An overview of magneto-inertial fusion on the Z Machine at Sandia National Laboratories

D. A. Yager-Elorriaga, M. R. Gomez, D. E. Ruiz, S. A. Slutz, A. J. Harvey-Thompson, C. A. Jennings, P. F. Knapp, P. F. Schmit, M. R. Weis, T. J. Awe, G. A. Chandler, M. Mangan, C. E. Myers, J. R. Fein, M. Geissel, M. E. Glinsky, S. B. Hansen, E. C. Harding, D. C. Lamppa, W. E. Lewis, P. K. Rambo, G. K. Robertson, M. E. Savage, I. C. Smith, D. J. Ampleford, K. Beckwith, K. J. Peterson, J. L. Porter, G. A. Rochau, and D. B. Sinars

ABSTRACT

- Magnetized Liner Inertial Fusion (MagLIF) is the first magneto-inertial fusion (MIF) concept to demonstrate fusion relevant temperatures, significant fusion production (>1e13 primary DD neutron yield) and magnetic trapping of charged fusion particles [1, 2]
- MagLIF is pursued on the Z Machine at Sandia National Laboratories, where an axially pre-magnetized, laser-preheated fusion fuel is imploded inside a cylindrical liner using ~20 MA to generate fusion conditions.
- MagLIF has the potential to achieve high gain and yield on a next generation pulsed power facility, and could provide an interesting path towards magneto-inertial fusion energy

BACKGROUND

- In MagLIF, a centimeter-scale beryllium tube or "liner" is filled with a fusion fuel, axially pre-magnetized, laser pre-heated and imploded using ~20 MA from the Z Machine in order to generate a thermonuclear column of plasma.
  - The laser preheat raises the initial adiabat of the fuel (100s eV)
  - The electrical current implodes the liner using ~20 MA and quasi-adiabatically compresses the fuel via the Lorentz force
  - The axial magnetic field (initially 10s T) limits thermal conduction losses from the fuel to the liner walls during the implosion, and is flux compressed to ~1000s T to increase trapping of charged fusion products

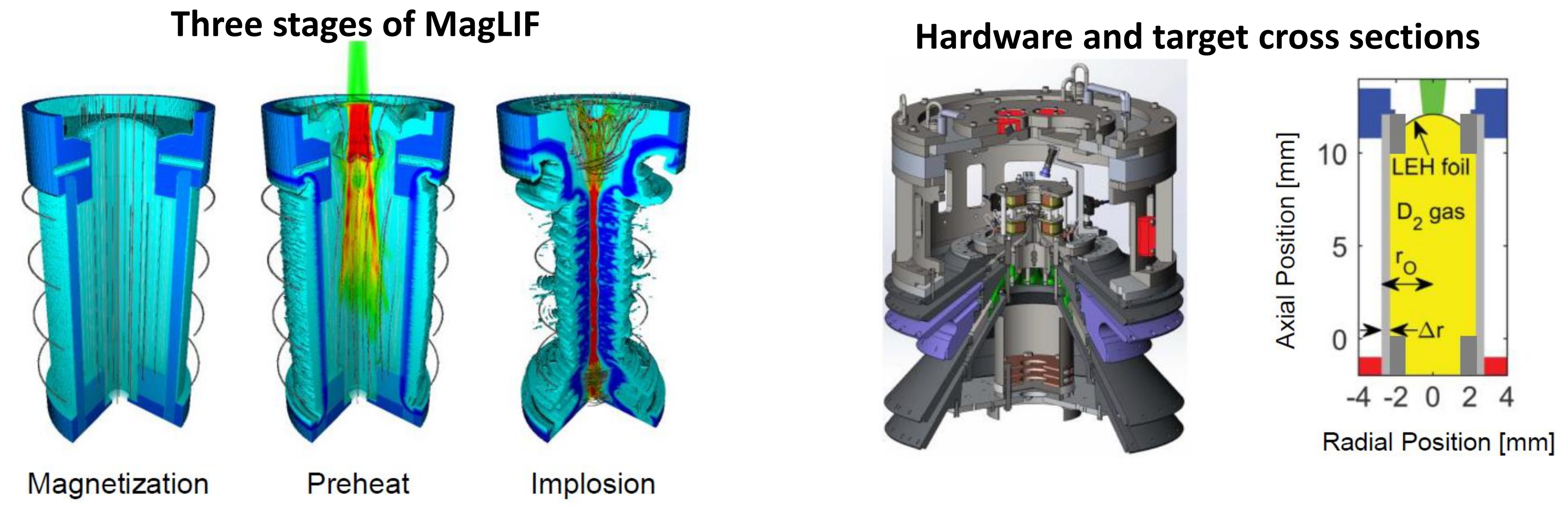


Fig 1. Three-dimensional simulation demonstrating the three stages of MagLIF (left) and load hardware and target cross sections (right)

- The magnetization relaxes the areal density requirements and opens a wide area of parameter space for self-heating. Present-day MagLIF has demonstrated relevant magnetization levels of BR = 0.3 - 0.5 MG-cm.

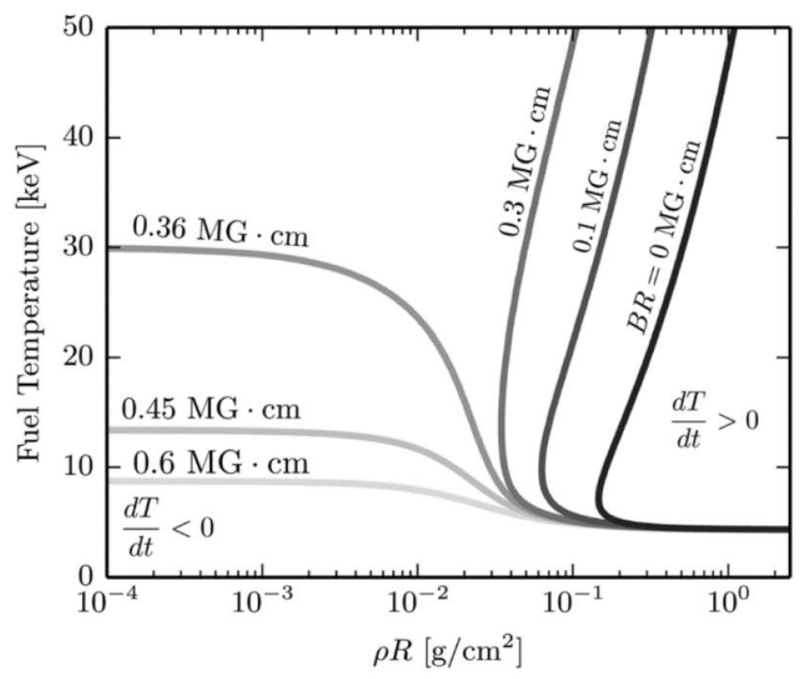
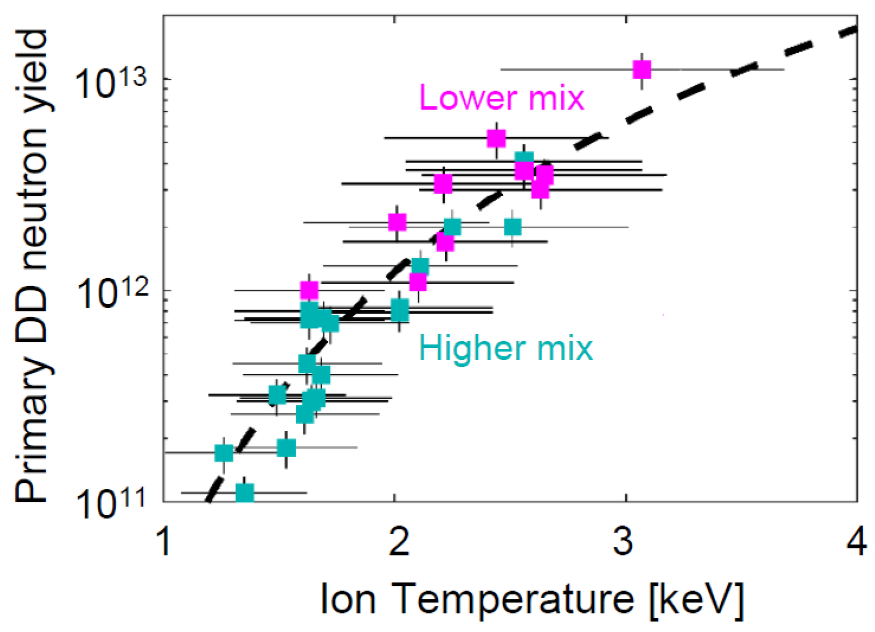


Fig 2. Lindl diagram showing self-heating contours for various magnetization values [3]

- MagLIF performance since the first 2013 experiments can be captured in a plot of primary DD yield vs ion temperature, which scales with the DD fusion reactivity. Early improvements to performance were accomplished by replacing fuel-facing components with beryllium to reduce mix.

Fig 3. DD neutron yield as a function of ion temperature [4]



MAJOR RESEARCH AREAS IN MagLIF

IMPLOSION STABILITY

- MagLIF is susceptible to the magneto Rayleigh-Taylor (MRT) instability, which may significantly affect the quality of the implosion, compression, and inertial confinement of the fusion fuel.
  - Experimentally benchmarked MRT simulations in pre-seeded liner implosions [5]
  - Demonstrated enhanced stabilization with dielectric coated liners to mitigate the electrothermal instability that seeds MRT [6, 7]

LASER PREHEAT

- The laser preheat protocol has been continuously upgraded to better reduce LEH window mix, increase the energy coupled to fuel, and optimize the propagation length of the laser
  - Beam profile smoothed using a distributed phase-plate [8]
  - Mix from the laser entrance hole foil reduced using a 24 J, 2 ns-long pre-pulse 20 ns prior to main preheat pulse [9]
  - 3d simulations suggest additional energy can be coupled using cryogenically cooled targets to allow thinner foils by reducing initial fuel pressure [10]

CURRENT DELIVERY AND APPLIED MAGNETIC FIELD

- The transmission line leading up to the target was re-designed to improve current coupling from 16 to 20 MA while simultaneously enabling the possibility of 30 T pre-magnetization
  - Experiments with simultaneous improvements to laser preheat, current delivery and applied axial magnetic field increased performance by an order of magnitude (2 kJ DT equivalent yield) [4]

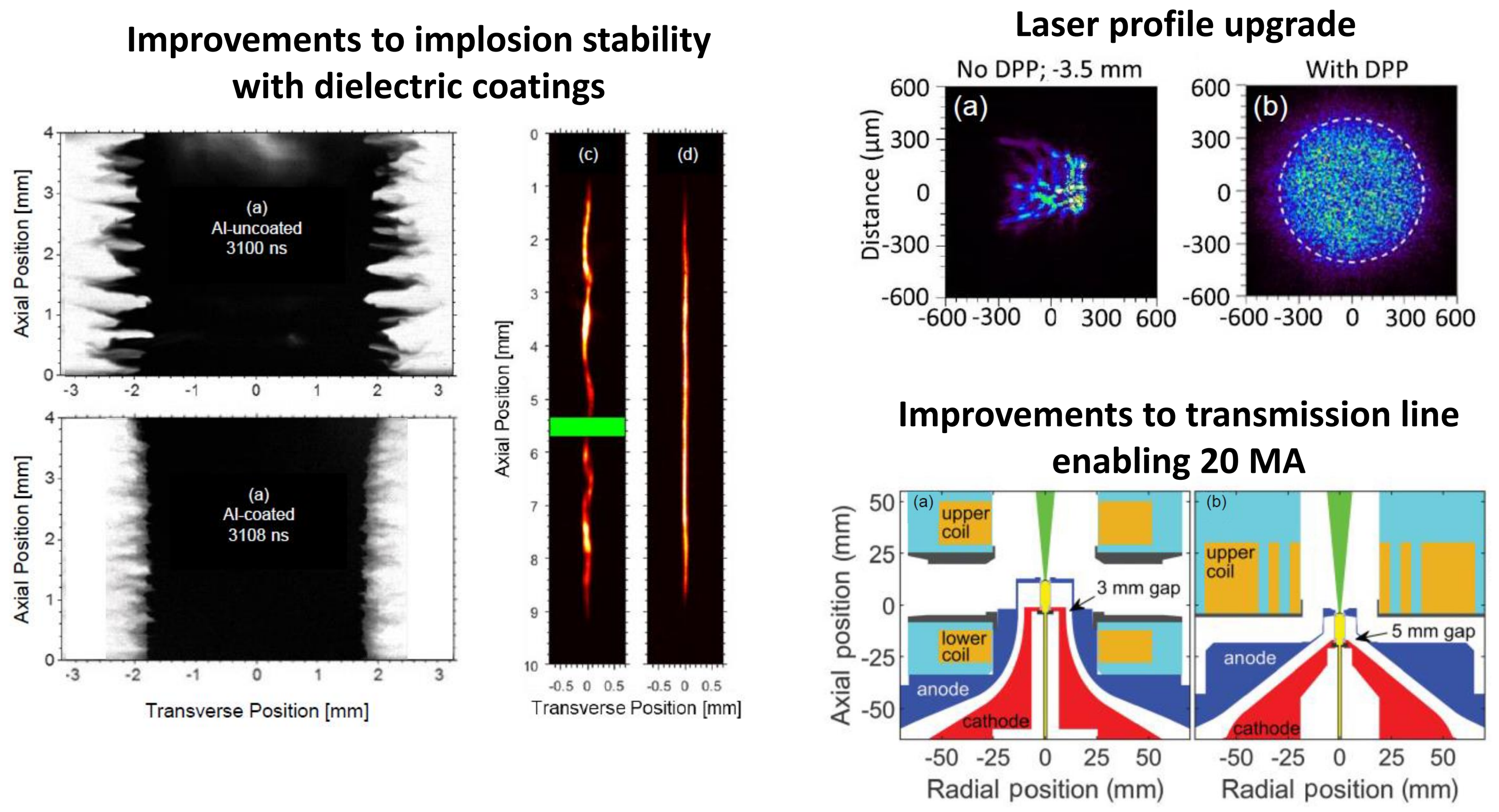


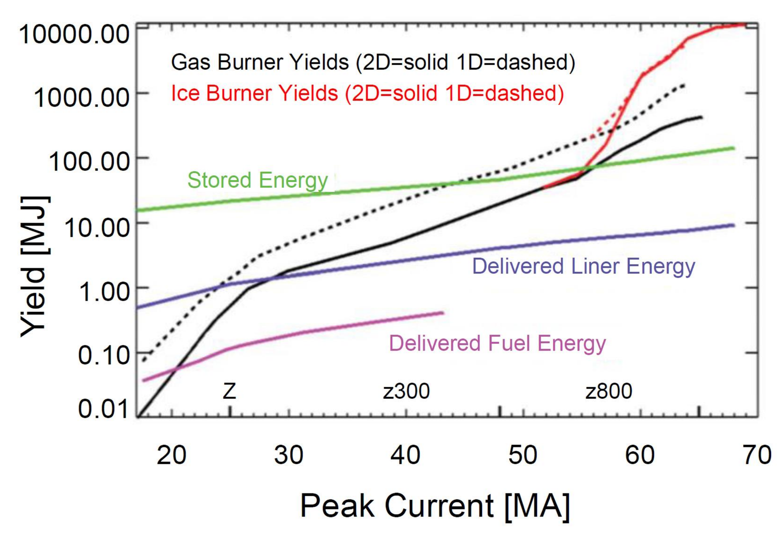
Fig 4. Images showing improvements to implosion stability in liners and stagnation columns via dielectric coatings (left), improvements to laser profile using distributed phase-plate smoothing (right, top) and transmission line cross-sections enabling 20 MA of current coupling to the target (right, bottom)

SCALING TO HIGH YIELD

2D simulations indicate MagLIF has the potential to scale to high yield at currents attainable on a next generation pulsed power machine (~60 MA)

- Performance can be drastically improved by propagating the fusion burn into an annulus of DT ice on the inside of the liner
- With simulated gains of ~70, MagLIF has the potential to be a viable source of fusion energy

Fig 5. Fusion yield as a function of peak current. At 56 MA, the fusion yield exceeds the stored energy in the capacitor bank [11]



REFERENCES

[1] S. A. Slutz *et al.,* Phys. Plasmas 17, 056303 (2010).
[2] M. R. Gomez *et al.,* Phys. Rev. Lett. 113, 155003 (2014).
[3] P. F. Knapp *et al.*, Phys. Plasmas **22**, 056312 (2015).
[4] M. R. Gomez *et al.,* Phys. Rev. Lett. **125**, 155002 (2020).
[5] D. B. Sinars *et al.,* Phys. Rev. Lett. **105,** 185001 (2010).
[6] K. J. Peterson *et al.,* Phys. Rev. Lett. 112, 135002 (2014).
[7] T. J. Awe *et al.,* Phys. Rev. Lett. **116**, 065001 (2016).
[8] M. Geissel *et al.,* Phys. Plasmas **25**, 022706 (2018).
[9] A. J. Harvey-Thompson *et al.,* Phys. Plasmas **25**, 112705 (2018).
[10] M. R. Weis *et al*, Phys. Plasmas **28**, 012705 (2021).
[11] S. A. Slutz *et al*, Phys. Plasmas **23**, 022702 (2016)

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.
This paper describes objective technical results and analysis. Any subjective views or opinions that might be expressed in the paper do not necessarily represent the views of the U.S. Department of Energy or the United States Government.
SAND No. ____________