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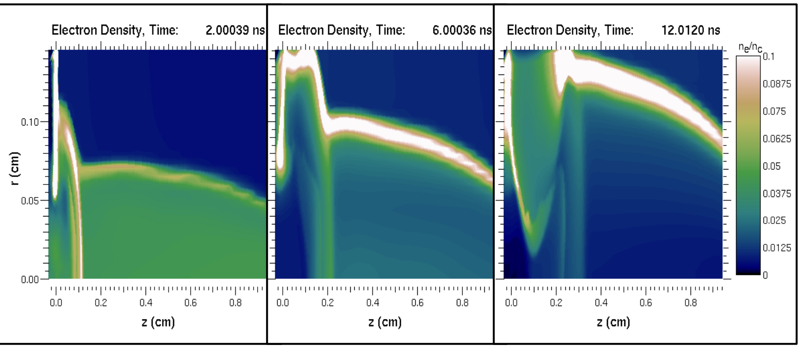

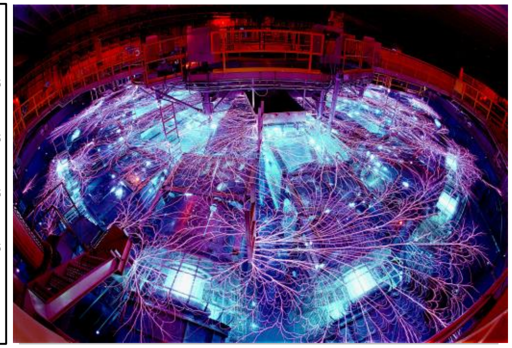

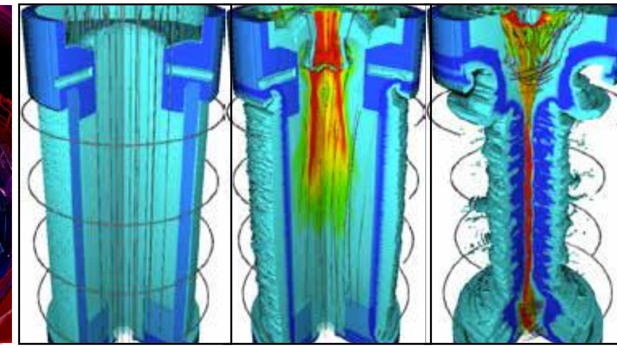

Window Decompression in Laser-Heated MagLIF Targets

D. Woodbury, K. Peterson, A. Sefkow

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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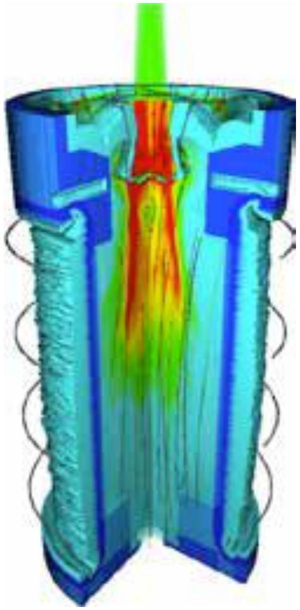
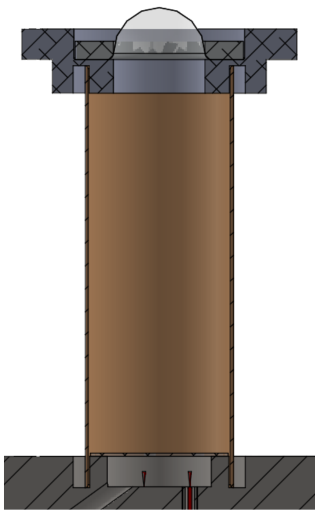
Contents

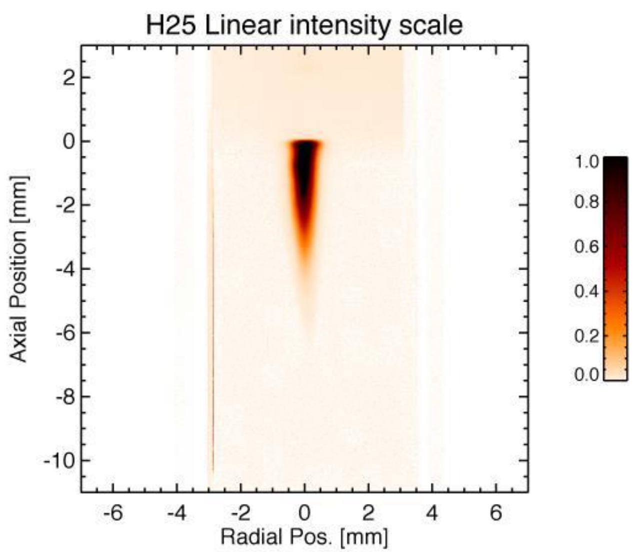
- Motivation for high resolution simulations
- Advantages and disadvantages of codes used
- Energy deposition in target windows
- Window decompression: parameter trends
- Overview of 2-D simulations
- Conclusions, recommendations and further work

Motivation

- Fuel preheat essential to MagLIF concept
- We suspect yield is limited by poor preheat
- Coupling is hard to measure experimentally







- Goal: Identify trends in laser deposition and window decompression with high resolution simulations

Hydrodynamics codes provide high-resolution modeling of window dynamics

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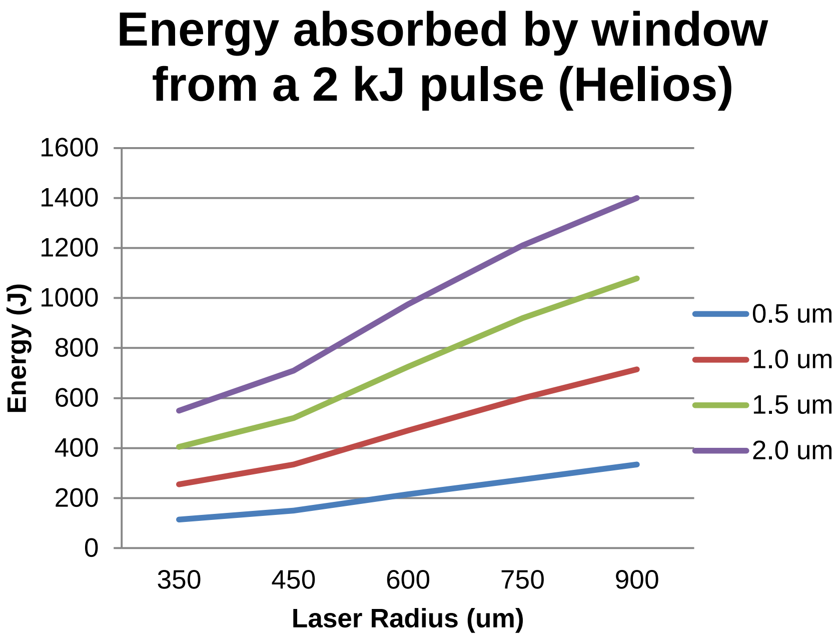
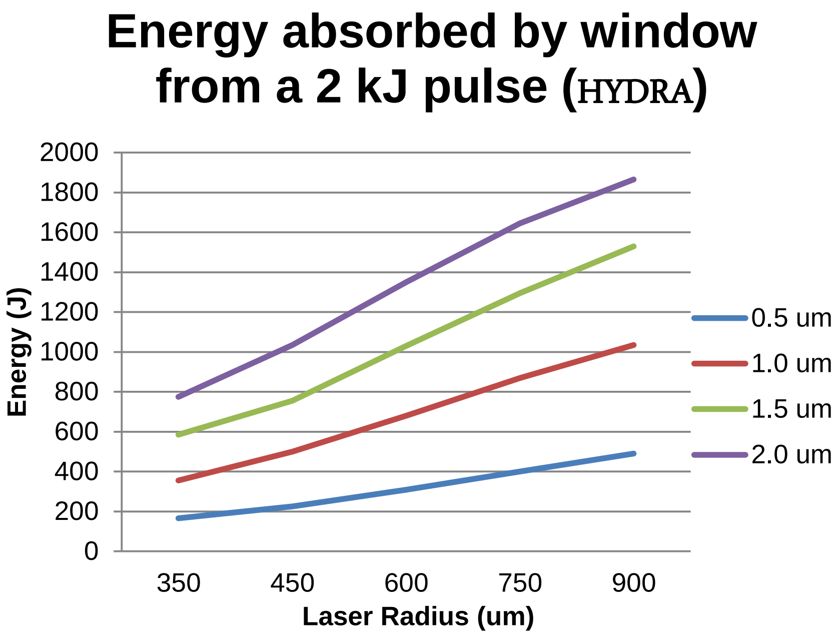
- Helios is a user friendly 1-D Lagrangian code
- HYDRA is a 2/3-D ALE code with extensive packages
- Both model inverse bremsstrahlung and absorption near the critical surface
- Codes cannot model laser-plasma interaction such as SBS, SRS, two-plasmon decay, etc.
- However, we can track window density and density scale lengths to assess risks for these effects

Window absorption shows quasi-linear dependence on thickness and laser radius

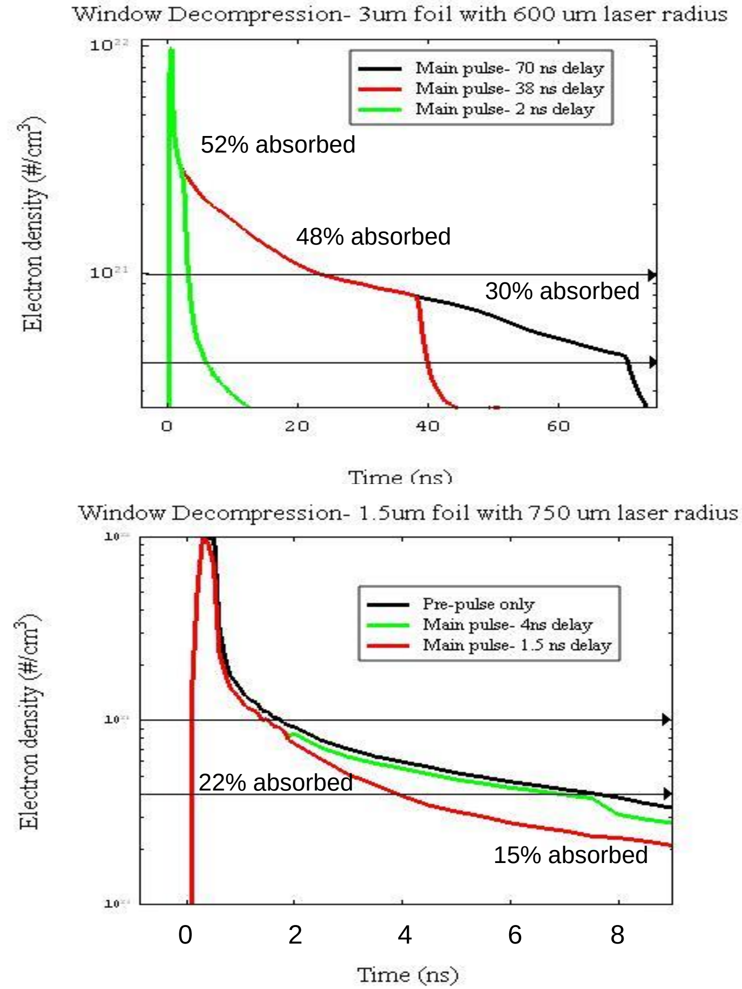




- A gas fill increases the energy absorbed and also arrests expansion and decompression of the window
- HYDRA shows more window absorption than Helios

A larger main pulse delay increases LEH transmission and reduces LPI

- Prepulse reduces energy absorbed by the window
- Longer main pulse delays don't always heavily impact energy lost to the window
- However, they decrease the amount of time during which the laser interacts with densities relevant for LPI ($n_c/4$ to $n_c/10$)



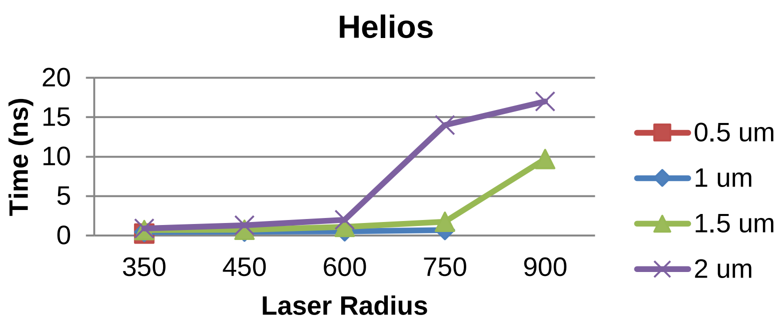
Window density throughout disassembly for different pulse delays after a 500 J prepulse. Percentage of a 2 kJ main pulse absorbed by the window is also listed, while horizontal lines indicate $n_c/4$ and $n_c/10$.

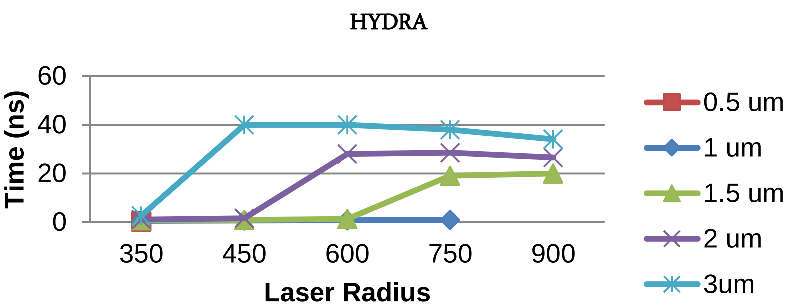
Window thickness and laser spot size can have dramatic effects on decompression time

- All windows reach critical density in 1-5 ns

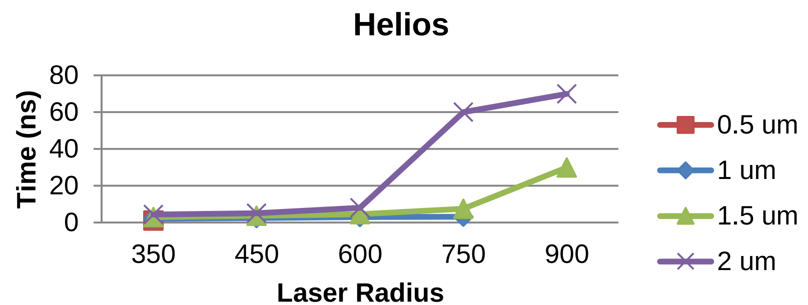
  (for 500 J pulse in first 0.5 ns, 0.7 mg/cc gas fill)
- Remaining decompression is more complicated

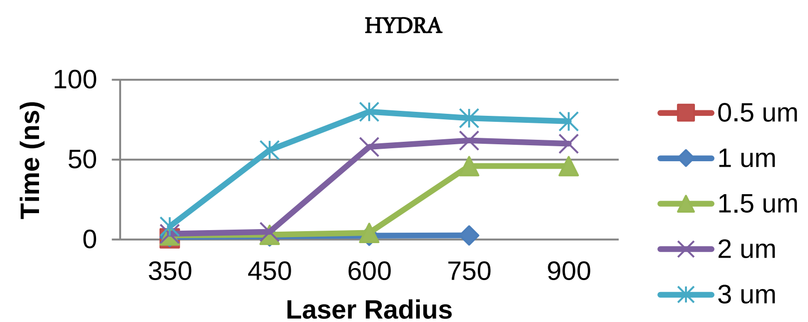
Time to reach $n_c/4$





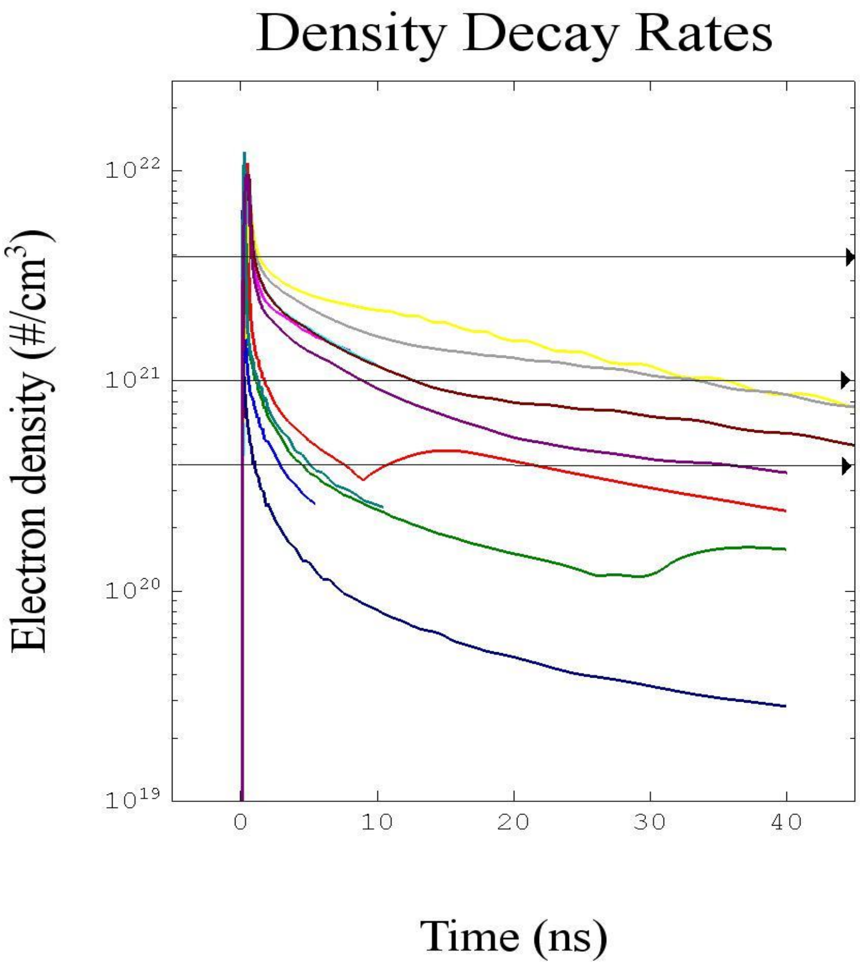
Time to reach $n_c/10$





Window decompression follows a two-stage process

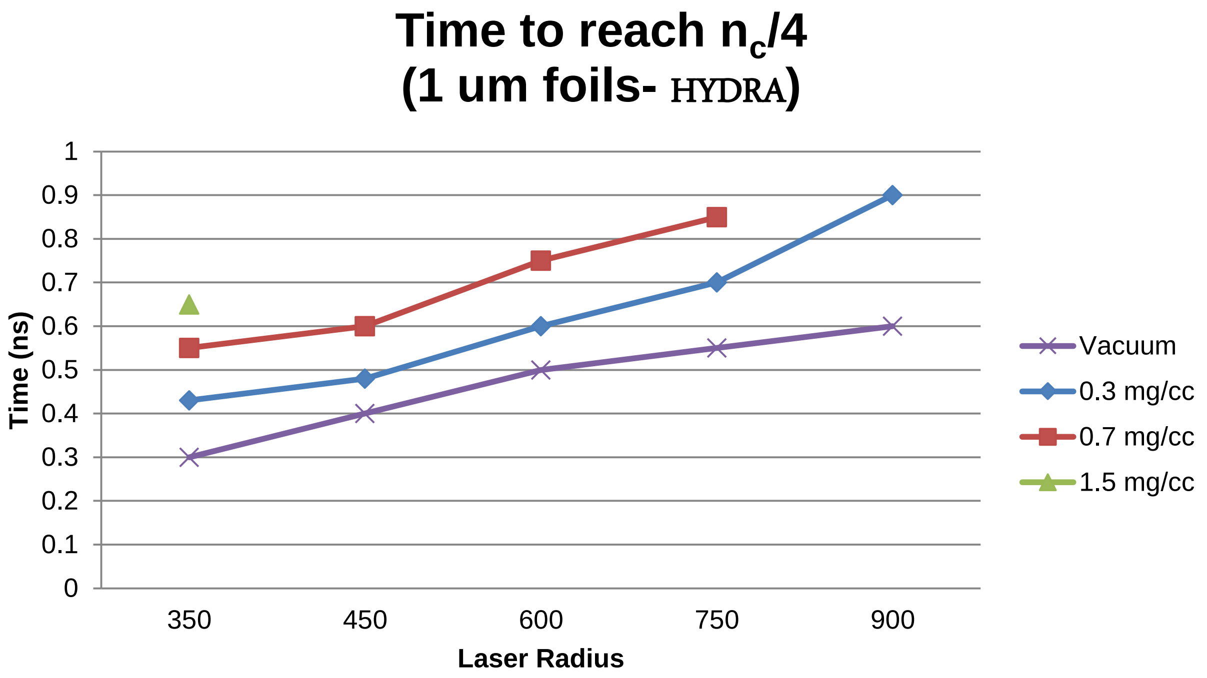
- May reflect process of explosion followed by hydrodynamic expansion
- Accounts for some discrepancies between codes
- Only the thinnest windows fully decompress within 10 ns



Window density at window gas interface for several window thicknesses and laser spot sizes after a 500 J prepulse. Lines indicate approximate values for electron density of n_c, $n_c/4$, and $n_c/10$.

Higher density gas fill slows window decompression

- (and also require thicker windows for similar laser radius)



Time for window to decompress to n_c /4 with various gas fills behind a 1 um window.

Laser Plasma Interactions (LPI) are an additional source of absorption

- Decreasing spot size to disassemble window faster leads to higher values of $I\lambda^2$ and greater LPI risk

- Primary concerns for main pulse are two-plasmon decay and stimulated Raman scattering (SRS) since other LPI effects predominate near critical density

- Thresholds (from presentation by David Montgomery & Mike Campbell):

$n_e \cong n_c/4$

2-ω_p: $I\left(\frac{W}{cm^2}\right) > \frac{5x10^{15}T_{keV}}{L_{\mu m}\lambda_{\mu m}}$

$n_e \leq n_c/4$

SRS: $I\left(\frac{W}{cm^2}\right) > \frac{4x10^{17}}{L_{\mu m}\lambda_{\mu m}}$

Simulations can track density gradients and the corresponding LPI risk

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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

Density scale lengths (um) of decompressing windows

2-ω_p: $L_{\mu m} > \frac{5x10^{15} T_{keV}}{I_{W/cm^2} \lambda_{\mu m}}$

SRS: $L_{\mu m} > \frac{4x10^{17}}{I_{W/cm^2} \lambda_{\mu m}}$

LPI risk is greatly reduced by allowing window to decompress to 1/10 critical density

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Window Thickness (um)

$n_e \cong n_c/4$

Window Thickness (um)	350	450	600	750	900
0.3 mg/cc					
0.5	300	370	775	1270	890
1	1430	3400	1330	860	235
0.7 mg/cc					
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					
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

$n_e \cong n_c/10$

Window Thickness (um)	350	450	600	750	900
0.5	190	205	220	225	235
1	360	365	430	790	2253
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
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

Density scale lengths when the plasma density reaches n_c, $n_c/4$, and $n_c/10$. Scale lengths which, combined with laser radius and wavelength, violate the relevant LPI threshold are highlighted in red.

Filamentation is a concern for MagLIF at all laser spot sizes

- Filamentation thresholds do not depend on density scale lengths (Montgomery & Campbell):

$$I_{fil} > \frac{1 \times 10^{14}(T_{keV})}{f^2 \lambda_{\mu m}^2} \frac{n_c}{n_e}$$

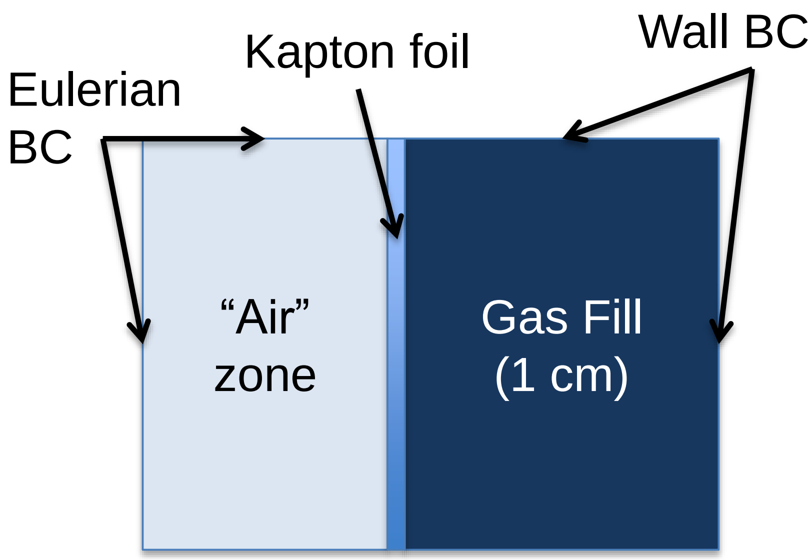
- For $\frac{n_e}{n_c} \approx 0.1, T \approx 1\ keV, f = 8$ this gives a threshold around 5.5 x 10^{13} W/cm^2

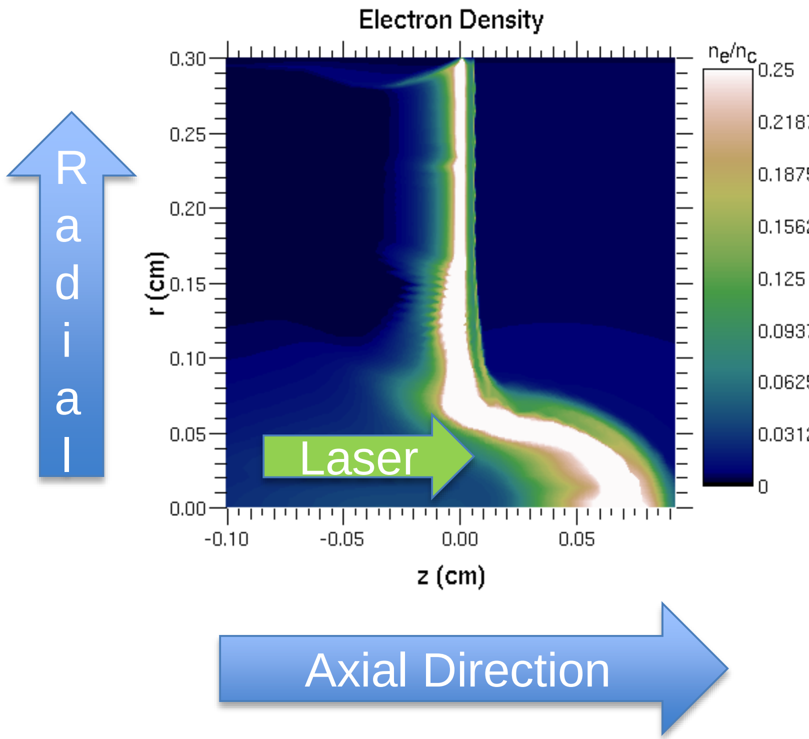
- Thermal filamentation can lower the threshold by 2-10x for higher Z materials

r_{las} (μm)	I (W/cm^2)
350	2.60×10^{14}
450	1.57×10^{14}
600	8.84×10^{13}
750	5.66×10^{13}
900	3.93×10^{14}

Intensities for different laser radii. Those which exceed the threshold for pondermotive filamentation are highlighted in red. Only the largest spot size satisfies the threshold condition.

2-D Simulations: Setup





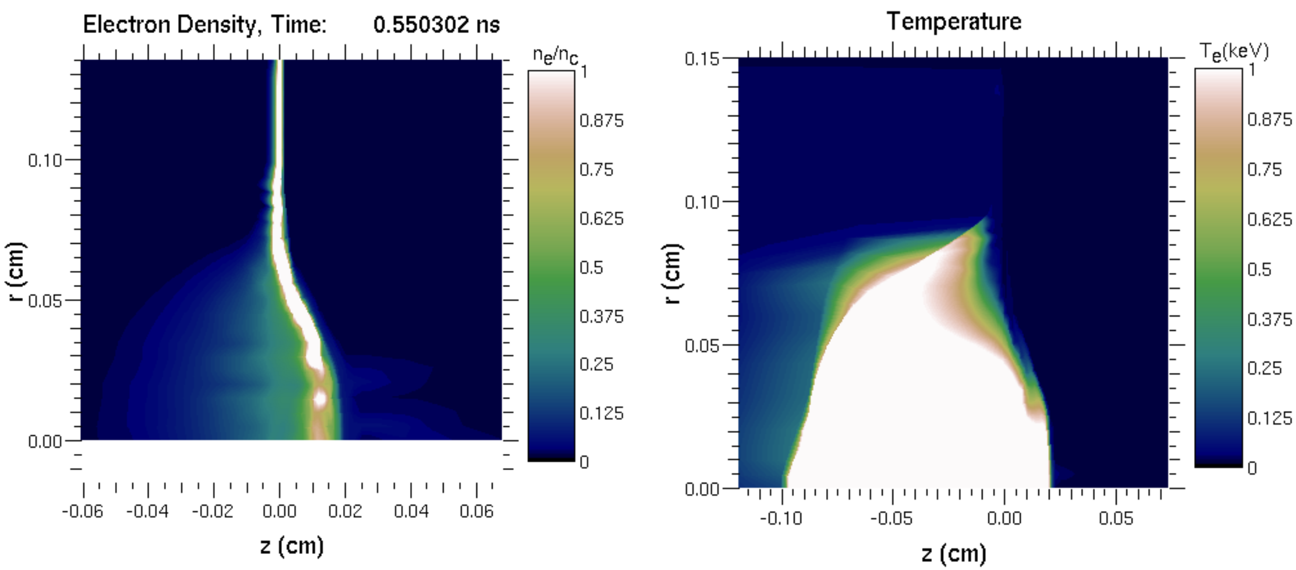
- **Note that axes are NOT scaled equally (approximately spherical shock waves appear deformed)**

- Radial extent of problem set to $3r_{las}$ for stability (1-3 mm)

Edge effects in 2-D only slightly change decompression times seen in 1-D simulations

- Runs in 2-D show good agreement with 1-D for decompression times overall

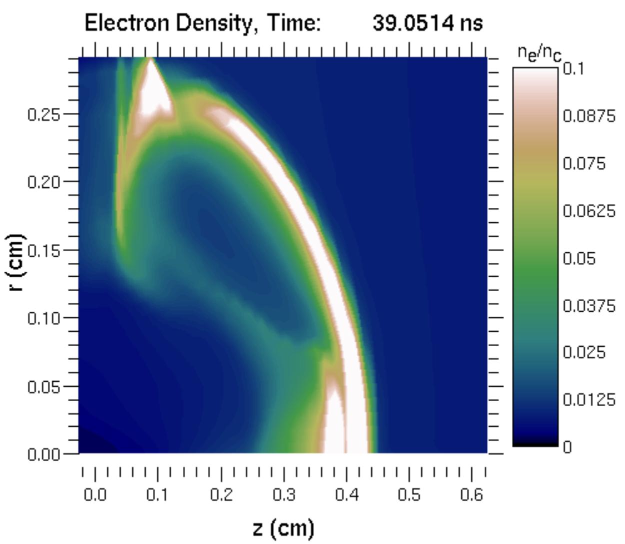
- At early times the edge of the laser-window hole lags the center in decompression



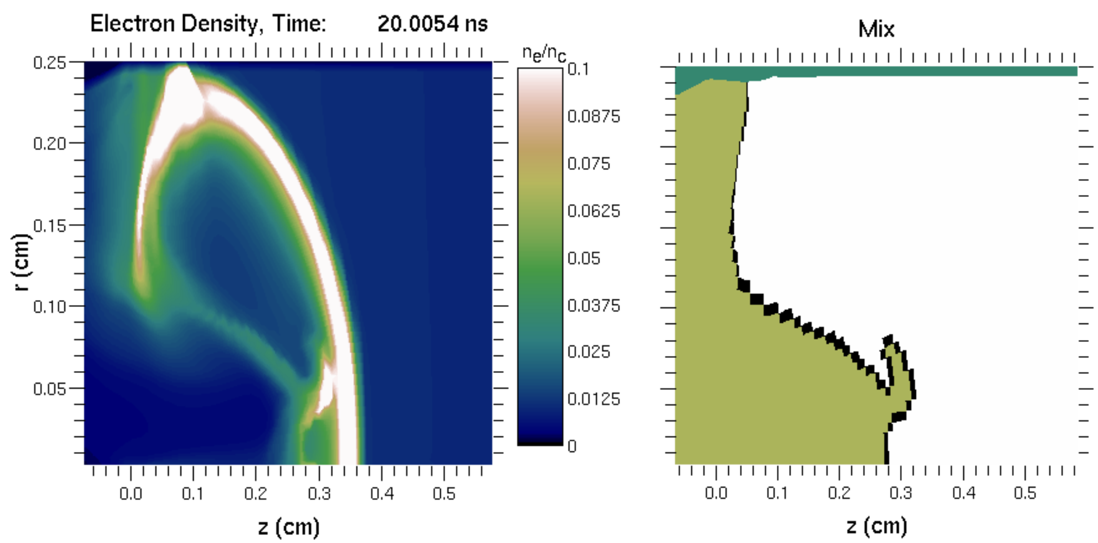
Electron density and temperature profiles for a 1.5 um window immediately after a 0.5 ns 500 J prepulse with a laser radius of 450 um. Both show evidence of heat transport at the laser edge which prevents the edge from going subcritical at the same time as the center of the window.

Edge effects in 2-D only slightly change decompression times seen in 1-D simulations

- Over long time scales the edge has more room to expand and density drops faster than the center of the window, except in cases with shearing, etc.



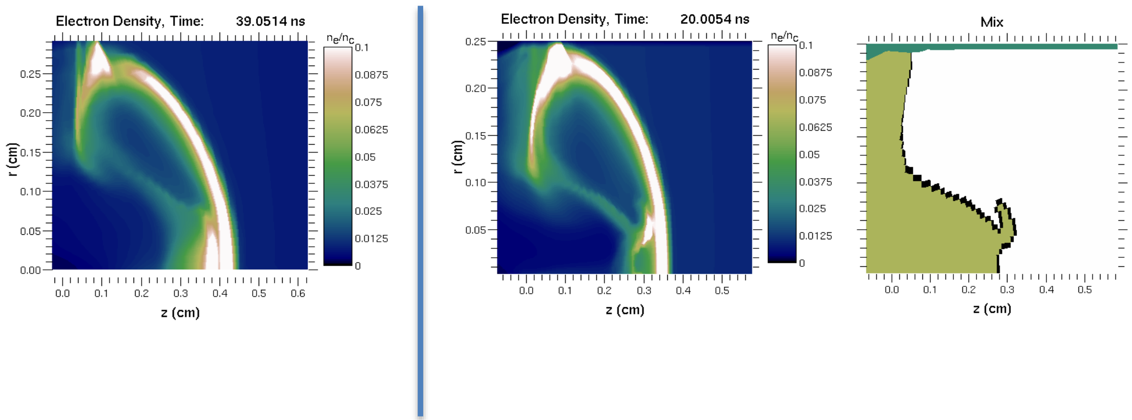
Electron density profile for a 2 um window 40 ns after a 0.5 ns 500 J prepulse with a laser radius of 900 um. The edge of the irradiated region trails the center of the window



Electron density profile for a 1.5 um window 40 ns after a 0.5 ns 500 J prepulse with a laser radius of 600 um. Part of the gas fill has sheared around the edge of the window, increasing the window density in that region.

Edge effects in 2-D only slightly change decompression times seen in 1-D simulations

- Over long time scales the edge has more room to expand and density drops faster than the center of the window, except in cases with shearing, etc.



- **The net effect on decompression times is minimal: some are slightly shorter, others are slightly longer**

2-D simulations indicate that the window can travel much farther in to the gas (vs 1-D)

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Mix extent (mm) 40 ns after a 500 J prepulse - 2-D HYDRA

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

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

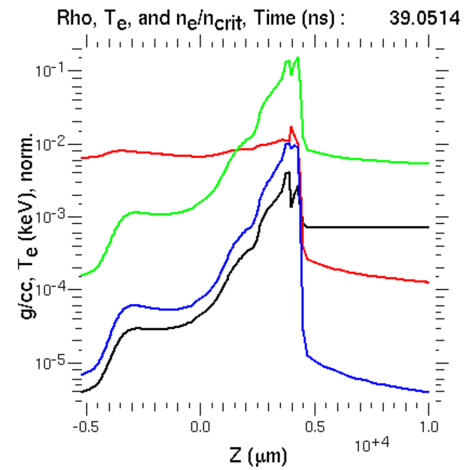
*0.3 mg/cc

2-D HYDRA

2 um foil

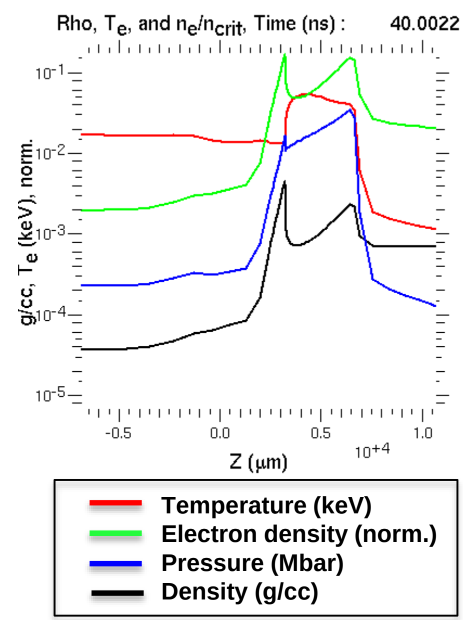
900 um radius

40 ns after prepulse



1-D HYDRA

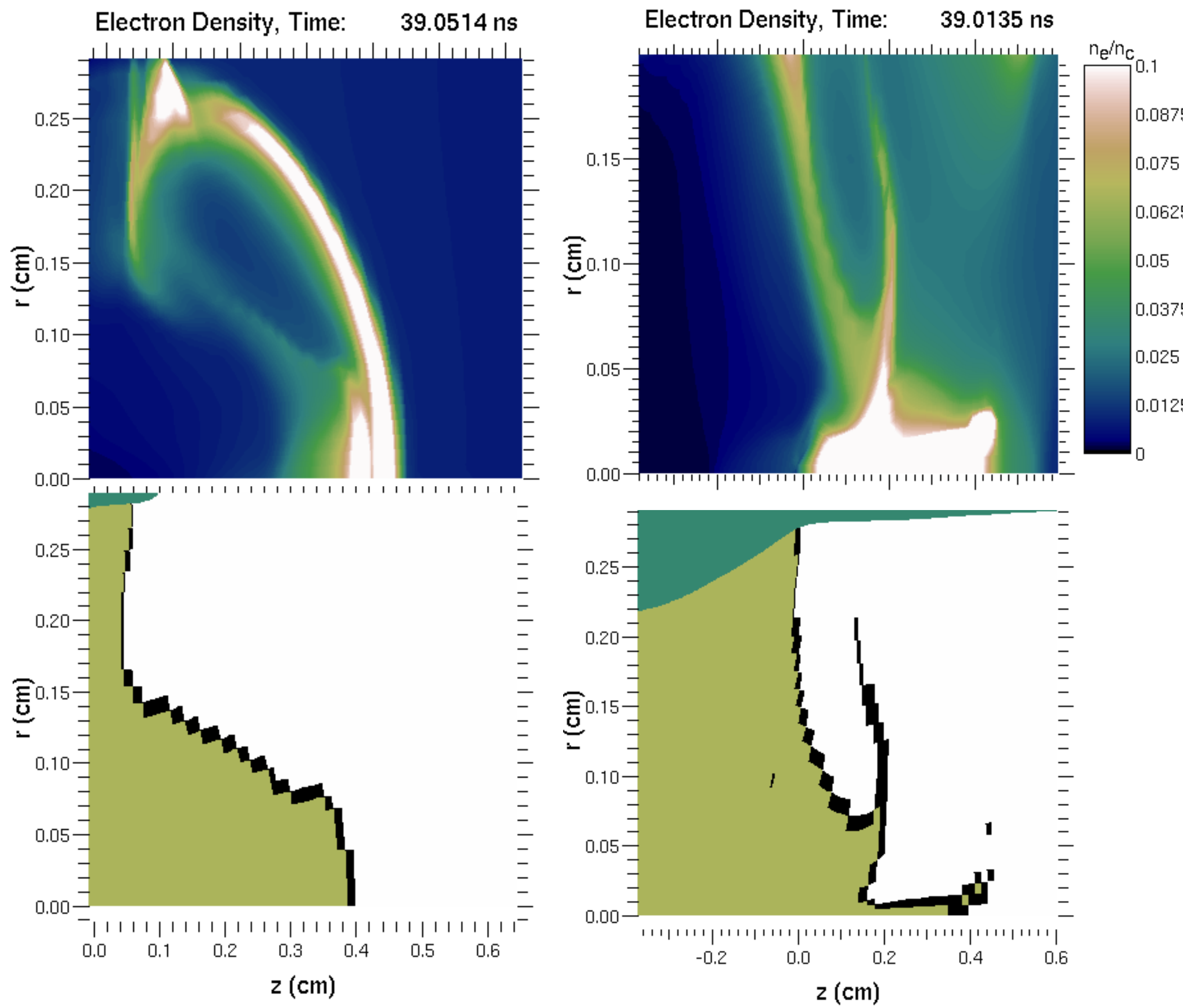
Same parameters



- Spherical vs. planar shock (and radiation) seems to reduce back pressure on the window in wake of the shock

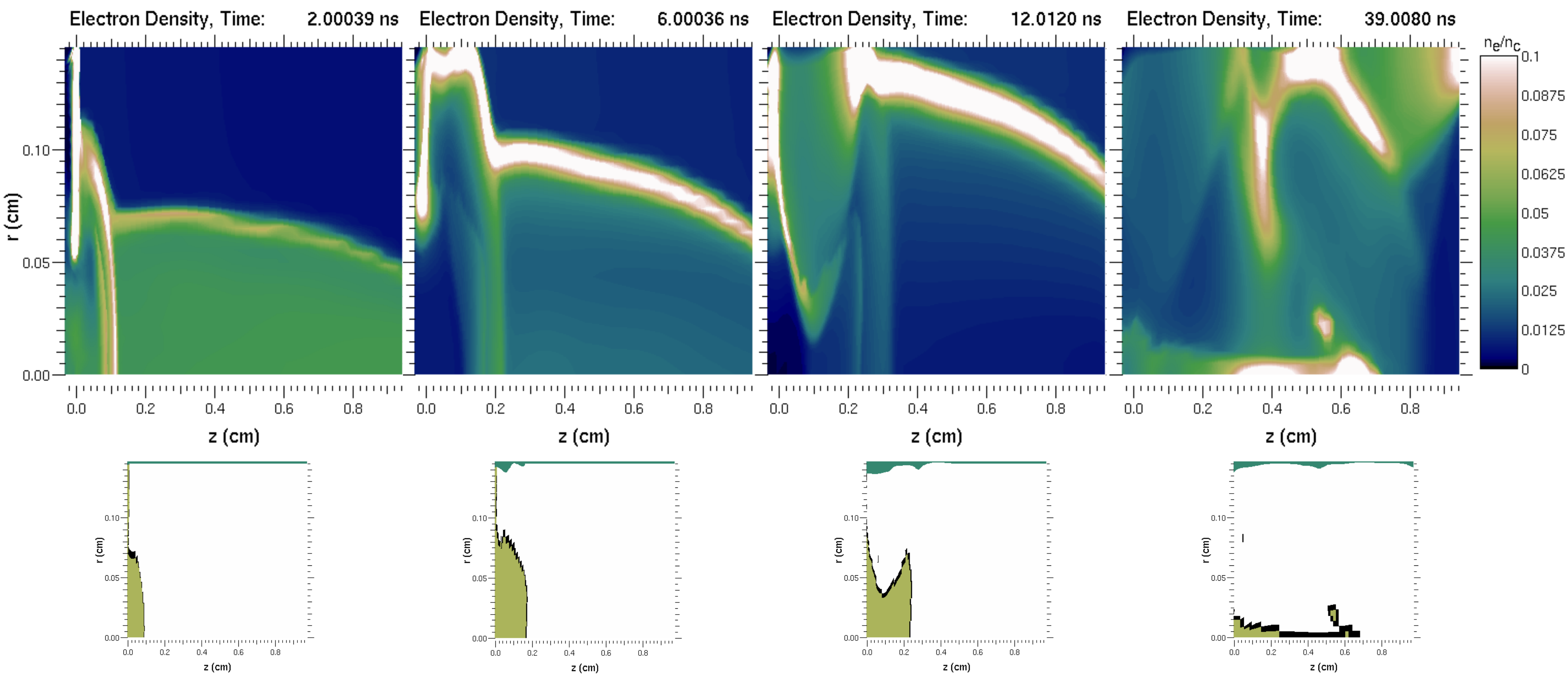
Adding a main pulse does not generally mitigate the problem

- While a main pulse heats up the gas, which then pushes on the window, the interaction is unstable (even with low resolution)



Electron density and region profiles for a 2 um window 40 ns after a 0.5 ns 500 J prepulse with a laser radius of 900 um both without a main pulse (right) and with a 2 kJ main pulse at 2 ns (left)

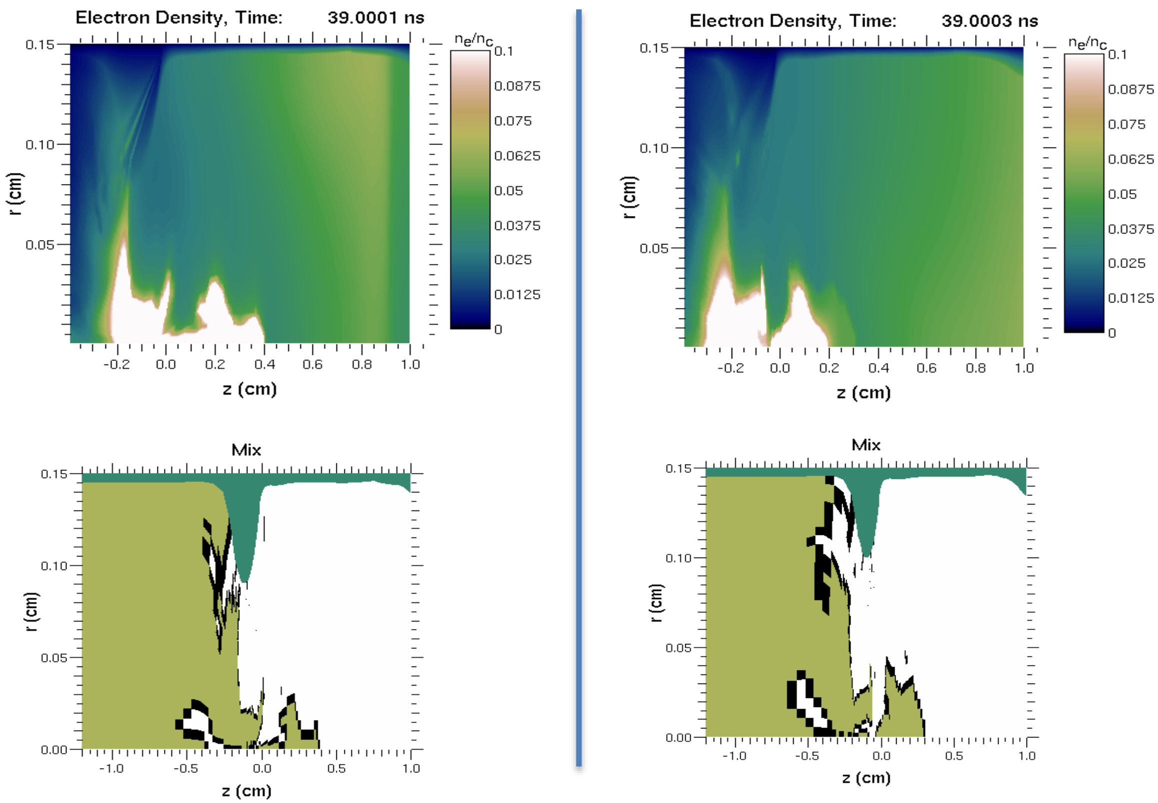
Shocks reflecting of the wall can surround the window, pushing it further in to the gas



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

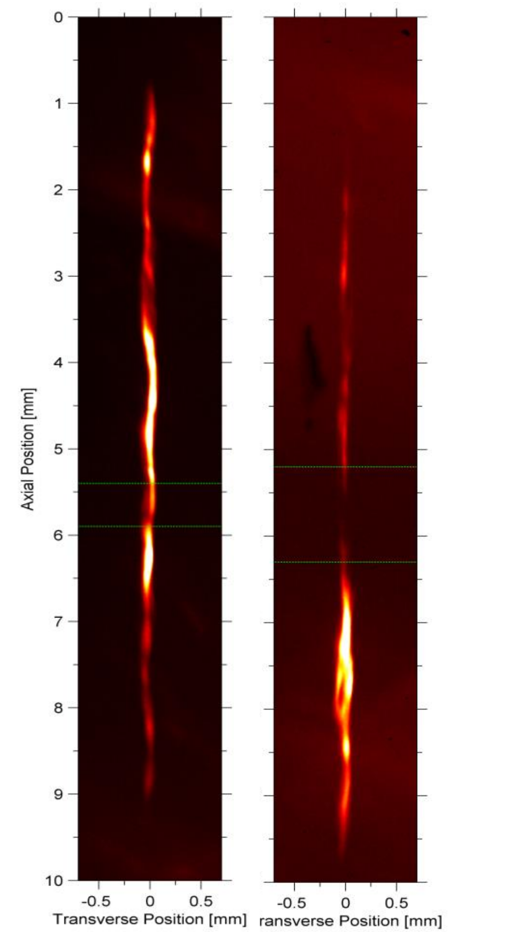
- Though different simulations needed different maximum radial extent, we cannot simply ignore these reflections

Simulations support Roosevelt Mix results, but don't replicate exact trend



2 kJ main pulse (right) and 4 kJ main pulse (left) after 500 J prepulse. 1.5 um window with 450 um laser radius.

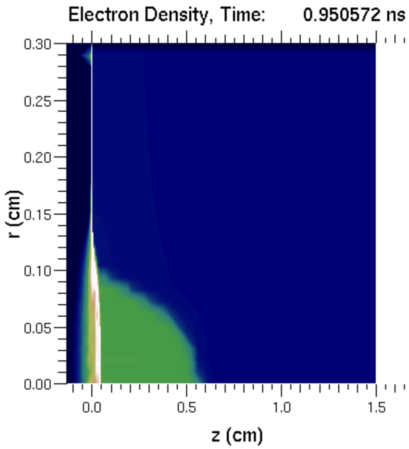
- This only accounts for window material, not the washer, liner, etc.

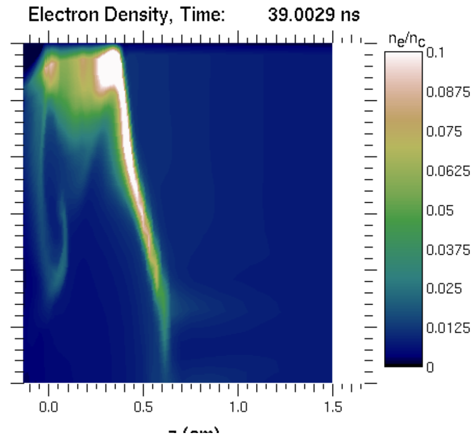


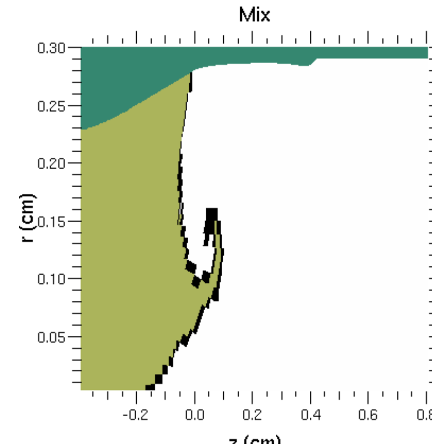
Stagnation images from Roosevelt Mix 1 series, 2 kJ pulse (right) and 4 kJ pulse (left). Axial position measured from 1.5 mm standoff, not from window.

Very thin windows show a sharp drop off in potential mix

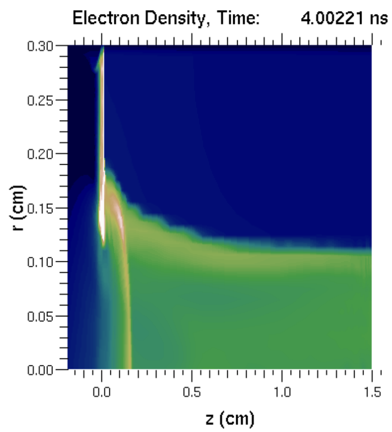
Pre pulse only

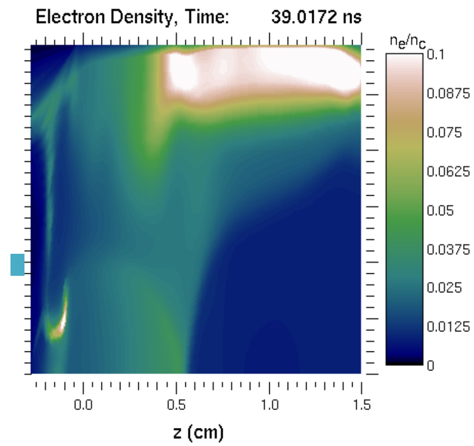


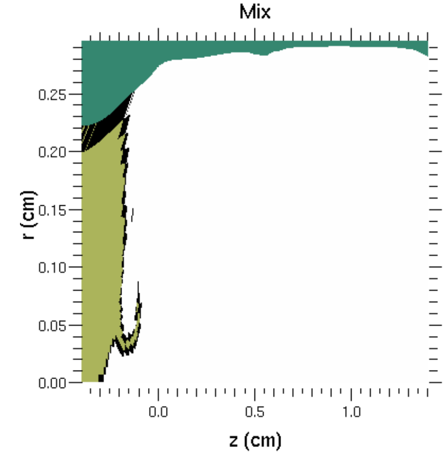




2 kJ pulse at 2 ns







Window evolution for a 0.5 um foil and incident laser with 900 um radius with **0.3 mg/cc** gas fill. Since the window disassembles before the end of the pre-pulse, some of this energy is deposited in the gas and helps to further arrest window motion.

Very thin windows show a sharp drop off in potential mix from the window

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Mix extent (mm) after 40 ns
Prepulse only

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

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

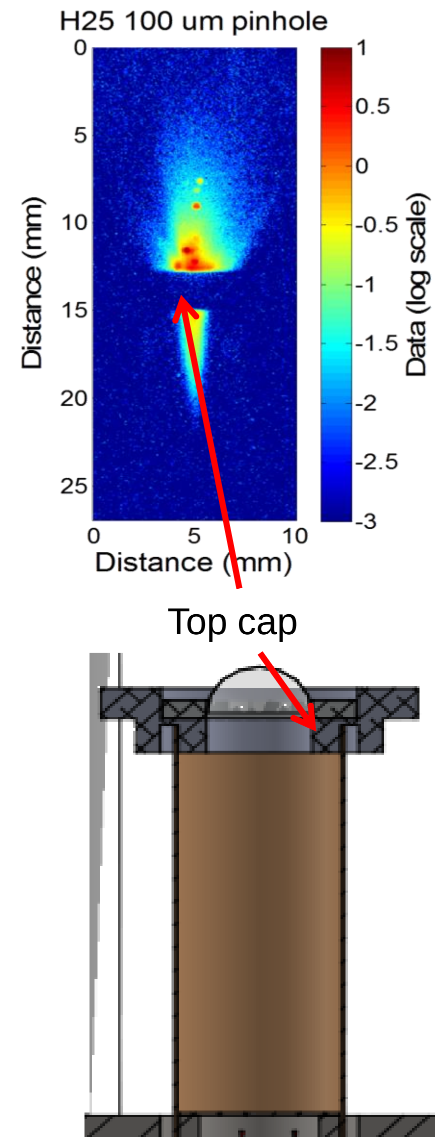
- Window thickness seems to be the predominant factor, not laser radius or gas density
- Simulations differ in radial extent (max radius ~3x laser radius): may complicate basic trend
- LPI may also drive window material farther, and implosion hydrodynamics will certainly affect window motion and mix

Recommendations: Near-term

- Use windows which are as thin as possible (0.5 – 1 um)

- Push laser spot size slightly smaller if gas fill requires a thicker window: balance quicker decompression and higher risk of filamentation

- Field laser only shots to diagnose window-gas interface (remove top cap and/or improve other diagnostic access)



Recommendations: Long-term/NextGen

- For higher gas fills, coinjection may allow the window to reach lower density for the main pulse
- However, for very high gas fills (5 mg/cc), the necessary increase in window thickness may completely preclude standard laser preheat
- **Cryogenic targets with lower pressure gas fill offer most promising results (transmission and mix)- pursue development now**
- Pulse shaping may have an effect on disassembly

Conclusions

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- 1-D simulations predict worse performance and decompression than low resolution in 2/3-D

- For near term targets, energy coupling may be enhanced by minimizing window thickness and laser radius while balancing with higher $I\lambda^2$

- More flexibility offered by cryogenic targets and coinjection

- Effects from pulse shaping, laser induced mix and magnetization require further work