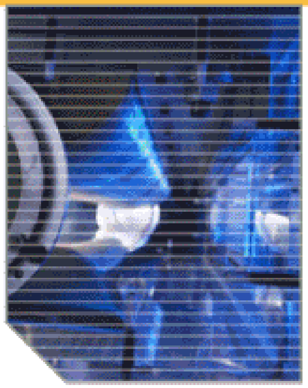
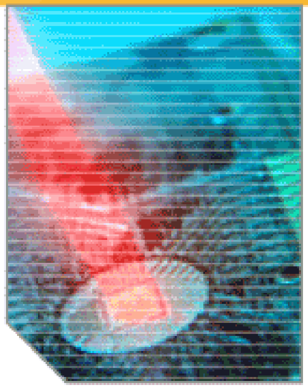
Computational Predictions of Laser Produced Plasma EUV Source Performance

Curt Rettig, I. Fomenkov, Cymer, Inc.
Joseph J. MacFarlane, Prism Computational Sciences

LPP Modelling: Goals and Approach

Goal for LPP modelling:

- Simulate illumination concepts to improve *conversion efficiency*.

Approach:

- Establish and validate a *quantitative* model for plasma dynamics, radiation transfer, and atomic kinetics.
- Compare with experimental results where possible.
  - Acquire a computational model available to experimentalists for validation,
  - conduct comprehensive model evaluations and sensitivity studies to identify limitations and model most accurate representation of reality,
  - Run the code on new concepts

- We have acquired modelling tools from *Prism Computational Sciences* and engaged them for assistance on more complicated issues.

CYMER®

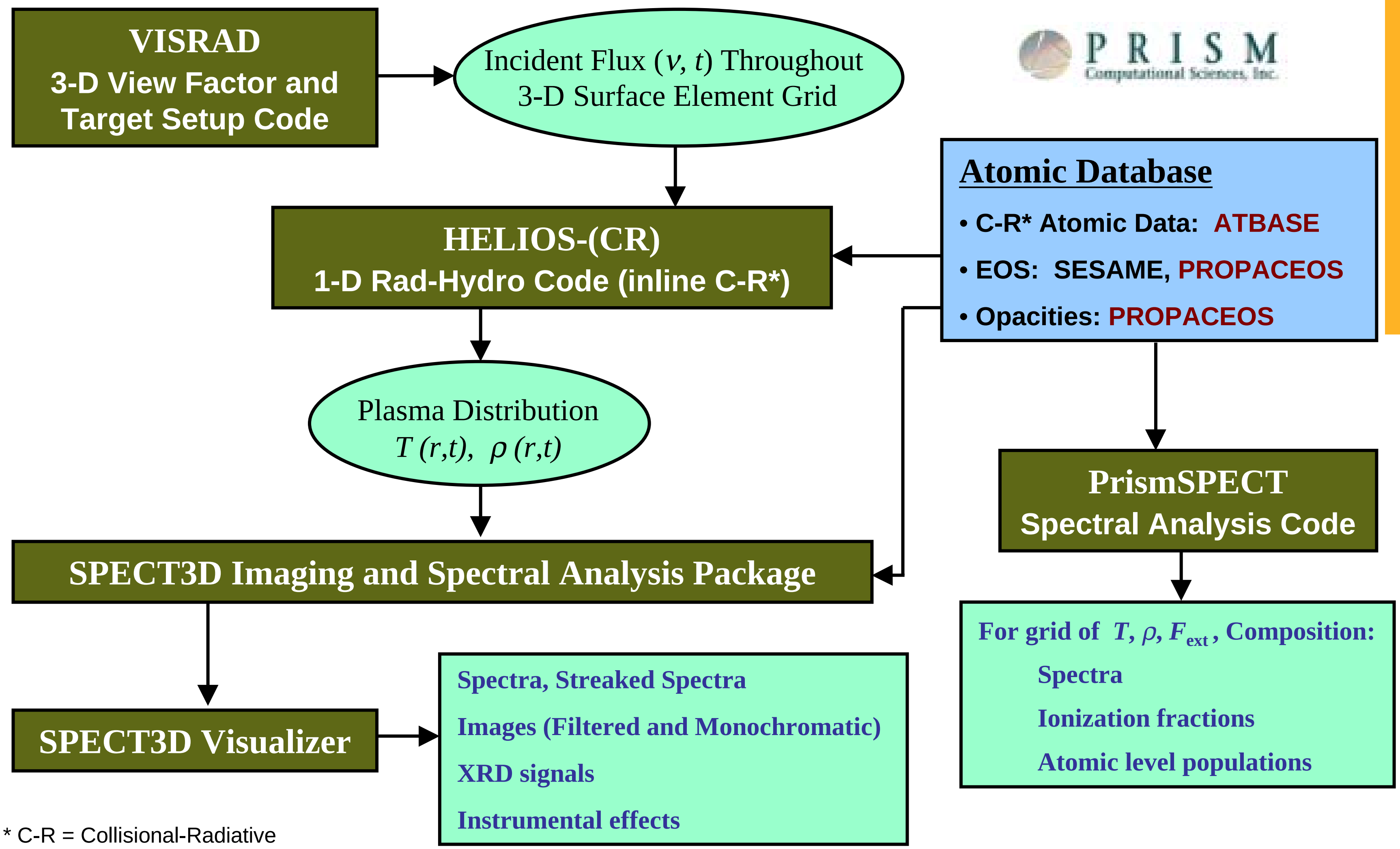
Overview of Prism Simulation Tools

- Prism has developed a suite of codes applicable to the study of laser-produced and z-pinch plasmas:
  - **HELIOS**: a 1-D radiation-hydrodynamics code (soon w/ MHD for cyl. geometry) (inline collisional-radiative modelling version also available.)
  - **SPECT3D**: Imaging and Spectral Analysis Suite: a code for computing spectra and images – based on 1-D, 2-D, or 3-D plasma distributions – that can be compared with experimental measurements.
  - **ATBASE**: a suite of atomic structure and collision cross-section codes
  - **PROPACEOS**: equation of state and opacity code (also SESAME EOS used)

PRISM Computational Sciences, Inc.

CYMER

Code Suite Used to Simulate Plasma Physics Experiments: ***HELIOS, SPECT3D, VISRAD, ATBASE, PROPACEOS, PrismSPECT***



* C-R = Collisional-Radiative

Major Features of HELIOS

- HELIOS is a 1-D Lagrangian radiation-hydrodynamics code (planar, cylindrical, spherical).
- Supports modeling 2-T or 1-T ($T_{ion} = T_{electron}$) plasmas.
- Radiation transport: flux-limited diffusion, multi-angle short characteristics.
- Supported EOS and opacity models:
  - SESAME EOS
  - PROPACEOS multigroup opacities and EOS
  - Ideal gas EOS
  - Non-LTE inline collisional-radiative modeling (HELIOS-CR (opacities)).
- External energy source models:
  - external radiation field
  - laser energy deposition (inverse Brehmstralung)
- HELIOS integrates with:
  - AtomicModelBuilder: for selecting energy levels and level bundling (C-R mode)
  - SPECT3D: for post-processing $T(r,t)$, $\rho(r,t)$ to generate spectra and images
  - HYDROPLOT: plots results of HELIOS simulations.

PRISM Computational Sciences, Inc.

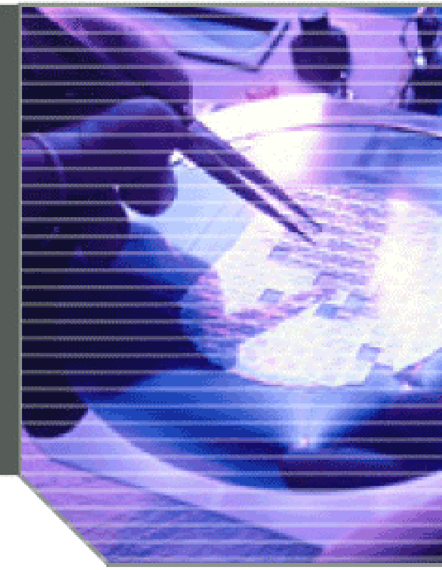
CYMER

Current Modelling Efforts

- At Cymer, we are simulating various experiments and comparing with measurements, quantitatively:
  - Conversion efficiency (CE), laser energy to 13.5 nm, 2% BW
  - intensity vs time,
  - detailed and time resolved spectra,
  - electron density profile evolution.
- Goal is to optimize target illumination configurations.

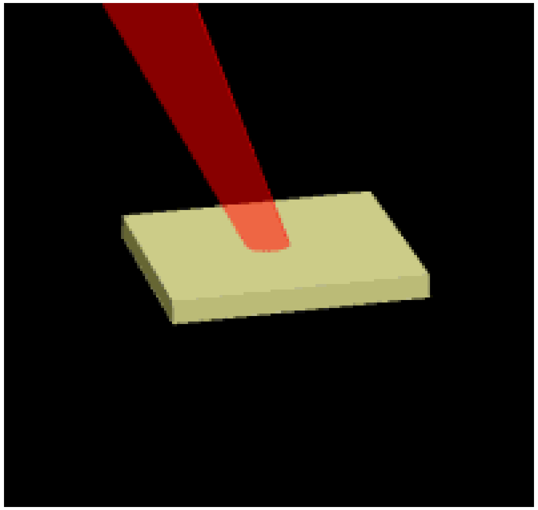
- Ongoing calculations at Prism include:
  - 2-D simulations of planar and spherical targets,
  - non-LTE calculations of radiation transport, to compare with calculations assuming LTE,
  - detailed ATBase atomic model of different target materials.

CYMER



Modelling 1-D Targets

Simulation Parameters of Laser-Produced Lithium Plasmas

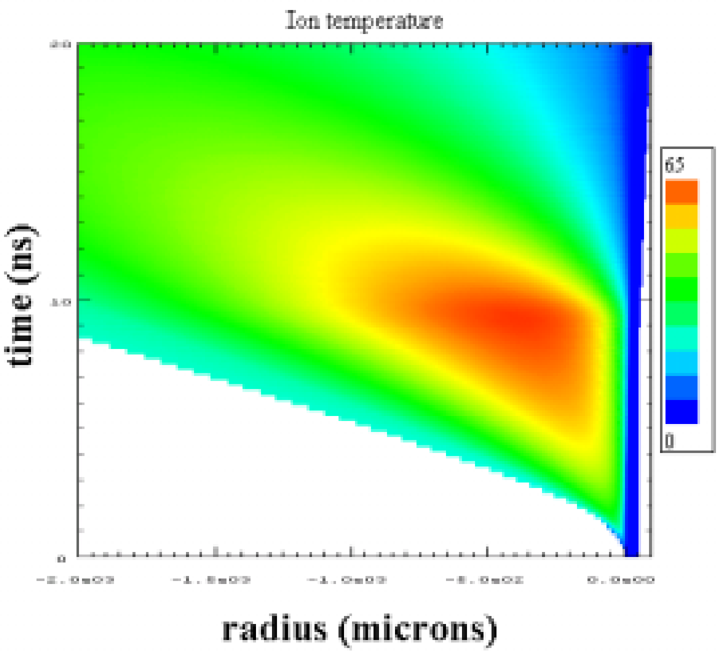


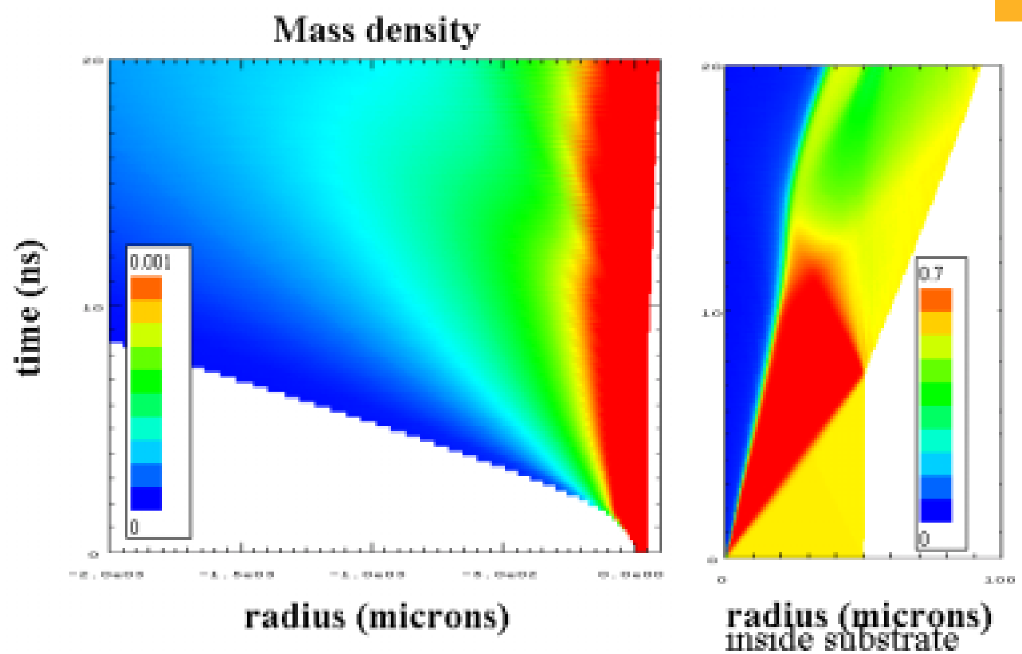
- Experimental parameters:
  - 100 µm-thick Li slab (ρ = 0.535 g/cm^3)
  - PROPACEOS multigroup opacities
  - SESAME equations of state (#2293)
  - Radiation modeling:
    120 groups, with 50 groups between 88 and 96 eV
    multi-angle transport (N_A = 2)
  - "Square" 8 ns laser pulse, with 1 ns rise and fall times
  - Peak laser power = 0.125 TW/cm^2
  - Laser wavelength = 355 nm
- Questions addressed:
  - What are the plasma conditions created in laser-produced Li plasmas?
  - What is the ionization distribution for Li?
  - What atomic processes are responsible for the Li Lyα emission?
  - At what depth is the laser energy deposited?
  - What are the plasma conditions at the location where the Lyα photons originate?
  - How does the 13.5 nm conversion efficiency vary with λ_L, P_L and Δt_L?
- Parameters varied (preliminary survey):
  - Laser wavelength
  - Laser peak power
  - Duration of laser pulse

PRISM Computational Sciences, Inc.

Fluid Dynamics During and Following Laser Pulse Illumination

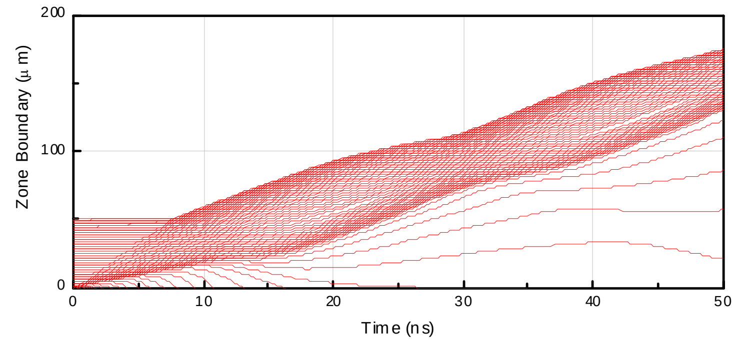
- Ion temperature peaks > 60 eV within the ablation plume
  - these ions, being fully stripped, must re-combine prior to emitting 13.5 nm – therefore the need to maintain electron density.
- Within substrate, acoustic mode is clearly observed (6250 m/s vs 6000).

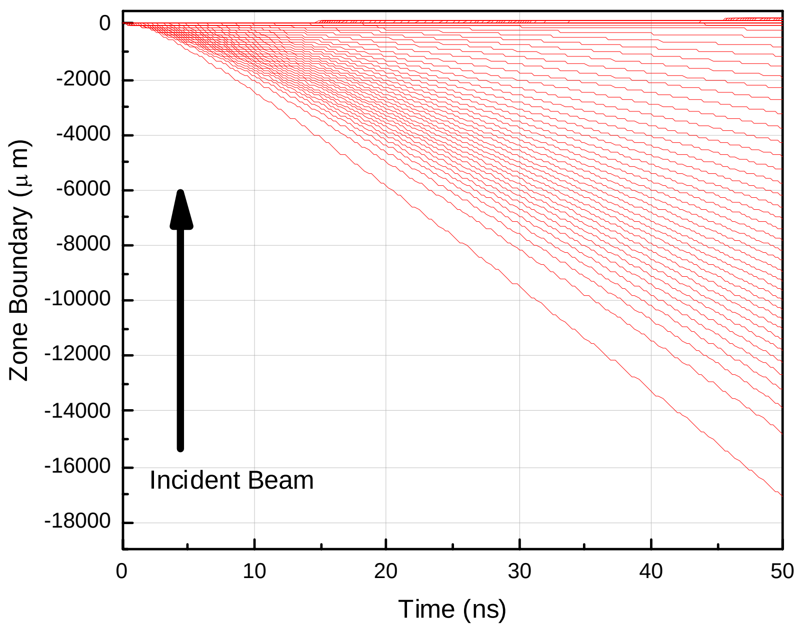




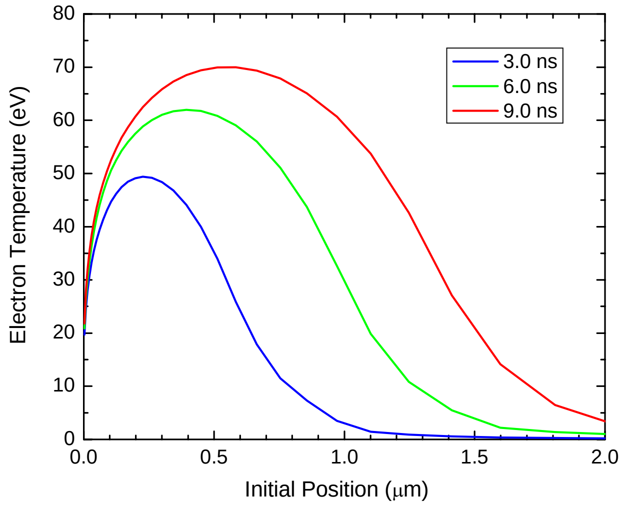
Zone Boundary Evolution during Laser Pulse

- Plot of zone boundaries – locations of zones of constant initial target mass.
- Front surface of target substrate is ablated away with significant velocity.
- Bunching of zone boundaries indicates a peak in the debris velocity spectrum approximately 2.4×10^7 cm/s.

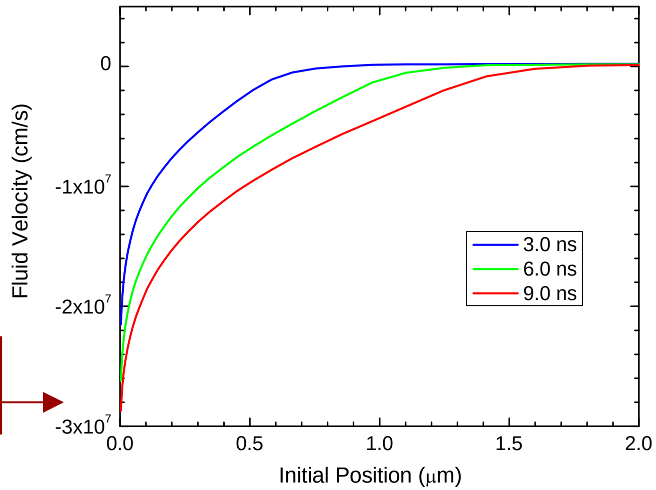




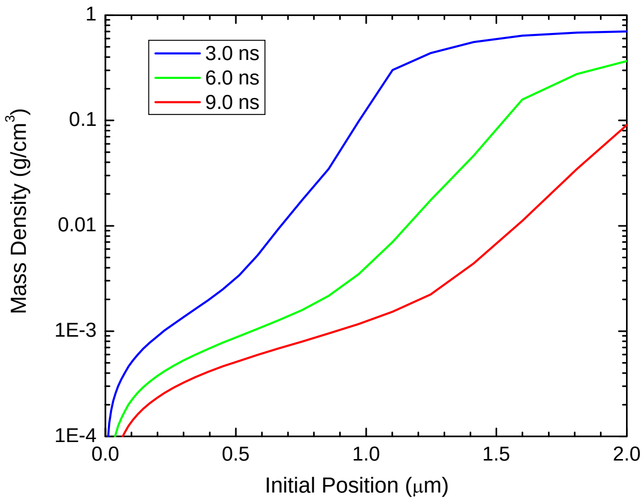
HELIOS Results:
Spatial Dependence of Plasma Conditions



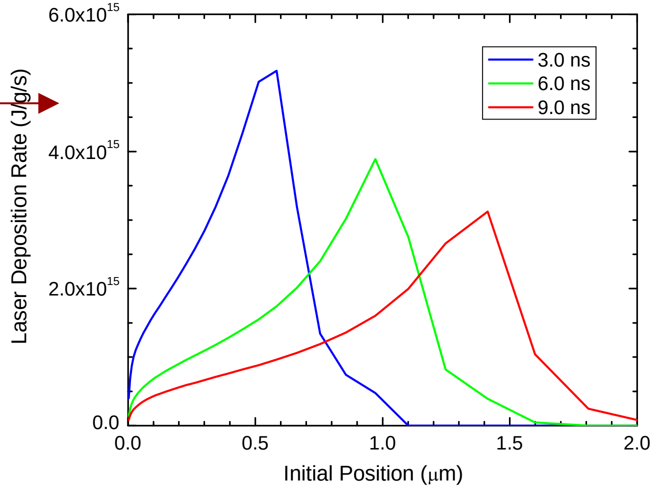
In ablation region, T ~ 50 – 70 eV.



Expansion velocities reach ~ 1 – 3 x 10^7 cm/s.



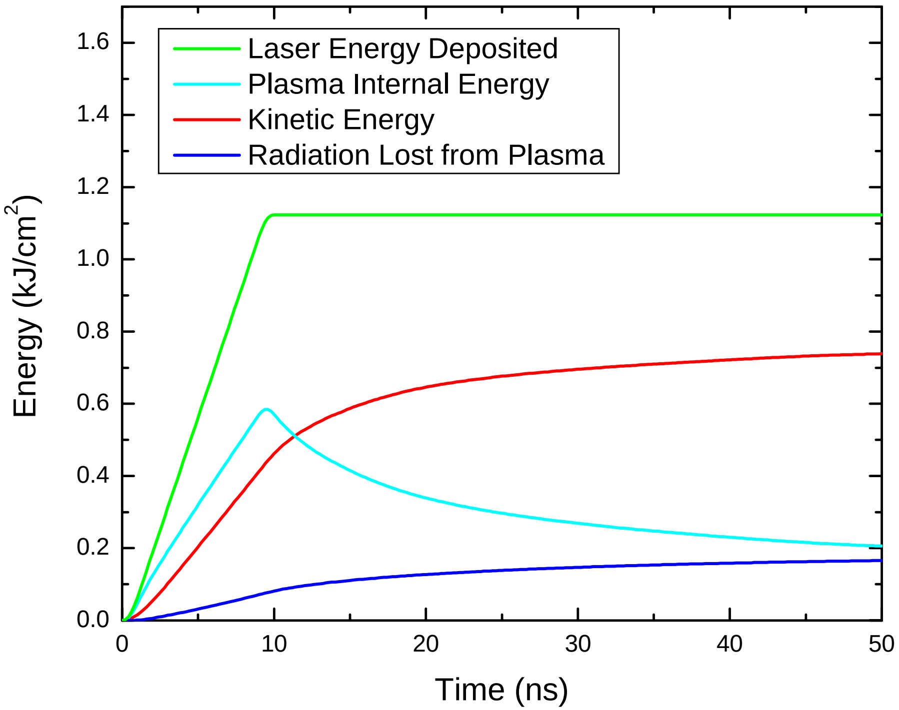
Laser energy deposition peak reaches a "depth" of ~ 1.5 μm by 9 ns.



ρ ~ 10^{-3} - 10^{-2} g/cc where bulk of laser energy is deposited.

Approximately 2 μm of mass is ablated by 9 ns.

Laser Energy Partitioned Mostly into Kinetic Energy



Of energy input by laser beam, by 50 nsec:

- ~ 66% is in fluid kinetic energy
- ~ 15% is radiated away from Li plasma

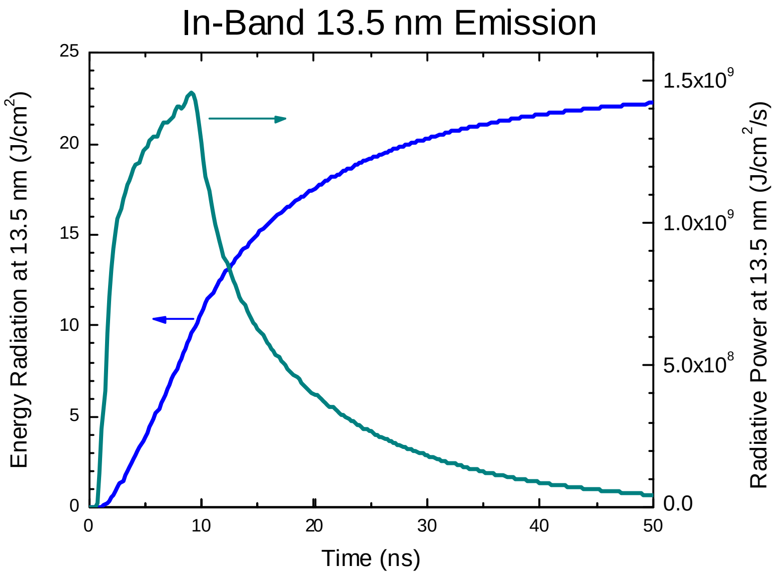
HELIOS Results: Radiation in 13.5 nm Band

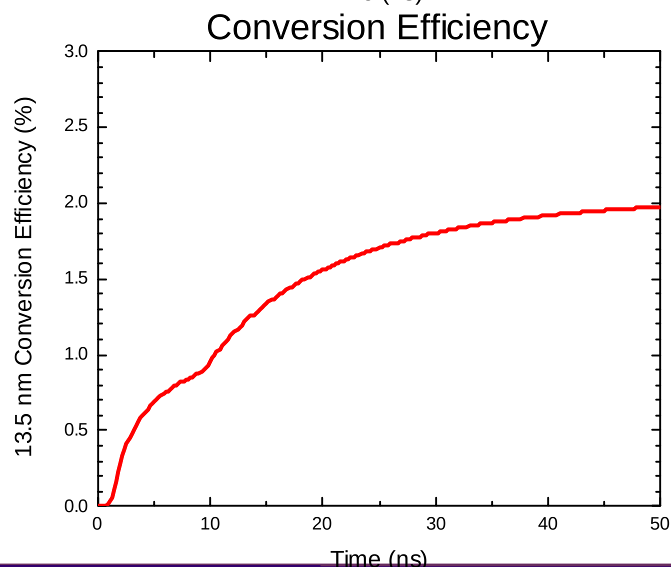
The time-dependent radiation power in the 13.5 nm band peaks at 9 ns (end of laser pulse).

The time-integrated radiation energy in the 13.5 nm band is ~ 22 J/cm^2.

This represents ~ 13% of the total radiated energy.

At 50 ns, the 13.5 nm conversion efficiency is 2.0%.

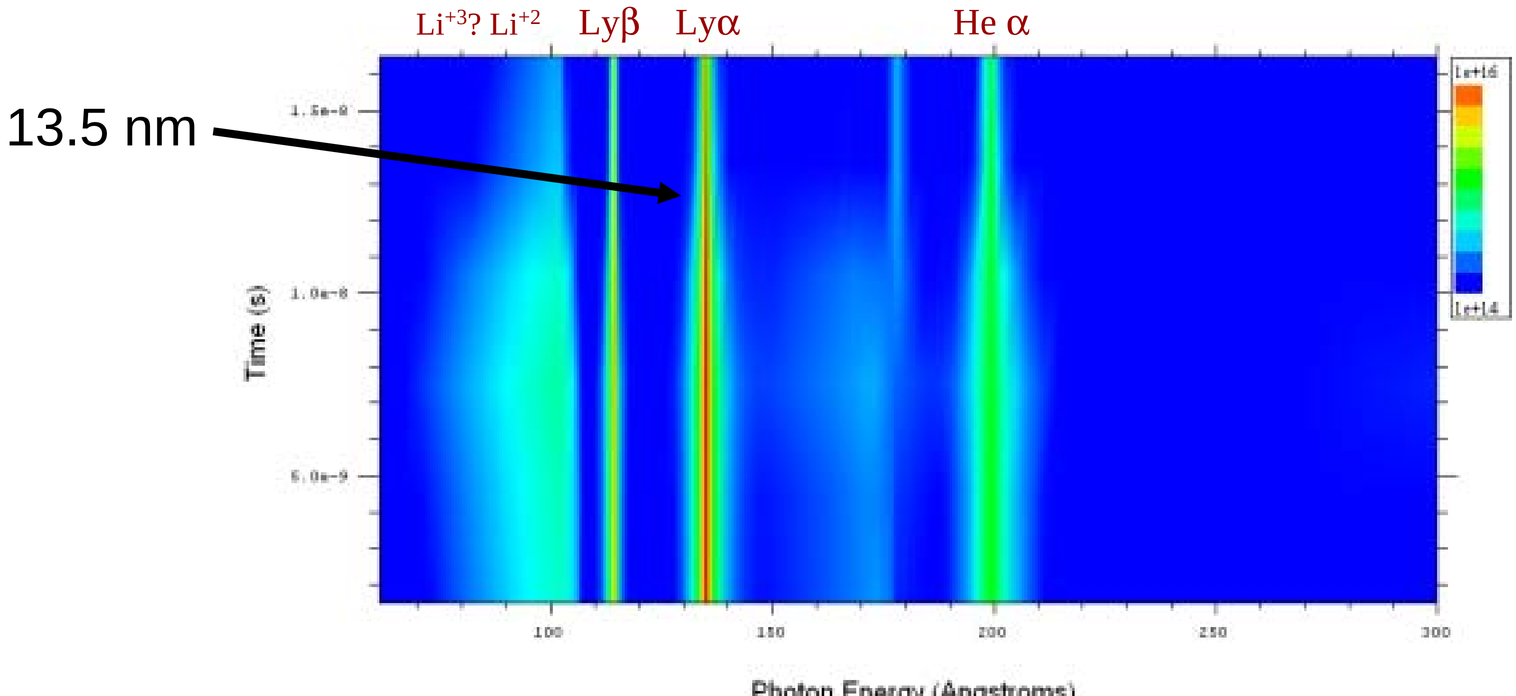




PRISM Computational Sciences, Inc.

Simulated Streaked EUV Spectrum

SPECT3D is used to post-process HELIOS output (*T*(*r*), *ρ* (*r*)) to produce simulated spectra and images.



- Lyα (2p?1s), Lyβ (3p?1s), and He α (1s2p ^{1}P?1s^2 ^{1}S) exhibit strong emission.
- Lines narrow at late time due to falling density.
- Continuum recombination edge is clear in this (log intensity) plot.

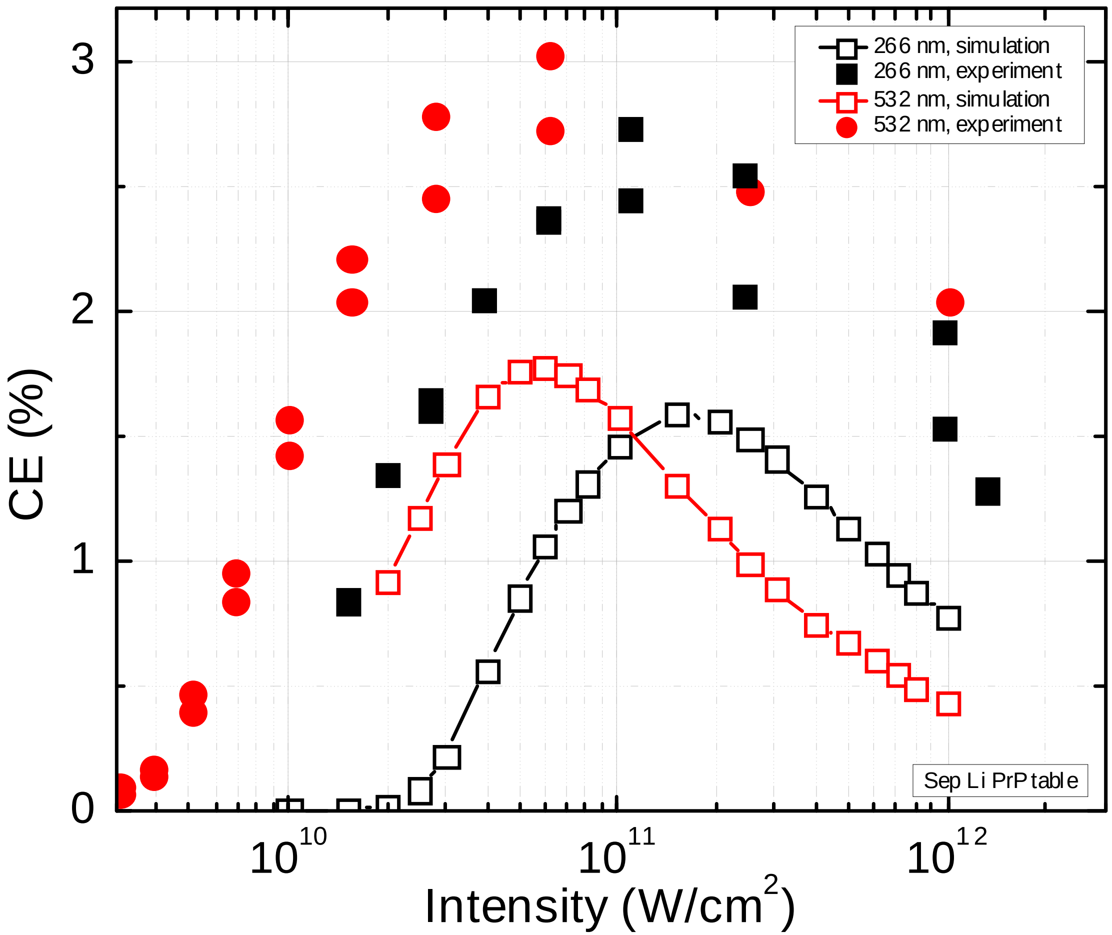
PRISM Computational Sciences, Inc.

CYMER

Experimental Comparison, Scaling, and Optimization

Conversion Efficiency: Comparison with Experimental Measurements

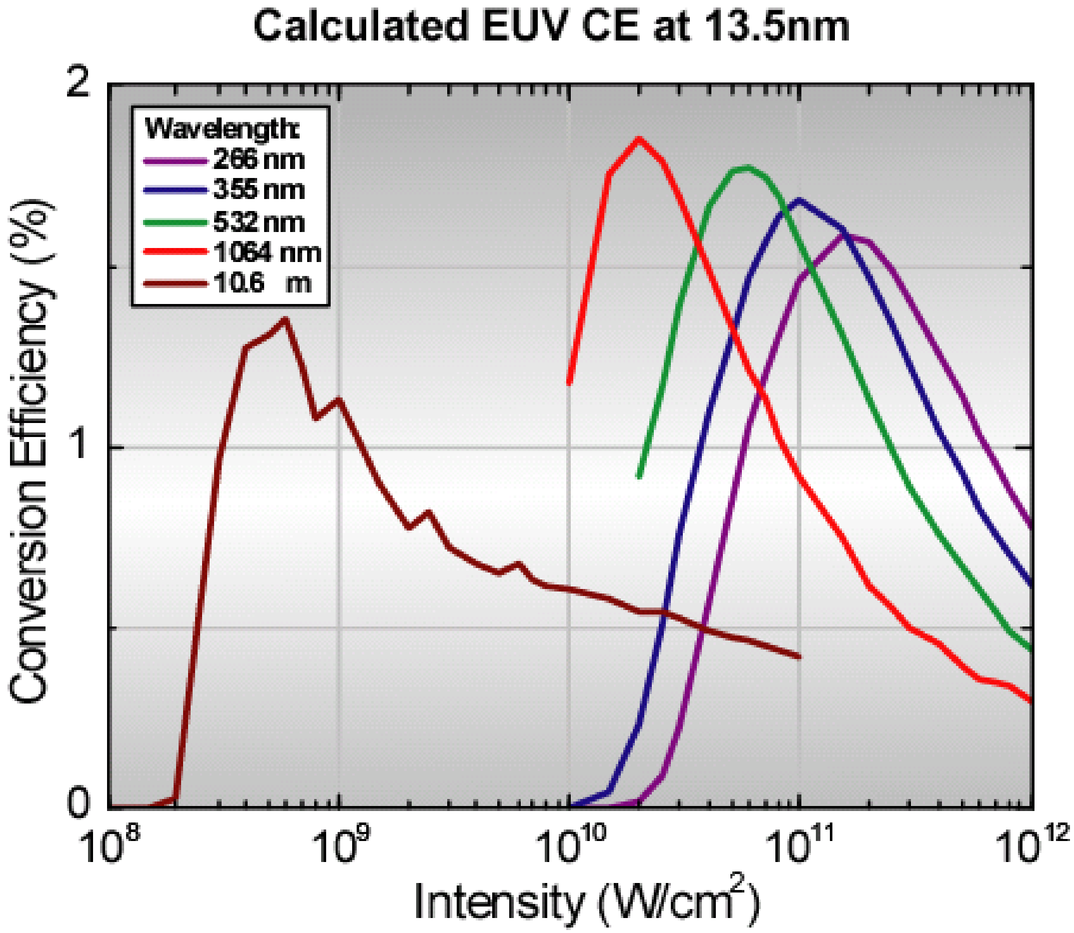
- For given wavelength and intensity, the conversion efficiency (2π Sr) to 13.5 nm (2%) is calculated from rad-hydro calculations.
- Experimentally measured CE for planar targets and two laser wavelengths are shown, respectively.
- Difference in threshold intensity can be partially attributed to non-uniform beam profile and non-flat-top time dependence.



CYMER

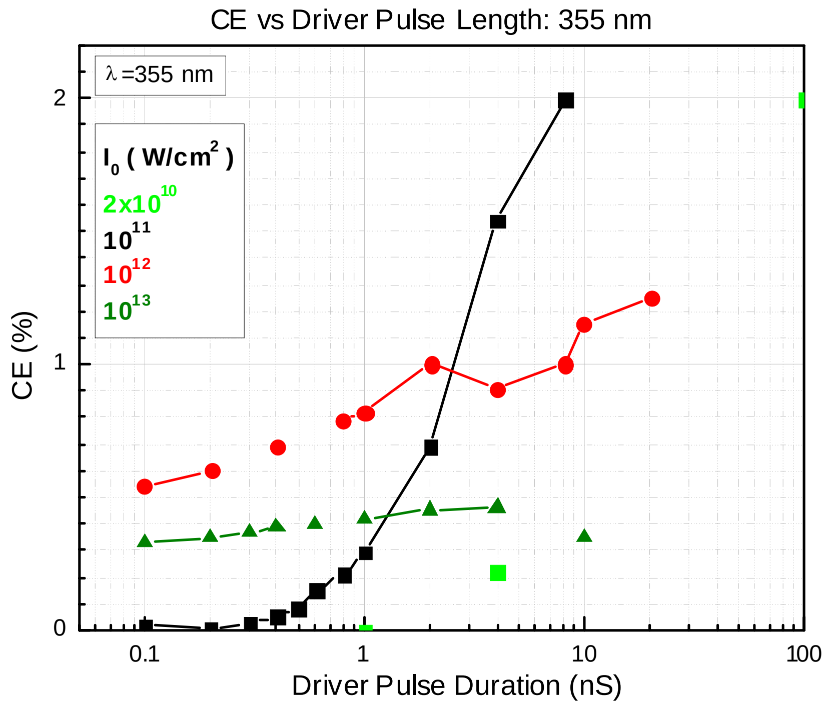
Wavelength Dependence of Conversion Efficiency

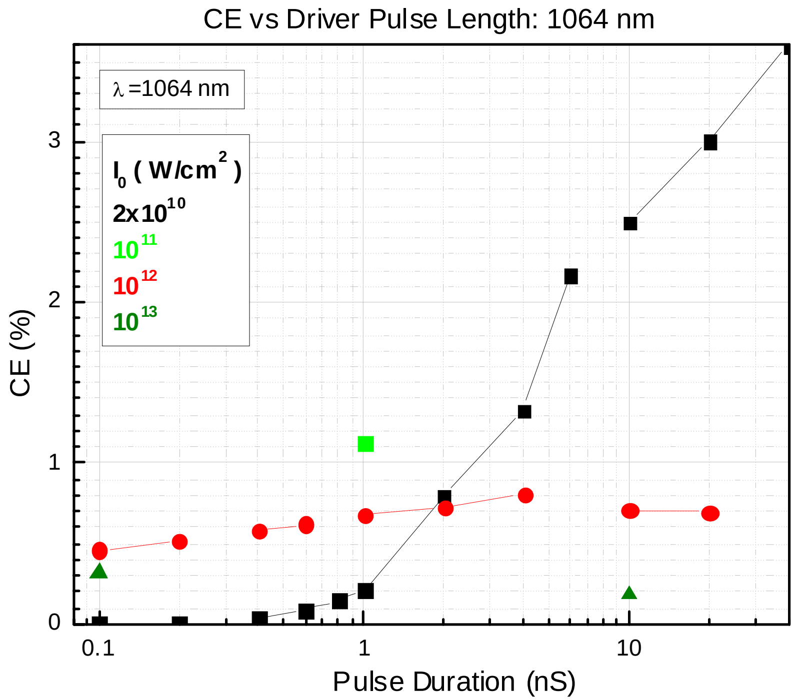
- Fairly weak dependence of optimum conversion efficiency on drive laser wavelength is predicted.
- At greater than optimum laser intensity, time for EUV emission increases.
- 1-D model implies perfectly uniform (in normal plane) laser beam profile.



Driver Pulse Length: CE Depends on Integrated Energy

- CE increases with pulse length when intensity is below optimum.
- With high intensity drive, target material is nearly completely ionized and CE is nearly independent of pulse length.
- For short pulse length, optimum intensity increases; CE is based approximately on pulse energy.





Conclusions and Ongoing Tasks

- For preliminary modelling of Li targets, reasonable quantitative agreement of Conversion Efficiency with experimental measurements is achieved.
- Scaling of experimental controls is also reasonable.

- Prism is currently engaged in
  - Evaluation of two-D illumination and expansion dynamics
  - Calculation of non-LTE radiation hydrodynamics and spectra.

- At Cymer, we are currently examining
  - Detailed experimental verifications.
  - Spherical illumination geometry
  - Other tamper materials
  - Convergent geometries

INSIST on CYMER™