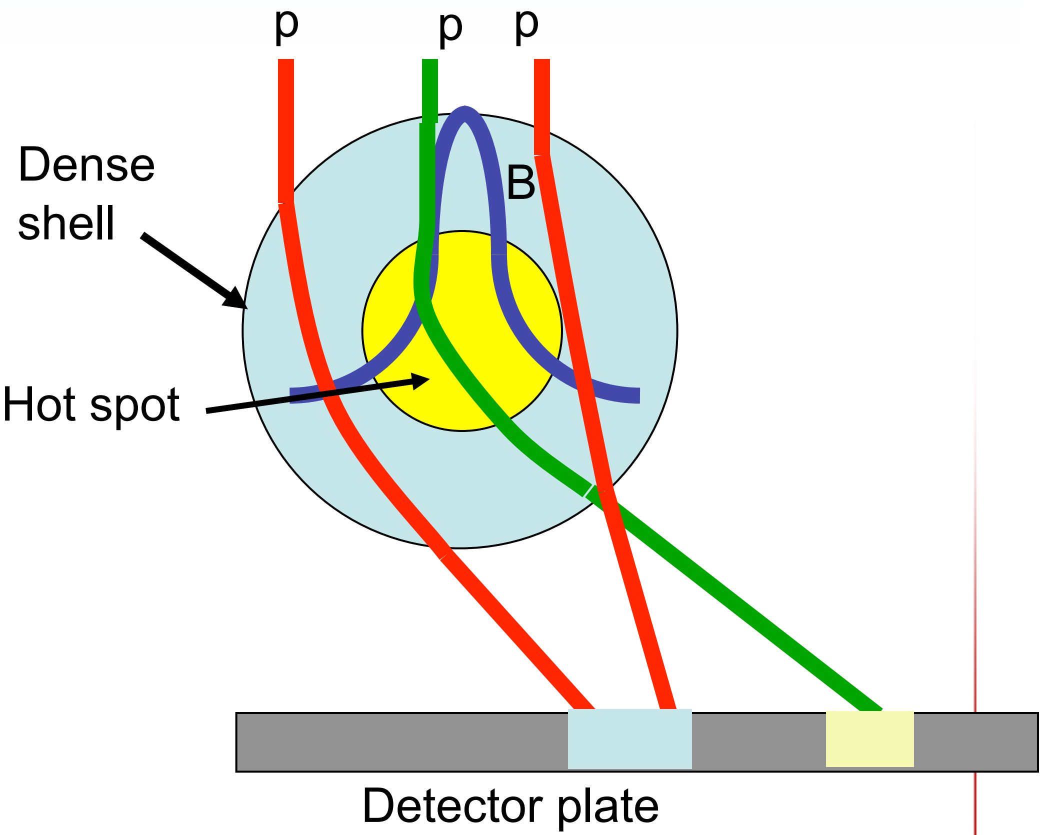
*O. V. Gotchev *et al.*, to be published in Phys. Rev. Lett.

Proton deflectometry is used to measure the magnetic field in the compressed core





<R*Bmax> ~ 0.052 MG-cm with 14.7 MeV protons
(30 MG hot-spot field, hot-spot radius ~17 microns)

vs. MagLIF: Seed field 30 T = 0.3 MG
Final field 13500 T = 135 MG
“Hot spot radius” ~ 125 microns