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Window Decompression in Laser-Heated MagLIF Targets

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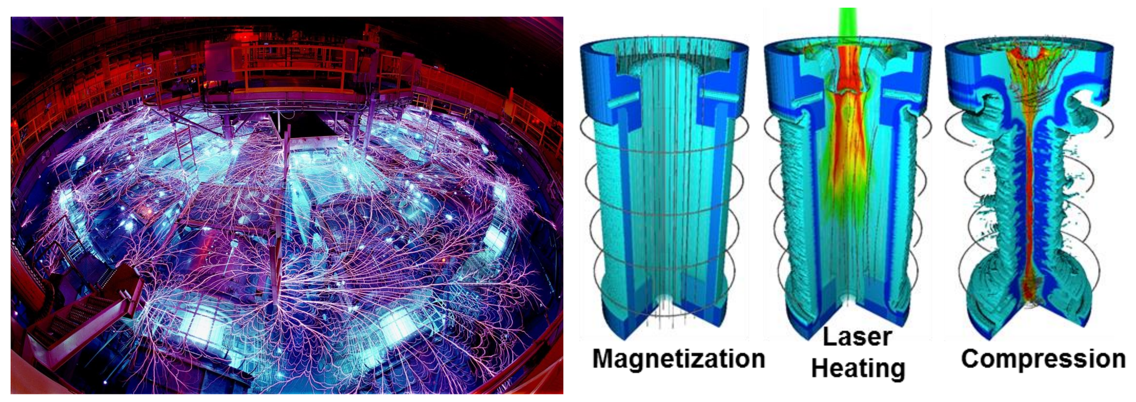
Background

- MagLIF (Magnetized Liner Inertial Fusion) experiments on Sandia's Z Machine have already produced significant fusion yield



- Fuel is heated and magnetized axially before liner compression, relaxing implosion requirements
- Experiments [1] and simulations [2] suggest yield is limited by poor preheat and laser-induced mix

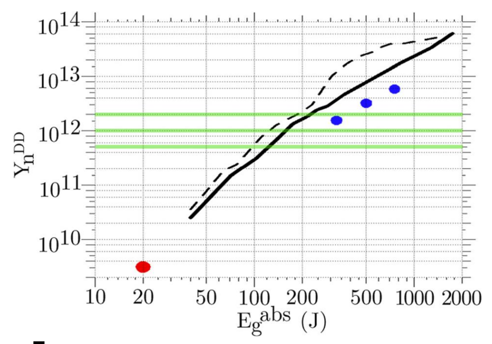
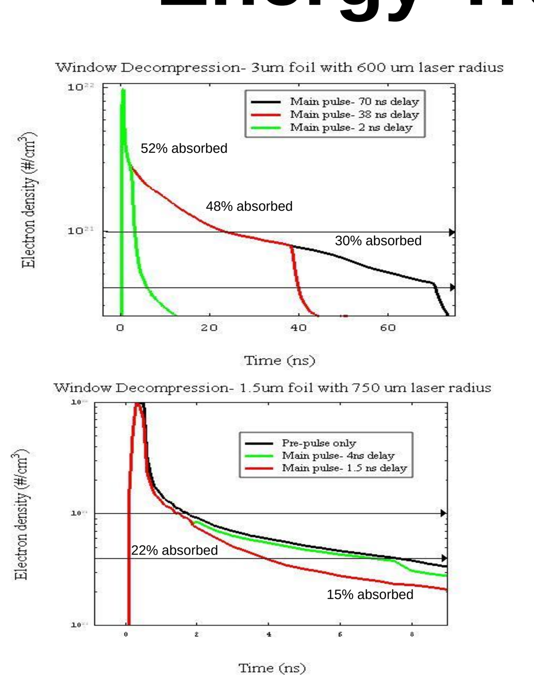


Figure 1. Graph from Sefkow et al. [2] relating expected DD yield to the amount of energy coupled into the fuel for 1.5 mg/cc (solid line) and 0.7 mg/cc (dashed) gas fill. Blue dots correspond to laser coupling only into the laser window (with varying amounts of backscatter) and the red dot corresponds to no laser preheat. Green lines indicate highest experimental yields to date.

Methods

- Laser preheat hard to measure, even in dedicated experiments
- We used hydrodynamics codes (Helios, HYDRA) to perform high resolution 1D/2D simulations of the Kapton pressure-holding window
- Goal: Identify trends in window decompression to find window that optimizes laser transmission

Energy Transmission



- Thicker Kapton windows and larger laser radii lead to lower transmission
- Adding a prepulse improves transmission
- Longer dwell times marginally increase window transmission
  - Also allow window to further decompress
  - Reduces risk for harmful LPI effects

Figure 2. Window density throughout disassembly for different pulse delays after a 500 J prepulse. Percentage of a 2 kJ main pulse absorbed by the window is also listed, while horizontal lines indicate $n_c/4$ and $n_c/10$.

Decompression Time

- Thicker windows show a sharp jump in time needed to decompress
- Trend stems from a two-stage process: explosion followed by relatively slow expansion (Fig. 3)
- Current capabilities limit dwell times to a few ns
  - Upgrades to Z Beamlet will allow dual beam injection
- Only thin windows reach $n_c/10$ within the first 10 ns

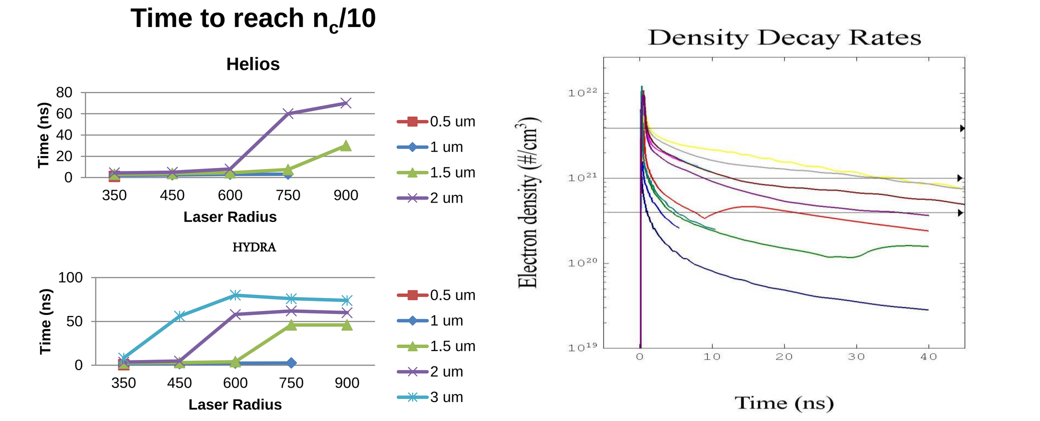


Figure 3. Time needed to reach $n_c/10$ for various windows modeled in Helios and HYDRA. The peak window density of many different windows is shown on the right, with horizontal lines indicating n_c, $n_c/4$ and $n_c/10$.

Laser Plasma Interaction

- Codes don't model wave effects (SRS, SBS, etc.) but we can track variables relevant to LPI
- For main pulse transmission, SRS and two-plasmon decay dominate ($n_e \le n_c/4$)
- Gain thresholds [3] depend on laser wavelength, plasma temperature and density scale length:

$n_e \cong n_c/4$ $\qquad$ $n_e \le n_c/4$

$$\text{2-}\omega_p:\quad I\left(\frac{W}{cm^2}\right) > \frac{5x10^{15}T_{keV}}{L_{\mu m}\lambda_{\mu m}} \qquad \text{SRS:}\quad I\left(\frac{W}{cm^2}\right) > \frac{4x10^{17}}{L_{\mu m}\lambda_{\mu m}}$$

- Numerical density scale lengths from simulations:
  - Those which violate thresholds are highlighted in red

Window Thickness (um)

$n_e \cong n_c/4$

0.3 mg/cc	350	450	600	750	900
0.5	300	370	775	1270	890
1	1430	3400	1330	860	235

0.7 mg/cc	350	450	600	750	900
0.5	200	x	x	x	x
1	265	220	200	260	x
1.5	360	265	2560	515	440
2	360	635	660	620	690
3	2050	1785	1845	1580	5640

1.5 mg/cc	350	450	600	750	900
0.5	x	x	x	x	x
1	225	x	x	x	x
1.5	345	455	x	x	x
2	705	1715	1650	1645	x

$n_e \cong n_c/10$

	350	450	600	750	900
0.5	190	205	220	225	235
1	360	365	430	790	2253

	350	450	600	750	900
0.5	305	x	x	x	x
1	610	690	1300	2335	x
1.5	1260	2550	5000	2465	2140
2	5225	5000	2285	4570	6100
3	7220	1735	3310	15000	30000

	350	450	600	750	900
0.5	x	x	x	x	x
1	750	x	x	x	x
1.5	1415	2445	x	x	x
2	5140	5285	6000	10000	x

  - LPI reduced when the window has reached $n_c/10$
- Thresholds [3] for filamentation (at $n_c/10$) satisfied only by large laser spot sizes ($r > 940\ \mu m$)

$$I_{fil} > \frac{1\times10^{14}(T_{keV})}{f^2\lambda_{\mu m}^2}\frac{n_c}{n_e} \qquad I_{fil} > 3.6\ x\ 10^{13}\ W/cm^2$$

- (Assumes $T \approx 1\ keV, f = 10, P = 1\ TW$)

2D Effects: Mix

- Similar trends in decompression and energy absorption
- 2D runs show window penetrates farther into the gas
- High Z materials from window can degrade yield if mixed with fuel

Mix extent (mm) 40 ns after a 500 J prepulse - 1D HYDRA

	350	450	600	750	900
0.5	-10				-2*
1	-7	-5	-3	-2	
1.5	-3	-1	0	2	2
2	0	1	2.5	2.5	3

Mix extent (mm) after 40 ns Prepulse only - 2D HYDRA

Thickness \ Radius	350	450	600	750	900
0.5	4				1*
1	7			3	
1.5		5	5		
2					4+
3.5		--			

Mix extent (mm) after 40 ns 2kJ main pulse - 2D HYDRA

Thickness \ Radius	350	450	600	750	900
0.5	0				-1*
1	4			3	
1.5		4	5		
2					5
3.5		5			

*0.3 mg/cc

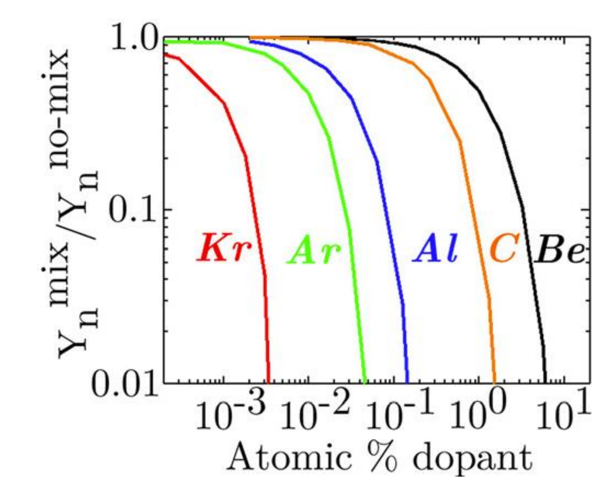


Figure 4. Matrices showing how far the laser entrance window travels in to the gas (0.7mg/cc) after 40 ns for various laser parameters.

Figure 5. To the right, a graph from Sefkow et al [2] demonstrates how yield is degraded in integrated simulations with various amounts of high Z elements mixed in the fuel. The Kapton laser entrance window includes carbon, oxygen and nitrogen.

- Change in 2D may stem from shock propagation
  - Shock spreads spherically, heating gas less and hence providing less back pressure

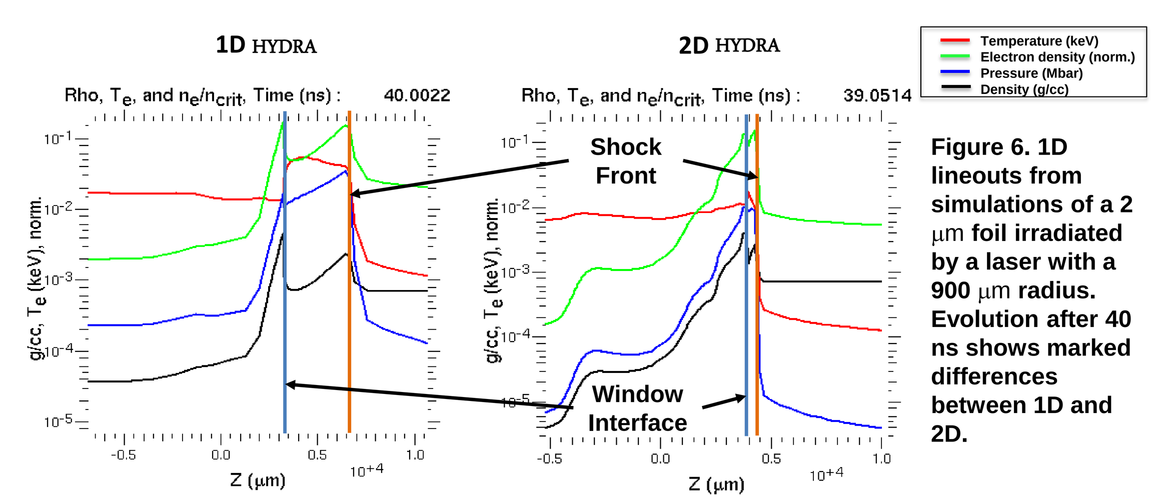


Figure 6. 1D lineouts from simulations of a 2 μm foil irradiated by a laser with a 900 μm radius. Evolution after 40 ns shows marked differences between 1D and 2D.

- Shocks can reflect off edges and push window even farther
  - Additional mix may be introduced from liner, washer, etc.

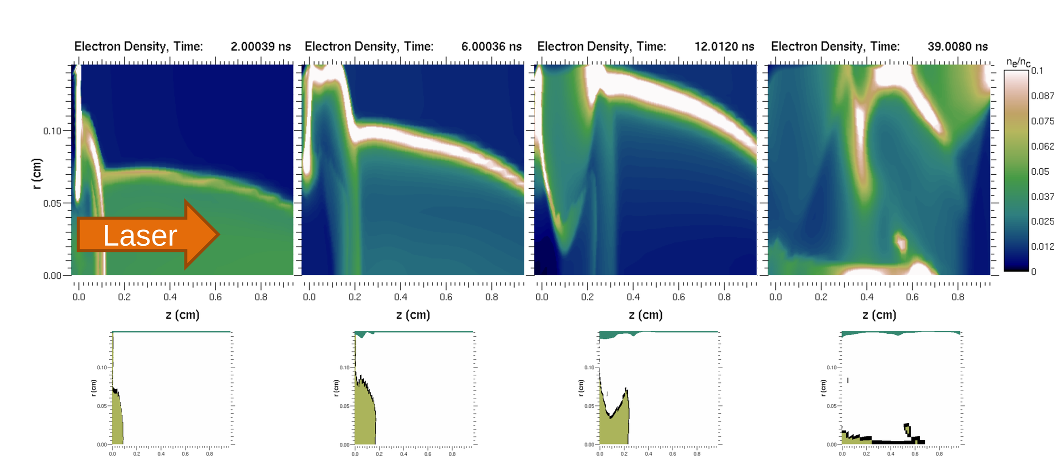
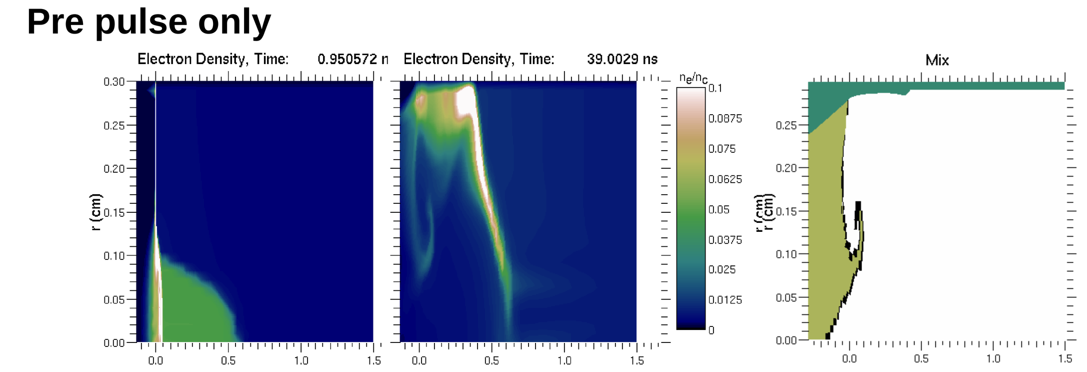


Figure 7. Electron density and region profiles for a 1 um window at different times after a 0.5 ns 500 J prepulse with a laser radius of 350 um. At 6 ns the shock wave has reached the edge of the region and reflects back to recompress the material in the center by 40 ns.

Optimal Windows

- Thin windows (0.5 μm) show best breakthrough and resistance to mix

Pre pulse only



2 kJ pulse after 2 ns

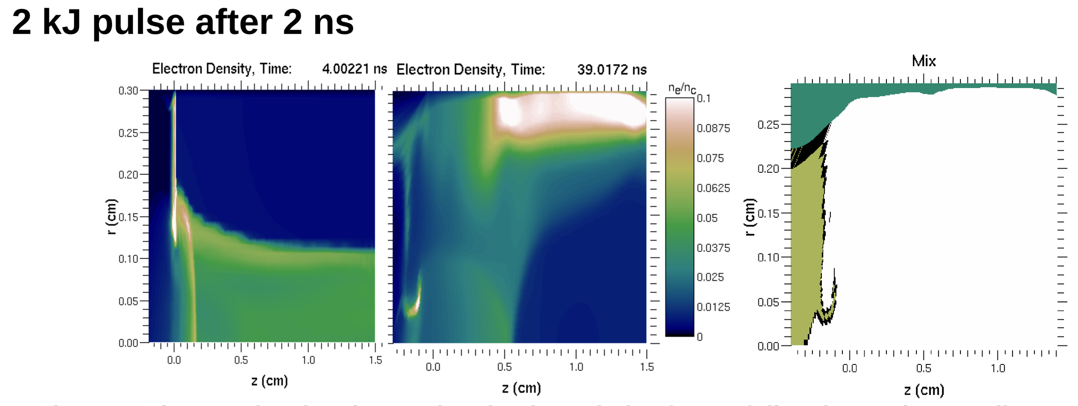


Figure 8. Electron density plots and region boundaries for a 2 foil and a 900 laser radius. Despite lower gas fill (0.3 mg/cc), the simulations show less potential mix.

- Laser breaks through foil during prepulse, launching it into the gas with less energy
- Cryogenics can lower gas pressure to allow windows this thin

Conclusions

- Simulations support using thin windows (0.5-1 μm) with large laser radius
- Upgrades to MagLIF capabilities like cryogenics and dual laser beam injection will allow use of thinner windows and longer dwell times
- Further work needed to diagnose effects of ablation from the liner and washer, magnetization, and implosion dynamics

References

- [1] M. R. Gomez, et. al., Phys. Plasmas 22, 056306 (2015)
- [2] A. B. Sefkow, et. al., Phys. Plasmas 21, 072711 (2014)
- [3] D. Montgomery, M. Campbell, Internal Presentation. See also W.L. Kruer, "The Physics of Laser Plasma Interactions," 1988.

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