Sandia National Laboratories

Overview of Fusion at Sandia National Laboratories

Keith Matzen

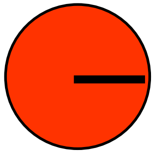
Pulsed Power Sciences Center, Sandia National Laboratories

in collaboration with many colleagues

Fusion Power Associates Annual Meeting and Symposium

December 2, 2009

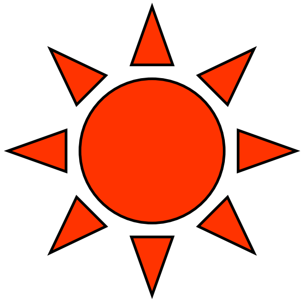
Under extreme conditions a mass of DT can undergo significant thermonuclear fusion before falling apart



ρ, R, T

- **Consider a mass of DT with radius R, density ρ, and temperature T**
- **How does the disassembly time compare with the time for thermonuclear burn?**

$$\tau_{disassembly} \sim \frac{R}{c_s} \sim \frac{R}{\sqrt{T}} \qquad \tau_{burn} \sim \frac{1}{n_i\langle\sigma v\rangle} \sim \frac{1}{\rho\langle\sigma v\rangle}$$



- **The fractional burn up of the DT (for small burn up) is:**

$$f_{burn} \approx \frac{\tau_{disassembly}}{\tau_{burn}} \sim \rho R \frac{\langle\sigma v\rangle}{\sqrt{T}}$$

- **At sufficiently high ρR and T the fractional burn up becomes significant and the energy deposited by alpha particles greatly exceeds the initial energy in the fusion fuel ("ignition")**

- **Typical conditions are:**

$$\rho R \approx 0.6\,\mathrm{g/cm^2}$$
$$T \approx 5\,\mathrm{keV}$$

The fusion fuel must be brought to a pressure of several hundred billion atmospheres to achieve the goal of ignition

For ignition conditions: $\left\{\begin{array}{l}\rho R \approx 0.6\,\mathrm{g/cm^2}\\ T \approx 5\,\mathrm{keV}\end{array}\right\}$ $\rho R T \approx 3.0\left(\dfrac{\mathrm{g\,keV}}{\mathrm{cm^2}}\right)$

$$P(\mathrm{Bar}) = 8 \bullet 10^{8}\,\rho\left(\mathrm{g/cm^3}\right)T_i\,(\mathrm{keV}) \qquad PR \sim 2.4 \bullet 10^{9}\,\mathrm{Bar-cm}$$

$$\mathrm{E} \sim \frac{3}{2}PV \sim \frac{3}{2}P\left(\frac{4\pi}{3}R^{3}\right) \sim 1.5 \bullet 10^{9}\,R^{2}\,(cm)(\mathrm{J})$$

$$\mathrm{E}_{\mathrm{NIF}} \sim 15\mathrm{kJ} \Rightarrow R \sim 30\mu\mathrm{m} \Rightarrow \quad P \sim 800\mathrm{GBar} \quad \text{and} \quad \rho \sim 200\,g/cm^{3}$$

$$\tau_{conf} \sim \frac{R}{c_s} \sim 30\,ps \qquad \mathrm{Power} \sim \frac{E}{\tau_{conf}} \sim 0.5 \bullet 10^{15}\,W$$

Note for magnetic confinement fusion ignition $\tau_{conf} \sim$ few seconds $\quad P \sim$ few Bars $\quad \rho \sim$ few $10^{-10}\,g/cm^{3}$

High velocity, low adiabat thin shells are needed to reach these pressures

In either direct or indirect drive, peak drive pressures are of order ~ 50-150 MBars

We need to get pressures to >1000X that for ignition

Spherical implosions enable us to store energy in the fusion fuel in the form of kinetic energy, which is converted to pressure at stagnation

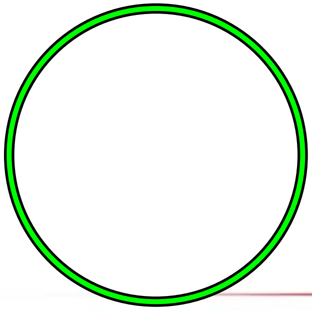
$$P_{stag} \sim \alpha\,\rho_{stag}^{5/3} \qquad \alpha\,\rho_{stag}^{2/3} \sim \mathrm{v}^2 \Rightarrow P_{stag} \sim \mathrm{v}^5 \big/ \alpha^{3/2}$$

$$\alpha \equiv P \big/ P_{Fermi}$$

Thin shell implosions can reach the 200-400 km/sec needed for ICF

$$\int P_{drive}\mathrm{dV} = \frac{1}{2} m\mathrm{v}^2 \qquad m \sim 4\pi R^2 \rho\,\delta R$$

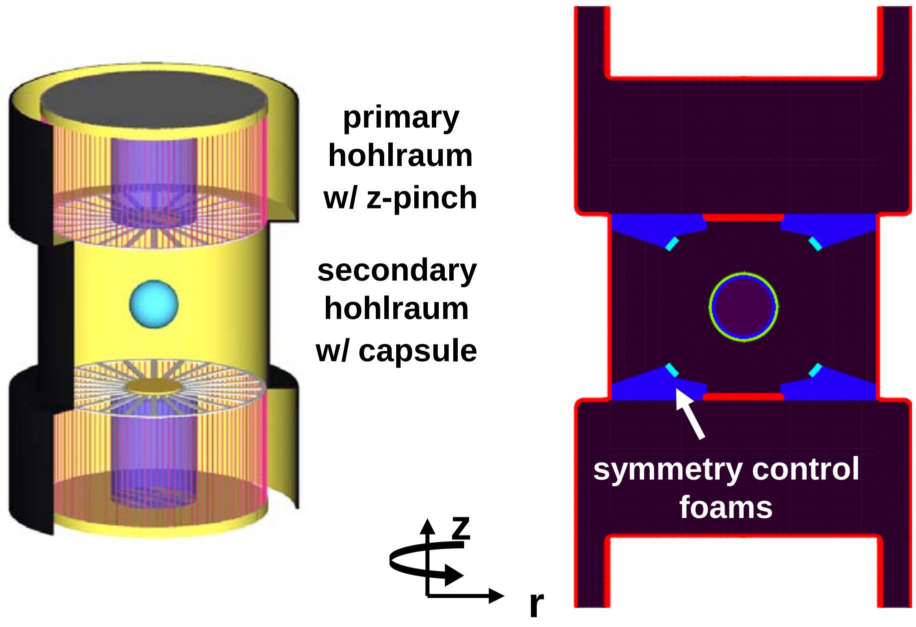
$$P_{drive} R^3 \sim R^2 \rho\,\delta R\,\mathrm{v}^2 \Rightarrow \mathrm{v}^2 \sim \frac{P_{drive}}{\rho}\frac{R}{\delta R}$$



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

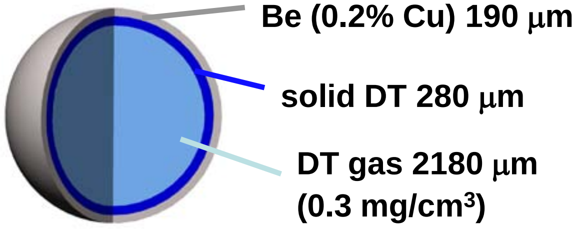
Double z-pinch hohlraum fusion concept

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

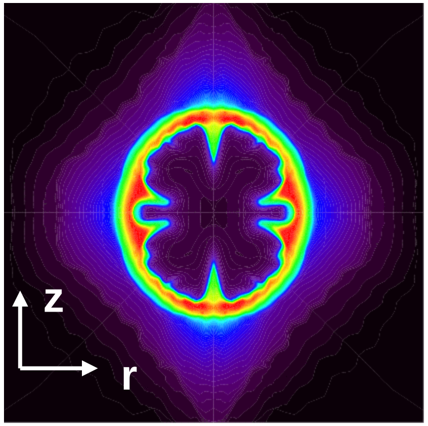


- **Two Z-pinches, each with 9 MJ x-ray output**
- **Symmetry control to 1% via geometry, shields**
- **Capsule absorbs 1.2 MJ, yields 400-500 MJ**

High yield capsule design

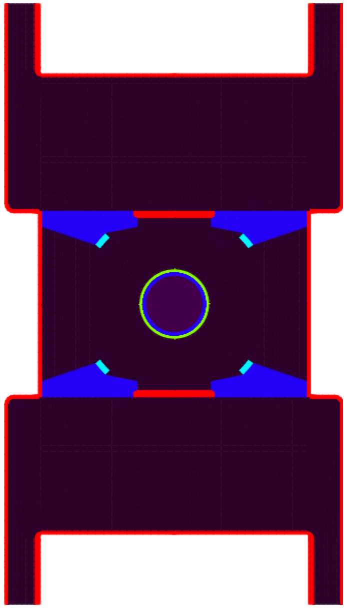


Fuel density at ignition

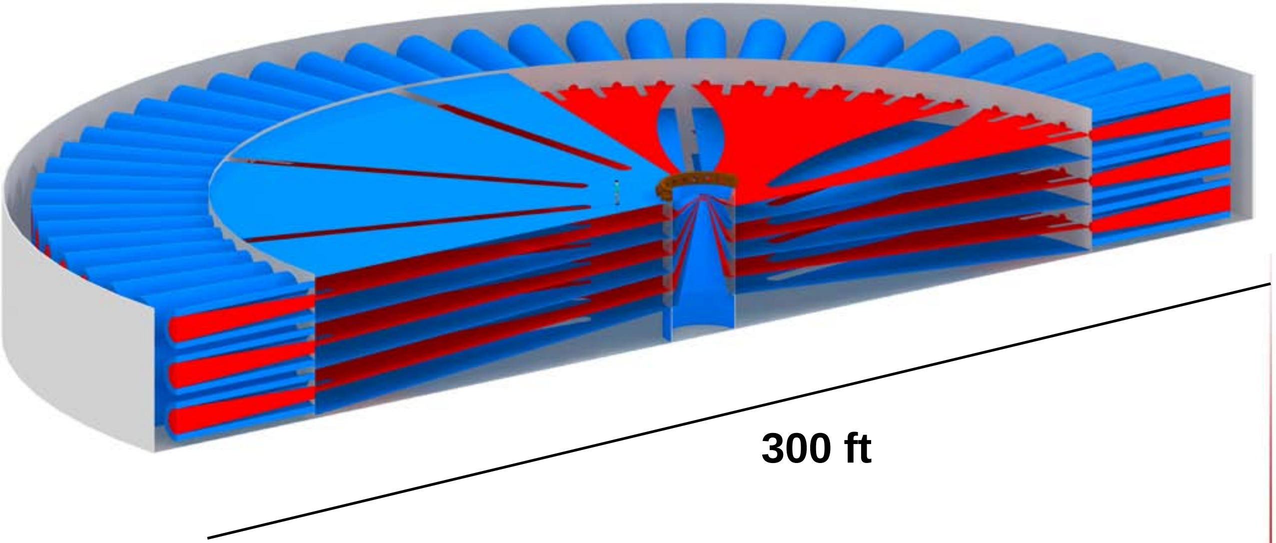


1D capsule yield 520 MJ
2D integrated yield 470 MJ

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



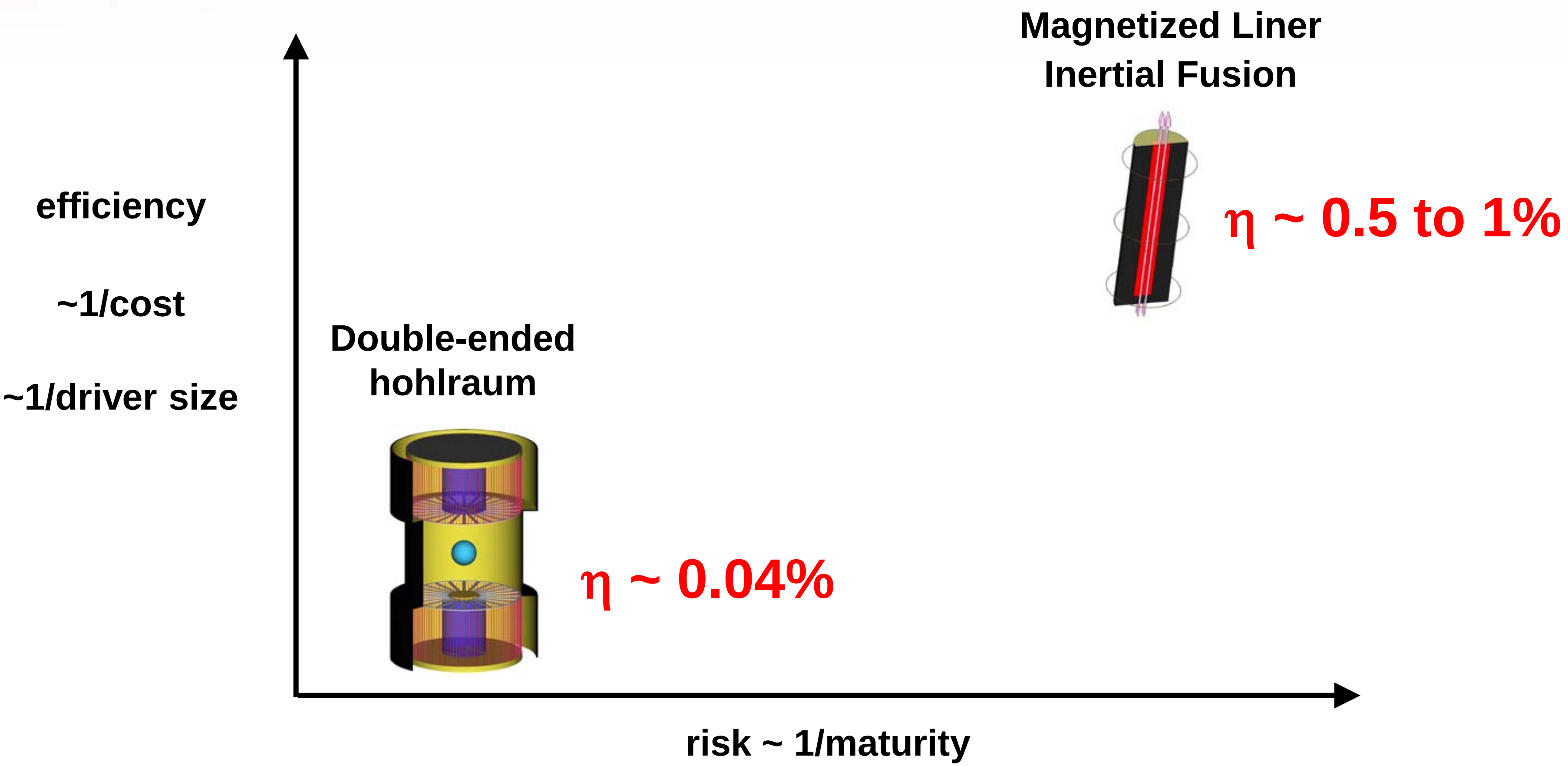
- **Power required (1 PW/pinch @ 20-mm-diam.)**
- **Energy required (8-9 MJ/pinch)**



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?

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



Magnetized Liner Inertial Fusion

η ~ 0.5 to 1%

efficiency

~1/cost

~1/driver size

Double-ended hohlraum

η ~ 0.04%

risk ~ 1/maturity

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

Magnetically driven implosions are a unique capability for pulsed power accelerators

Direct magnetically driven implosions could be over an order of magnitude more efficient than indirect radiation driven implosions

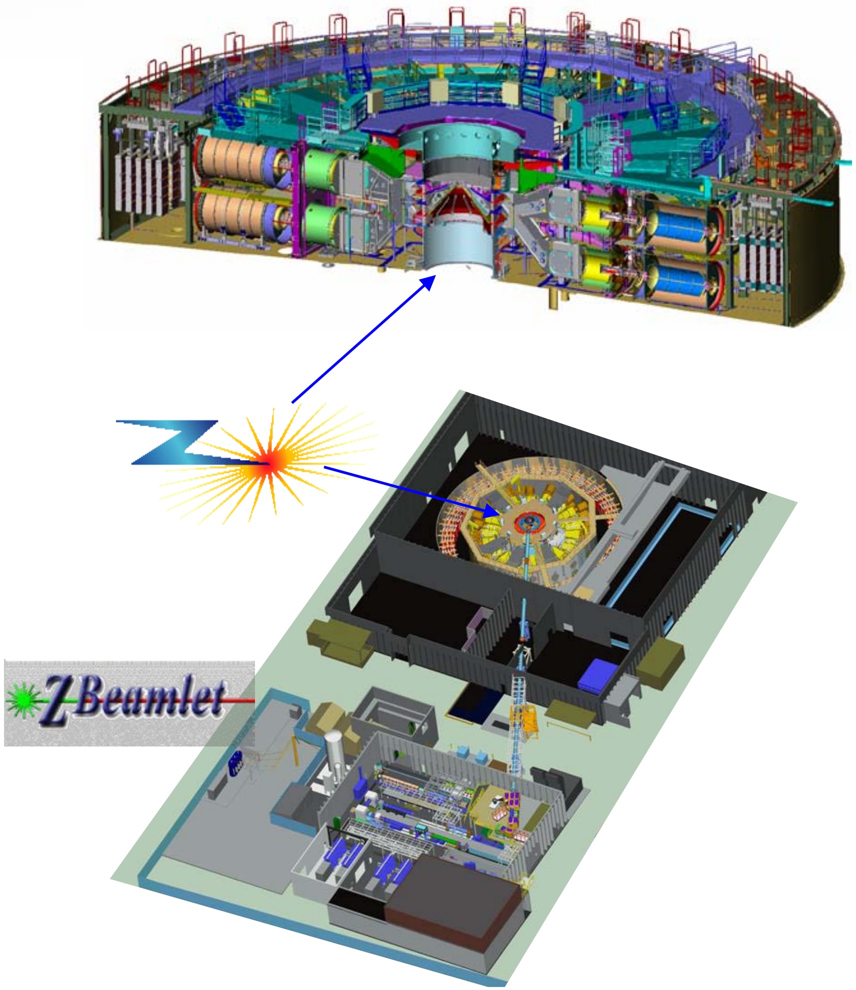
Natural geometry is cylindrical

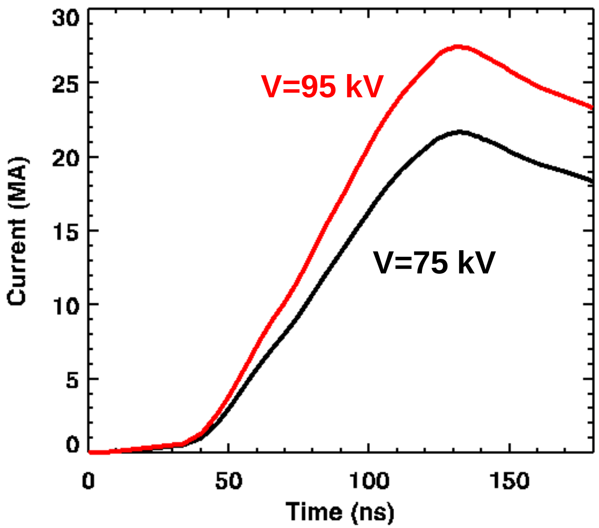
- **reduced volume compression (ρr and T_{ig} difficult)**
- **implosion velocity is slow V_{imp} ~ 12 cm/μs for instability-robust liners**

Fuel magnetizing and preheating is a potential solution

- **the attainment of ignition conditions with slow implosions and modest radial convergence**

The Z facility contains the worlds largest pulsed power machine and the Z-Beamlet and Z-Petawatt lasers





Magnetically-Driven Cylindrical Implosion

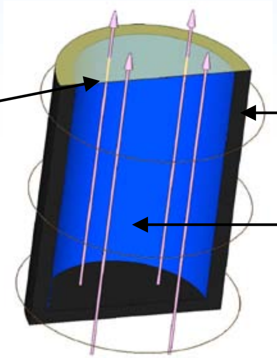
$$P = \frac{B^2}{2\mu_o} = 140\left(\frac{I_{MA}/30}{R_{mm}}\right)^2 MBar$$

140 MBar is generated by 300 eV radiation drive

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

1. A 10-50T axial magnetic field

is applied to inhibit thermal conduction and enhance alpha particle deposition before the implosion begins

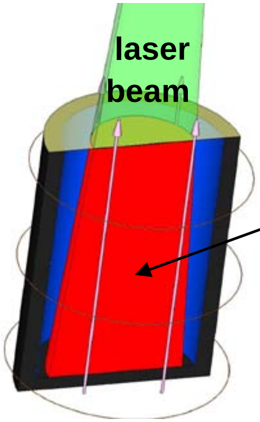


Metal (beryllium) Cylindrical Liner

cold deuterium/tritium gas (fuel)

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

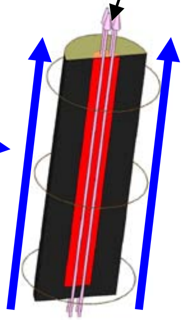
to reduce the require compression needed



Laser preheated fuel

compressed axial field

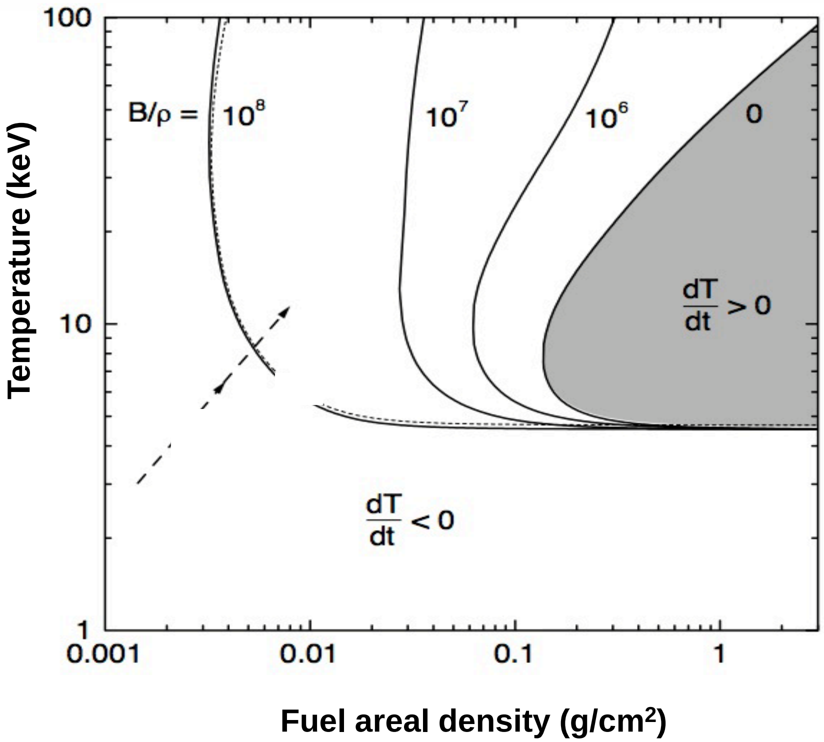
3. The Z accelerator can provide the drive current which generates an azimuthal drive field (pressure) to efficiently implode the liner (Z pinch) at 50-100 km/sec and compress the axial field by factors of 1000



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

Magnetization significantly increases the ignition space

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



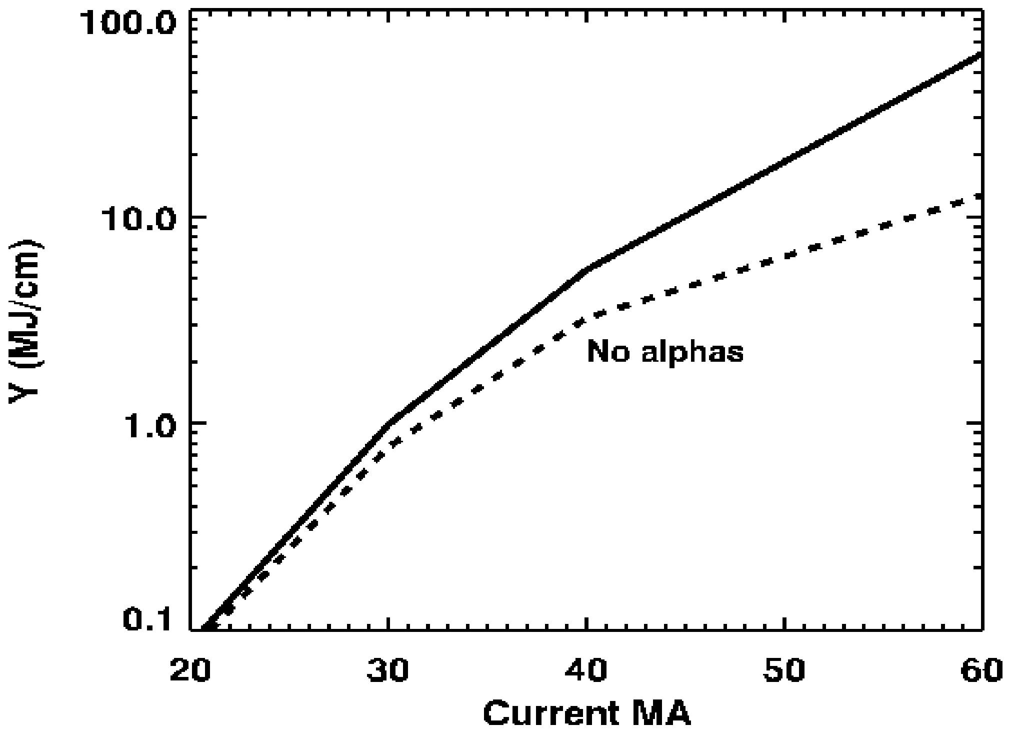
The ρr needed for ignition can be significantly reduced by the presence of a strong magnetic field inhibit electron conduction and confinement of alpha particles

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

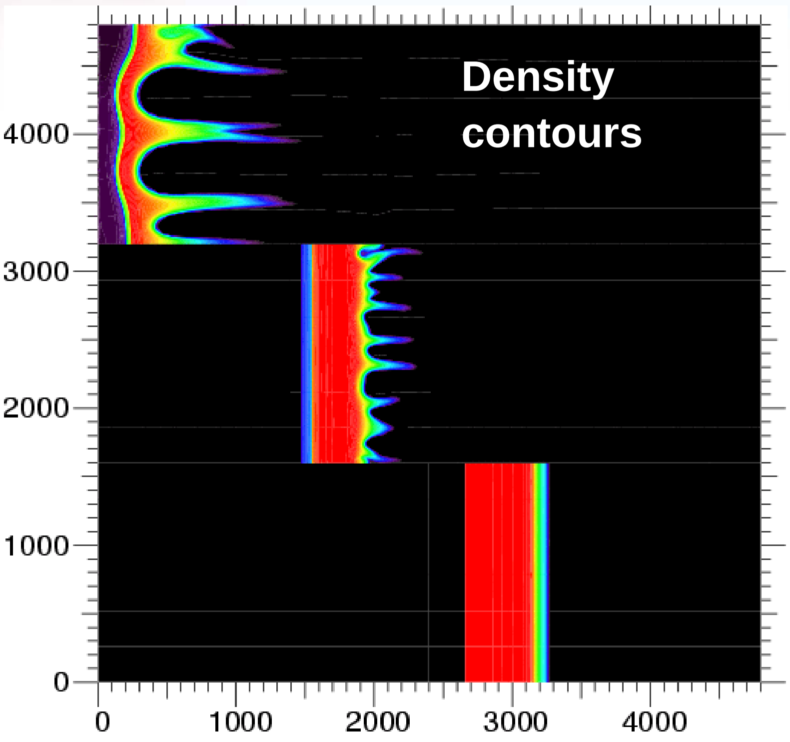
The yield is a strong function of drive current



Liner parameters

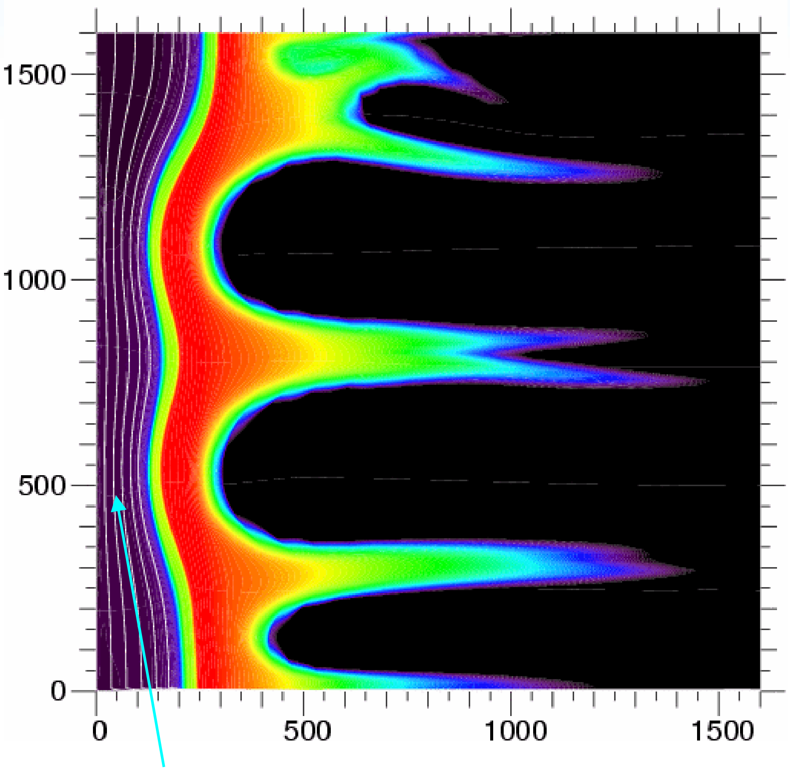
- Aspect Ratio, $R_0/\Delta R = 6$
- CR = 20
- B=30 T
- Preheat temp~250 eV
- Initial fuel density 2 - 5 mg/cc

2D simulations of MagLIF show some yield degradation for low aspect ratio liner



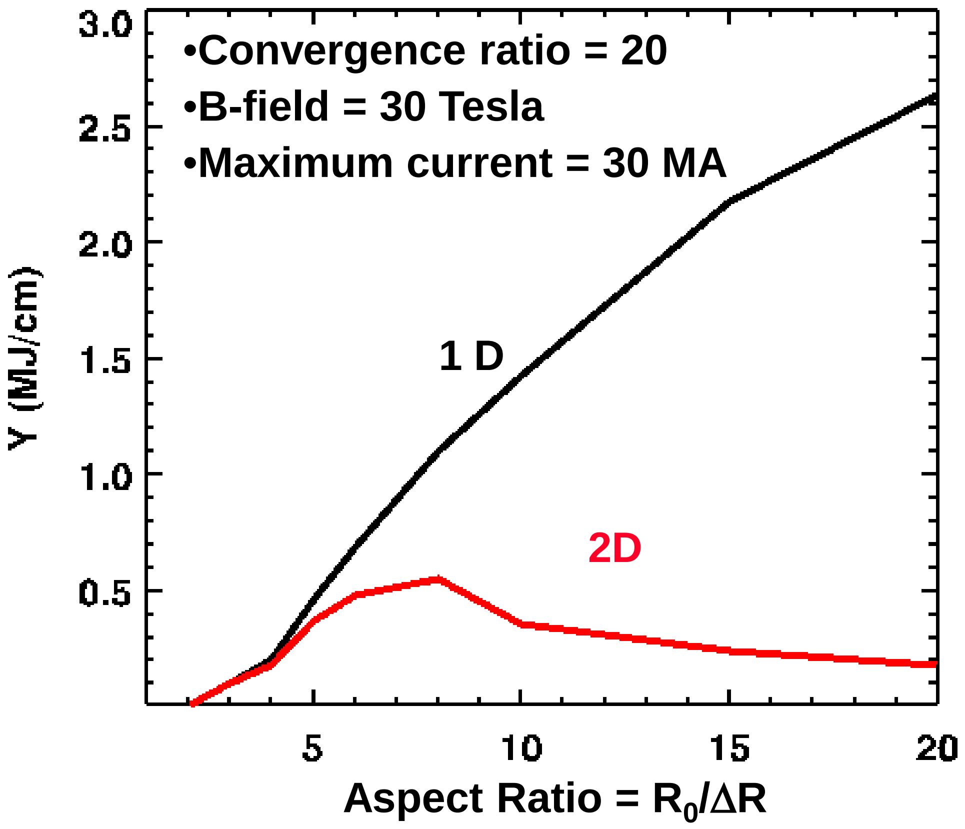
Beryllium liner

- **Aspect Ratio, $R_0/\Delta R = 6$**
- **60 nm surface roughness**
- **80 μ waves are resolved**
- **Yield ~ 70% 1D**



Compressed axial magnetic field has a stabilizing effect

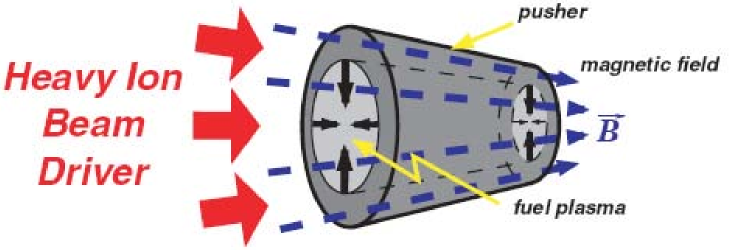
There is an optimum liner aspect ratio when instabilities are considered



- **In the absence of instability the liner yield would increase with aspect ratio**
- **The Magneto-Rayleigh-Taylor instability has an increasingly strong degrading effect on the yield as the aspect ratio is increased**

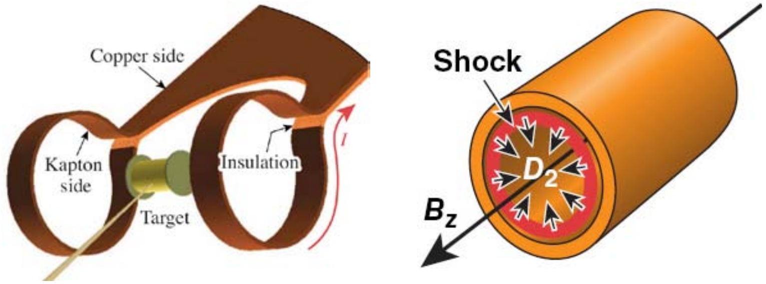
The parameter space for magnetized ICF is large, allowing a diverse set of approaches

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

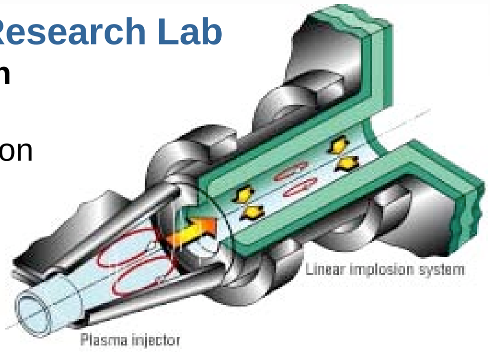


Direct drive laser implosion of cylinders
-- shock pre-heating, high implosion velocity

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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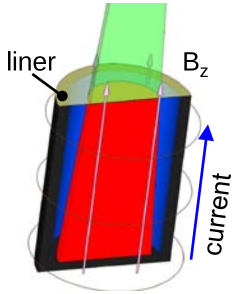
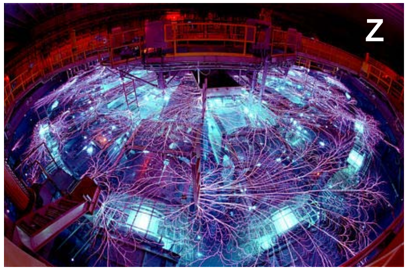
Magnetized Liner Inertial Fusion

Laser preheated magnetized fuel

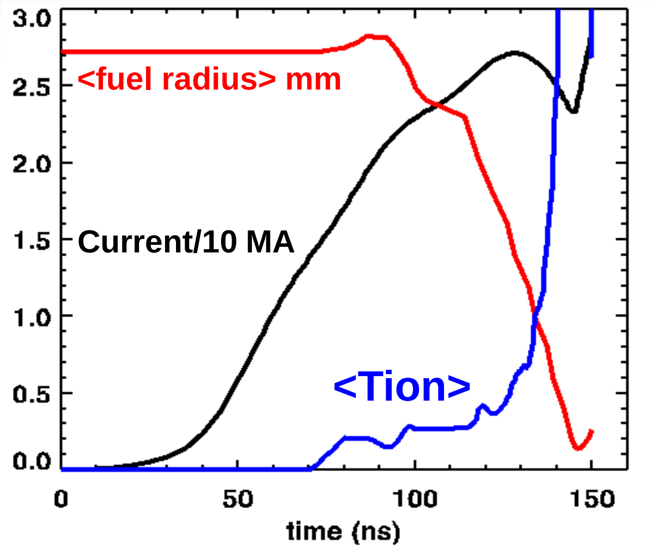
LASNEX simulations indicate interesting yields

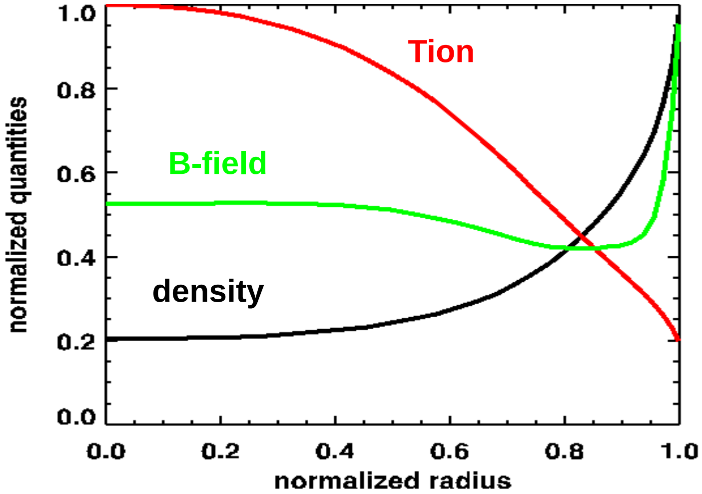




Slutz *et al.*submitted to Phys. Plas.

We are working toward a point design for Z





We are using Lasnex to simulate MagLIF

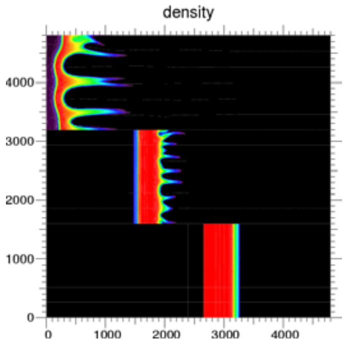
- **Well benchmarked**
- **Radiation hydrodynamics**
- **Includes the effect of B on alphas**

Preliminary point design parameters

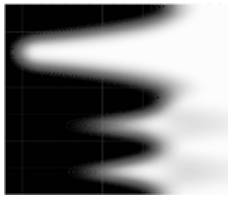
•Beryllium liner R_0	2.7	mm
•Liner length	5.0	mm
•Aspect Ratio $R_0/\Delta R$	6	
•Initial fuel density	0.003	g/cc
•Final fuel density <on axis>	0.5	g/cc
•Preheat temperature	250	eV
•Peak central averaged Tion	8	keV
•Initial B-field	30	Tesla
•Final peak B-field	13500	Tesla
•Peak current	27	MA
•1D Yield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

We are assembling the elements needed for integrated simulations of MagLIF targets

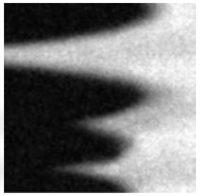
- **2D simulation of liner stability**



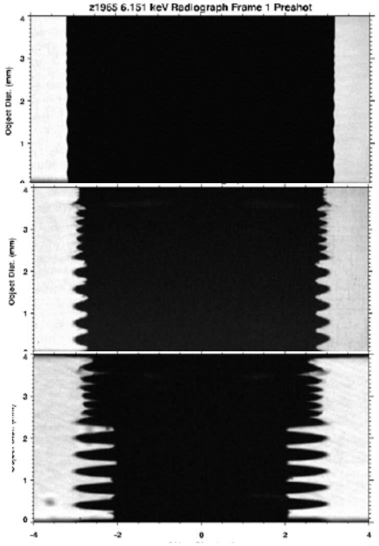
LASNEX



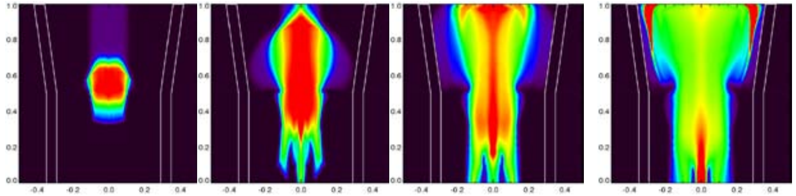
Z data



Benchmarking on Z



- **Laser ray-trace energy deposition in 2D with applied B_z fields**



- **2D transport of poloidal fields (B_r,B_z) in imploding liner system**

- **Fusion burn in magnetized fuel**

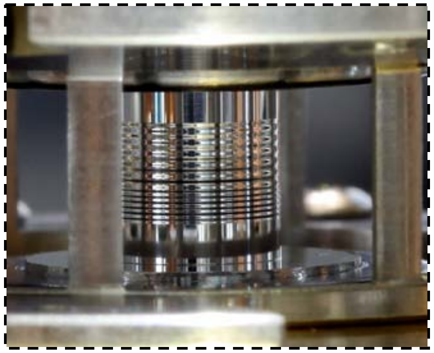
We are building the integrated simulations needed to find self-consistent design solutions, e.g. balancing the requirements of laser heating physics with the desired preheat level for a desired implosion history and final fuel condition

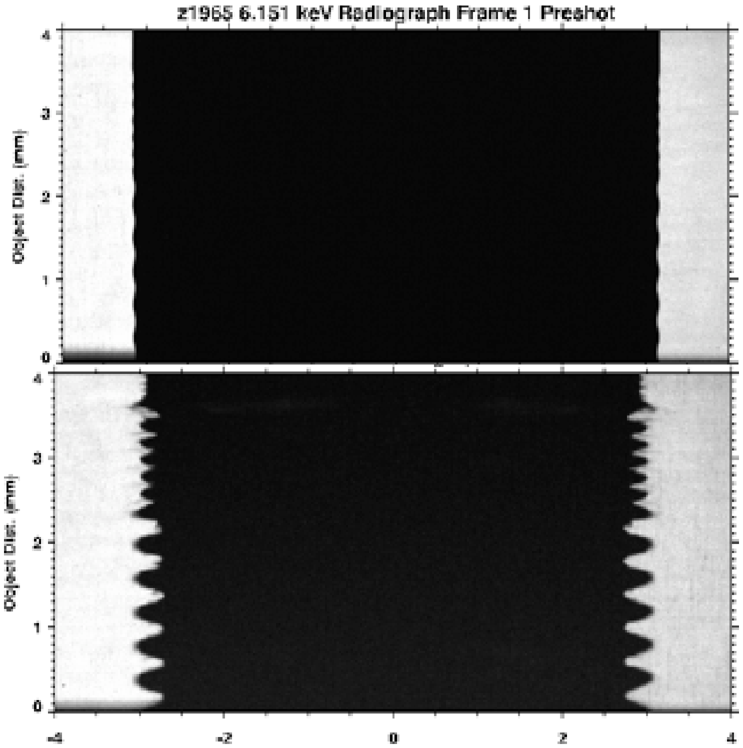
Experiments to measure the growth of the magnetic Rayleigh-Taylor instability on the 100 ns timescale have begun

Al liner target with initial perturbations

λ = 400 μm, A=20 μm

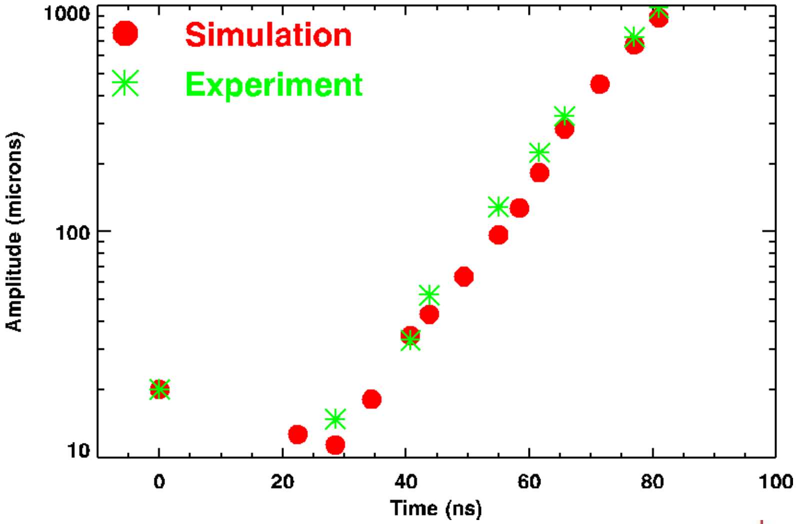
λ = 200 μm, A=10 μm





X-ray radiographs at 6.151 keV of Al liner

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



Summary: Magnetized Liner Inertial Fusion (MagLIF) shows promise and should be studied

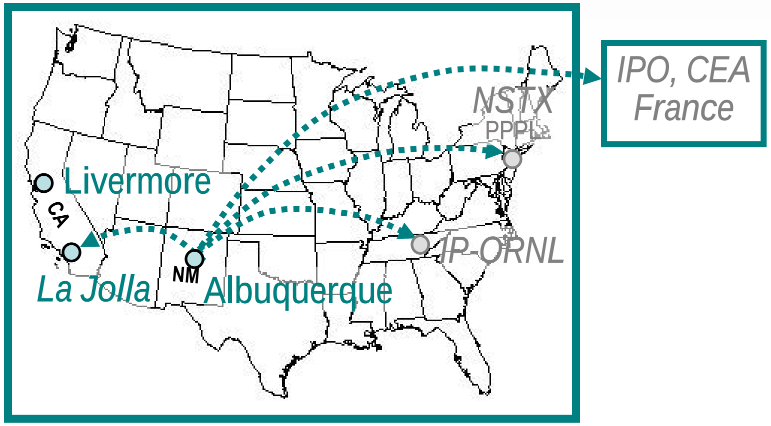
Both 1D scaling and 2D stability simulations indicate MagLIF could be an interesting path toward fusion

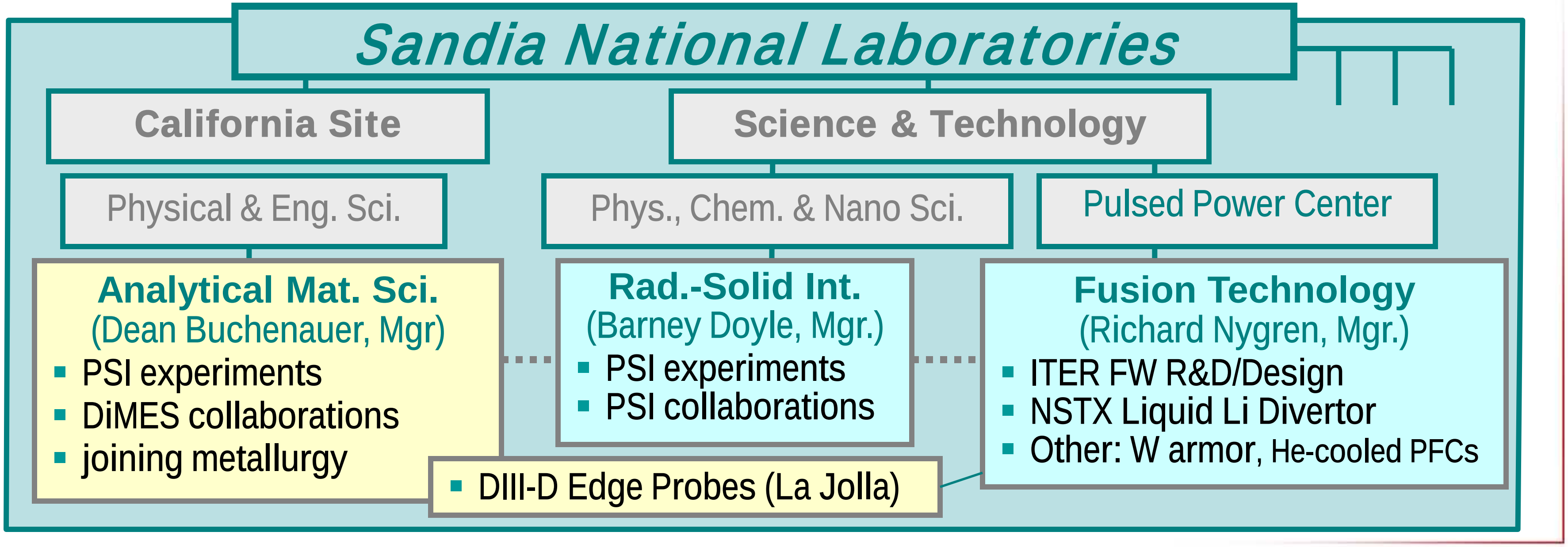
- **Both magnetization and fuel preheat are necessary**
- **We propose laser preheating of the DT fuel with the Z-Beamlet laser**
- **Magnetized liners are expected to be robust to anomalous transport, since $\omega\tau$ is modest**
- **2D simulations indicate that low aspect ratio liners (5-10) are robust to the MRT instability**
- **The fusion yield is relatively insensitive to mixing of the liner material into the fuel (low Z liner)**

MFE Fusion at Sandia

We design, develop and tests Plasma Facing Components (PFCs)

- **Plasma edge, plasma wall interactions, tritium retention and permeation**
- **PFC design & development; modeling, high heat flux tests, joining, fabrication**
  - ***ITER first wall***
  - ***NSTX liquid lithium divertor***
  - ***He-cooled refractory PFCs***
- **Plasma Materials Test Facility**





Sandia National Laboratories

California Site

Physical & Eng. Sci.

Analytical Mat. Sci.
(Dean Buchenauer, Mgr)

- PSI experiments
- DiMES collaborations
- joining metallurgy

Science & Technology

Phys., Chem. & Nano Sci.

Rad.-Solid Int.
(Barney Doyle, Mgr.)

- PSI experiments
- PSI collaborations

Pulsed Power Center

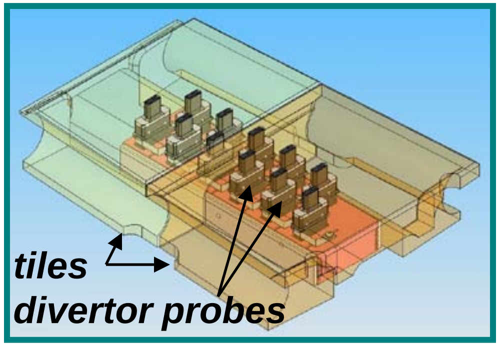
Fusion Technology
(Richard Nygren, Mgr.)

- ITER FW R&D/Design
- NSTX Liquid Li Divertor
- Other: W armor, He-cooled PFCs

- DIII-D Edge Probes (La Jolla)

Our history includes many successful national and international collaborations

JET, TEXTOR, Tore Supra, JT-60, LHD, KSTAR, …
DIII-D, C-MOD, TFTR, PISCES ..



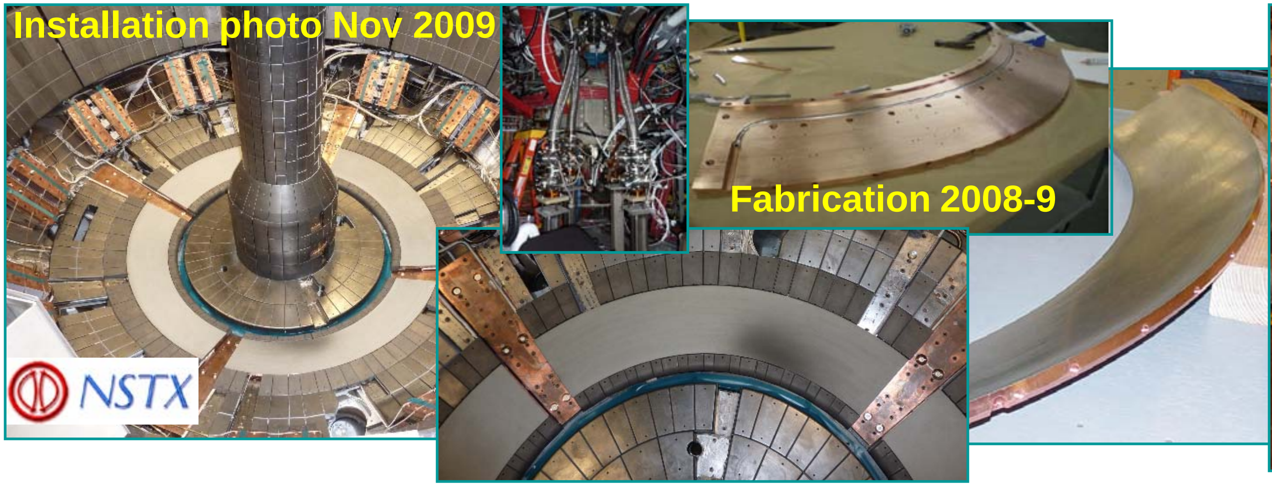
DIII-D
GENERAL ATOMICS

- Sandia edge probe array
- ELM control studies

(Jon Watkins)

NSTX
PPPL
PRINCETON PLASMA PHYSICS LABORATORY

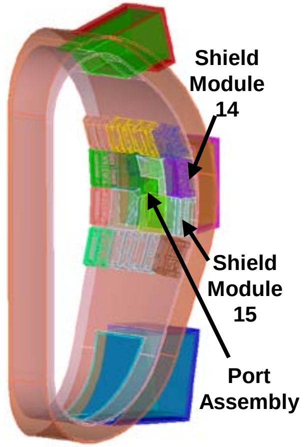
- Li jet experiments, B field like NSTX divertor
- Measurements of deposited Li (Bill Wampler)
- Liquid Lithium Divertor plates & heater control


Installation photo Nov 2009
Fabrication 2008-9

Sandia National Laboratories

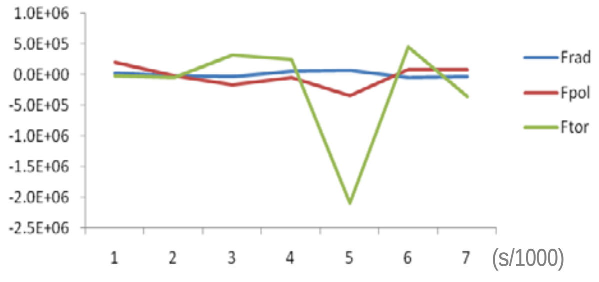
ITER first wall R&D is our largest program

- Sandia tested Be, C, W (PFC options)
- Sandia/Boeing built divertor cassette
- ITER Design Reviews
- US Technical lead (Mike Ulrickson)



Electromagnetic analysis

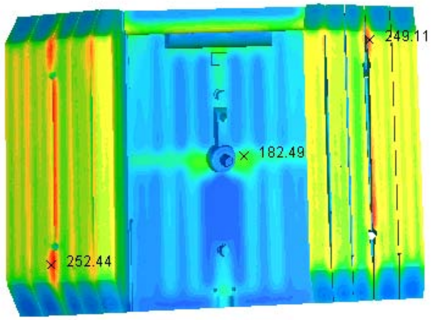
forces vs. time in vertical upward disruption



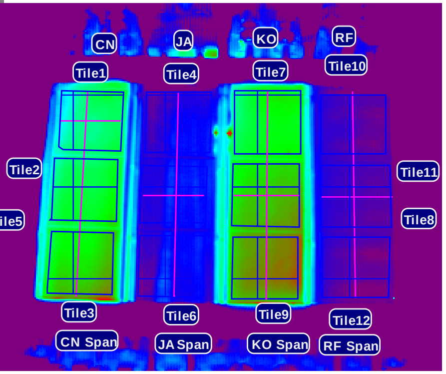
High heat flux tests

Plasma Materials Test Facility
EB1200 Electron Beam

Thermal & stress analyses

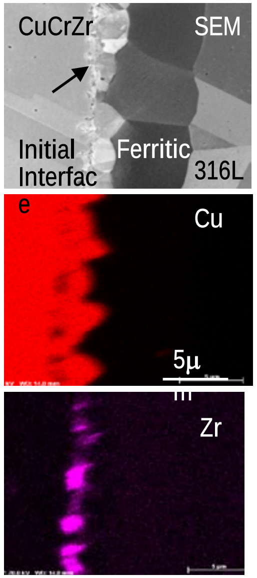


IR thermograph - 12,000 cycles, first wall quality mockups from Japan, Russia, China & Korea



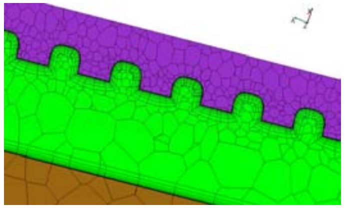
Thermal-hydraulic analysis

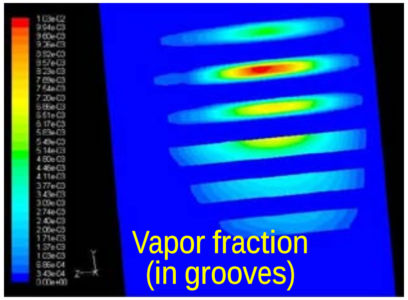
Pioneering work on coolant flow and heat transfer that established reference calculations for ITER.



Joining R&D

CuCrZr/316SS joint showed deleterious BCC phase formation





Vapor fraction (in grooves)

Hypervaportron model (FLUENT) of ITER first wall

The Z facility provides a unique, alternative research path to fusion ignition

- **Z facility**
  - **Z: 26 MA in 100 to 600 ns risetime**
  - **Z-Beamlet: multi-kJ in few ns**
  - **Z-Petawatt: kJ in ps**
  - **Sophisticated diagnostics**
  - **Routinely operating at 1 shot per day**

- **MagLIF – Magnetized Liner Inertial Fusion**
  - **Utilize axial magnetic field and laser preheat to significantly reduce requirements for fusion ignition (P, ρR)**
  - **Greater than an order of magnitude increase in efficiency of coupling driver energy to fusion fuel**

Sandia National Laboratories