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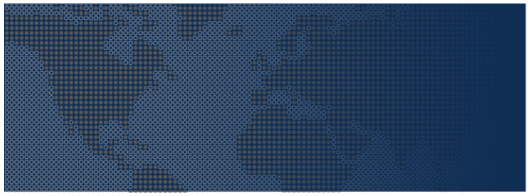

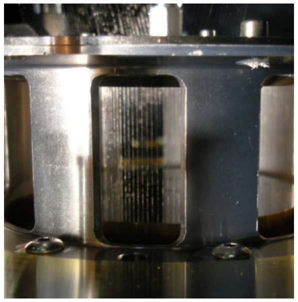

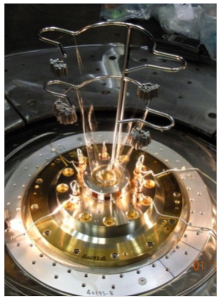

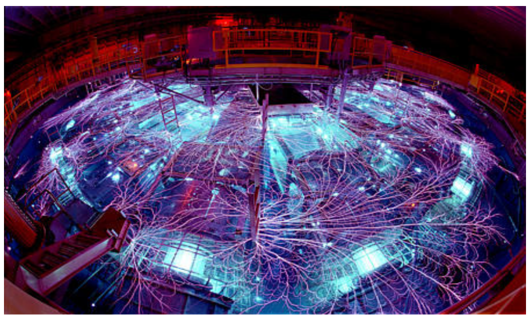

Atomic Processes in Magnetized ICF Plasmas

S.B. Hansen, D.B. Sinars, S.A. Slutz, R.D. McBride, R.A. Vesey, A. Harvey-Thompson, T. Awe, K.J. Peterson, M. Gomez, C. Jennings, P. Knapp, G.A. Rochau, M.C. Herrmann

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Introduction

- The challenges of ICF
  - Creating and confining plasma at extreme temperatures and densities
  - Ignition requires alpha-heating > radiative and conductive losses
  - For clean burn, this implies $\rho R > 0.3$ g/cm^2 and T > 4 keV
- Magnetized Liner Inertial Fusion (MagLIF) at Sandia
  - Cylindrical implosions of magnetized, pre-heated fuel
  - Modest CR ~ 15 mitigates instabilities and high-Z mix
  - Magnetic field mitigates conduction losses and enhances alpha heating
  - Reduced ignition requirement $\rho R \sim 0.03$ g/cm^2
- Atomic-scale physics plays a critical role in design and diagnostics
  - Spectroscopy is a powerful diagnostic
  - Radiative loss rates, stopping powers, and conduction control ignition
  - High-Z mix can reduce κ and increase dE/dx: can a high-opacity liner reduce the attendant radiative losses?

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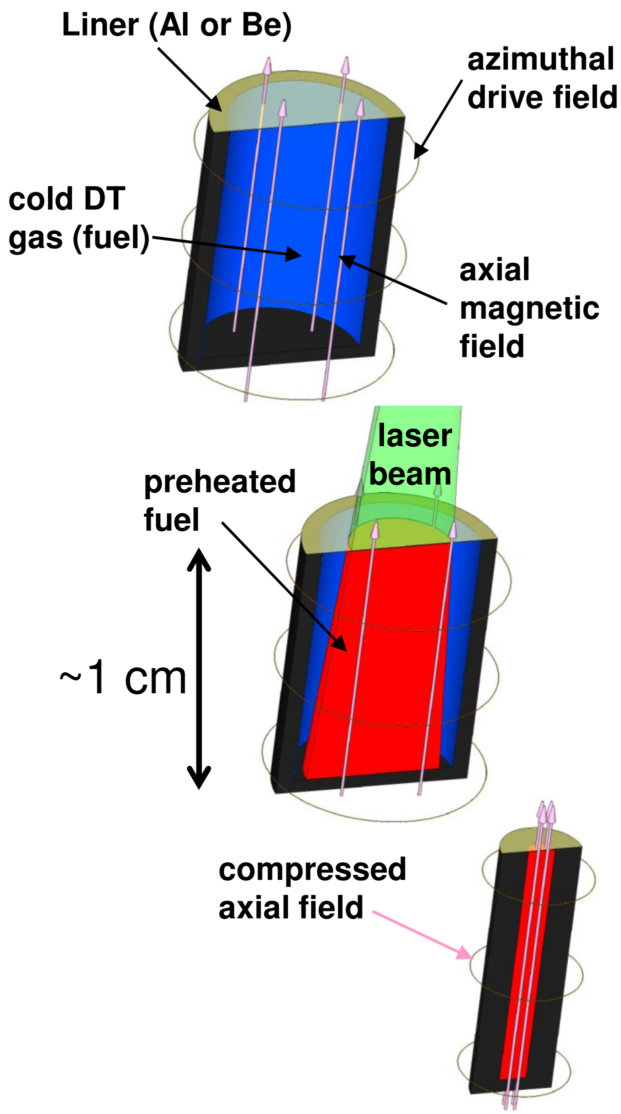
The Magnetized Liner Inertial Fusion (MagLIF)* concept



- An initial 30 T axial magnetic field inhibits thermal conduction losses, enhances alpha particle energy deposition, and may help stabilize implosion at late times.
- During implosion, the fuel is heated using the Z-Beamlet laser (about 6 kJ). This reduces the convergence ratio needed to obtain ignition temperatures to about 25 on Z and reduces the implosion velocity needed to ~100 km/s, allowing us to use thick liners that are more robust against instabilities.
- ~50-250 kJ energy in fuel; 0.2-1.4% of capacitor bank
- Stagnation pressure required is ~5 Gbar
- Gain = 1 may be possible on Z using DT (fusion yield = energy into fusion fuel)

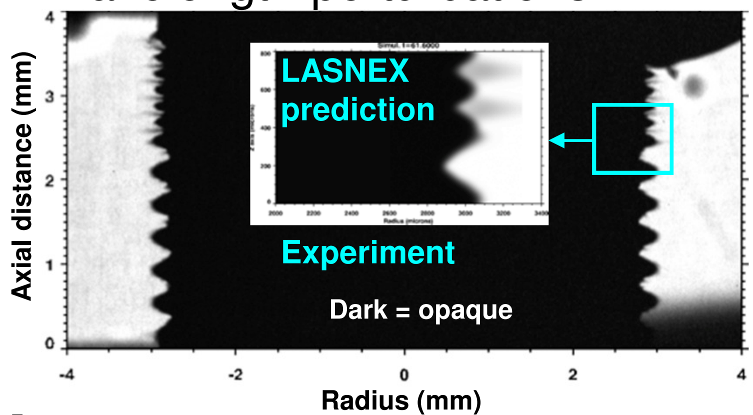
*S.A. Slutz *et al.*, Phys. Plasmas 17, 056303 (2010). S.A. Slutz and R.A. Vesey, Phys. Rev. Lett. (2012).

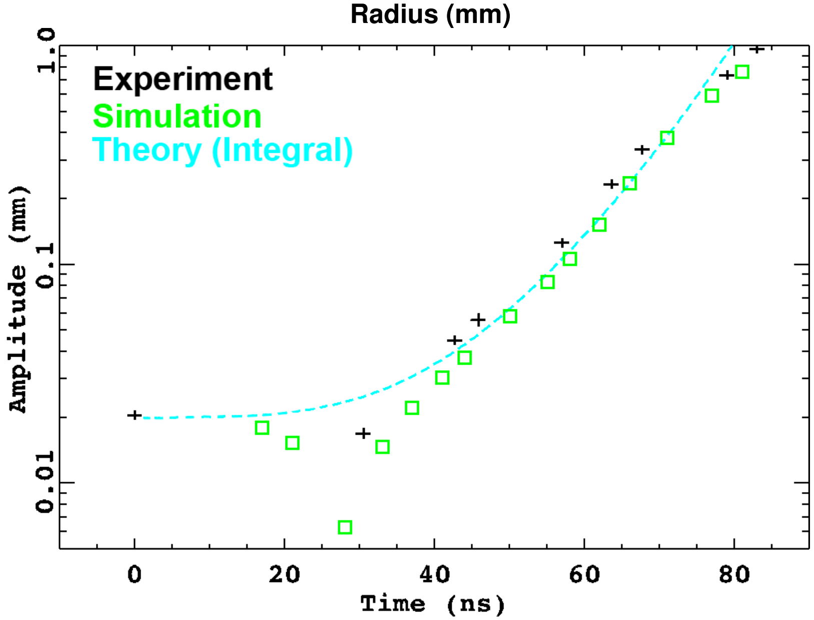
We have made significant progress toward our initial capability goals for testing MagLIF in FY13

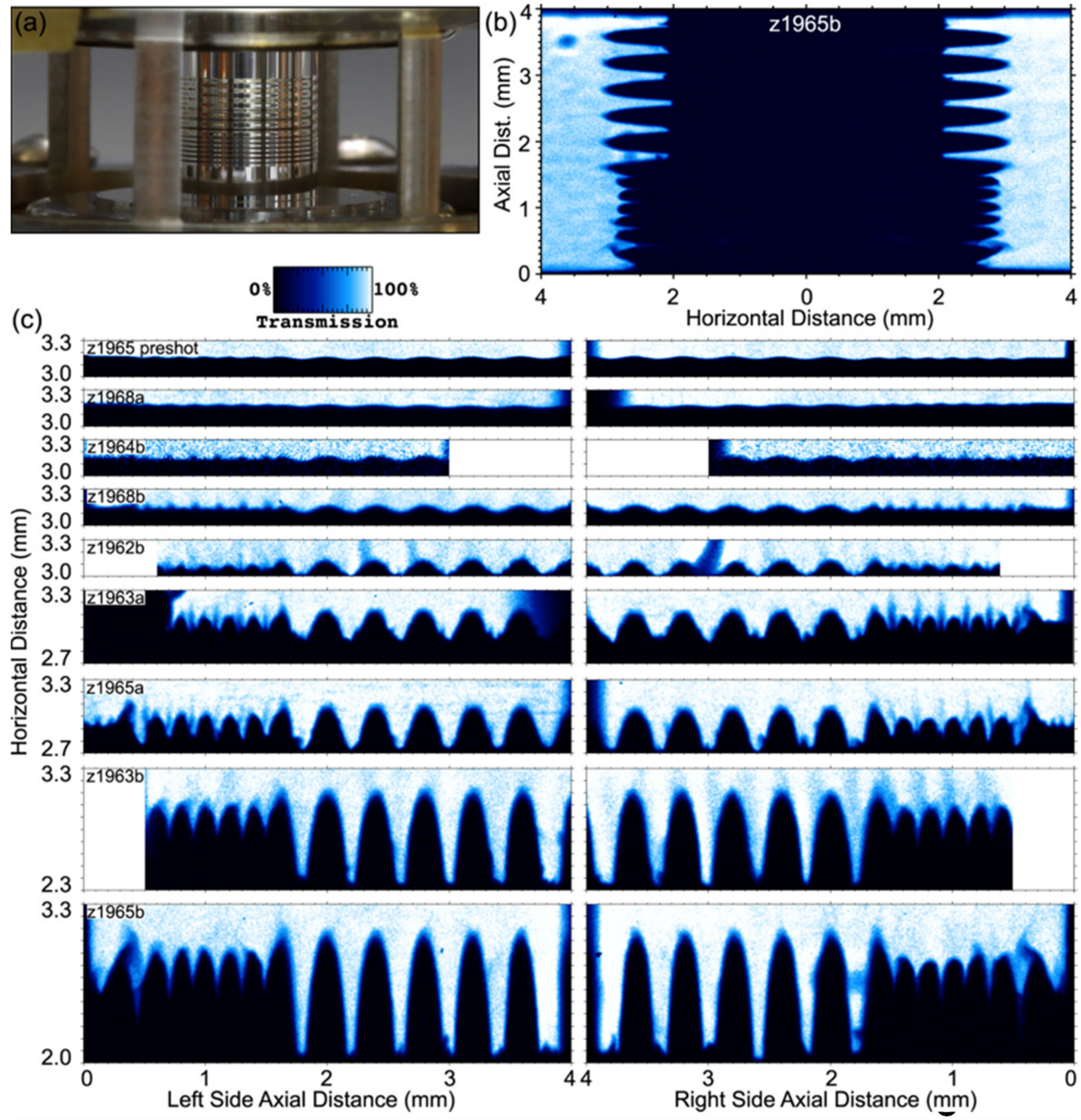
- Load hardware compatible with magnetic field coils and laser preheating has been developed and fielded
- Capacitor banks capable of driving up to 30 T fields have been installed on Z and have been tested up to 10 T
- New final optics assembly for Z-Beamlet preheating has been installed
- The first integrated experiments were planned for late August, combining a liner implosion (20 MA), an axial magnetic field (10 T), and laser preheat (2-2.5 kJ). However, aiming and firing problems prevented the desired test.

Controlled experiments provided a critical test of our understanding of the Magneto-Rayleigh Taylor instability

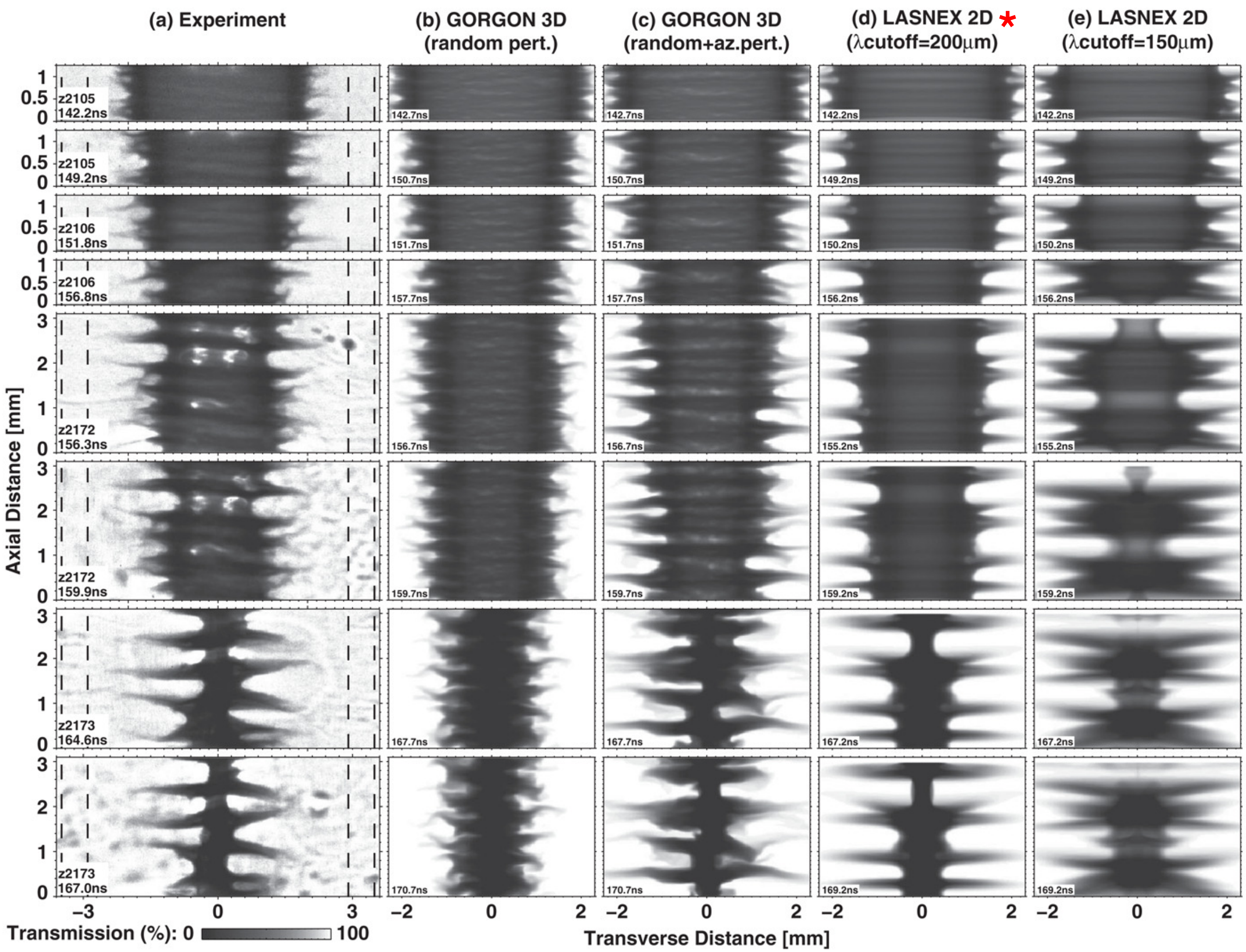
Radiographs captured growth of intentionally-seeded 200, 400-μm wavelength perturbations





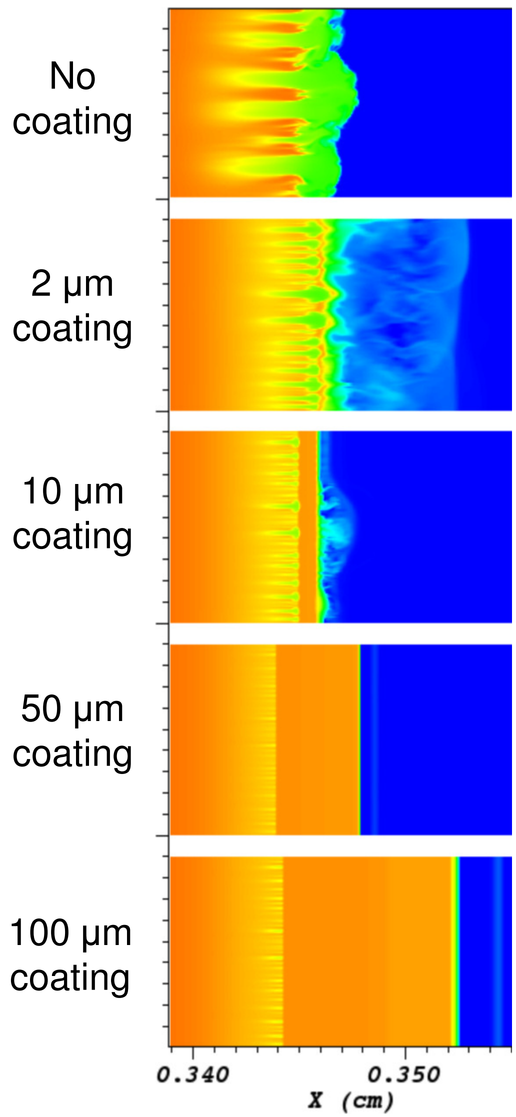


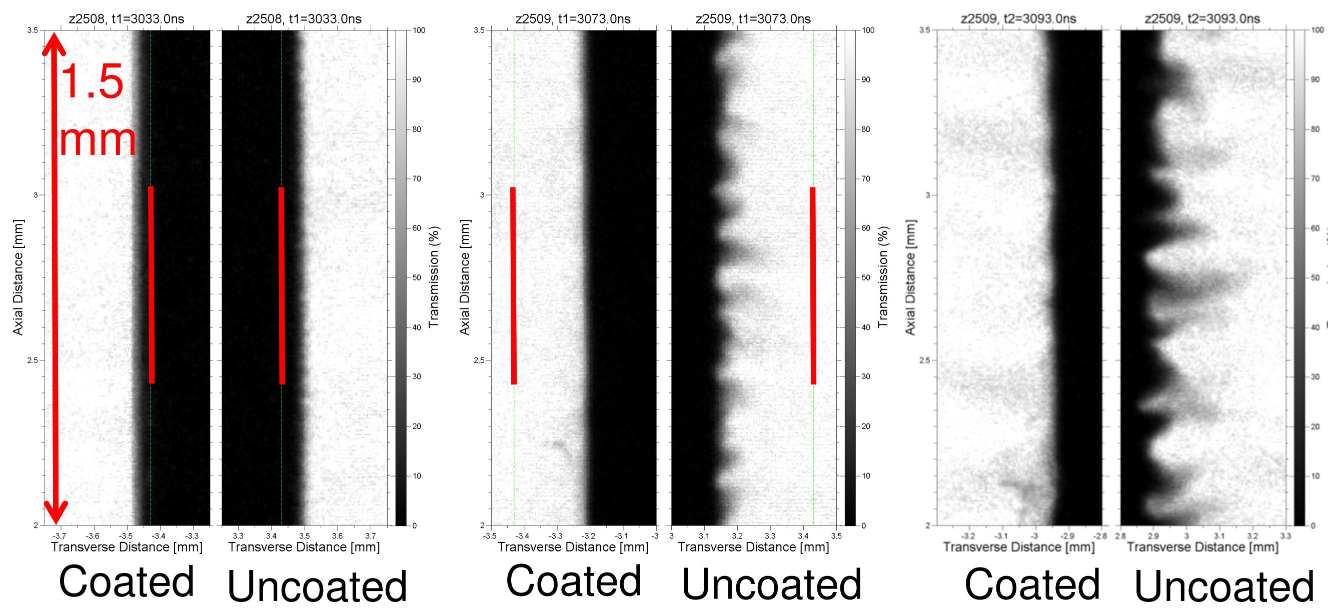
Beryllium experiments show surprisingly correlated instability growth at late times that may imply a highly-correlated initial perturbation



R.D. McBride *et al.*, Phys. Rev. Lett. (2012); R.D. McBride *et al.*, Phys. Plasmas 20, 056309 (2013).

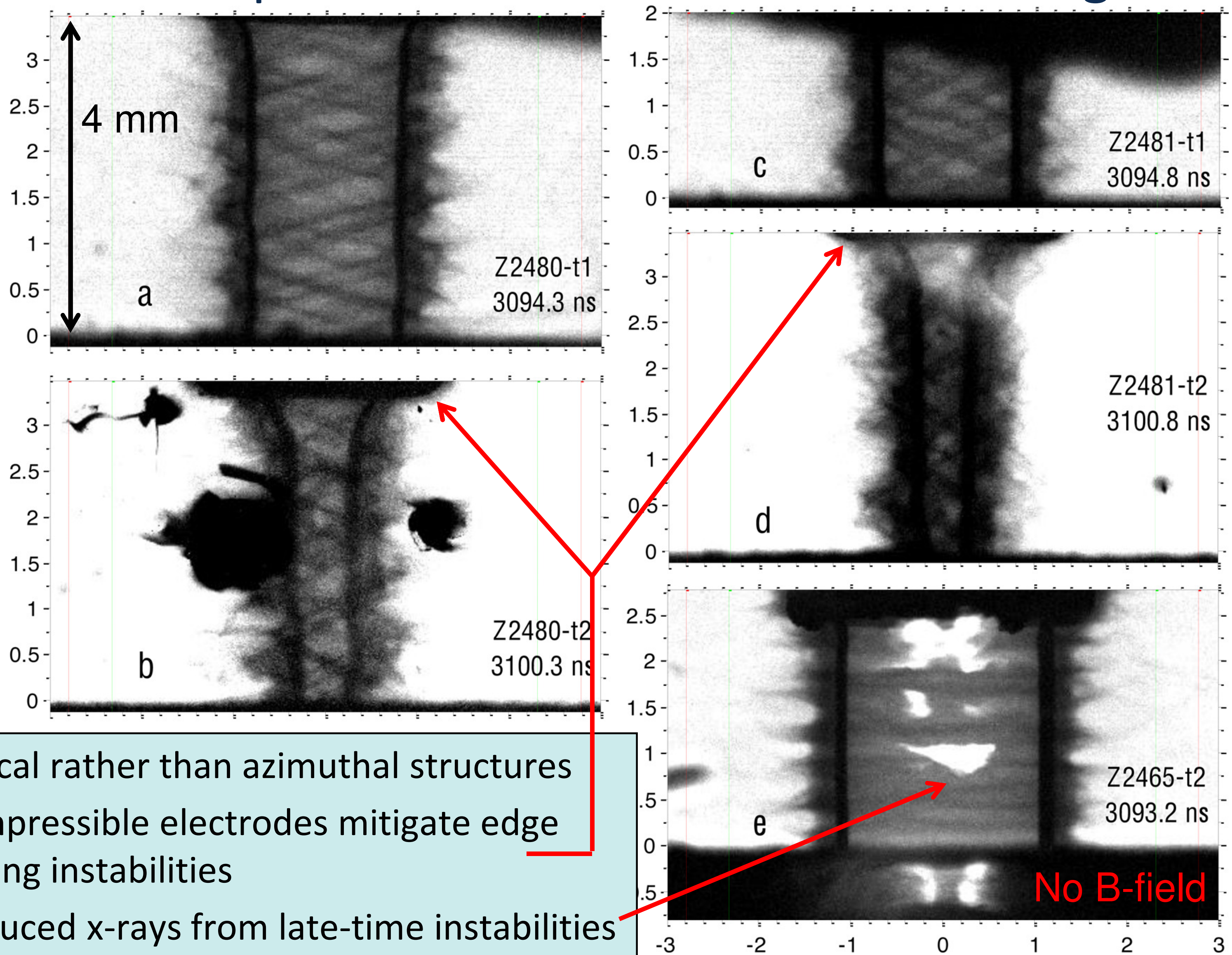
The electro-thermal instability (ETI) is one possible mechanism for seeding MRT growth – and it can be mitigated by an outer coating





- ETI: regions with higher T have higher resitivity and are heated further; pressure variations eventually redistribute mass
- A plastic coating carries very little current and is theoretically ETI stable, with resistivity that decreases with temperature
- A thin coating significantly reduces the mass redistribution and provides a more stable implosion

Our first axially-magnetized liner implosion experiments provided us with several new insights



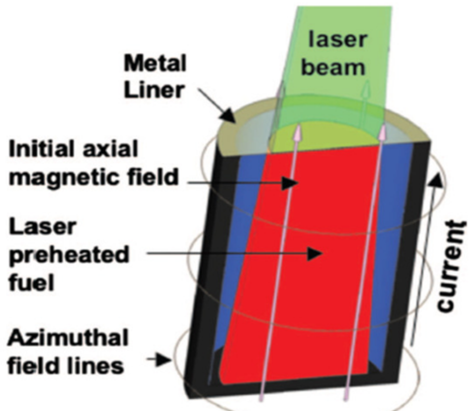
- helical rather than azimuthal structures
- compressible electrodes mitigate edge jetting instabilities
- Reduced x-rays from late-time instabilities

T.J. Awe *et al.*, submitted to Phys. Rev. Lett.

We started testing our preheating model predictions of energy deposition in laser-only experiments

Motivation/aims

We want to ensure that laser preheat energy can be absorbed by MagLIF fuel

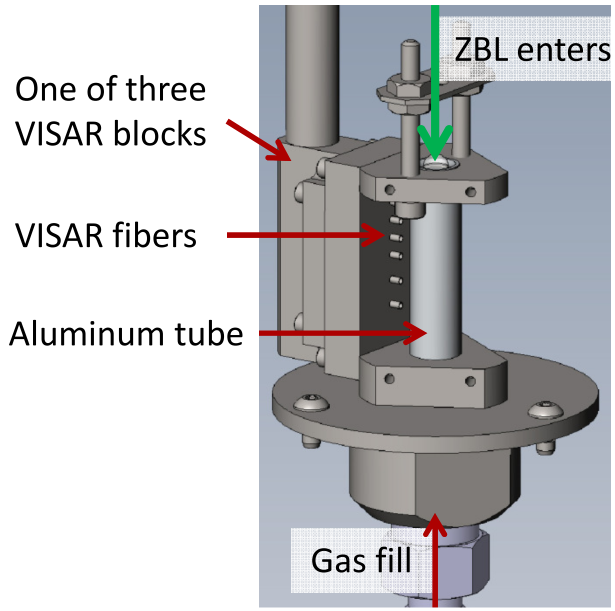


Laser blast wave targets aim to:

1. Reproduce first integrated MagLIF setup as closely as possible
2. Measure laser energy deposition in the fuel by measuring time/velocity of blast wave

Experimental design

ZBL (~2 kJ, 2 ns) enters into thin-walled tube target containing dense D2 gas

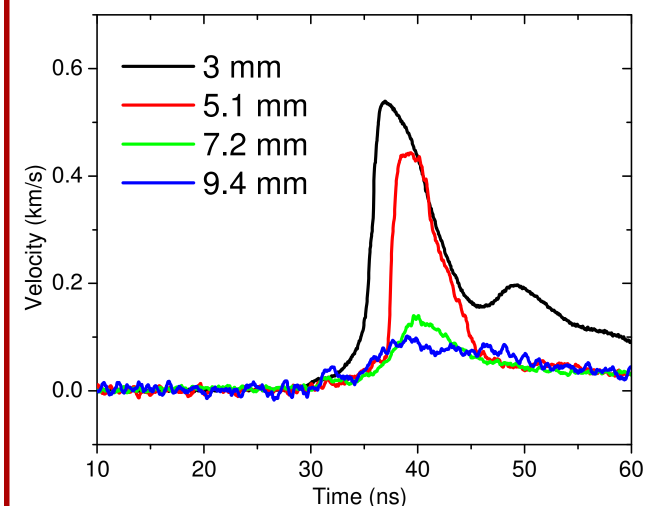


Blast wave in fuel driven by laser energy absorption

Time/velocity of tube wall motion monitored by 21 VISAR probes (3 azimuthal, 7 axial positions)

Results/conclusions

VISAR data shows velocity and time of tube wall motion consistent with laser energy deposition



Data analysis is underway. There is concern that poor beam focal spot quality is affecting transport through the foil

Comparisons to detailed HYDRA and LASNEX simulations are underway

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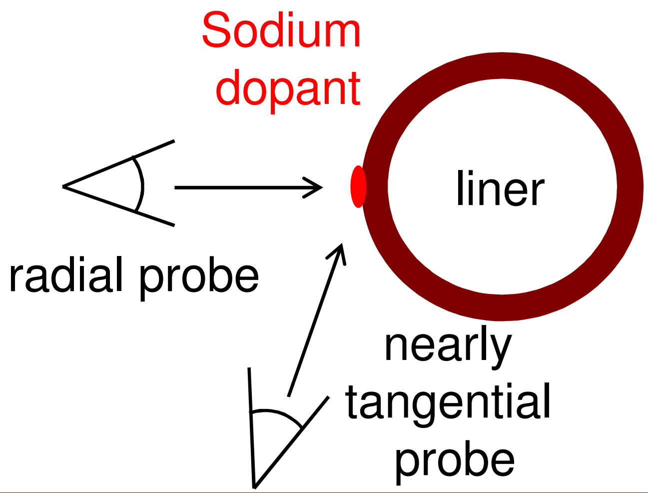
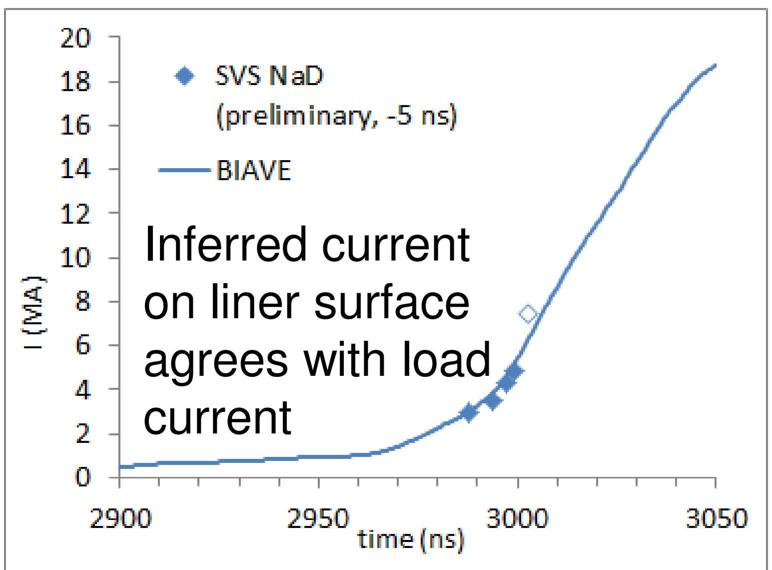
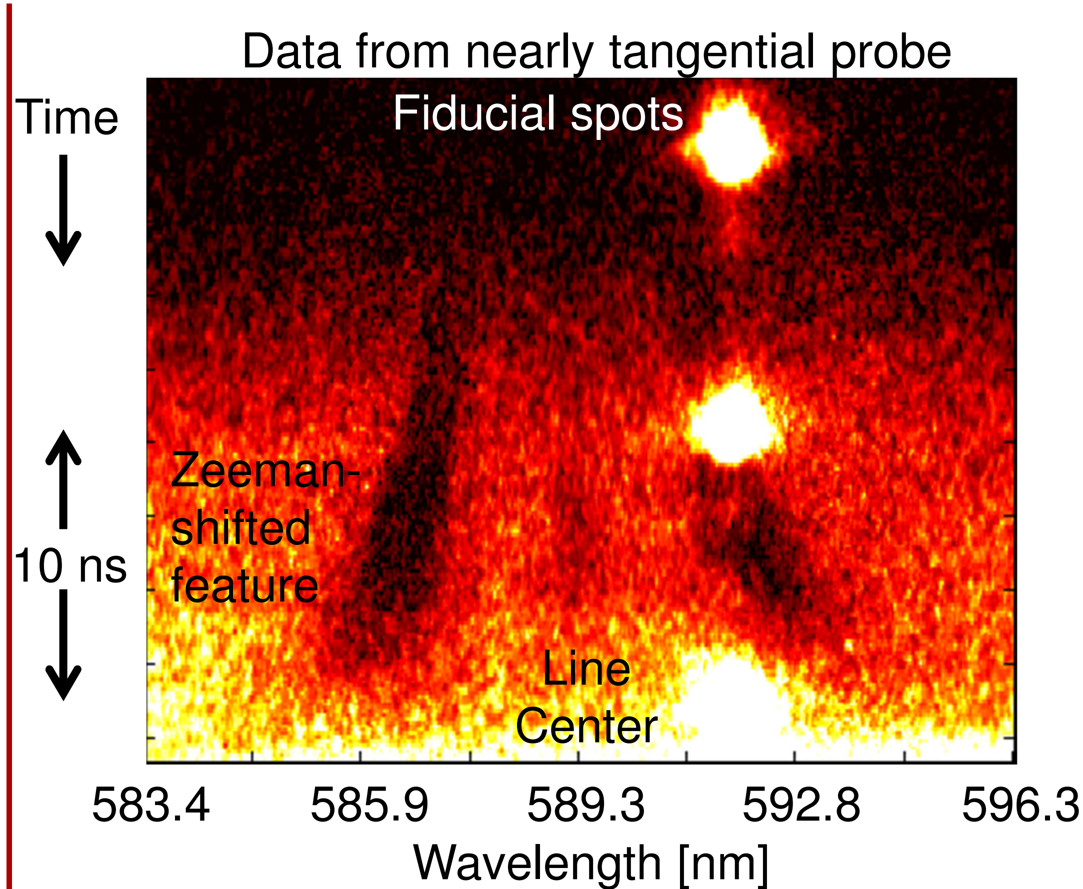
Zeeman splitting in optical absorption spectra provides a measure of load currents and possibly flux compression



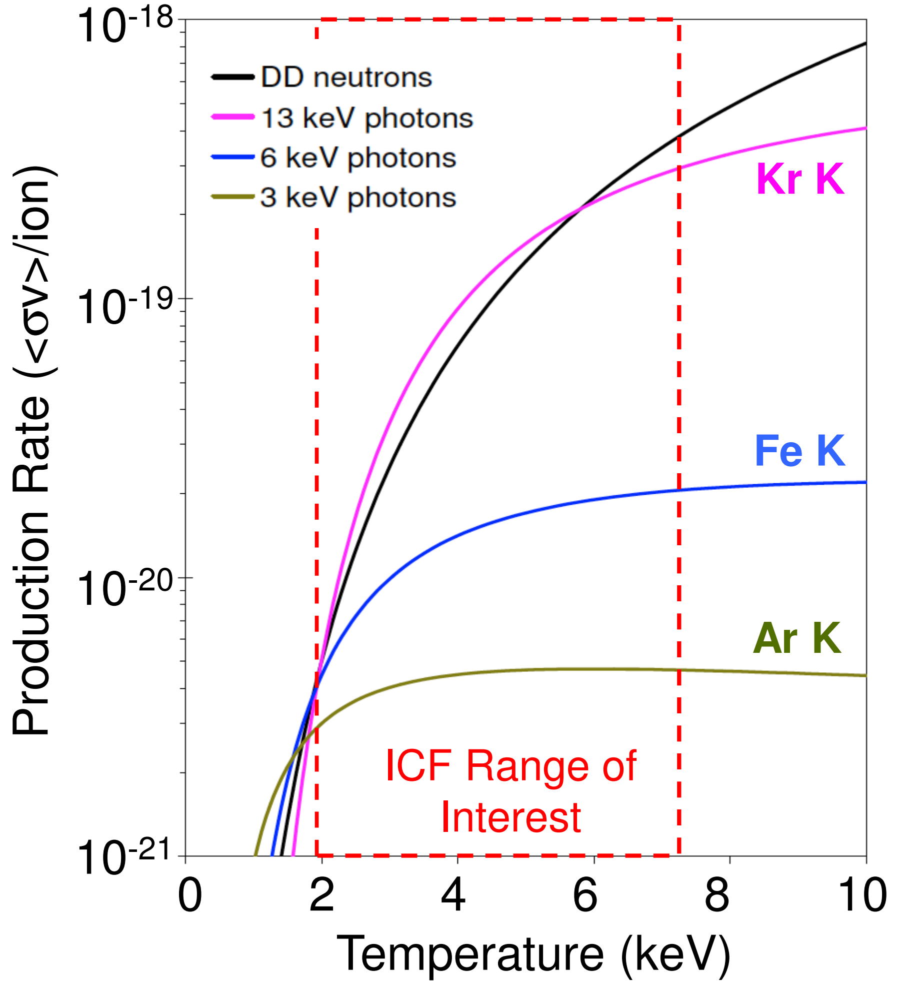




Time-dependent Zeeman splitting of neutral sodium line seen in absorption—splitting is proportional to magnetic field strength

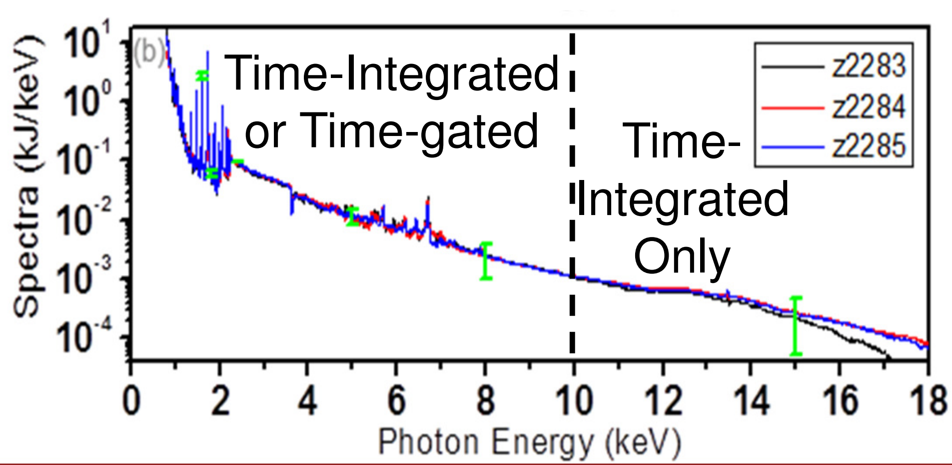
K-shell Kr x-rays are a good proxy for neutrons and offer valuable diagnostic information on T, ρ, R, Dt, and beams

Photon and Neutron Production Scaling

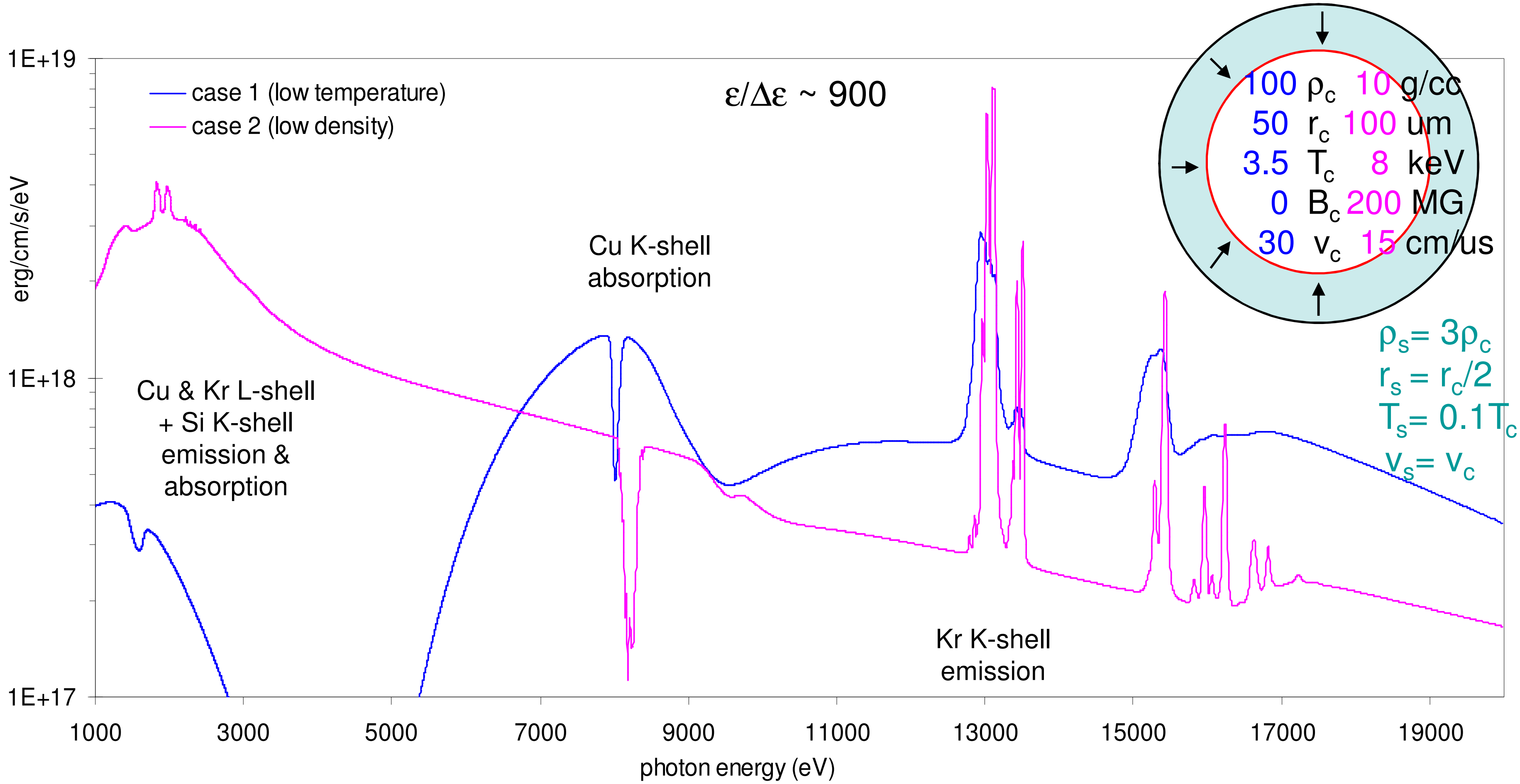


- Kr K-shell production scales well with DD neutron reactivity
- 13 keV photons easily escape thick liner
- K-α production sensitive to beams
- He-like K-shell production sensitive to thermal conditions

Kr emission approximates the size and duration of the DD fusing plasma

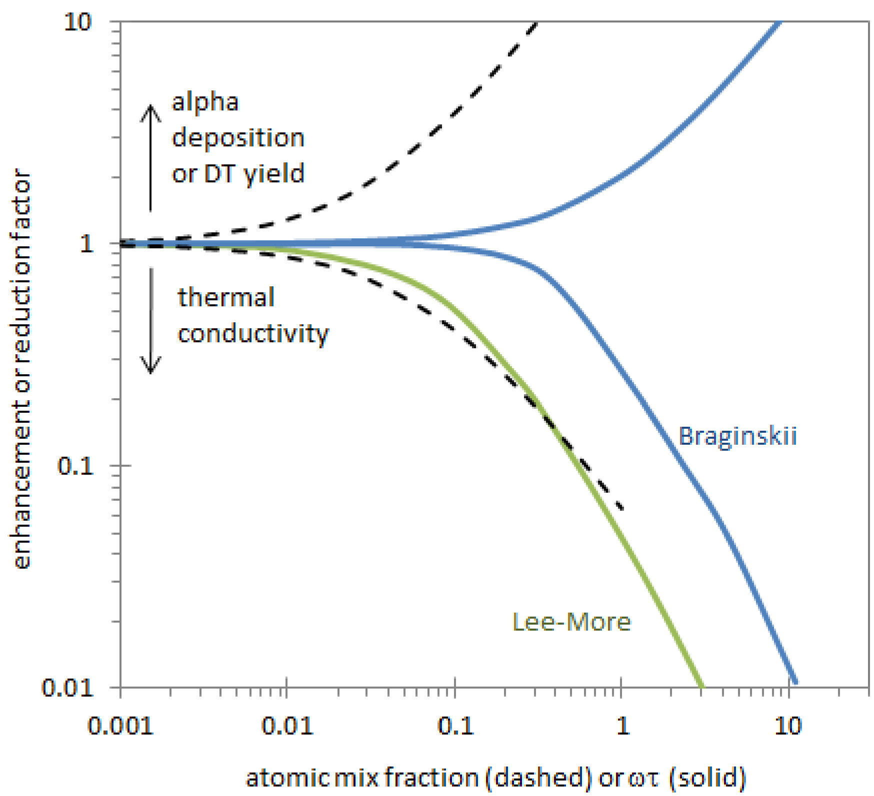


Stagnation plasmas that produce similar neutron yields can have dramatically different x-ray emission spectra



Profound differences in the widths of emission & absorption features, emission line ratios, and the depth and position of absorption lines depend on the detailed conditions of the stagnation and pusher plasmas.

Atomic-scale transport plays a key role in target performance and is sensitive to T, ρ, B, and composition

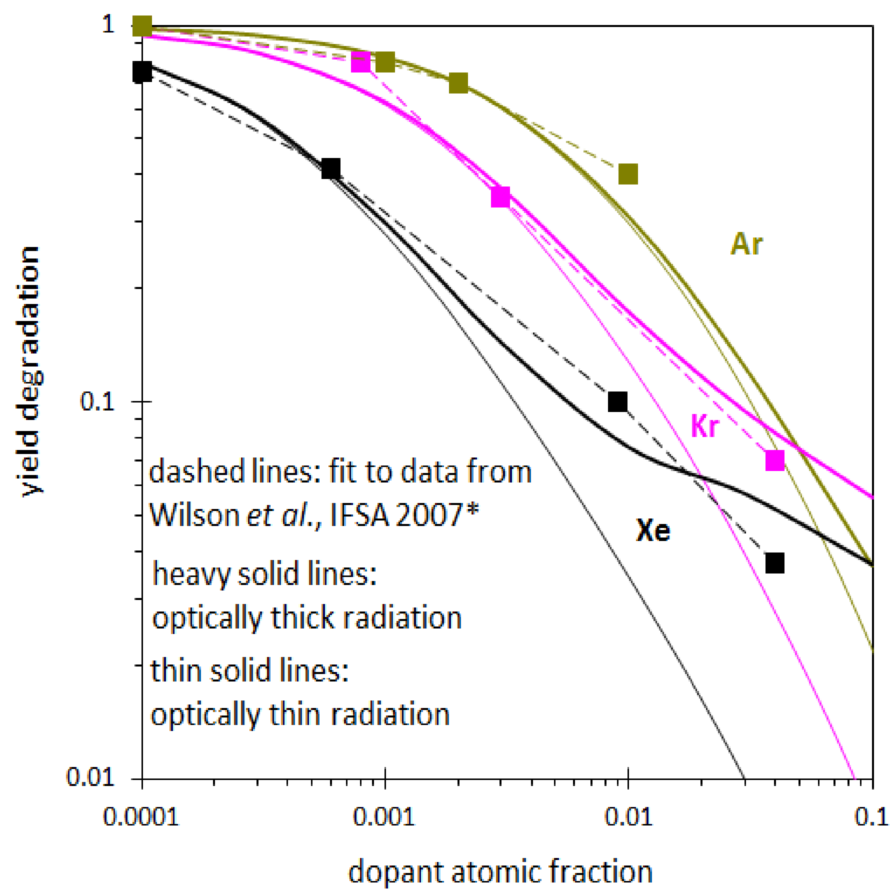


Note the significant disagreement in the ωτ dependence of conductivity from different models

- This is the promise of MagLIF: in a strongly magnetized plasma with fuel ρR = 0.03 g/cm^2, T = 4keV, and few-kT fields (ωτ ~ 3), thermal conductivity is reduced ~10x and α deposition is enhanced ~5x. Together, these effects reduce the ρR ignition requirement tenfold.
- Similar effects can be achieved with the addition of ~10% mix of a mid-Z dopant (Z* = 30): extra electrons increase dE/dx and high-Z scattering reduces κ.
- However, even small dopant fractions contribute catastrophic radiative losses, scaling with ~ Z^3

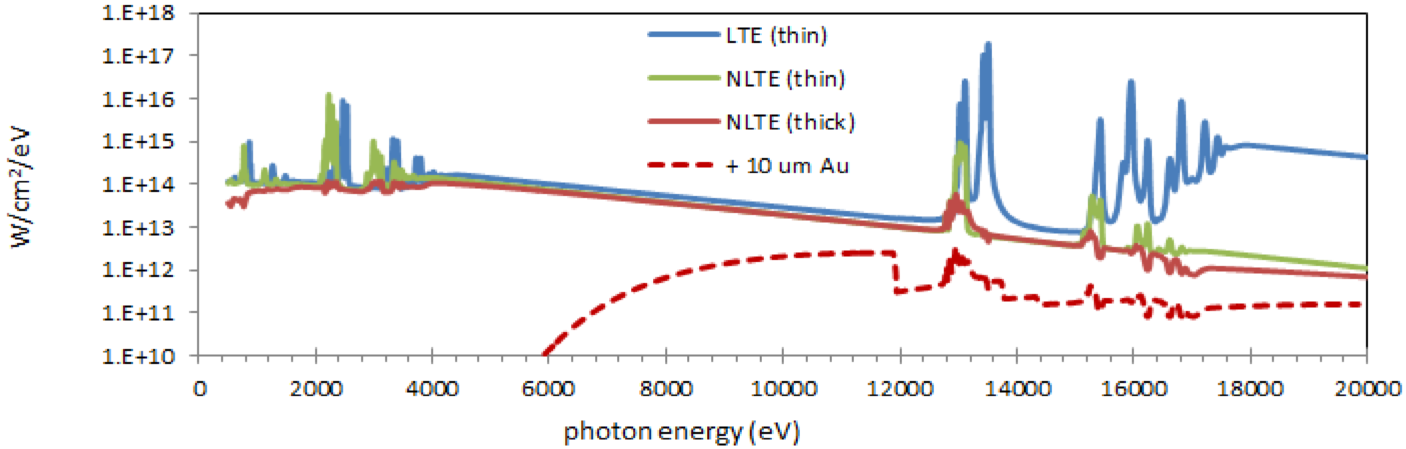
Measured yield degradation from exploding pushers on Omega confirms the deleterious effects of high-Z radiation

- Various dopants (Ar, Kr, Xe) were introduced into D_2 gas fills on Omega
- Measured neutron yields decreased dramatically with dopant fraction f and nuclear charge Z
- Miles *et al.* show that the conditions at stagnation were not substantially changed by dopants, but burntime was reduced by increased cooling – fitting the data required reasonably good NLTE radiation models
- A simple model setting burn duration to $(1-f)^2 T_{burn}/[W_r(f,Z) + W_\kappa(f,Z)]$ roughly captures the observed degradation, with some indication that radiation trapping mitigates the radiative losses

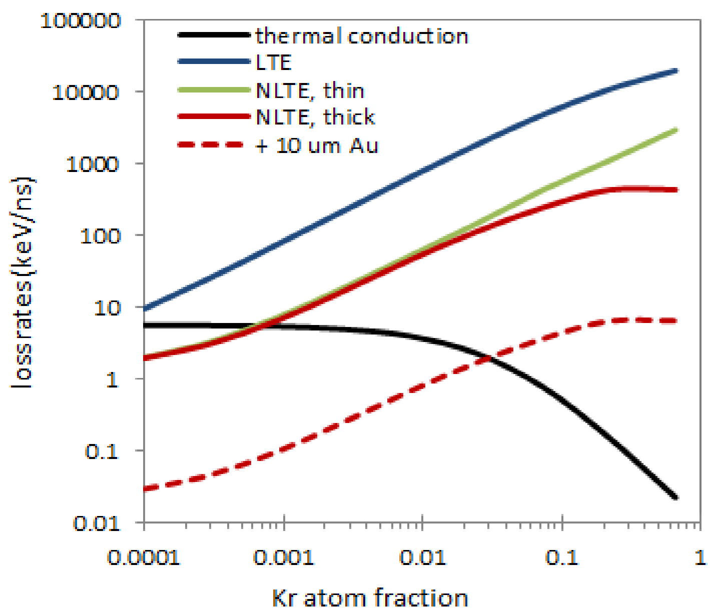


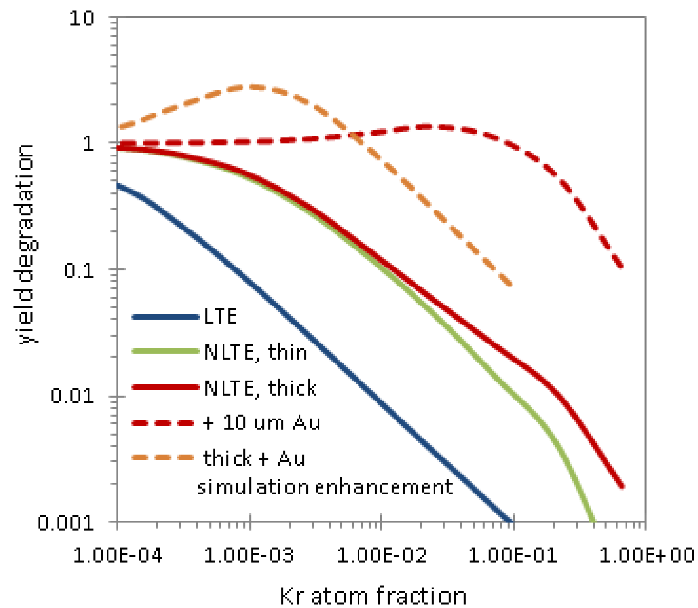
Mix of CH into fuel appears to affect NIF target performance: T. Ma, PRL 111, 085004 (2013)

A cold, high-Z layer could further mitigate radiation losses



Here, opacity is treated self-consistently but the gold layer is cold and perfectly reflective.





Both the simple loss model at fixed stagnation conditions and 1-D simulations indicate significant yield enhancement with a gold layer.

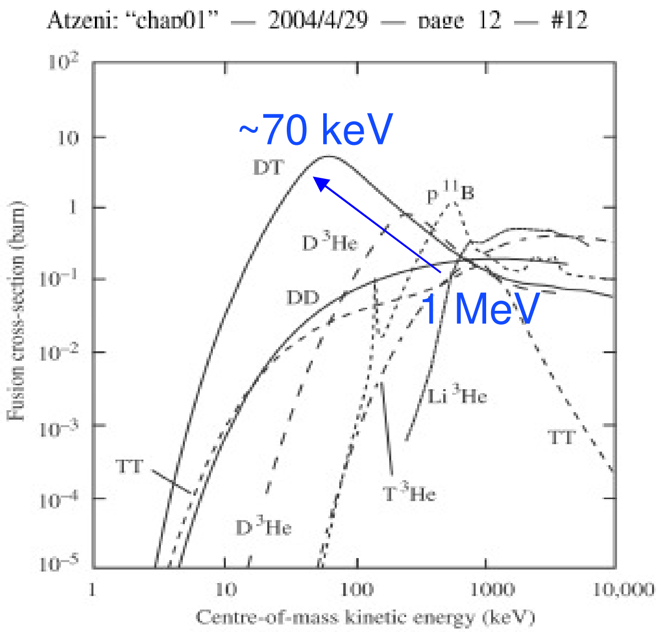
Although there will be no α-heating with D_2 fuel, DT/DD yield ratios will reflect changes in dE/dx

$D + D \rightarrow {}^3He + 2.45\ \text{MeV}\ n$

$\quad\ \ \searrow p + 1\ \text{MeV}\ \mathbf{T}$

$D + \mathbf{T} \rightarrow {}^4He + 14\ \text{MeV}\ n$

DT cross section



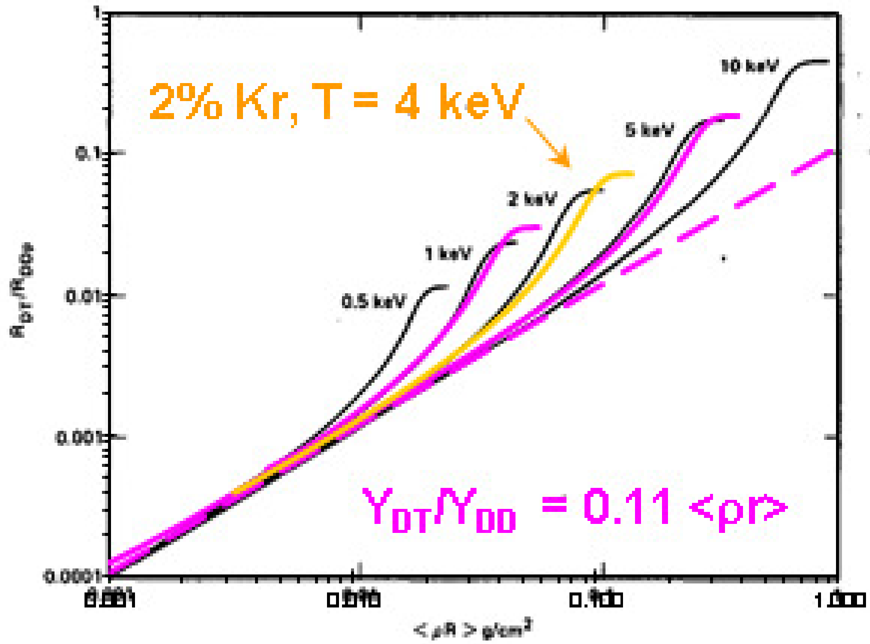


FIG. 1. R_{dt}/R_{ddp} as a function of $\langle \rho R \rangle$ for several fuel electron temperatures. The model used assumes a large uniform density and temperature fuel region with a negligibly small central "hot spot" from which all tritons originate (see text). Curves end at the value of $\langle \rho R \rangle$ where the tritons have thermalized in the fuel. Fuel density used was 21 g/cm³.

Stopping powers from MUZE DFT model reproduce Cable & Hatchett for pure D2 and indicate significant effects for few-% Kr at ρR ~ 0.03 g.cm²

Summary

- The MagLIF concept significantly reduces pressure and ρR requirements for ignition, and we are making progress towards integrated experiments
- X-ray and visible spectroscopy will be valuable diagnostics, helping us understand preheat and stagnation plasma conditions and drive currents
- Target performance has a strong dependence on the atomic-scale transport physics, including $\kappa(\omega\tau, T, \rho, f)$, $dE/dx(\omega\tau, T, \rho, f)$, and non-LTE radiation losses and transport, and these generally lack benchmark data in the WDM and HEDP regimes.
- Although we are designing stable implosions to minimize high-Z mix, we are exploring ways to exploit its advantageous effects on κ and dE/dx while minimizing radiative losses.

The electro-thermal instability is an important mechanism that could seed MRT growth*

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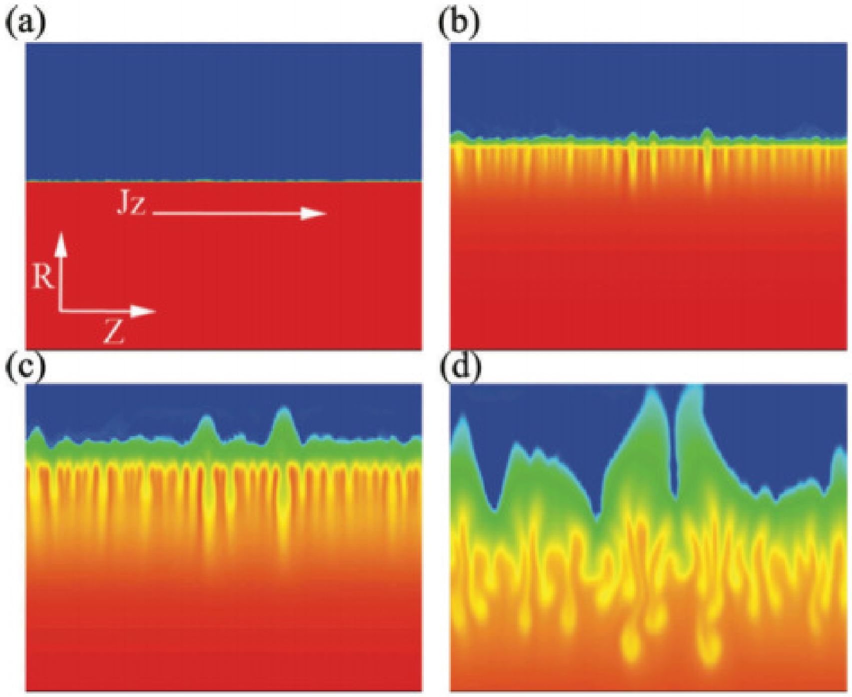
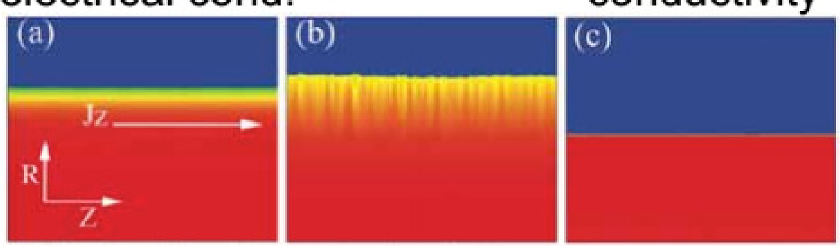
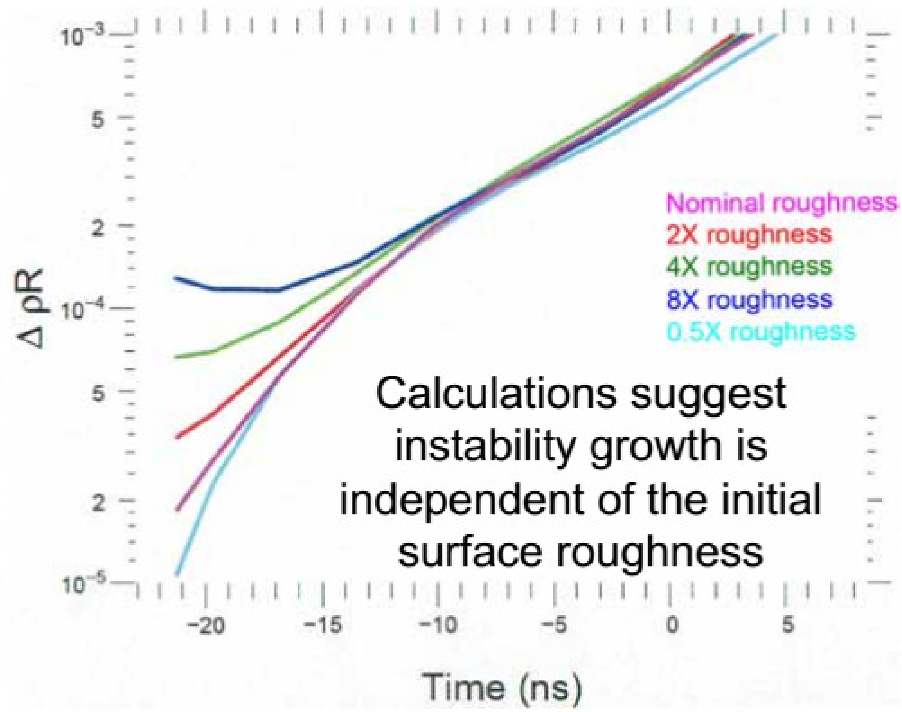




Constant electrical cond.   Nominal   10x thermal conductivity



Temperature perturbations give rise to pressure variations which eventually redistribute mass

*K.J. Peterson *et al.*, Phys. Plasmas (2012); K.J. Peterson *et al.*, Phys. Plasmas 20, 056305 (2013).