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Magnetized High Energy Density Plasma Physics

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NNSA National Nuclear Security Administration

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High Energy Density Physics Research Needs Workshop

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It’s an exciting time to be working in Magnetized HED plasmas

- Our understanding of Magnetized HED plasmas is being applied to important applications
- Ever more extreme conditions are being reached using magnetized HED plasmas
- We are poised for exciting advances in inertial confinement fusion using magnetized concepts
- New resources, computational tools, diagnostics, and facilities access can enable a rapid advance in our understanding of Magnetized HEDP

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

Our 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**

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Large currents and the corresponding magnetic fields can create and manipulate high energy density matter

$$\rho\left(\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u}\cdot\nabla)\mathbf{u}\right) = \frac{\mathbf{J}\times\mathbf{B}}{c} - \nabla P \approx \frac{1}{4\pi}\mathbf{B}\bullet\nabla\mathbf{B} - \nabla\left(P + \frac{B^2}{8\pi}\right)$$

Magnetic fields have some unique advantages when creating HED plasmas:

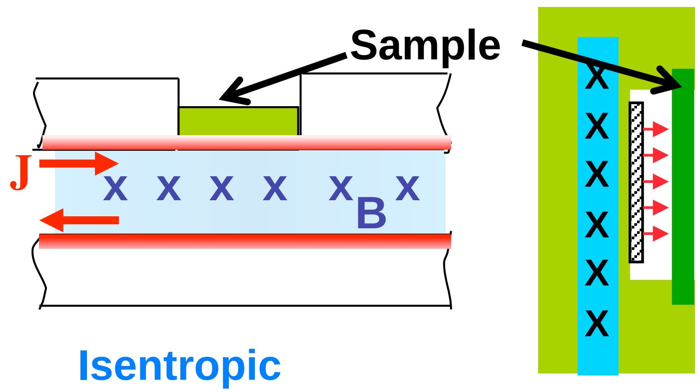
- **Magnetic fields are very efficient at creating HED matter enabling large samples and energetic sources**
- **Magnetic fields have very interesting properties in converging geometry**

Magnetic fields have interesting contrasts with other ways of generating HED:

- **Magnetic fields can create high pressures without making material hot**
- **Magnetic fields can be generated over long time scales with significant control over the time history**

Significant applications have emerged which apply our knowledge of Magnetized HED

Materials Properties

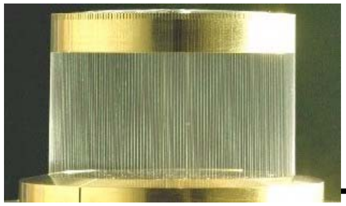


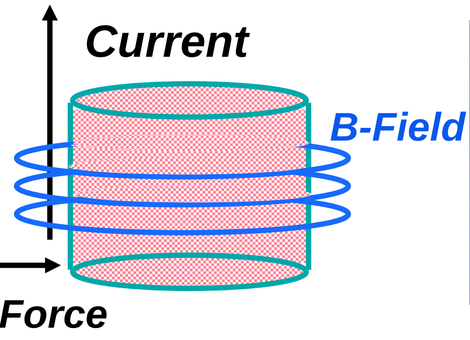
Isentropic Compression

Flyer Plate

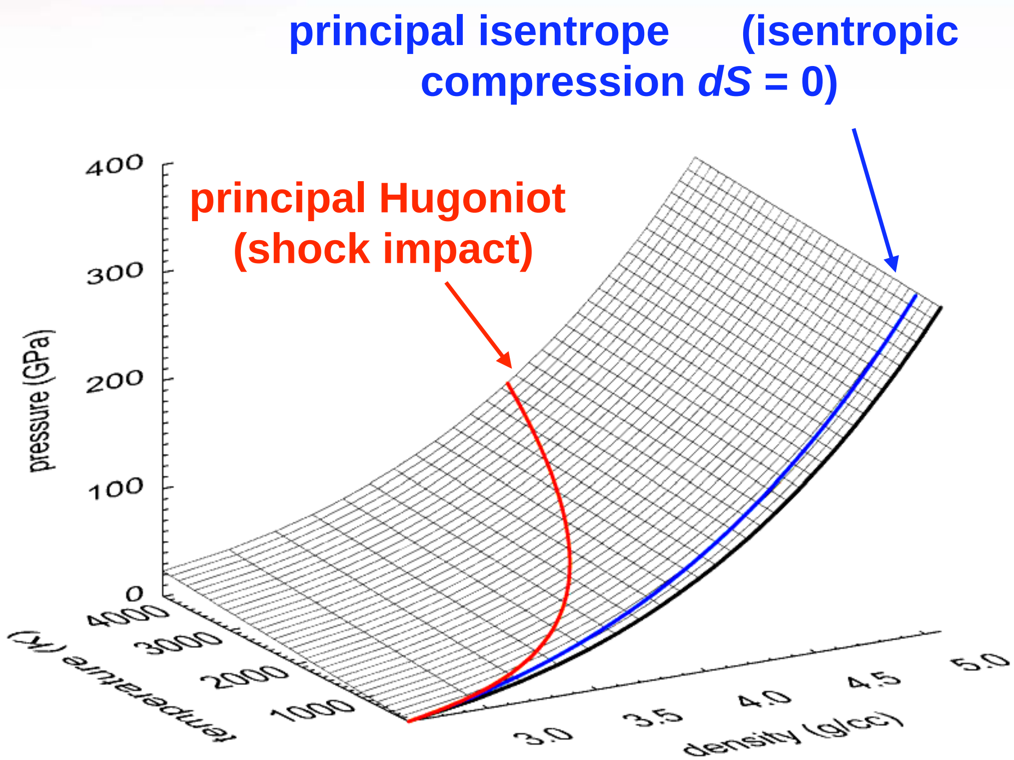
Z-Pinch X-ray Sources

wire array

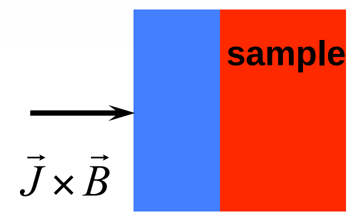




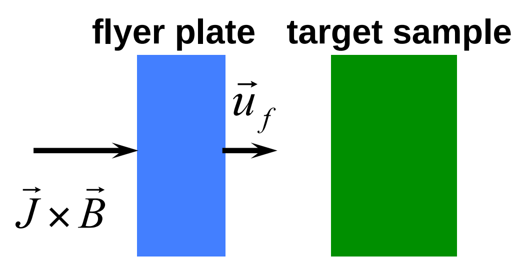
Understanding of Magnetized HED plasmas enables the design of experiments to isentropically compress or shock impact materials and obtain high accuracy data on material properties



- **Isentropic Compression**



- **Shock Impact from flyer plates**



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What advances are possible over the next 10 years using magnetic fields as a driver to create HED materials?

In the next 3 years:

- **What velocities can be reached in magnetically driven flyer plate experiments?**
- **What pressures can be reached isentropically in magnetically driven material samples?**
- **What are the limits of control of the pressure loading profile that we can apply with magnetic drivers?**
- **What new diagnostics (e.g. X-ray Thomson Scattering) can be brought to bear on magnetically driven materials?**
- **What are the unique measurements that might be made if we placed a magnetic driver at a light source?**

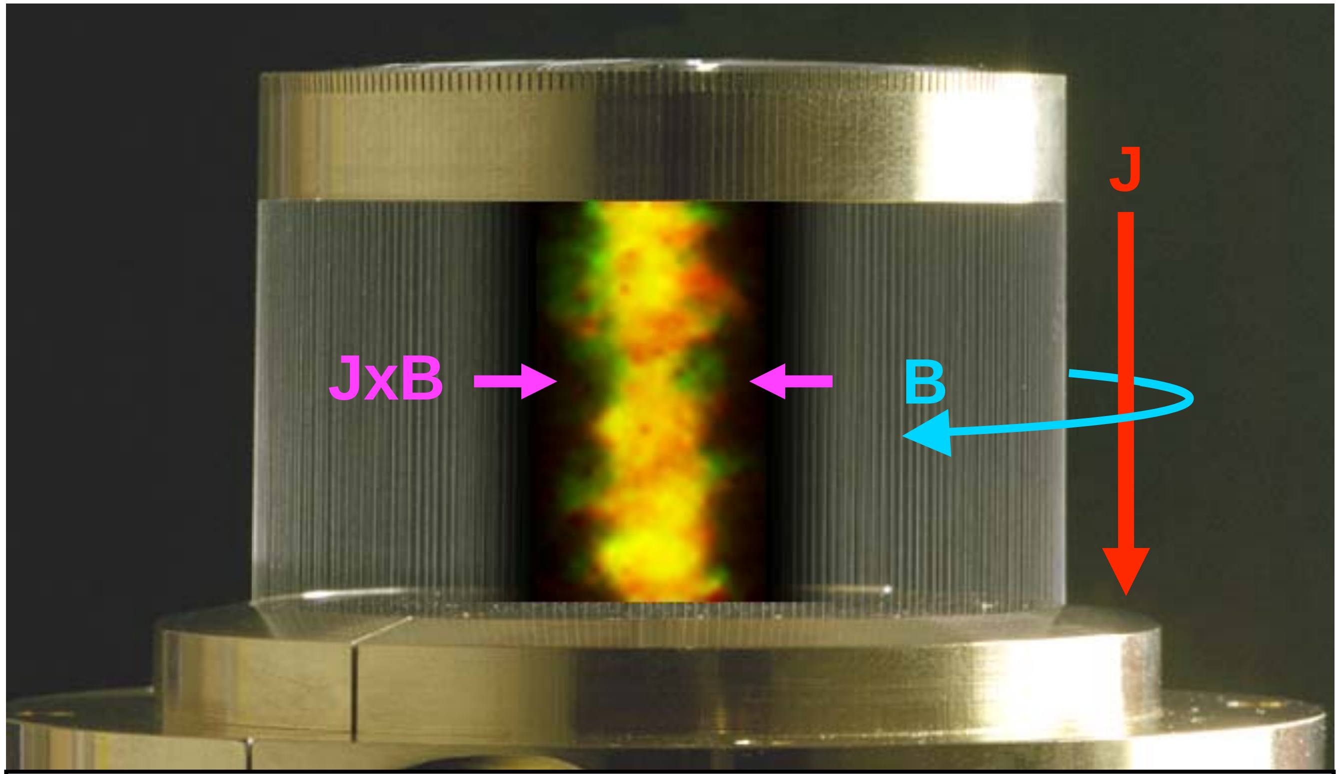
In the next 5 years:

- **Are there other applications of the uniform, high pressure states accessible with magnetically driven flyers?**
- **How do large magnetic fields affect material properties?**
- **Do cylindrical isentropic compression experiments enable higher pressures to be obtained? How can they be diagnosed?**

In the next 10 years:

- **Is a higher current, more flexibly pulse shaped driver needed to reach higher pressures?**

Magnetically driven implosions are efficient, powerful, x-ray sources from 0.1 to 10 keV



P_{rad} ~ 330 TW, Y_{rad} ~ 2 MJ

~ 10-15% wall plug efficiency

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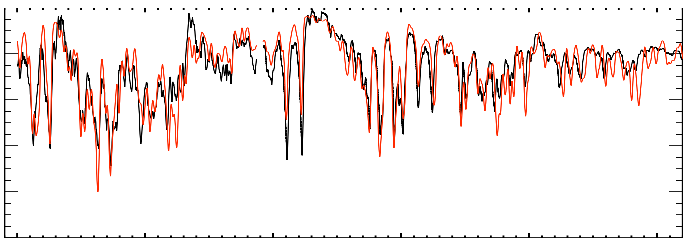
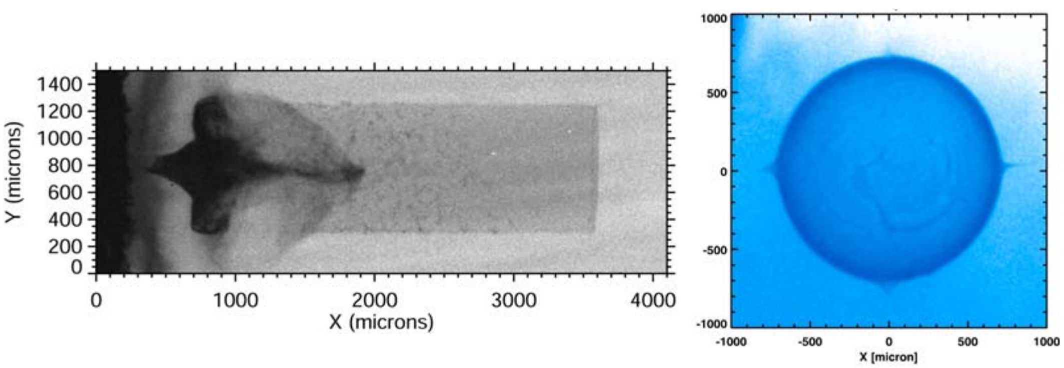
Magnetically driven X-ray sources can be used for a variety of applications

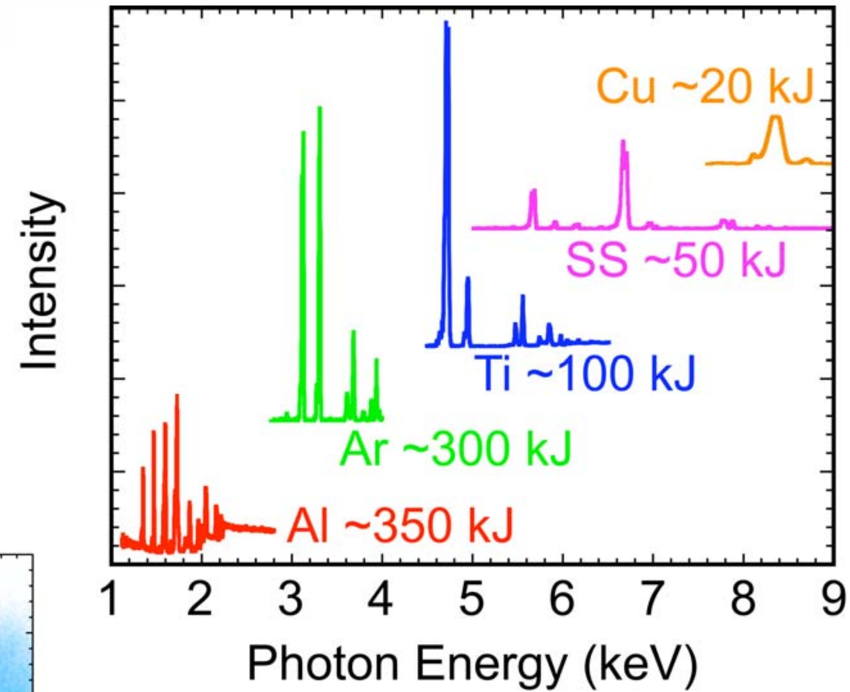
Opacity Measurements and Photo Ionized plasmas[1]



Radiation Hydrodynamics[2]



K-Shell Sources[3]



[1] J.E. Bailey, et al, Phys. Rev. Lett. 99, 265002 (2007)

[2] G.R. Bennett, et al., Phys. Rev. Lett. 205003 (2007)

[3] C. A. Coverdale et al., IEEE T. Plasma Sci. 35, 582 (2007).

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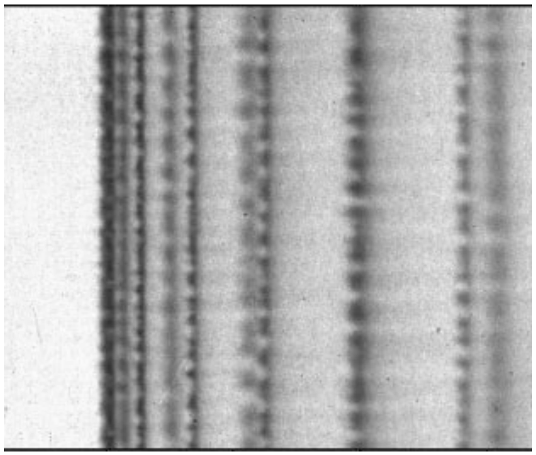
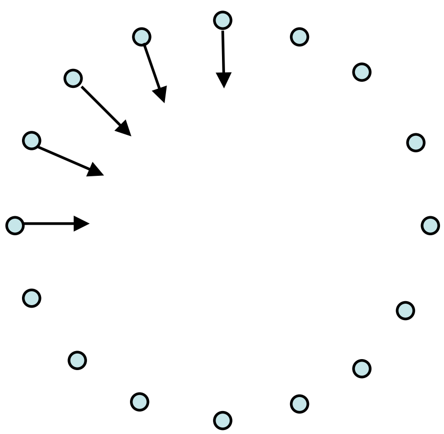
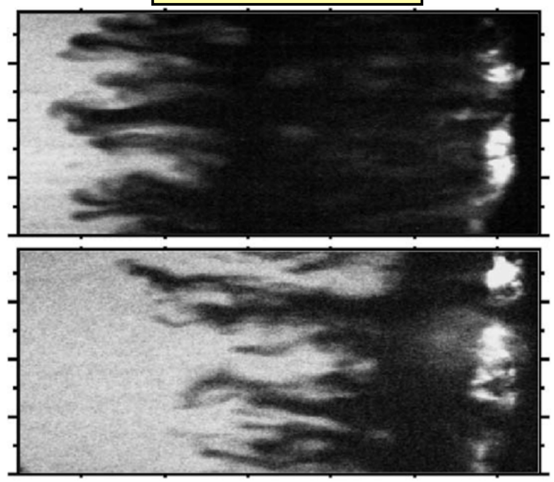
Significant progress has been made in understanding and improving wire array performance based on diagnostic advances and work on smaller scale drivers

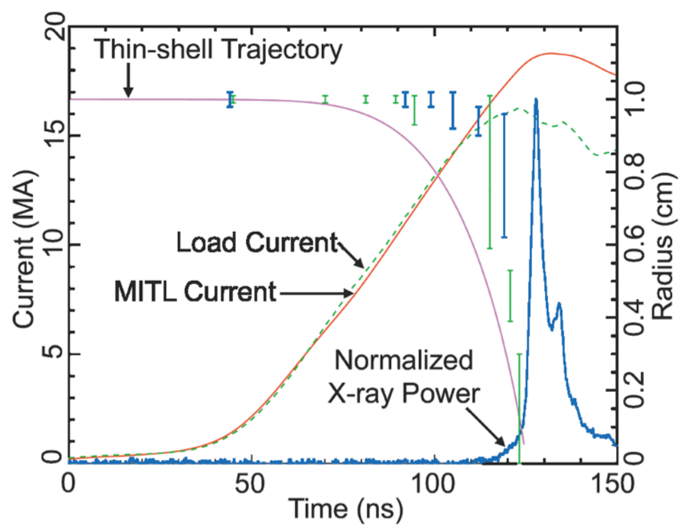
Ablation



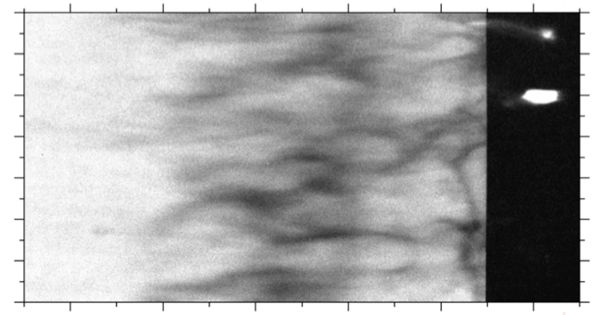


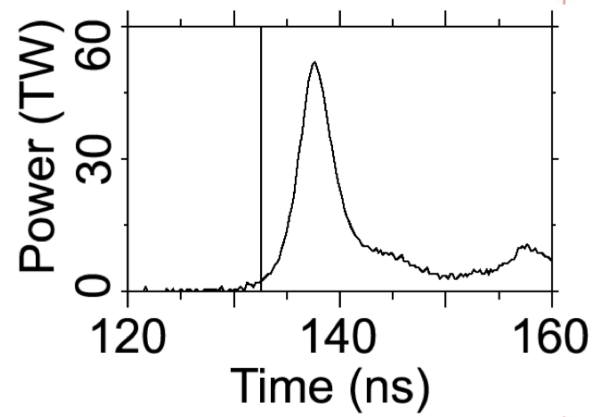
Implosion





Stagnation & X-ray production





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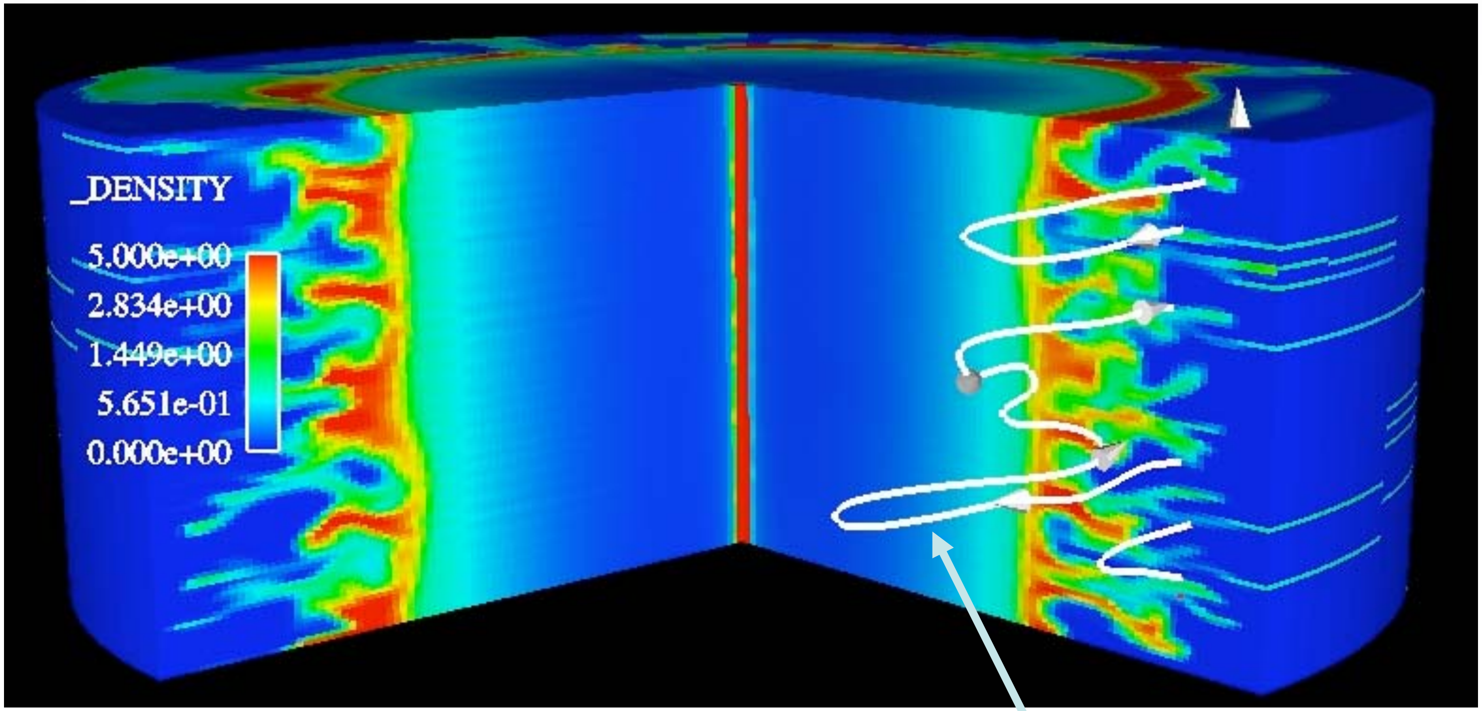
3D Rad/MHD simulations are beginning to be applied to magnetically-driven implosions



current streamline

3D (and even 2D!) Rad/MHD codes are just now becoming usable tools. Many issues remain to be worked through and benchmarked with experimental data.

The physics of shorting/current delivery is important to study and understand

Yu, et al., Phys. Plasmas (2008)

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How can we use our increasing understanding to optimize and apply magnetically driven x-ray sources?

In the next 3 years:

- **How well can we measure the Magneto-Rayleigh Taylor instability and other instabilities which affect Z-pinch performance?**
- **What limits the power and efficiency of magnetically driven x-ray sources?**
- **For soft x-ray sources, how compact can we make our sources? What hohlraum temperatures can be reached with Z-pinches?**
- **How do arrays optimized as K-Shell sources differ from soft x-ray sources?**
- **What control do we have over the radiation pulse shape?**

In the next 5 years:

- **How well can we control the Magneto-Rayleigh Taylor instability?**
- **Can 3D radiation-magnetohydrodynamics computational models capture the dynamics of wire array implosions sufficiently to be a predictive tool?**
- **Can we use our very bright line sources to enable interesting materials properties measurements?**
- **Can we confidently predict how these sources scale to a larger driver?**

In the next 10 years:

- **What applications could be addressed on higher current, more flexible driver?**

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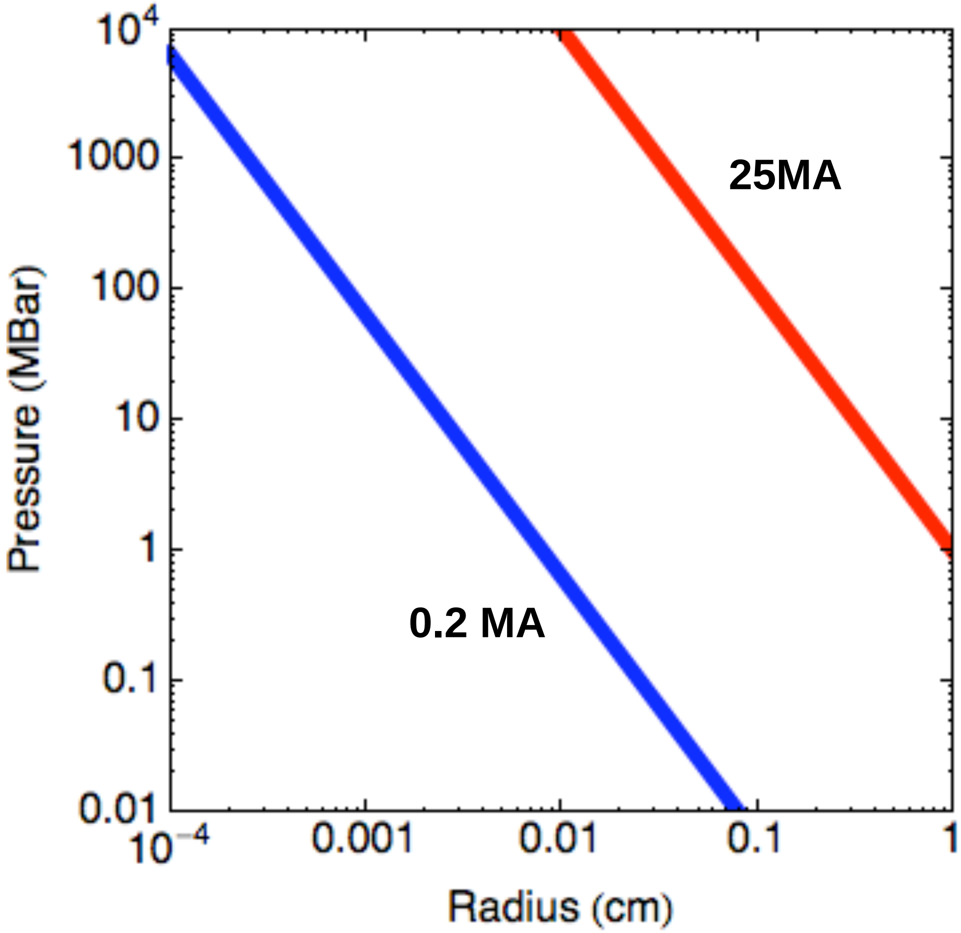
Magnetic implosions can reach very high pressures, if the current can reach small radius

Magnetic Pressure versus radius for a cylinder carrying current



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

$$P \sim \frac{B^2}{8\pi} \sim \frac{I^2}{R^2}$$

A current carrying cylinder is driven more strongly the farther it converges

A magnetic implosion continues to extract energy as it implodes:

$$E_{kin} \sim I^2 \log\left(\frac{R_0}{R_f}\right)$$

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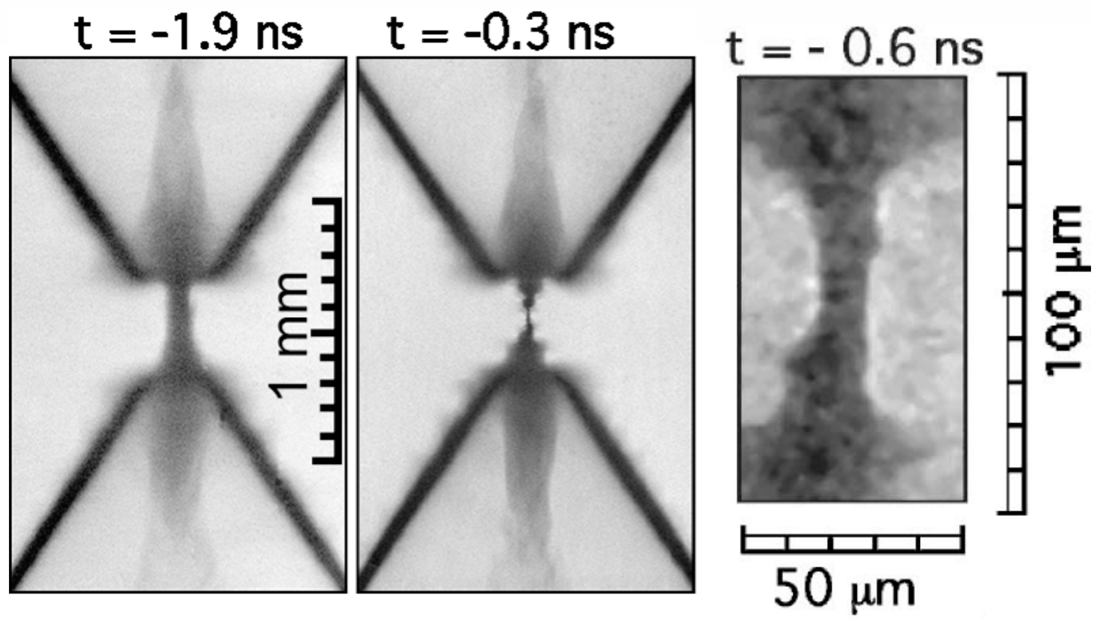
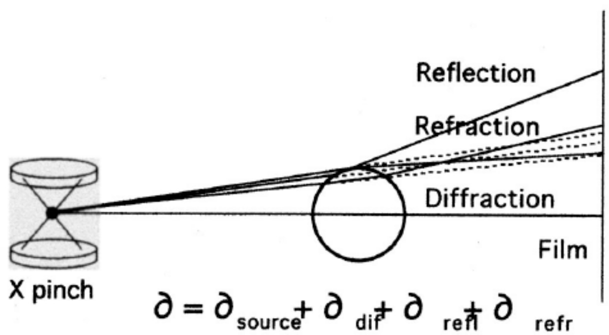
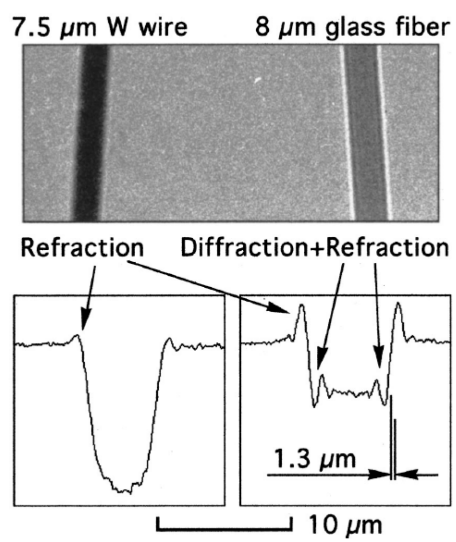
X pinches driven by 200 kA currents are an extreme example of current reaching small radius

- 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).

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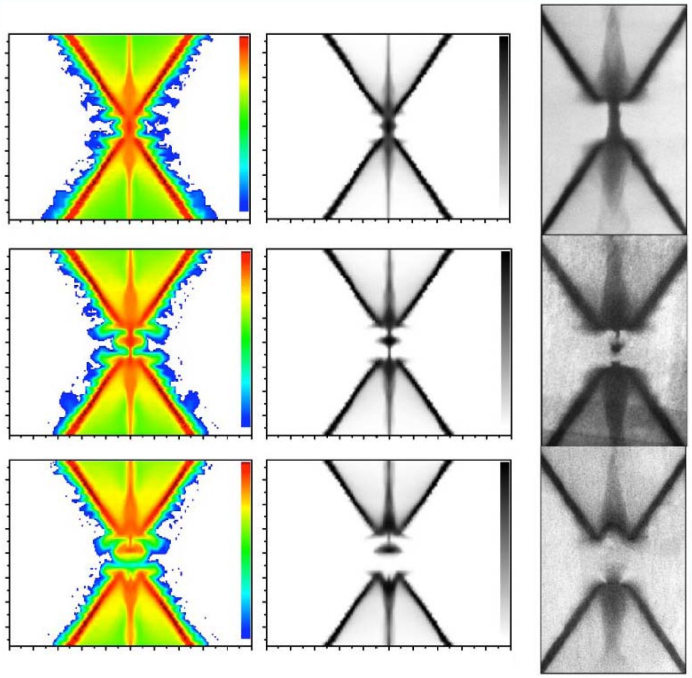
What happens as the current in X-pinches is increased?

- **0.2 MA Mo X-pinch modeling reproduces data[†]**
  - **Model based on approximate Bennett equilibrium conditions and a balance between blackbody radiation and thermal heating**
  - **Axial mass flow leads to a collapse that is halted when the electron drift velocity exceeds the ion sound speed (critical line density)**
- **At 1 MA the model breaks down**
  - **Predicts ~30 nm, 1290x solid density!**
- **Assume all current collapses to 1 μm radius**
  - **1 MA: 10x solid density**
  - **10 MA: 250x solid density**



What limits the collapse of current to small radius?
What states of matter can be created using large currents at small radii?

† **Chittenden *et al.*, Phys. Rev. Lett. 98, 025003 (2007).**

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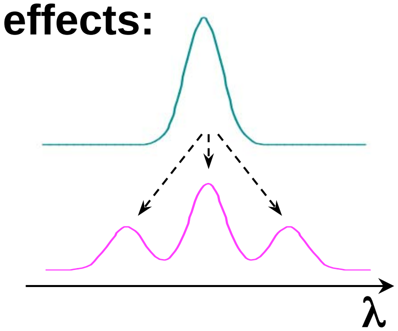
Very large magnetic fields can significantly affect atomic orbits

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

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

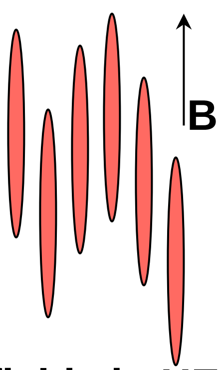
For near-neutrals (Z~1), magnetic fields can give the following effects:



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

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

$E^B \gg E^C \gg E^{SO}$ → 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

  $B/4B_0 \gg Z^3$

- binding energies increase from $\sim Z^2/n^2$ to $\sim Z(B/2nB_0)^{1/2}$; 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)

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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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What are the most extreme states of matter attainable in a magnetically driven system?

In the next 3 years:

- **How can we diagnose the extreme states of matter we are creating in laboratory X pinches (Peak B-field, peak ρ, peak T_e)?**
- **How do X-pinches scale from 0.2 MA to 1-5 MA?**

In the next 5 years:

- **Can we scale X-pinches to higher currents (10 - 25 MA)?**
- **Can we compress magnetic flux to > 100 Megagauss?**
- **What sets the minimum radius of magnetic compression in a Z-pinch?**

In the next 10 years:

- **Can we achieve fields greater than 1 Gigagauss?**
- **Can we observe changes in the behavior of atoms at large magnetic fields?**

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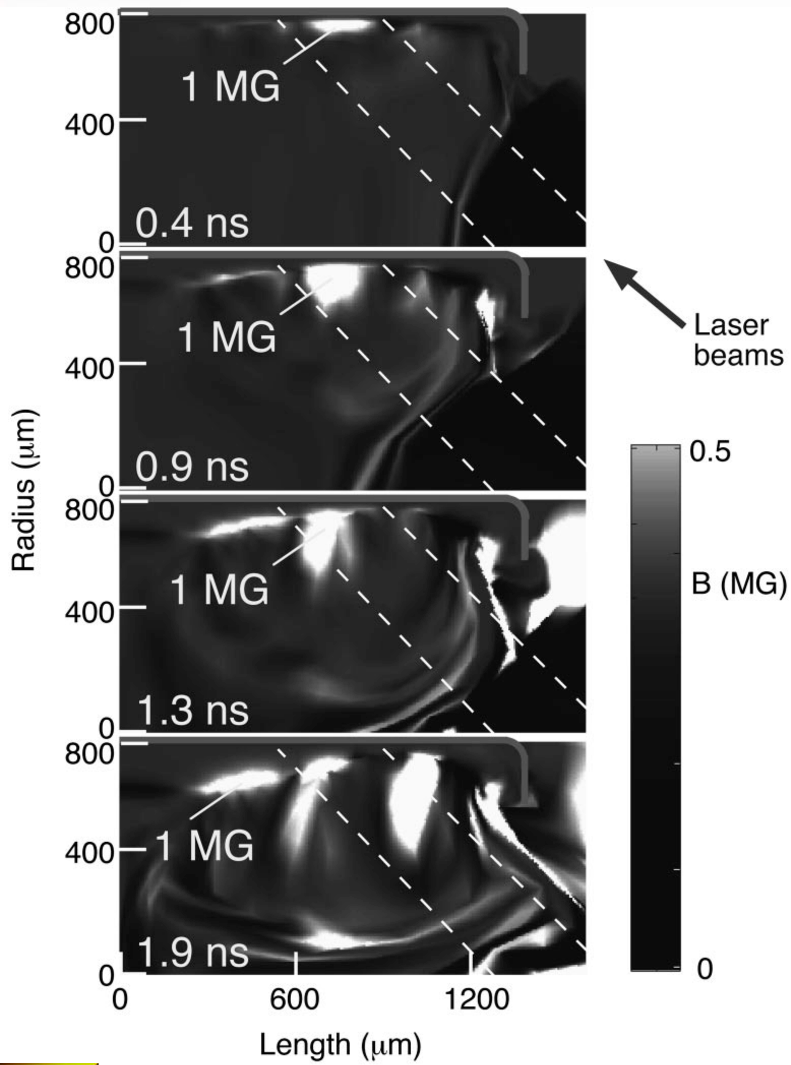
Magnetic Fields can be spontaneously generated from plasma gradients in HED plasmas



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

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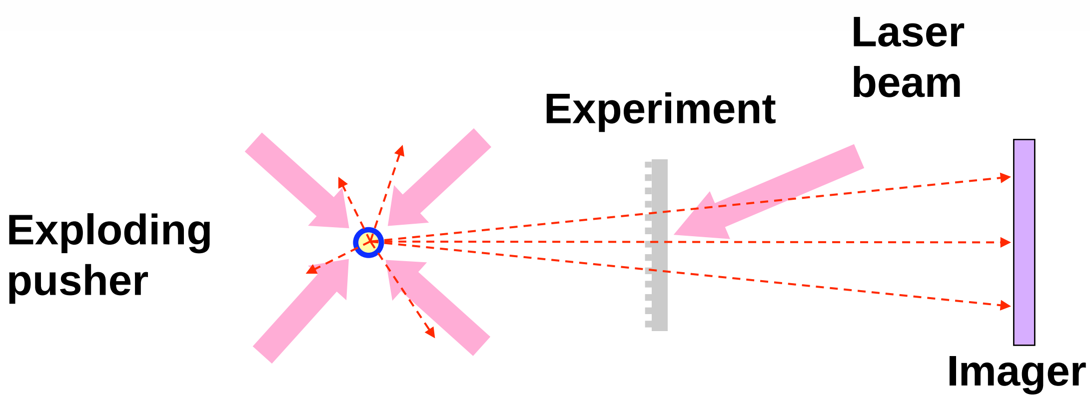
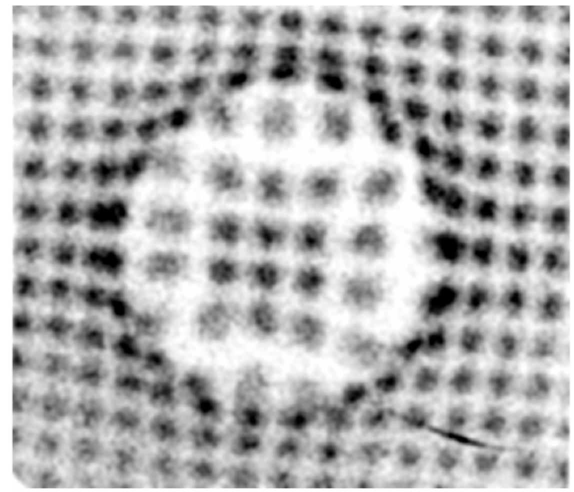
A powerful diagnostic technique for detecting electric and magnetic fields in HED plasmas is proton radiography



$D + {}^{3}He \rightarrow \alpha\ (3.6\ MeV) + p\ (14.7\ MeV)$

$D + D \rightarrow T + p\ (3.0\ MeV)$



Proton image of an expanding plasma bubble

FSC UR LLE NLUF MIT

C. K. Li et al., Phys. Rev. Lett. 97, 135003 (2006)

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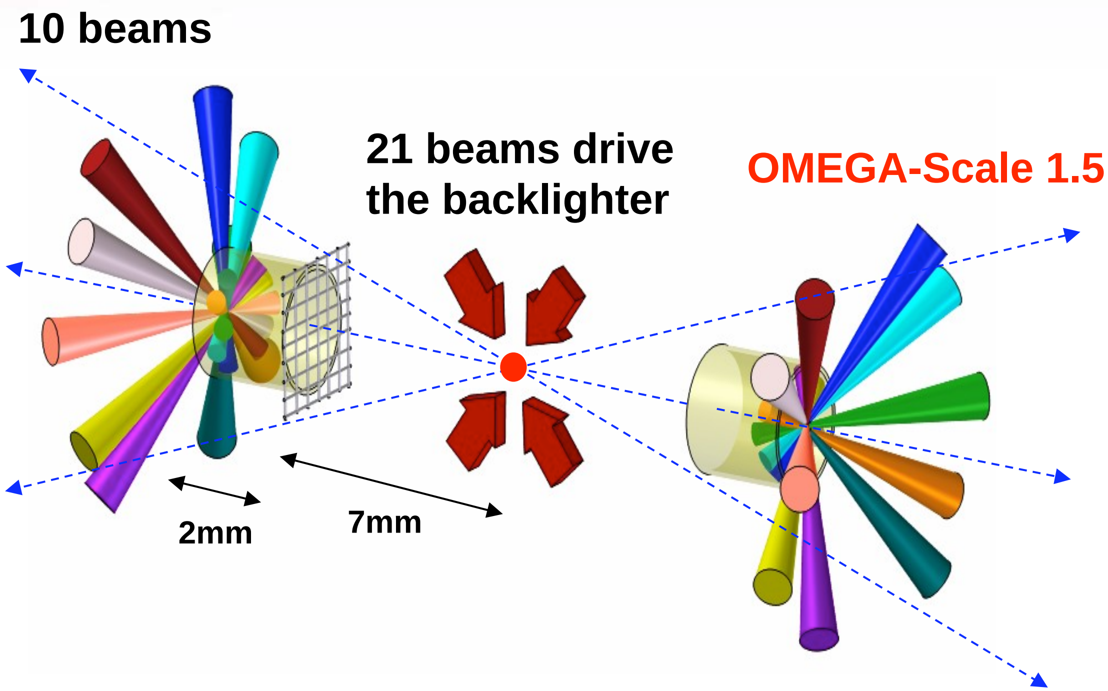
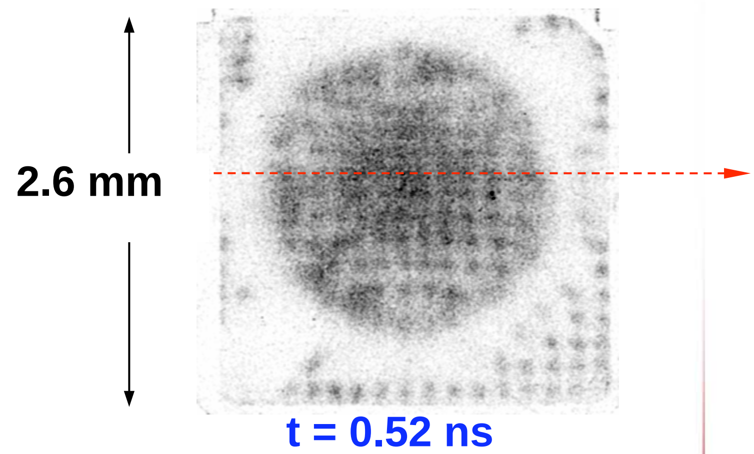
Spontaneous fields of ~10^6 gauss B field have been observed in hohlraums





Field is inferred from deflection of beamlets.
By using 2 different proton energies can distinguish between an electric field and a magnetic field.

C. K. Li et al., Phys. Rev. Lett. 102, 205001 (2009)

How can we measure, understand, and apply spontaneously generated magnetic fields in HED plasmas?

In the next 3 years:

- **How important are spontaneously generated fields in ignition scale hohlraums?**
- **How important are spontaneously generated fields in direct drive implosions?**
- **How important are spontaneously generated fields in relativistic HED plasmas?**
- **How good is our predictive capability of field generation?**

In the next 5 years:

- **What control do we have over spontaneously generated fields?**
- **Can we use spontaneously generated fields to create and study magnetized HED plasmas of interest?**
- **Can we use our understanding of spontaneously generated fields and their effects on transport to our advantage?**

In the next 10 years:

- **Can we achieve fields greater than 1 Gigagauss and use them?**

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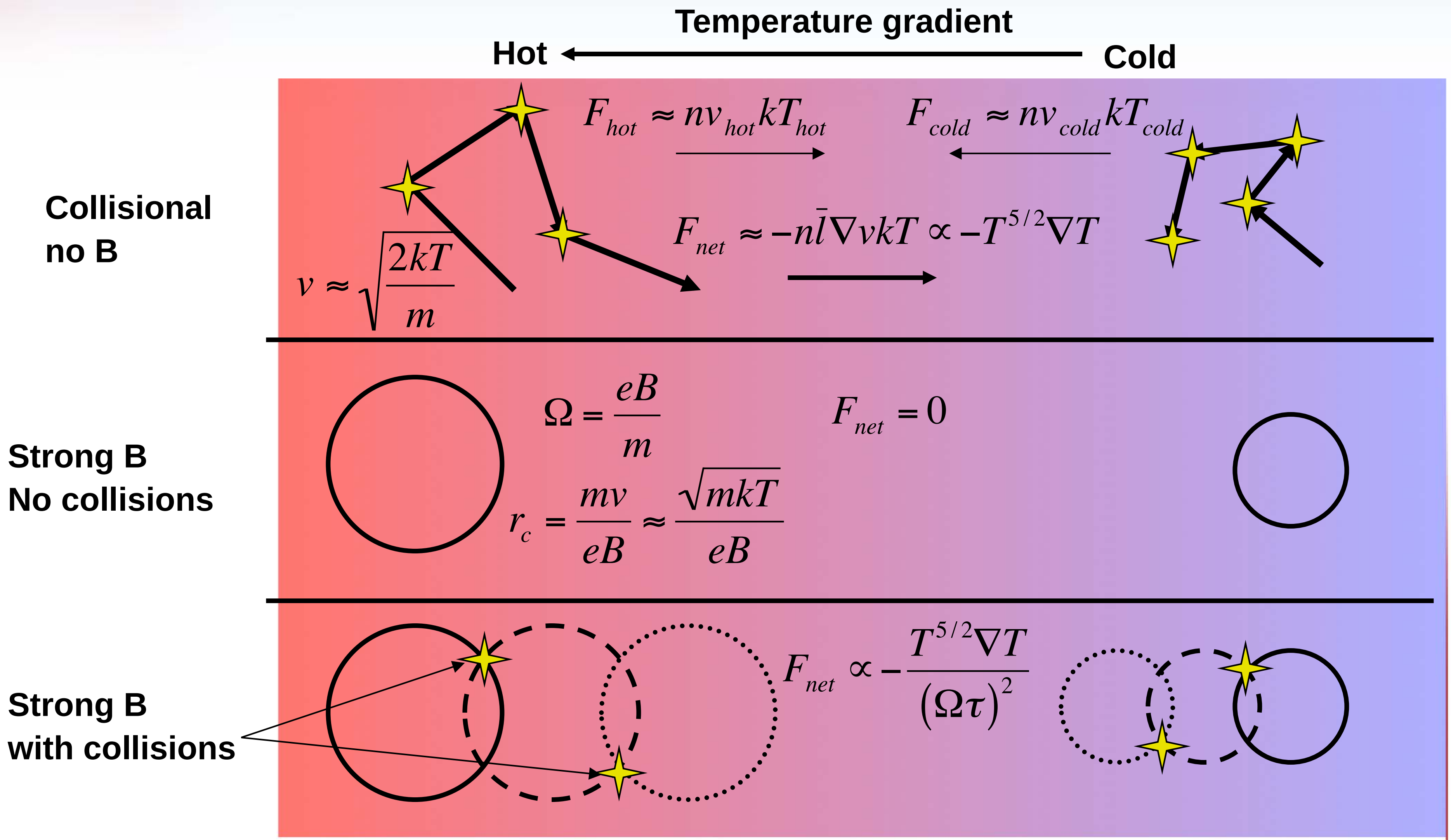
The presence of a magnetic field can strongly affect transport properties, e.g. heat conduction



Energetic particles can also be strongly affected by magnetic fields

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Magnetization significantly reduces the implosion velocities needed for heating fusion fuel

Fusion fuel must be heated to several keV for fusion:

$$P\frac{dV}{dt} - P_{Brem} - P_{cond} > 0$$

$$P\frac{dV}{dt} \approx C_w L\left(\rho r\right) T \mathrm{v} \qquad P_{Brem} = C_b L\left(\rho r\right)^2 T^{1/2} \qquad P_{cond} \approx C_c L\, T^{7/2}$$

Reducing electron conduction losses enables plasma to be heated at much slower implosion velocity.

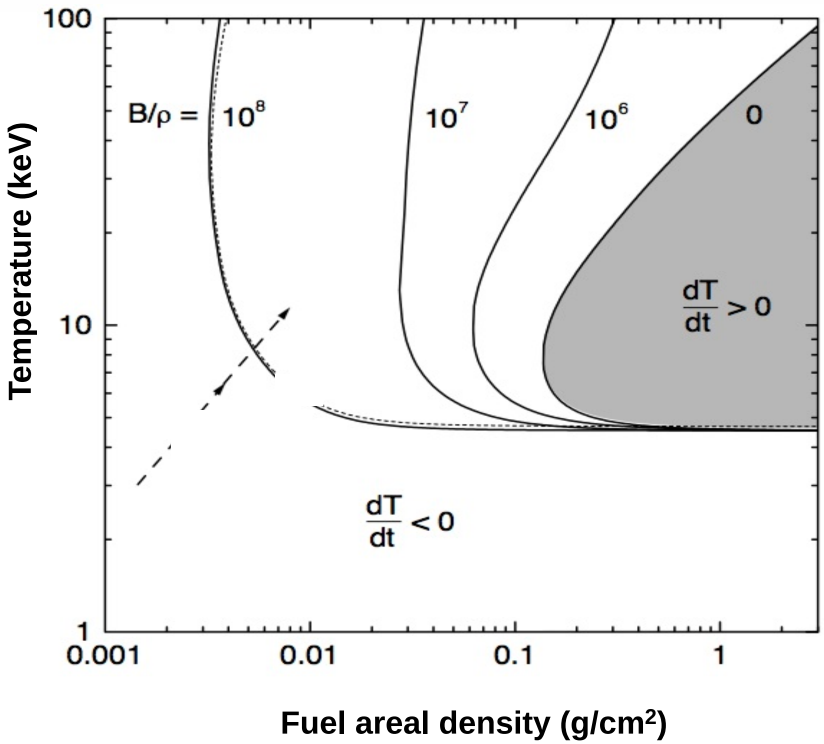
Slower implosion velocities can enable more stable implosions. Slower implosion velocities also allow lower power drivers to access fusion regime.

In this regime fuel is not self heating (no alpha deposition), but if the implosion is efficient enough, and the inertial confinement time is long enough, gain can be achieved

These fusion schemes are "batch" burn.

Magnetization also significantly reduces the self heating (ignition) requirements for inertial confinement fusion

**Basko et al. Nuc. Fusion (2000)*



The ρr needed for ignition can be significantly reduced by the presence of a strong magnetic field inhibit electron conduction and confinement of alpha particles

Lower ρr means lower densities are needed (10^{-3}-1 g/cc)

Pressure required for ignition can be significantly reduced to ~5 Gbar (<< 500 Gbar for hotspot ignition)

Large values of B/ρ are needed and therefore large values of B are needed.

B~ 50-150 Megagauss >> B_0 -> flux compression is needed

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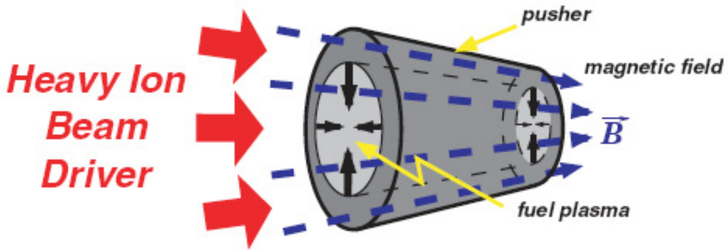
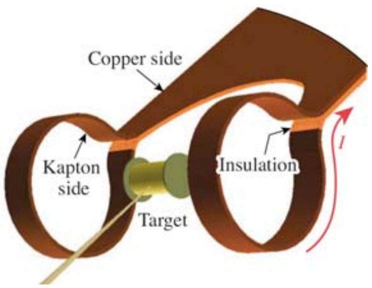
The parameter space for magnetized ICF is large allowing a diverse set of approaches

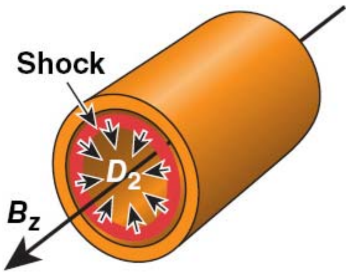
Max Planck / ITEP



Basko, Kemp, Meyer-ter-Vehn, *Nucl. Fusion* **40**, 59 (2000)
Kemp, Basko, Meyer-ter-Vehn, *Nucl. Fusion* **43**, 16 (2003)

U. Rochester LLE





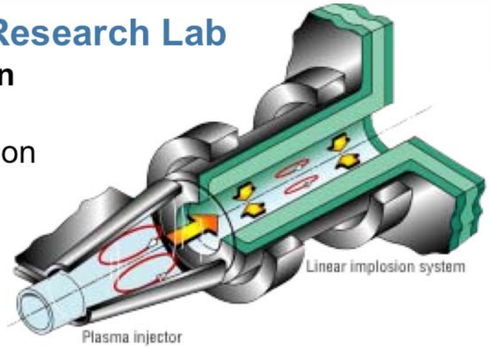
Direct drive laser implosion of cylinders
-- shock pre-heating, high implosion velocity

Gotchev *et al.*, *Bull. Am. Phys. Soc.* **52**, 250 (2007)
Gotchev *et al.*, *Rev. Sci. Instr.* **80**, 043504 (2009)

Los Alamos / Air Force Research Lab

Field Reversed Configuration
Shiva Star generator
~20 μs, 0.5 cm/μs liner implosion

Taccetti, Intrator, Wurden *et al.*, *Rev. Sci, Instr.* **74**, 4314 (2003)
Degnan *et al.*, *IEEE Trans. Plas. Sci.* **36**, 80 (2008)



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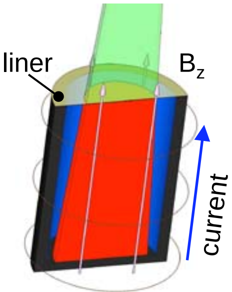
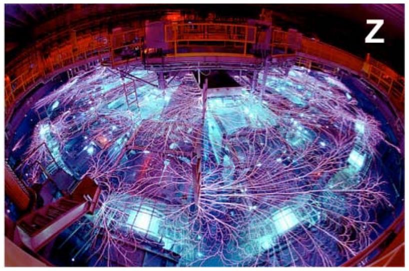
Magnetized Liner Inertial Fusion

Laser preheated magnetized fuel

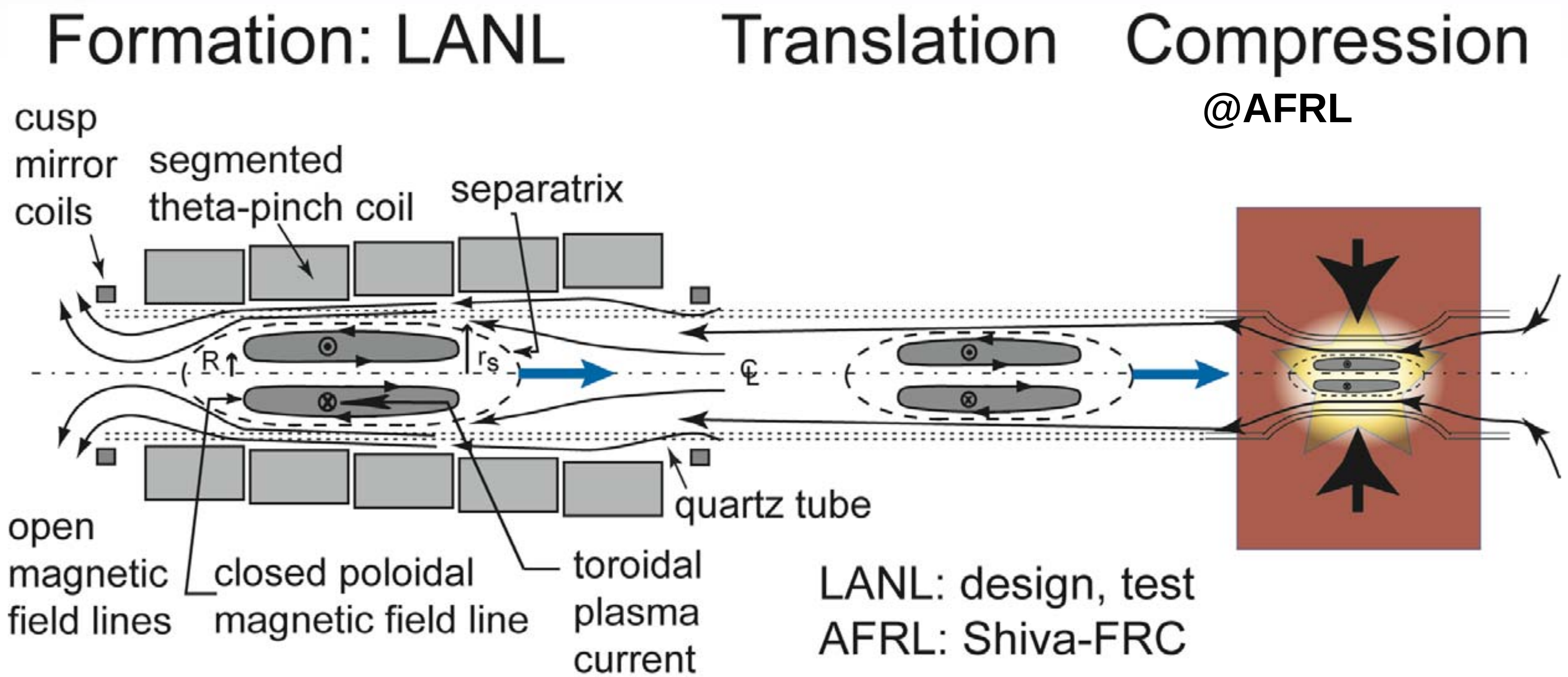
LASNEX simulations indicate interesting yields





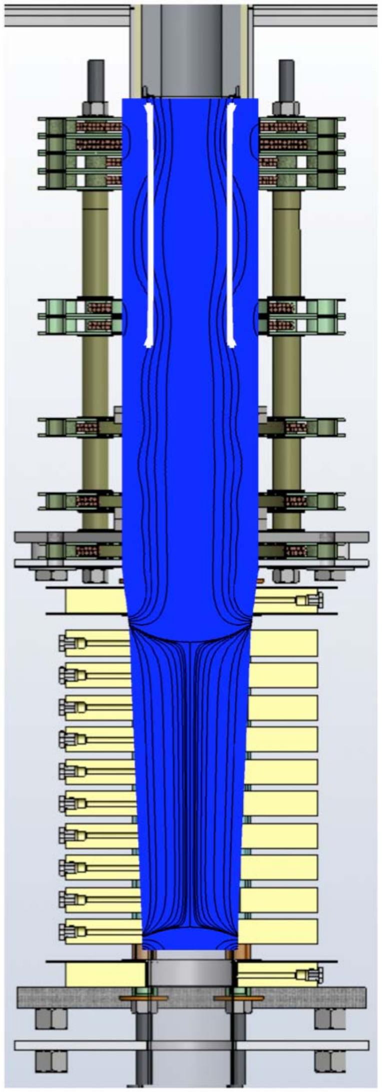
Slutz *et al.*submitted to Phys. Plas.

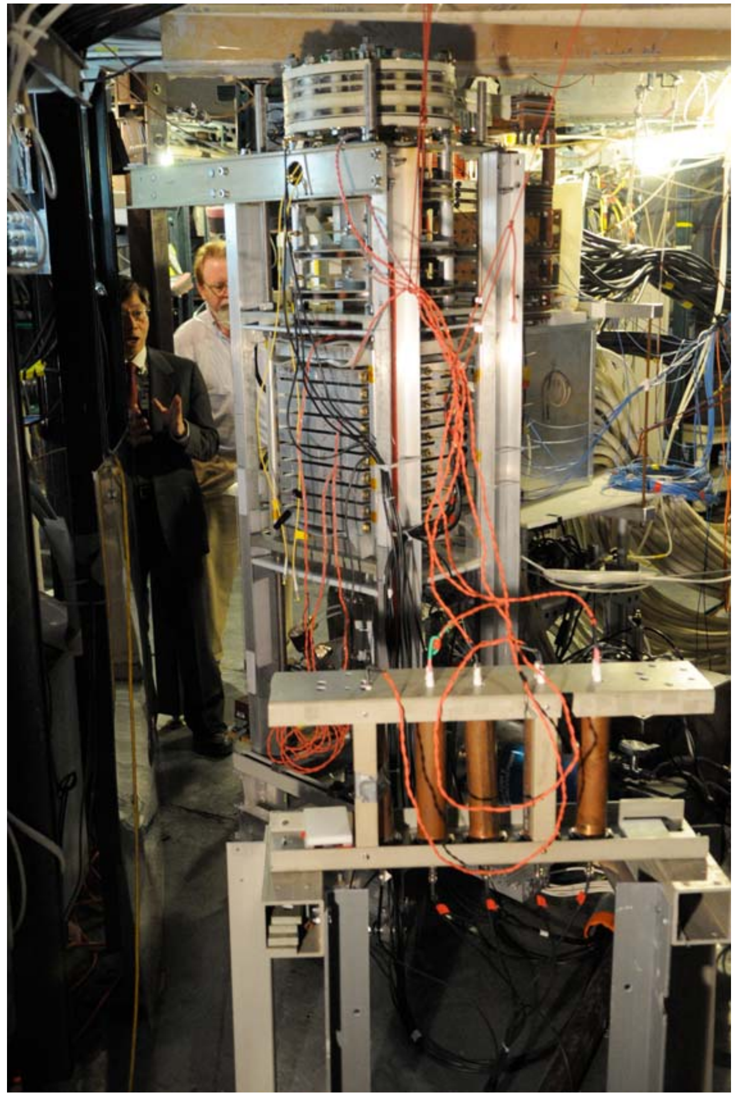
The LANL/AFRL approach uses a translated Field Reversed Configuration



- FRC formation and translation has been demonstrated
- Low pressure (~MB), long pulse drive means liner does not melt and retains material strength
- Low density enables unique diagnostics for stagnated plasma

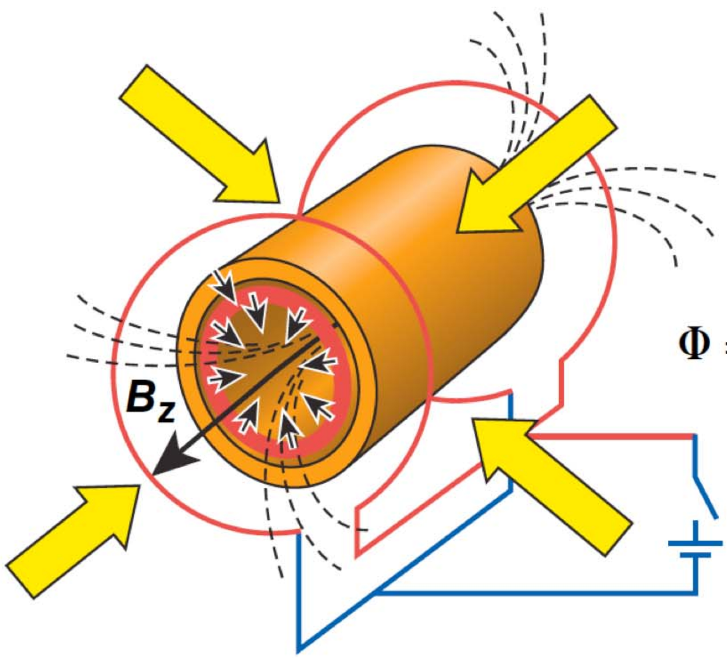
Progress on this approach is expected in the next 1-2 years!



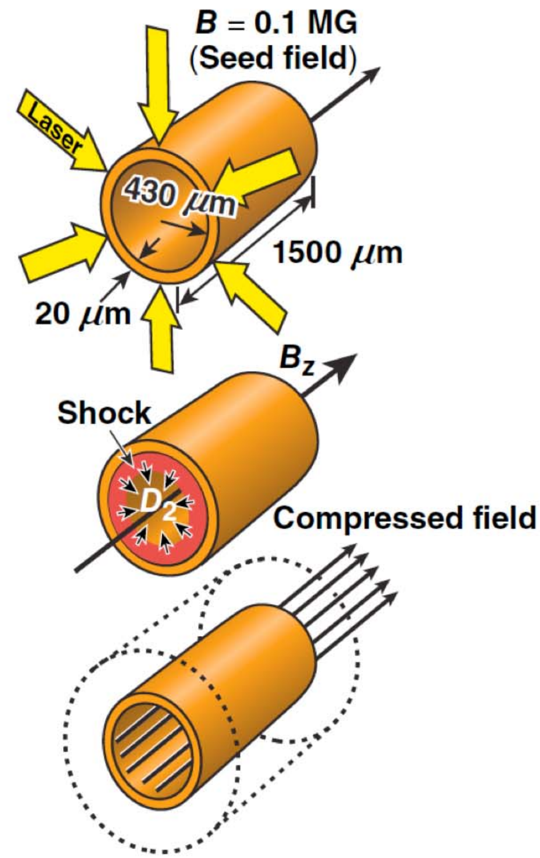


The UR/LLE approach uses lasers to directly drive a cylinder with a preimposed magnetic field

- 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



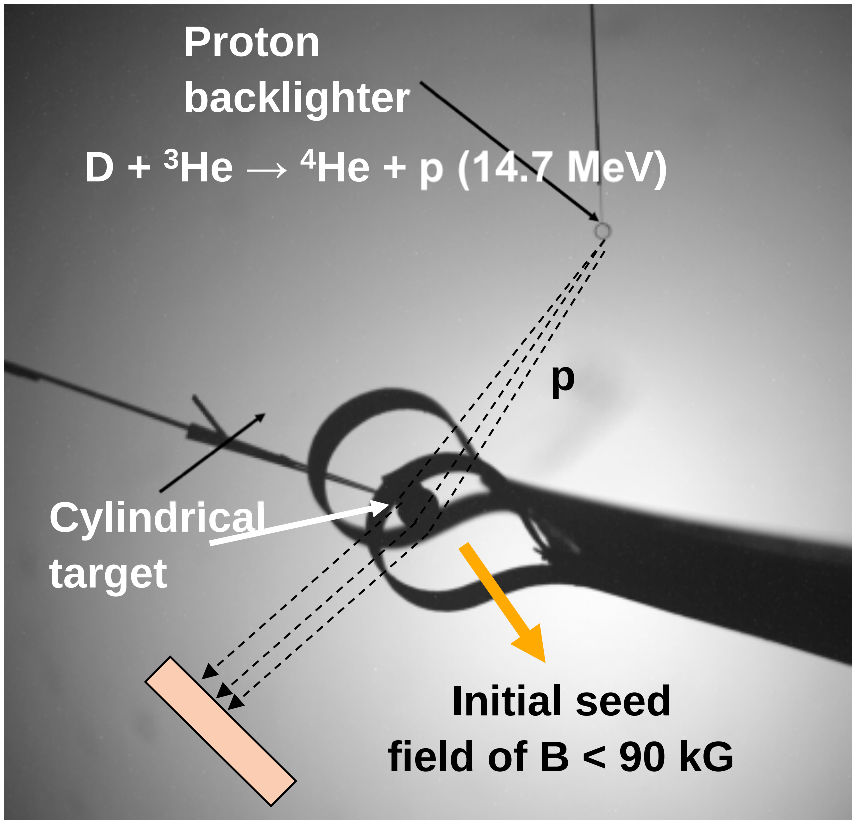
$$\Phi = \pi B_z R^2 \approx \text{const}$$

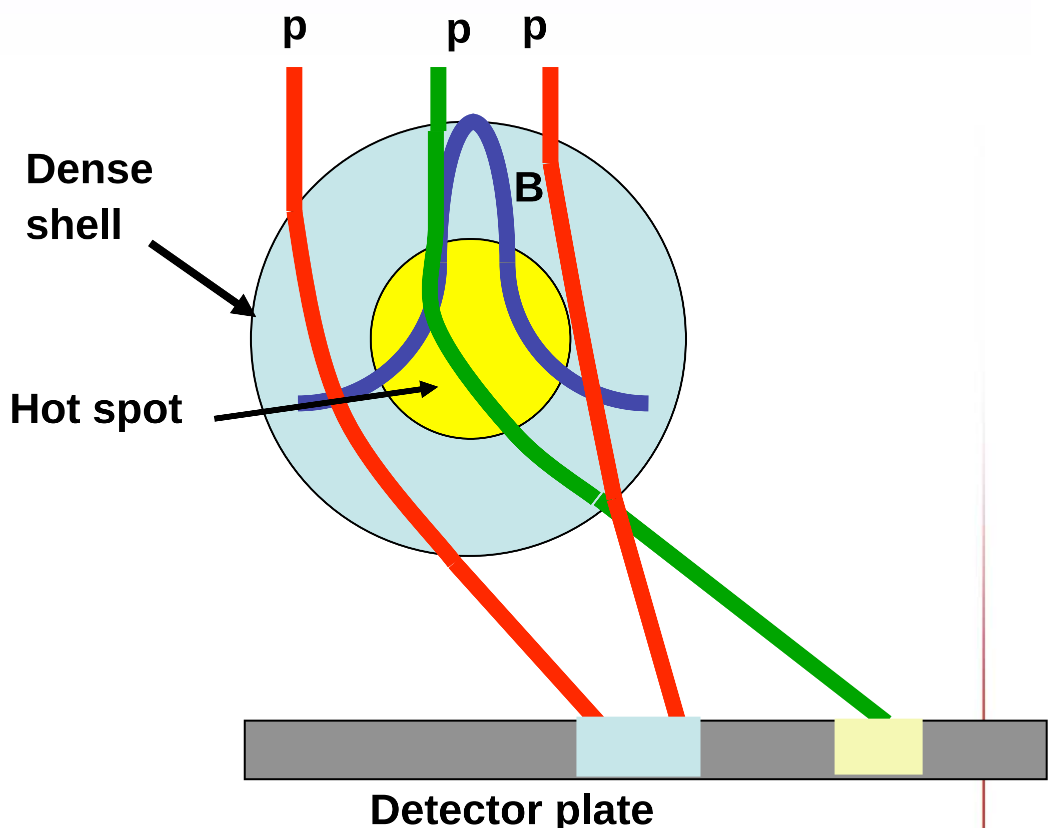


E17764a

*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





FSC UR LLE

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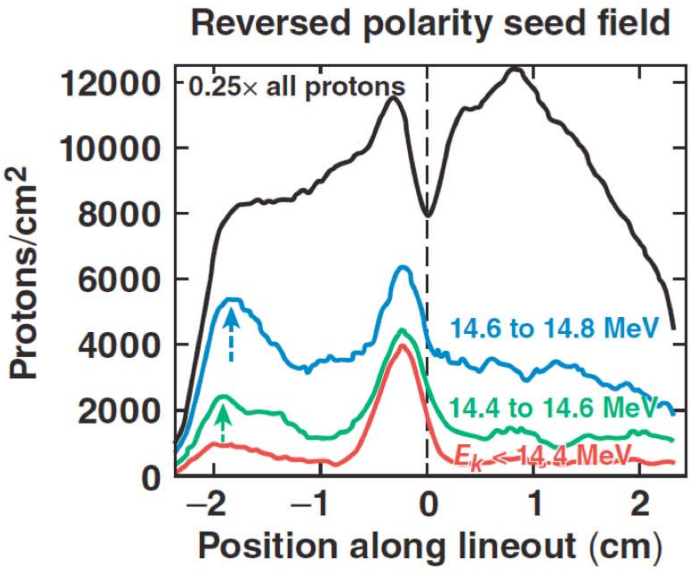
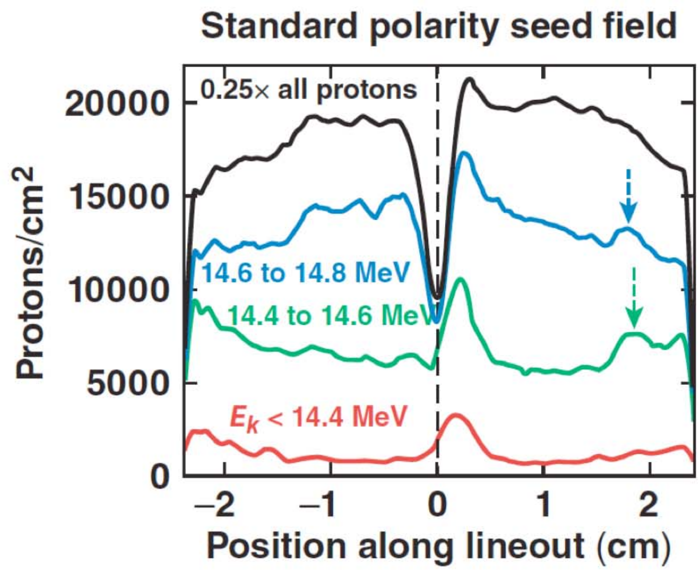
The deflectometry data shows a peak field of ~ 40 MG, 500 x the initial seed field





The minimum average magnetic field matching this deflection is 40 MG.

The minimum average magnetic field matching this deflection is 30 MG.

E18431

The next step is to determine if the field is altering the hot spot dynamics of a spherical capsule and affecting the neutron yield.

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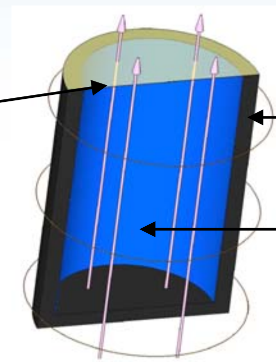
The Z facility provides an opportunity to test the benefits of fuel magnetization and preheat

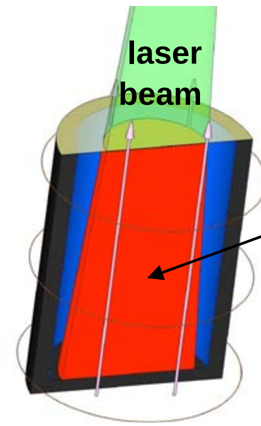
1. A 10-50T axial magnetic field

is applied before the implosion

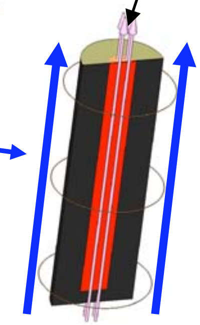


2. Z Beamlet can preheat the fuel to ~100 - 1000 eV

to reduce the require compression needed



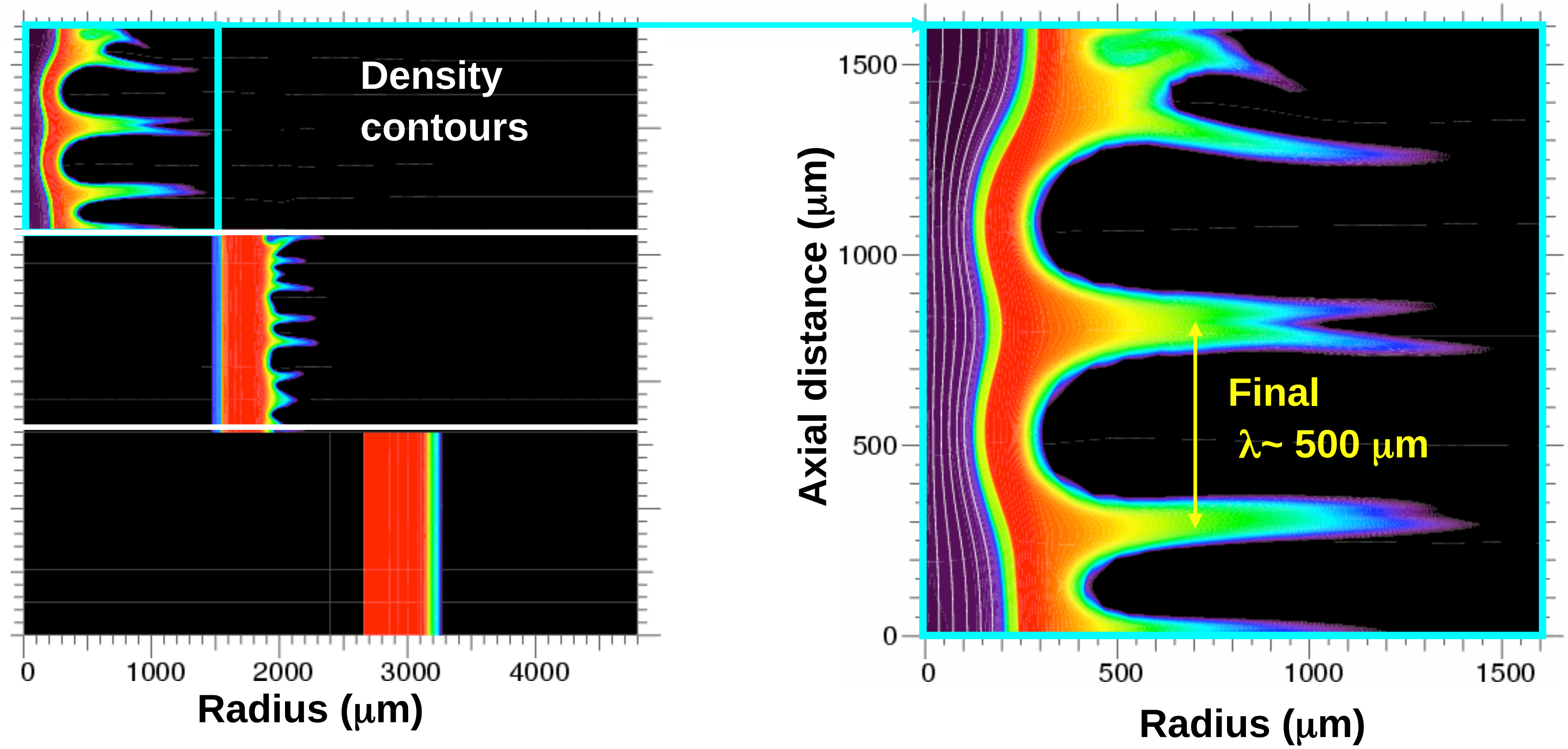
3. The Z accelerator can provide the drive current which generates an azimuthal drive field (pressure) to efficiently implode the liner (Z pinch) at 50-100 km/sec and compress the axial field by factors of 1000



Simulations indicate scientific breakeven
(fusion energy out = energy deposited in fusion fuel) may be possible on Z

The point design for magnetized fusion experiments on Z looks interesting

60 nm surface roughness, 80 μ waves are resolved



•Peak central averaged T_{ion}	8 keV
•Final peak B-field	135 MG
•1D Yield	500 kJ
•Peak Pressure	3 Gbars
•Convergence Ratio	23

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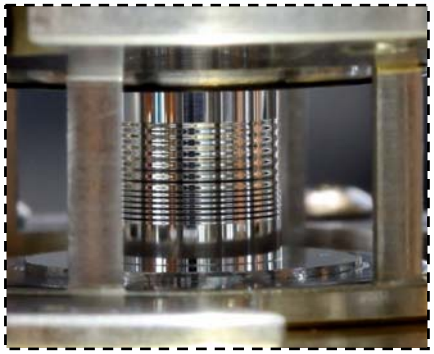
Experiments to measure the growth of the magnetic Rayleigh-Taylor instability on the 100 ns timescale have begun

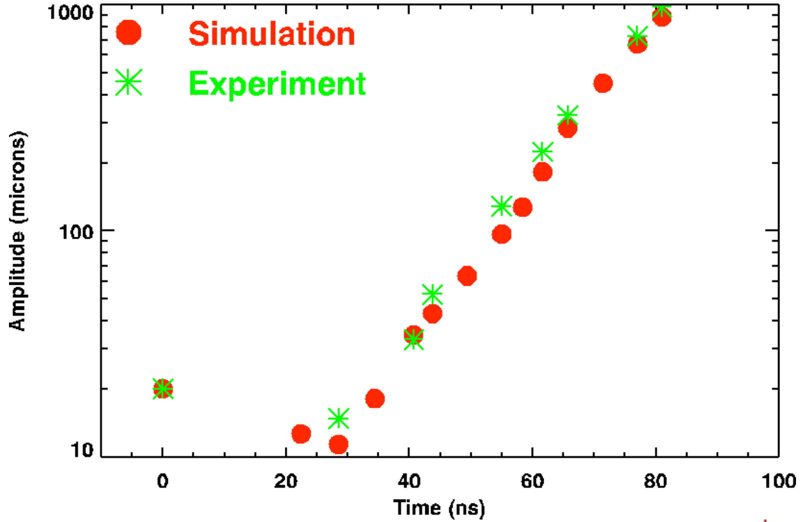
Al liner target with initial perturbations

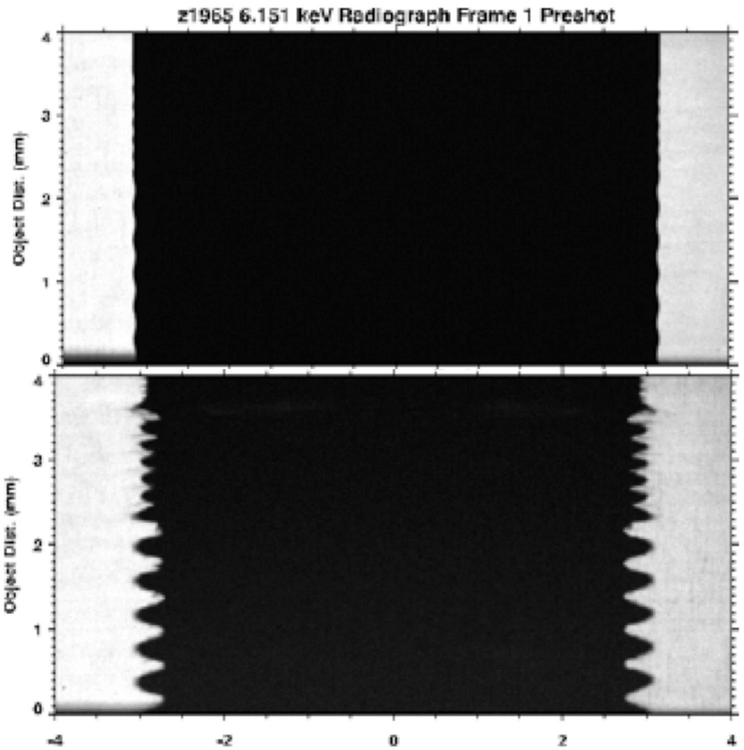
λ = 400 μm, A=20 μm

λ = 200 μm, A=10 μm



Comparison of numerical simulations and measured amplitude for λ = 400 μm perturbation





X-ray radiographs at 6.151 keV of Al liner

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We are poised for exciting advances in inertial confinement fusion using magnetized concepts

In the next 3 years:

- **Can we compress magnetic flux using a magnetic driver?**
- **Can we use magnetization to reduce heat losses in fusion fuel?**
- **How can we use multiple platforms to maximize our progress in magnetized HEDP?**
- **Can we apply the large fields generated in magnetized inertial confinement fusion plasmas to other applications?**

In the next 5 years:

- **Can we demonstrate scientific breakeven with a magnetized inertial confinement fusion concept?**
- **What are the implications of magnetized ICF for Inertial Fusion Energy?**
- **What are the limits of compressed fields that can be obtained in magnetized inertial confinement fusion targets?**

In the next 10 years:

- **How can we used magnetized inertial confinement fusion concepts to achieve Inertial Fusion Energy?**
- **Can we develop new, lower cost driver approaches to enable Inertial Fusion Energy based on magnetized concepts?**
- **Can we obtain high gain with a magnetized inertial confinement fusion target?**

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It's an exciting time to be working in Magnetized HED plasmas

- **Our understanding of Magnetized HED plasmas is being applied to important applications**
- **Ever more extreme conditions are being reached using magnetized HED plasmas**
- **We are poised for exciting advances in inertial confinement fusion using magnetized concepts**
- **New resources, computational tools, diagnostics, and facilities access can enable a rapid advance in our understanding of Magnetized HEDP**

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Many facilities can access regimes of interest for magnetized HEDP

Facility, location	Energy per pulse	Typical pulse length	Electric current, MA (for pulsed-power facilities)	Shot rate at full capacity	Type of experiments
Z, SANDIA	22 MJ (Up to 5 MJ on the load)	150 ns	25	2/day	Magnetized fusion, Radiation source, Materials under extreme conditions, Opacities, LabAstro
Z-BEAMLET, SANDIA	2 kJ/ pulse	1-2 ns, 4 pulses /shot	N/A	3/day	(Used in conjunction with Z)
Z- PETAWATT, SANDIA	0.5 kJ/ pulse	1 ps	N/A	3/day	(Used in conjunction with Z)
OMEGA, LLE, Rochester	30 kJ	0.1-4 ns	N/A	10/day	Laser-driven magnetized targets
MAGPIE, Imperial College	0.6 MJ	250 ns	2	2/day	Lab. astrophysics with magnetized jets, z-pinch physics
COBRA, Cornell University	0.1 MJ	100 ns	1	4/day	Lab. astrophysics, basic HED plasma physics
ZEBRA, Univ. of Nevada, Reno	0.1 MJ	100/200 ns rise	1/0.6	3/day	Radiation source, Matter under extreme conditions, Magnetized Lab Astro
LEOPARD, Univ. of Nevada, Reno	15/25 J	0.35ps/ 1ns	N/A	8/day	(Used in conjunction with Zebra)
MAIZE, Univ. of Michigan, Ann Arbor	16 kJ	200 ns	1	4/day	Research on Magneto-Rayleigh-Taylor Instability
SHIVA-STAR AFRL	4.5 MJ	4-5 µs rise	12	1/month	Magnetized target fusion, FRC plasmas
ATLAS (NTS), dormant	36 MJ	4-5 µs rise	30-50	1/month	Materials, shocks, 20 Mbar in a few cm^3
Explosive pulsed power current sources (Ranchero, Procyon)	100 MJ	1-10 µs	80	Several/ year	Highest energy pulsed power HEDLP drivers
PLX, Los Alamos, under construction	0.3-1.5 MJ	5 µs	N/A	Dozens/ day	Imploding plasma liners, magnetization of dense plasmas

A diverse group of university scale and large scale facilities are being used to study magnetized HEDP

Very significant cross fertilization has occurred and continues to occur between university scale and large scale facilities in the area of magnetized HEDP

A key concern of our panel is access to large scale HEDP facilities to pursue magnetized HEDP studies:

Can we set up a NLUF like program for Z?

Can Z be operated at lower current to increase rep rate?

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As in all areas of HEDP, diagnostics need attention

For magnetized HEDP the ability to measure the magnetic field is critical

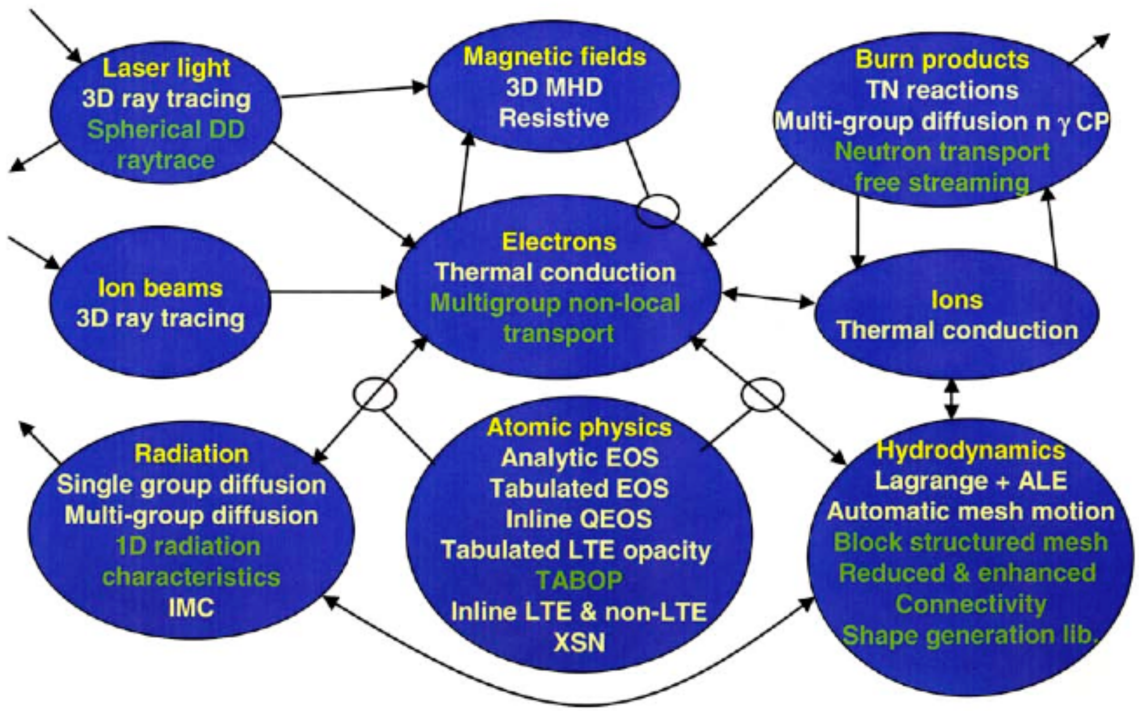
- **Proton Radiography has rapidly emerged as a powerful tool for measure electric and magnetic fields on Omega**
- **The large theta fields on Z and Shiva significantly constrain proton radiography on these facilities (protons get deflected before they reach the plasma of interest)**
- **Pulsed Polarimetry[1] is a proposed diagnostic to measure the local B field in Magnetized Target Fusion experiments on SHIVA Star**
- **New approach to spectroscopic B-field measurements[2] does not require anisotropy or polarization detection as in the Zeeman technique**

R. J. Smith, Rev. Sci. Instrum. 79, 10E703 (2008)

E. Stambulchik, K. Tsigutkin, & Y. Maron, PRL 98, 225001 (2007)

Multiphysics computational tools are indispensable in studying the science of magnetized HEDP

As one example: HYDRA Physics Schematic from M. Marinak



Almost all interesting magnetized HED problems are not single physics issues, rather they have complicated interplays across physics areas

In developing the HEDP community more open access to better simulation tools is critical

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It’s an exciting time to be working in Magnetized HED plasmas

- **Our understanding of Magnetized HED plasmas is being applied to important applications**
- **Ever more extreme conditions are being reached using magnetized HED plasmas**
- **We are poised for exciting advances in inertial confinement fusion using magnetized concepts**
- **New resources, computational tools, diagnostics, and facilities access can enable a rapid advance in our understanding of Magnetized HEDP**

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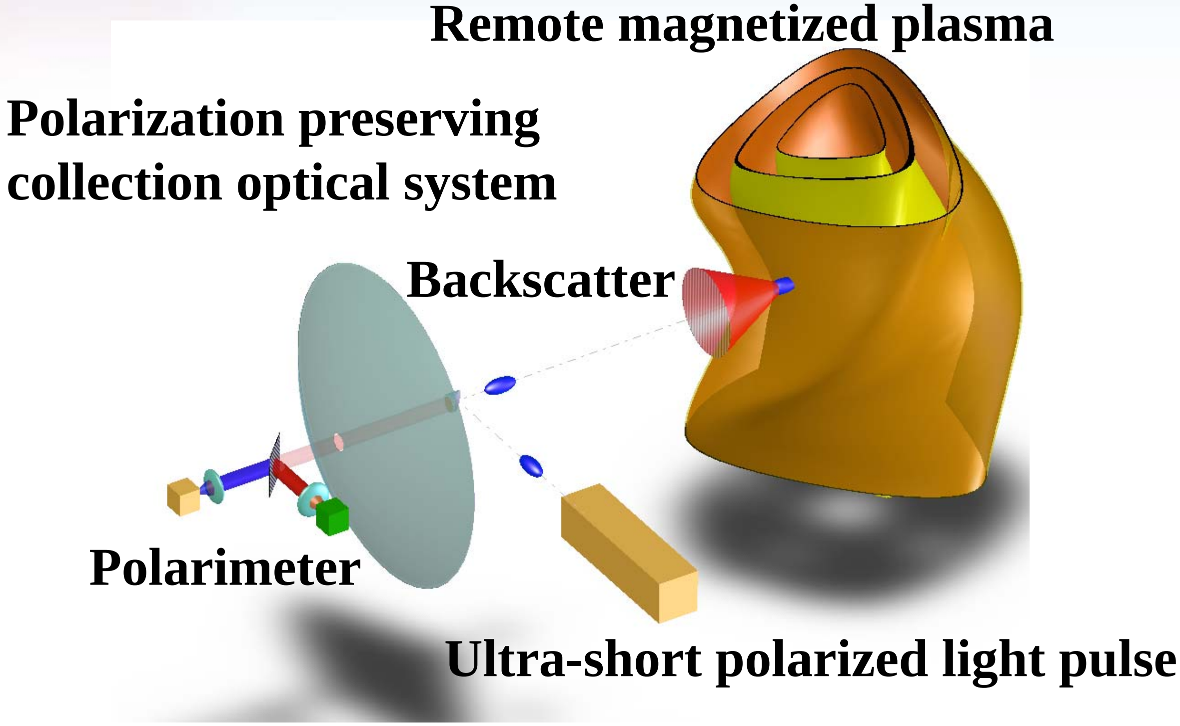
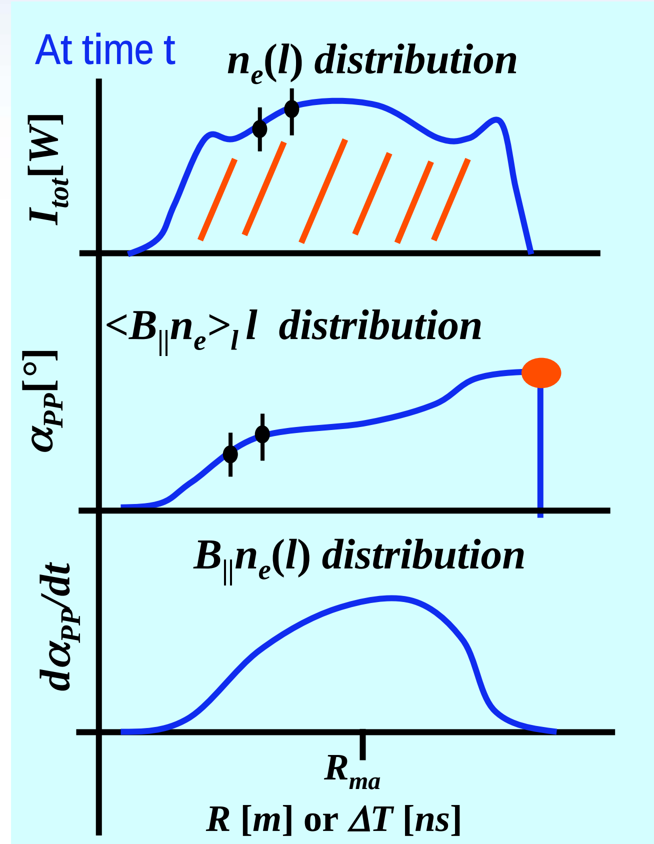
Backups

Determination of *local B* using Pulsed Polarimetry diagnostic





$$\alpha_{PP}(l) = \mathbf{2}\cdot 2.63x10^{-13}\ \lambda_o^{\,2}\int_0^l n_e B_{||}(s,t)\, ds$$

A Lidar-*like non-local* remote sensing of, α_{PP}, yields a *local* measurement of $n_e B_{||}$ upon differentiation

$$n_e B_{||}(l) \propto d\alpha_{PP}(l)/ds$$

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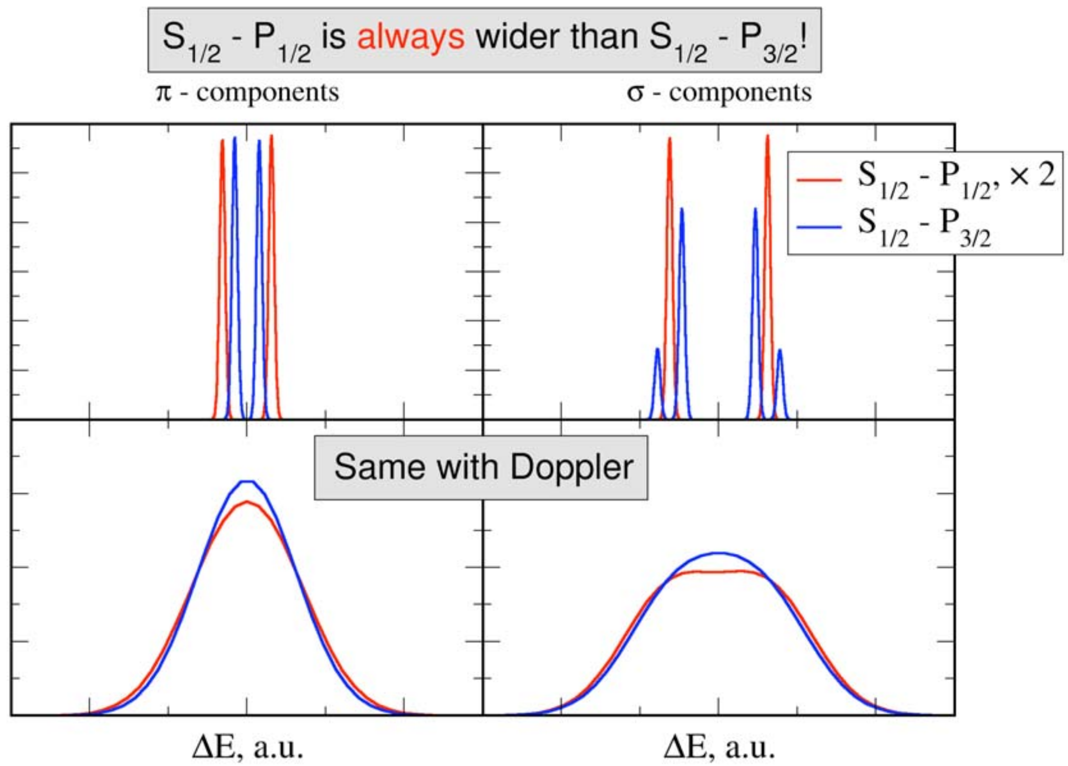
R. J. Smith, Rev. Sci. Instrum. 79, 10E703 (2008)

New approach to spectroscopic B-field measurements does not require anisotropy or polarization detection as in the Zeeman technique

- **Different fine-structure components of the same multiplet undergo different splittings under the magnetic field.**
- **On the other hand, Stark and Doppler effects broaden the components equally.**
- **Therefore, a comparison of the line-shapes of these components can reveal the presence of the magnetic field.**



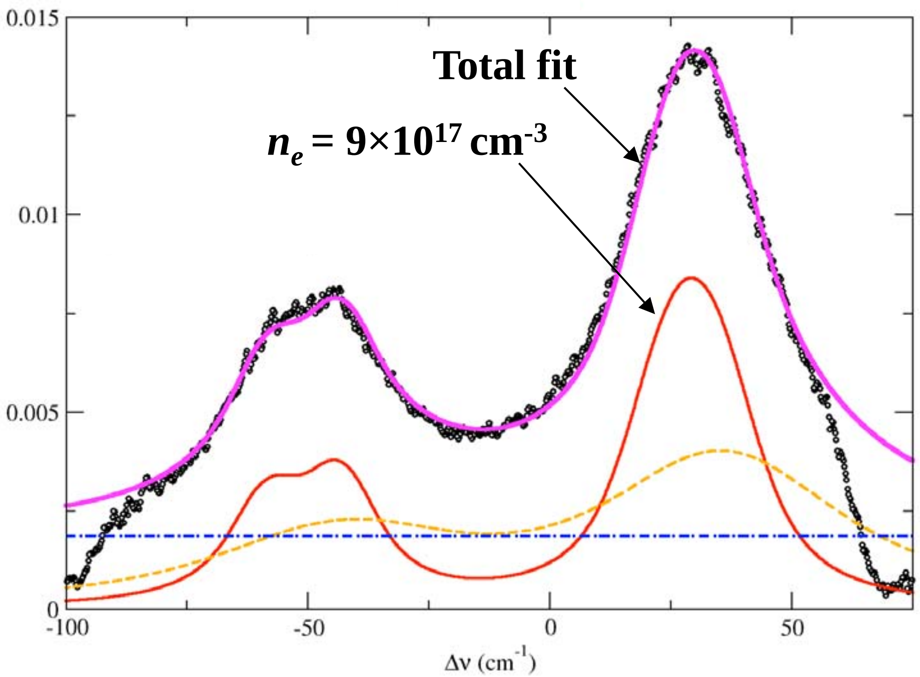
Demonstration of tecnique at 1 Tesla: E. Stambulchik, K. Tsigutkin, & Y. Maron, PRL (2007)

Uses detailed line shape calculations: E. Stambulchik and Y. Maron, *J. Quant. Spectr. Rad. Transfer* 99, 730 (2006).

The technique has been extended to higher magnetic fields and higher electron densities

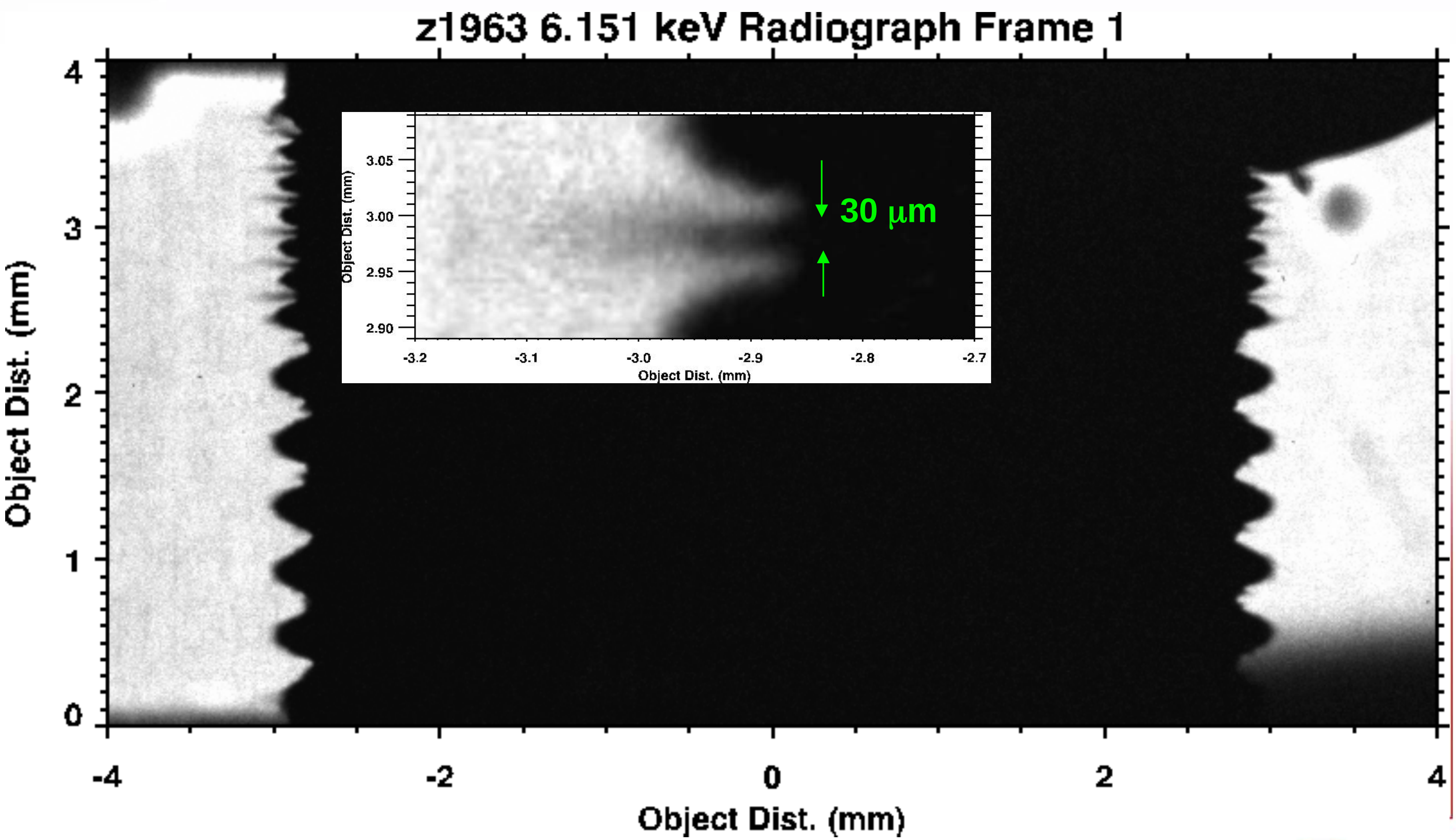
S. Tessarin, Y. Maron et al. Weizmann Institute (2009)

B = 16.5 T ± 10%



- Technique requires high signal to noise to detect small differences in the widths of the two lines
- Here use Al III 4s - 4p lines: Measure up to $B \leq 35$ T and $n_e \leq 5\times10^{18}$ cm^{-3}
- Extend the technique further: use VUV spectroscopy (~500 Å) of Ti XII 5p-6s lines and measure up to $B \leq 500$ T and $n_e \leq 10^{21}$ cm^{-3}

Initial data has been obtained on the growth of the Magneto-Rayleigh Taylor Instability in solid liners



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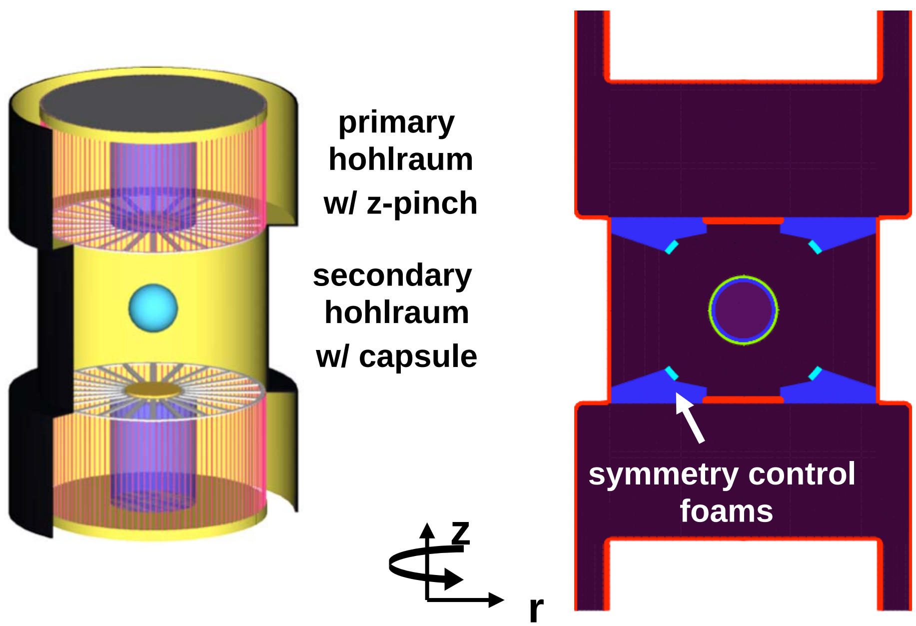
Integrated LASNEX simulations demonstrate 400+ MJ fusion yield in a pulsed-power z-pinch driven hohlraum

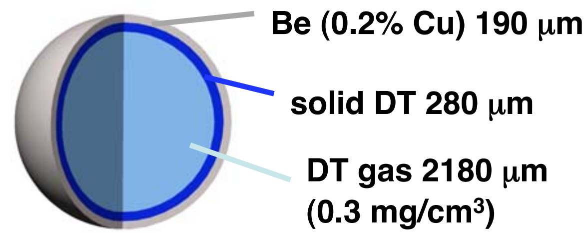
Double z-pinch hohlraum fusion concept

R. A. Vesey, M. C. Herrmann, R. W. Lemke *et al.*,
Phys. Plasmas (2007)

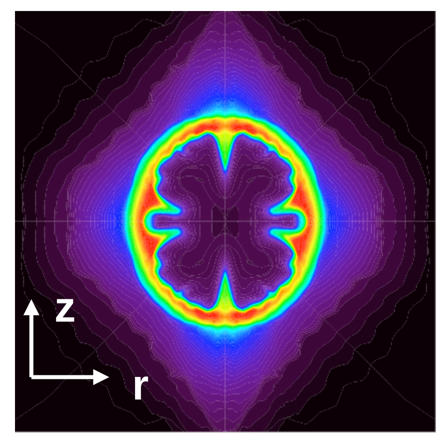


- Two z-pinches, each with 9 MJ x-ray output
- Symmetry control to 1% via geometry, shields
- Capsule absorbs 1.2 MJ, yields 400-500 MJ

High yield capsule design



Fuel density at ignition



1D capsule yield 520 MJ
2D integrated yield 470 MJ

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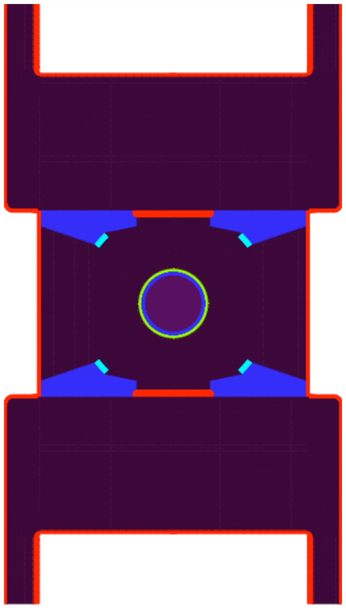
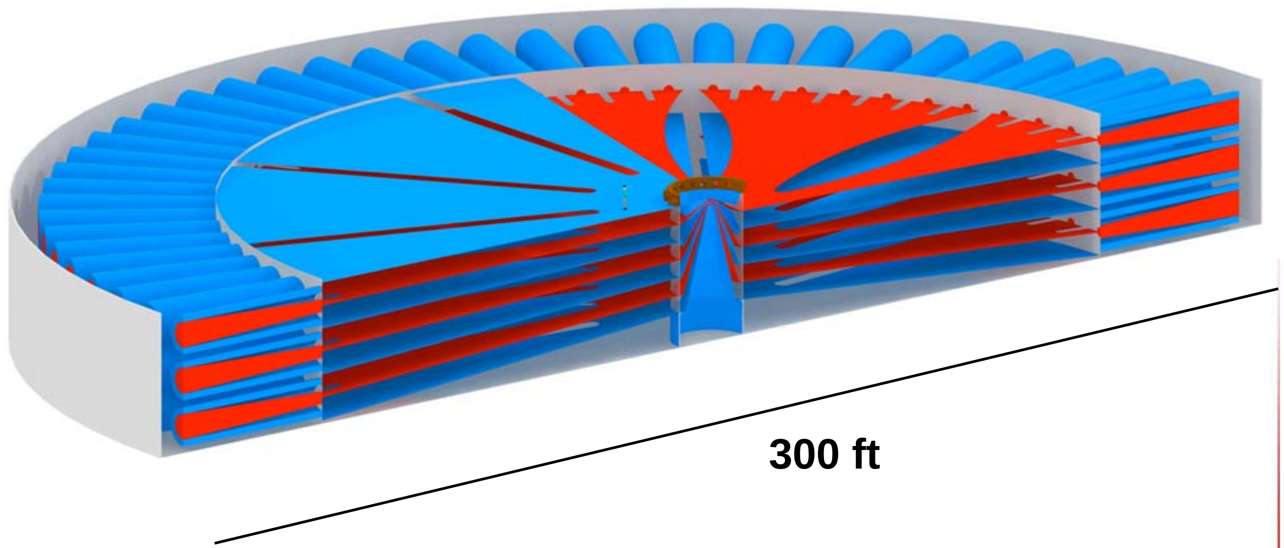
A large driver (beyond ZR) is needed is needed to drive the high yield double ended hohlraum

- **Power required (1 PW/pinch @ 20-mm-diam.)**
- **Energy required (8-9 MJ/pinch)**





Because of the inefficiencies in this concept only 0.04% of the driver energy gets to the fusion fuel

Are there more efficient concepts? Is there any way to lower the required pressure?

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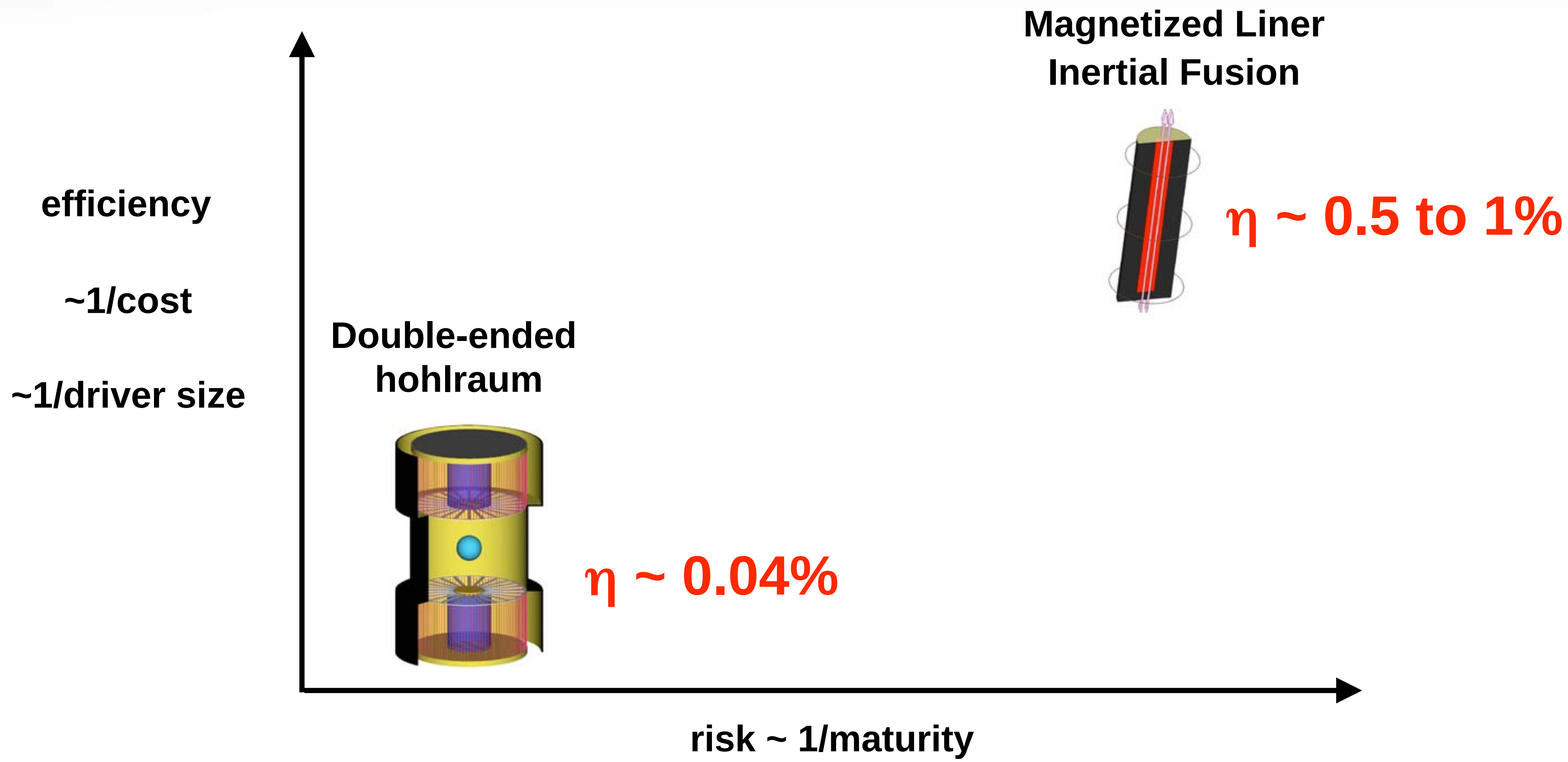
Magnetic Implosions are far more efficient at putting energy into fusion fuel



- Pulsed power can flexibly drive many target types
- Direct fuel compression and heating with the magnetic field could be up to 20X more efficient

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