Optimization of EUV Lithography Plasma Radiation Source Characteristics Using HELIOS-CR

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Introduction

- EUV Lithography requires bright, efficient radiation sources at wavelengths near 13.5 nm.

- Prism Computational Sciences has developed a suite of plasma simulation tools that are ideal for optimizing the radiation source characteristics of:
  - laser-produced plasmas
  - z-pinch plasmas

- These simulation tools:
  - simulate the dynamic evolution and spectral properties of radiating plasmas
  - utilize state-of-the-art atomic physics databases
  - are easy-to-use, with intuitive user interfaces and graphics for displaying results
  - can be easily used in batch mode for optimization studies
  - are tailored for making direct comparisons with experimental data

- These tools have been applied to the study of Lithium and Tin laser-produced plasmas, and show good agreement with published experimental data.

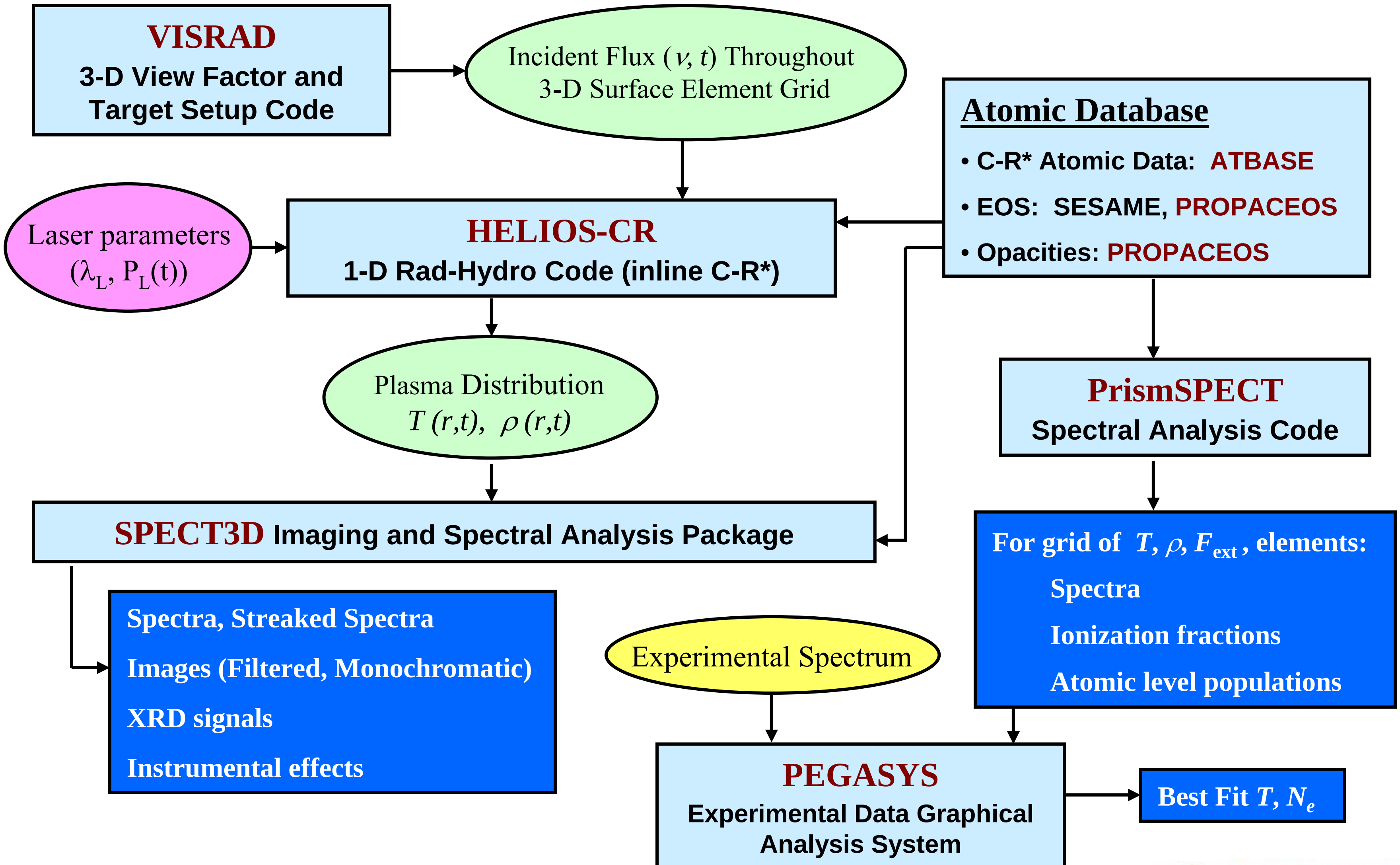
Optimization studies show 13.5 nm conversion efficiencies ~ 10% can be achieved for Tin LPPs.

Overview of Prism Simulation Tools

- Prism has developed a suite of codes that are being applied to the study of laser-produced and z-pinch plasmas. These include:
  - HELIOS: 1-D radiation-hydrodynamics code for simulating laser- and z-pinch plasmas.
  - HELIOS-CR: HELIOS with inline non-LTE atomic kinetics package.
  - PROPACEOS: Equation of state and multi-frequency opacity code.
  - ATBASE: A suite of atomic structure and collision cross-section codes.
  - SPECT3D: Code suite for computing spectra and images – based on 1-D, 2-D, or 3-D plasma distributions – that can be compared with experimental measurements.
  - PrismSPECT: Single-cell (0-D) ionization dynamics, spectral analysis package.
- In developing these codes, we have put a substantial emphasis on making them easy to use, both for setting up simulations and viewing results. These codes are well-suited for:
  - commercial and government laboratory research and development
  - graduate and undergraduate student research and education
- These codes are currently being used at:
  - Major U.S. laboratories (Sandia NL, LANL, U. Rochester Laboratory for Laser Energetics, …)
  - Universities (Princeton, MIT, Michigan, Illinois, Wisconsin, UCSD, Ecole Polytechnic, …)
  - Corporations (Siemens, Starfire, Cymer, …)
- We are applying these well-tested codes in the study of EUVL radiation sources (Li and Sn LPPs).

PRISM Code Suite for Simulating Plasma Physics Experiments

HELIOS, SPECT3D, VISRAD, PrismSPECT, ATBASE, PROPACEOS, PEGASYS



* C-R = Non-LTE Collisional-Radiative Modeling

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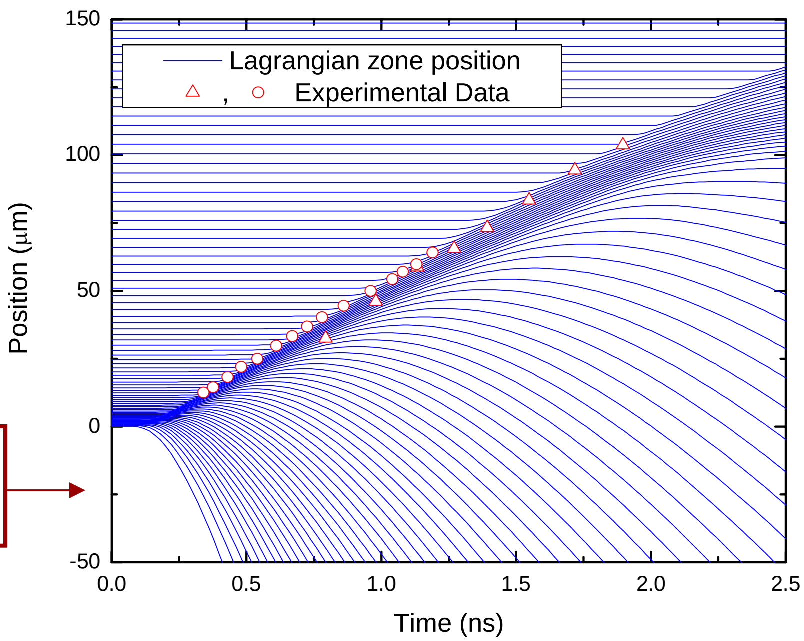
PRISM Codes Are Benchmarked Against Experimental Data and Analytic Models

- A critical step in scientific software development is the testing and benchmarking of simulation codes by comparing with experimental data.
- Prism is involved in state-of-the-art experiments at major U.S. gov't labs, and performs extensive benchmarking and testing of its plasma simulation and atomic physics codes.

Example – HELIOS-CR simulation of Al foil irradiated with thermal radiation in LLNL experiment:

- Radiation drive provided by experimental data
- 180 µm-thick Al foil
- 2 ns flat-topped laser pulse
- Material properties:
  - PROPACEOS opacities
  - SESAME EOS
- Radiation transported using 100-group diffusion.

Shock trajectory in Al foil agrees well with shock breakout experimental measurements.*

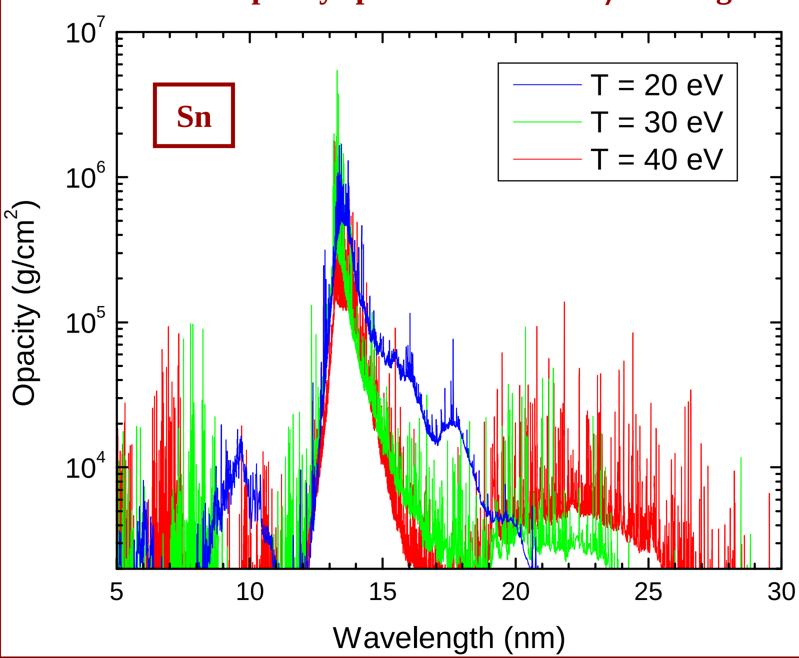


* R. E. Olson *et al.*, Phys. Plasmas **4**, 1818 (1997).

Calculation of Tin Radiative Properties Requires Detailed Modeling of Complex Atomic Systems

- The primary emission feature at 13.5 nm arises from 4p-4d and 4d-4f transitions.
- In computing Sn atomic data, we have included:
  - relativistic and configuration interaction (CI) effects.
  - ~ 10^5 - 10^6 fine structure energy levels.
  - ~ 10^7 calculated oscillator strengths.
- Data is computed for all ions of Sn. To date, greater emphasis has been placed on ions Sn^{6+} - Sn^{20+}.
- In our atomic model, all doubly-excited configurations of the type $4p^k\,4d^n\,4f^m$ are included.

Calculated opacity spectrum for Sn at $\rho = 10^{-3}$ g/cm^3.



- CI effects are important for both low-lying states and more highly excited states.
- Including CI effects results in the dominant transitions being more tightly clumped around 13.5 nm.

Evaluation of accuracy of atomic, radiative, and hydrodynamic models requires detailed comparison with experimental measurements.

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Major Features of Atomic Physics Models ***(ATBASE)***

- The ATBASE suite of atomic physics codes is used to generate high-quality atomic data for simulating plasma radiative properties over a wide range of conditions.
- It utilizes several atomic structure and modeling codes, including Hartree-Fock, Dirac-Fock, configuration interaction, and distorted wave codes.
- ATBASE generates a comprehensive set of atomic data for all ions of any atomic element.
- The ATBASE database has been used extensively to analyze spectra (UV/EUV/X-ray) from a wide variety of plasmas, including: laser-produced plasmas, z-pinch plasmas, and astrophysical plasmas.

- Models include:
  - Atomic energy levels and oscillator strengths
    - Computed using Hartree-Fock, Dirac-Fock and configuration interaction (CI) models. When available, experimentally-based energy levels and radiative data are utilized.
  - Photoionization cross-sections
    - Cross-sections from Hartree-Fock calculations are utilized for both valence-shell and inner-shell transitions. Radiative recombination rate coefficients are calculated from the photoionization cross-sections.
  - Electron collisional excitation and ionization cross-sections
    - Distorted-wave (DW) calculations are performed to generate cross-sections and rate coefficients.
  - Autoionization rates
    - Configuration interaction (CI) calculations are performed to generate autoionization rates.
  - Dielectronic recombination (DR) rate coefficients
    - For DR related to K- and L-shell spectra, electron capture rates are computed using autoionization rates and the detailed balance relationship. For lower ionization stages, total DR rate coefficients are based on semi-empirical models.

Major Features of HELIOS Radiation-Hydrodynamics Code

- 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 and multi-angle models.
- Supported EOS and opacity models:
    - SESAME EOS
    - PROPACEOS multigroup opacities and EOS
    - Ideal gas EOS
    - Non-LTE inline collisional-radiative modeling (HELIOS-CR).
- External energy source models:
    - laser energy deposition
    - discharge current
    - external radiation field
- HELIOS integrates well with:
    - SPECT3D: generates spectra and images using hydro $T(r,t)$, $\rho(r,t)$ for comparison w/ expt.
    - HydroPLOT: for visualizing results from HELIOS simulations.
- It is designed to be easy to use:
    - setup via graphical user interface
    - on-line documentation.
    - automated zoner
    - graphical progress monitor.

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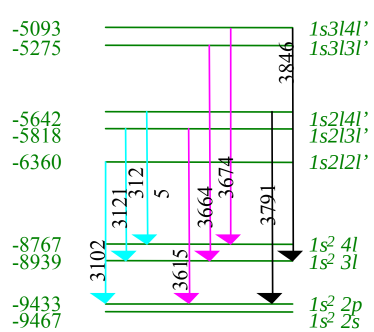
HELIOS-CR is HELIOS with Inline Collisional-Radiative Modeling

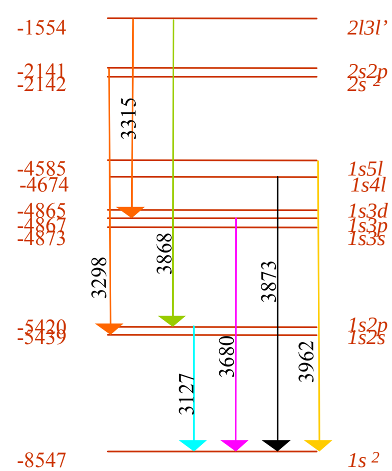
- At each time step in the HELIOS-CR rad-hydro simulation, non-LTE atomic level populations are updated by solving time-dependent atomic rate equations.
- Radiation transport options in C-R mode:
  - flux-limited diffusion (sph/cyl/planar) or MA short characteristics (planar);
  - frequency grid resolves bound-bound transitions and bound-free edges;
  - effects of external radiation fields are included.
- Atomic processes included in computing non-LTE level populations:
  - collisional ionization, recombination, excitation, and deexcitation;
  - spontaneous emission; radiative recombination;
  - autoionization, electron capture;
  - dielectronic recombination;
  - photoionization and photoexcitation.

HELIOS-CR utilizes physics/numerical algorithms contained in our SPECT3D spectral analysis code.

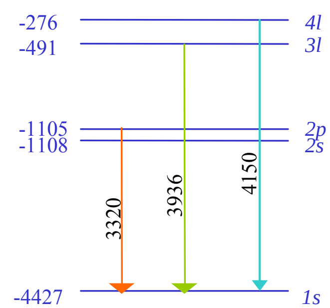
Example:
Argon K-shell
atomic energy levels.



Li



He



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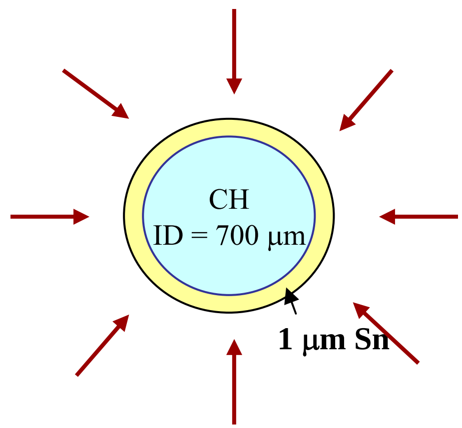
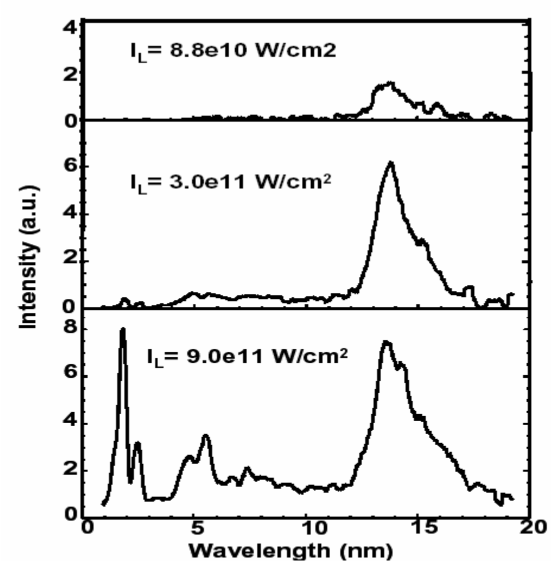
Simulation of GEKKO Experiments Provide Good Benchmark for HELIOS and Tin Atomic Database

To test HELIOS ability to simulate Sn LPP experiments, we have compared results with measurements obtained in GEKKO XII experiments (Fujima *et al.* 2004*).





Spectra from Fujima *et al.* (2004)

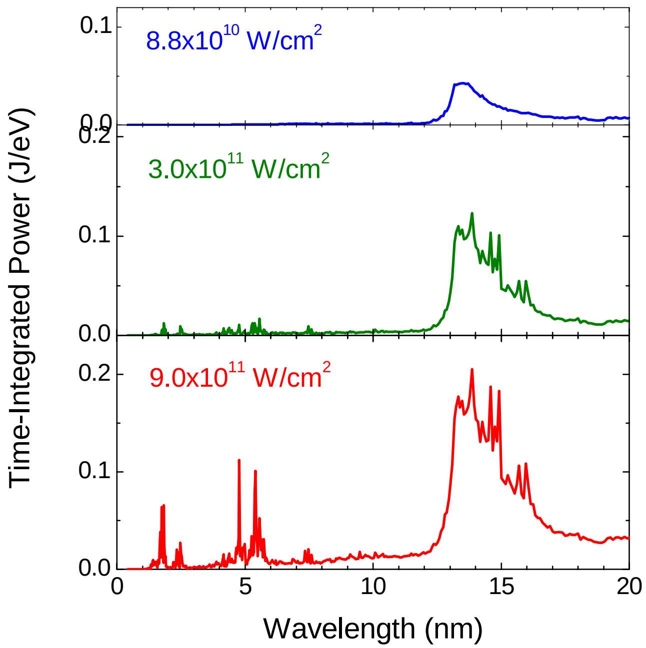
HELIOS parameters:

- 700 μm-diameter CH sphere, coated with 1 μm of Tin
- PROPACEOS multigroup opacities for CH and Sn
- SESAME equations of state
- 400 radiation frequency groups
- Gaussian laser pulse, with 1.2 ns FWHM
- Laser wavelength = 1.06 μm
- Peak laser power varied: 0.09, 0.3, and 0.9 TW/cm^2

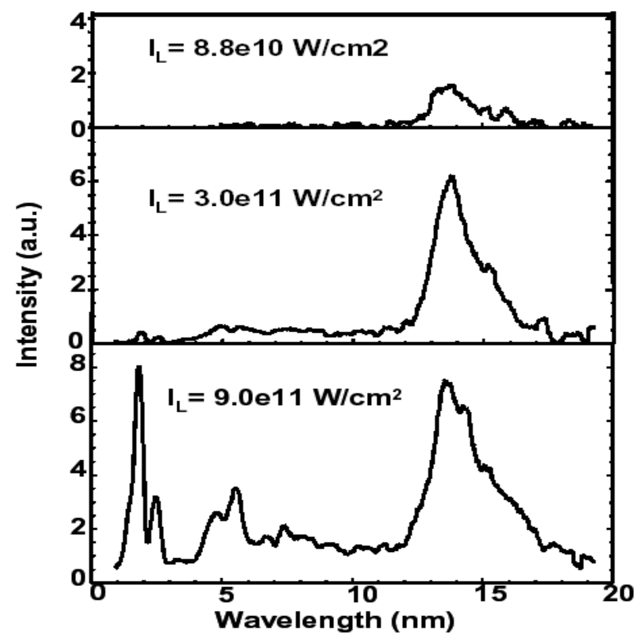
*From Fujima et al., Emerging Lithographic Technologies, Proceeding of SPIE, Vol. 5374, p. 405 (2004).

Simulated LPP Tin Spectra Agree Well With Experimental Spectra

Simulation



Experiment (Fujima *et al.* 2004)



- Simulated time-integrated spectra are in good agreement with experimental spectra.
- Calculated 13.5 nm conversion efficiencies (2.2 - 3.4%) are consistent with estimates reported by Fujima *et al.* (2004).

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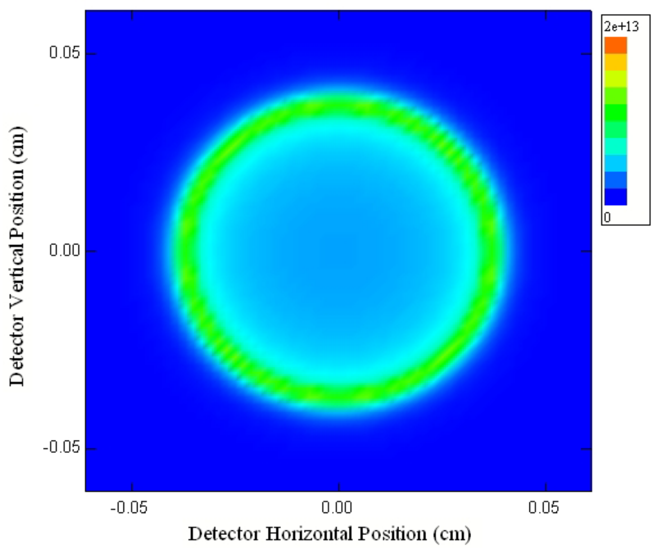
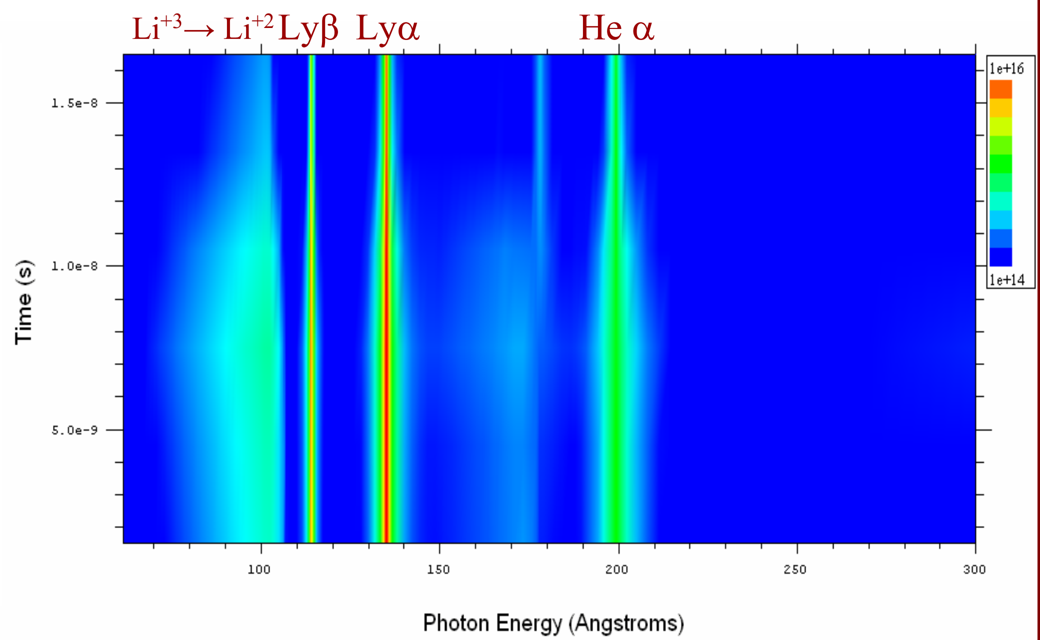
SPECT3D is Used to Post-process ***HELIOS*** Output [$T(r,t)$, $\rho(r,t)$] to Generate Simulated Spectra and Images for Comparison with Experiment

Simulated Framing Camera Image for GEKKO Tin experiment ($t = t_{Peak}$)



Significant limb brightening is observed.

Example of Simulated Streaked Spectrum for Lithium Laser-Produced Plasma



- Ly α, Ly β, and He α exhibit strong emission.
- Lines narrow at late time due to falling density.
- Continuum recombination edge is clear in this (log intensity) plot.

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Example Simulation Tool: ***PrismSPECT*** Spectral Analysis Code

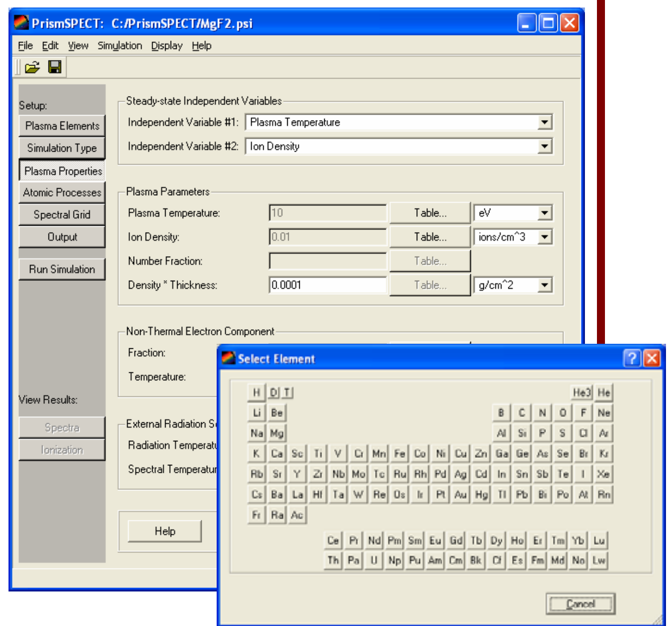
- PrismSPECT is a collisional-radiative spectral analysis code designed to simulate the atomic and radiative properties of laboratory and astrophysical plasmas.

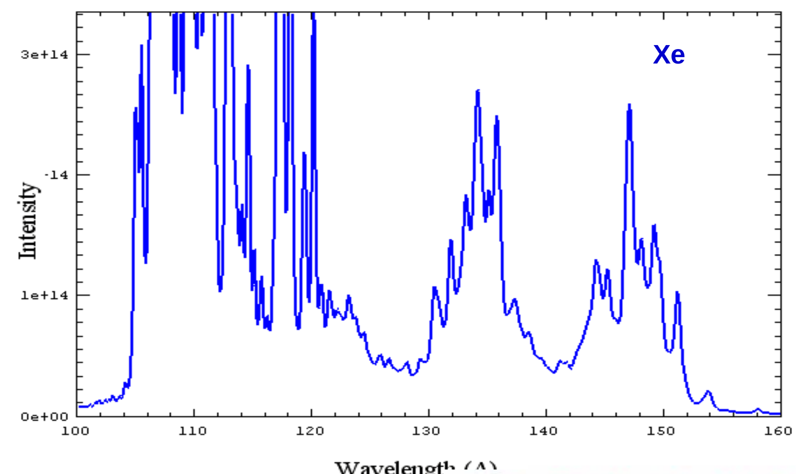
- For a grid of user-specified plasma conditions, PrismSPECT computes spectral properties (emission and absorption) and ionization properties for LTE and non-LTE plasmas.

- It is designed to be very easy to use. It includes
  - graphical user interfaces for simulation setup
  - on-line documentation
  - graphics package for viewing results

- PrismSPECT can model plasmas with:
  - time-dependent ionization distributions
  - non-Maxwellian electron distributions
  - external radiation sources
  - backlighters (for absorption spectroscopy)

- PrismSPECT utilizes ***ATBASE*** atomic data (collisional and radiative x-sections).
  While we generally distribute PrismSPECT with atomic data for ***Z*** = 1 – 18, our codes are capable of simulating both high-Z and low-Z plasmas.





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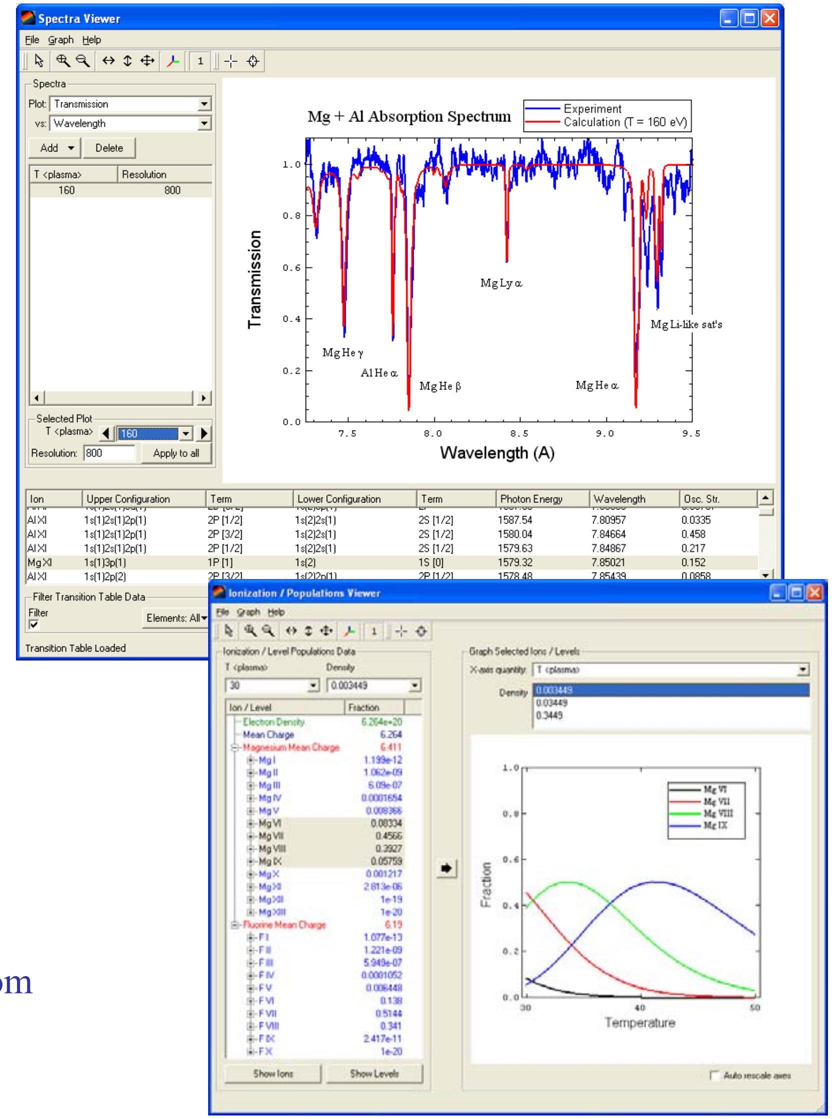
Example Application: PrismSPECT Spectral Analysis Code

- PrismSPECT computes plasma properties over a 2-D grid of independent variables (any 2 of the following):
  - Temperature
  - Density
  - Plasma Size
  - External radiation field
  - Non-Maxwellian electron distribution parameters

- PrismSPECT displays results for:
  - Emission spectra
  - Transmission spectra
  - Opacity / optical depth
  - Ionization fractions
  - Atomic level populations
  - Line powers and intensity ratios

- PrismSPECT interfaces with other Prism applications:
  - •*AtomicModelBuilder*: for generating custom atomic models (levels, level splitting)
  - •*PrismPLOT* graphics library



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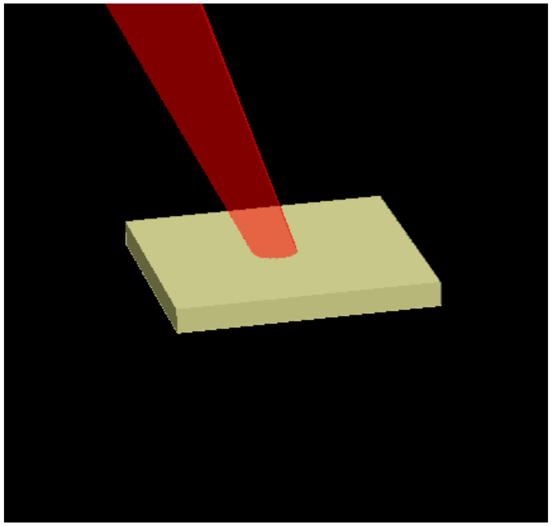
HELIOS Simulations of Tin Laser-Produced Plasmas



HELIOS LPP simulation setup:

- Planar Sn foil
- PROPACEOS multigroup opacities
  (from atomic models with ~ 10^7 transitions)
- SESAME equations of state
- Radiation modeling: multi-angle transport at 200 frequencies
- Laser wavelength: 10.6 µm, 1.0 µm, and 0.35 µm series
- "Square" laser pulse, with 0.1 ns ramp up and ramp down
- Duration of peak laser power: varied from 0.1 to 1000 ns
- Peak laser intensity: varied from 10^9 to 10^{12} W/cm^2

Questions addressed:

- What are the temperatures created in laser-produced plasmas?
- What is the ionization distribution?
- What physical processes affect the 13.5 nm band emission?
- At what depth is the laser energy deposited?
- What are the plasma conditions at the location where the escaping 13.5 nm photons originate?
- How does the 13.5 nm conversion efficiency vary with λ_L, P_L and Δt_L?

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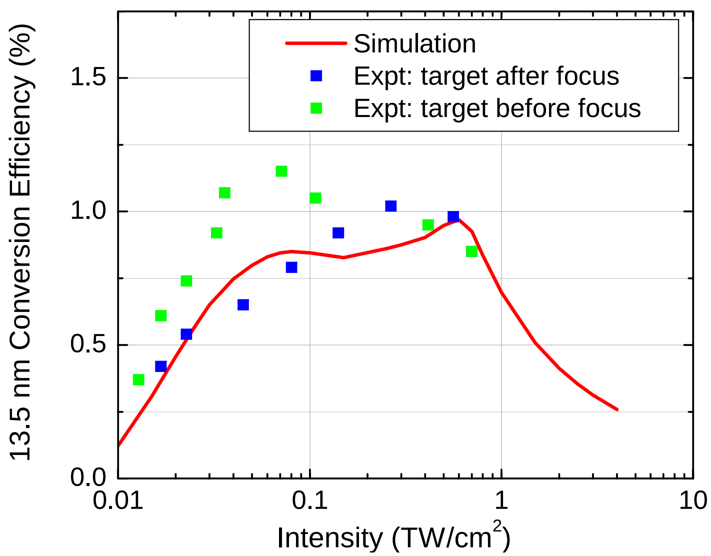
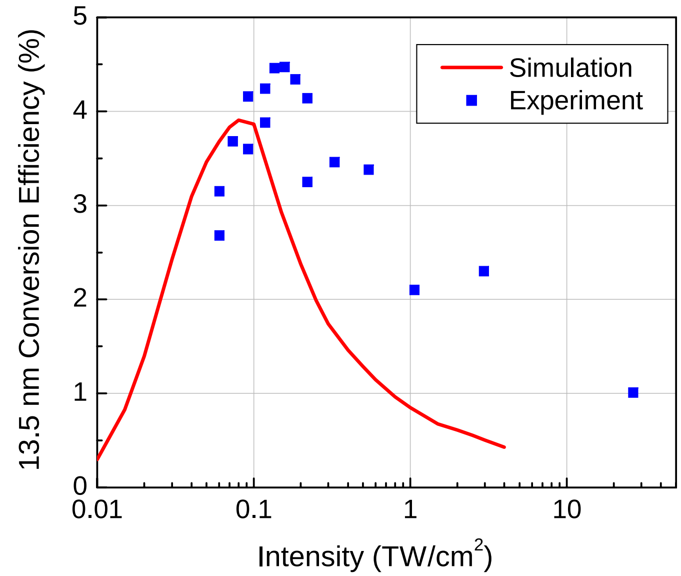
Comparison of Calculated and Experimental 13.5 nm Conversion Efficiencies

λ = 0.355 µm, pulse width = 10 ns
Sn planar foils



λ = 1.06 µm, pulse width = 1 ns
Sn planar foils



In the λ = 1.06 µm series, the simulated CEs decrease more rapidly than experiment at $I_L \gtrsim 0.2$ TW/cm². In this regime, $\langle Z \rangle_{LTE} \gtrsim 20$ (where our atomic model is less detailed).

HELIOS conversion efficiencies are in good general agreement with experimental measurements for both Tin* and Lithium targets.**

* Tin comparisons presented in J. J. MacFarlane, *et al.*, Emerging Lithographic Technologies IX, SPIE, p. 588 (2005).
** Lithium results presented at EUVL Source Modeling Workshop, C. L. Rettig, *et al.*, Miyazaki, Japan (2004).

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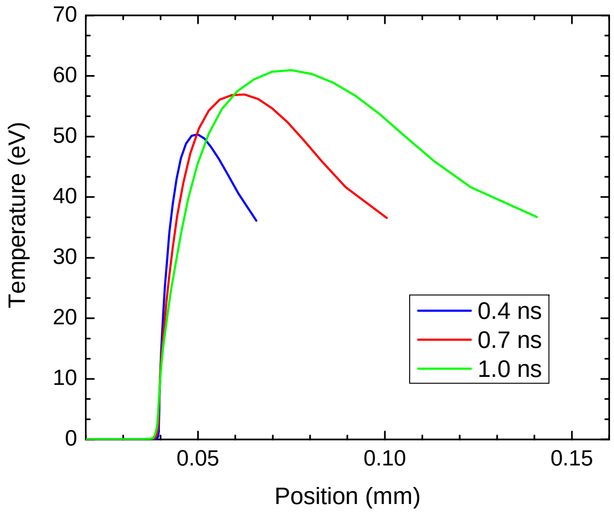
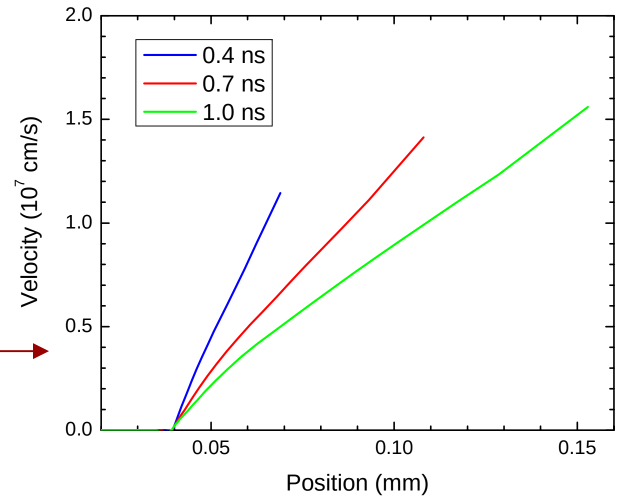
HELIOS Results for Spatial Dependence of Plasma Conditions (Sn foil)

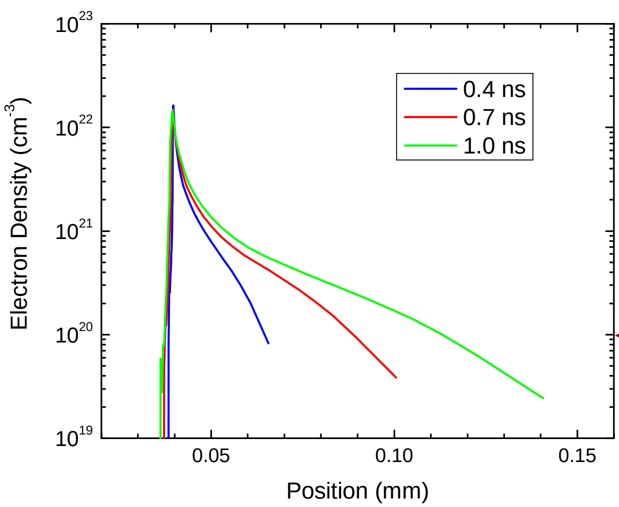
$\lambda_L = 0.355\ \mu m$, $P_L = 0.32\ TW/cm^2$, $\Delta t = 1$ ns



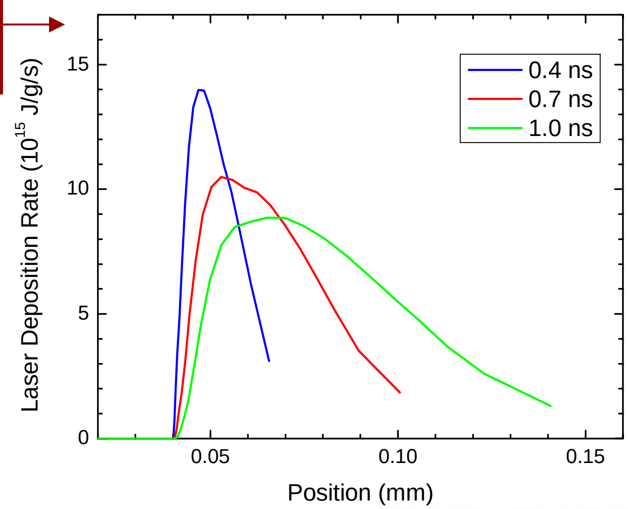
In ablation region, $T \sim 40 - 60$ eV.



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



Laser energy is deposited in ablation plasma.



$N_e \sim 10^{20}$ - 10^{21} cm^{-3} where bulk of laser energy is deposited.

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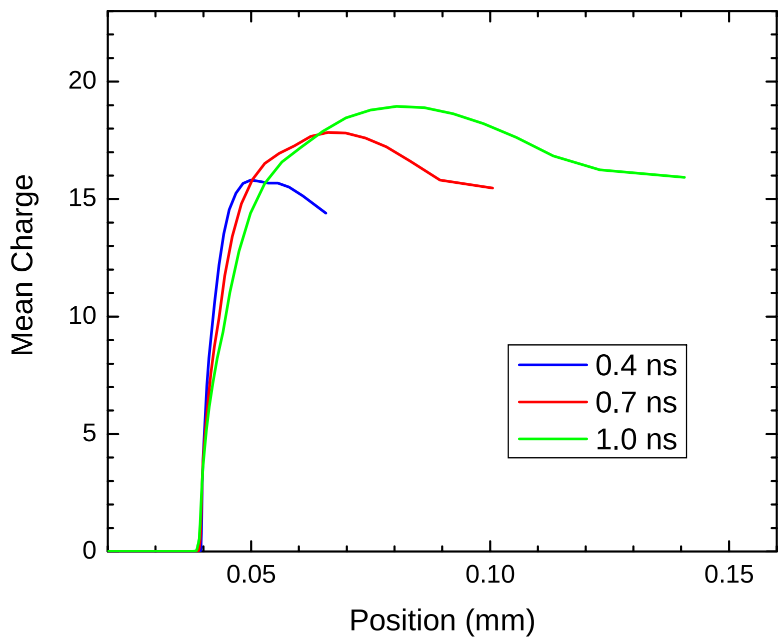
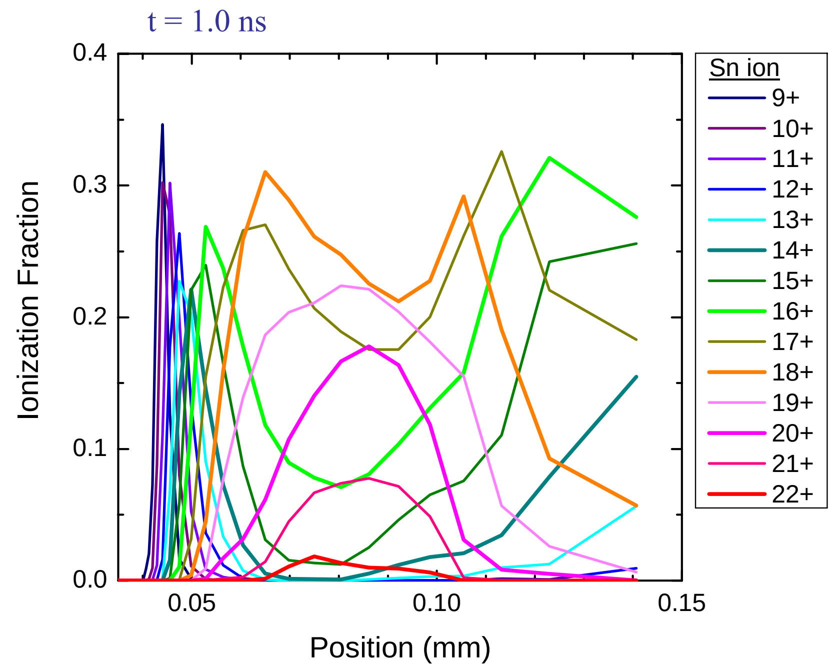
HELIOS Results for Spatial Dependence of Sn Ionization Distribution

$\lambda_L = 0.355\ \mu m$, $P_L = 0.32\ TW/cm^2$, $\Delta t = 1$ ns





- Near the end of the laser pulse, <Z> reaches ~ 19.
- In region where laser energy is deposited, ionization ranges from ~ 14+ to 21+.

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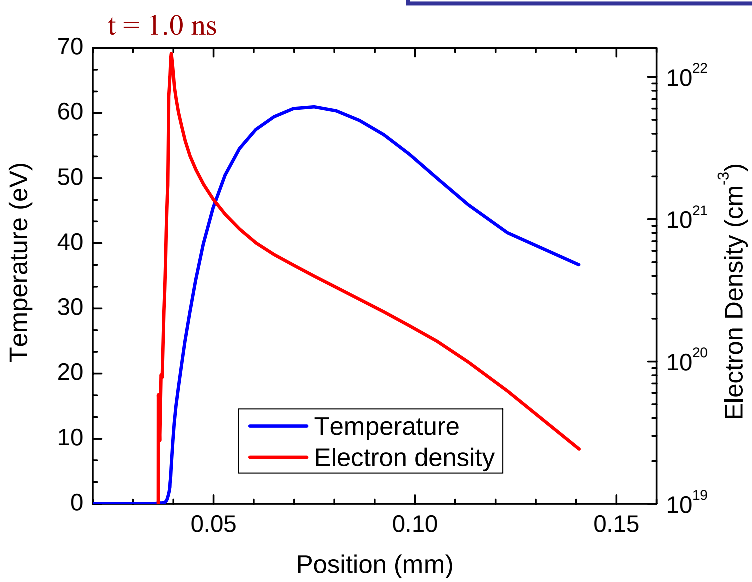
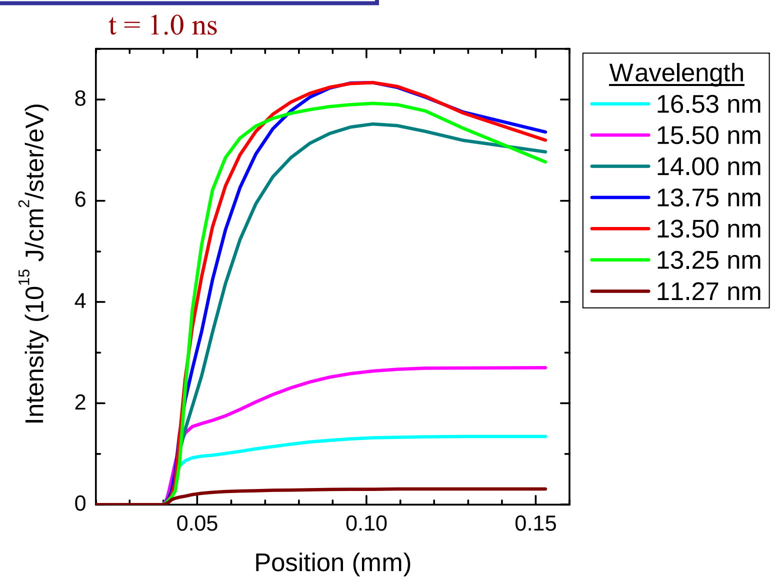
"Drilldown" Capability in **SPECT3D** Shows Where Photons Originate

$\lambda_L = 0.355$ µm, $P_L = 0.32$ TW/cm^2, $\Delta t = 1$ ns
(Laser incident from right. Detector at right.)





- Drilldown plots show that peak specific intensities occur at $r \sim 0.1$ mm ($T \sim 50$ eV, $N_e \sim 1\text{x}10^{20}$ cm^{-3})
- Optical depth ~ 1 for $\lambda = 13.5$ nm photons is reached at $r \sim 0.06$ mm.
- Some of the 13.5 nm radiation is reabsorbed in outer cooler region before escaping the plasma.

Drilldown capability provides insights into key physics in simulations and experiments
=> Insights on how to optimize plasma radiation characteristics

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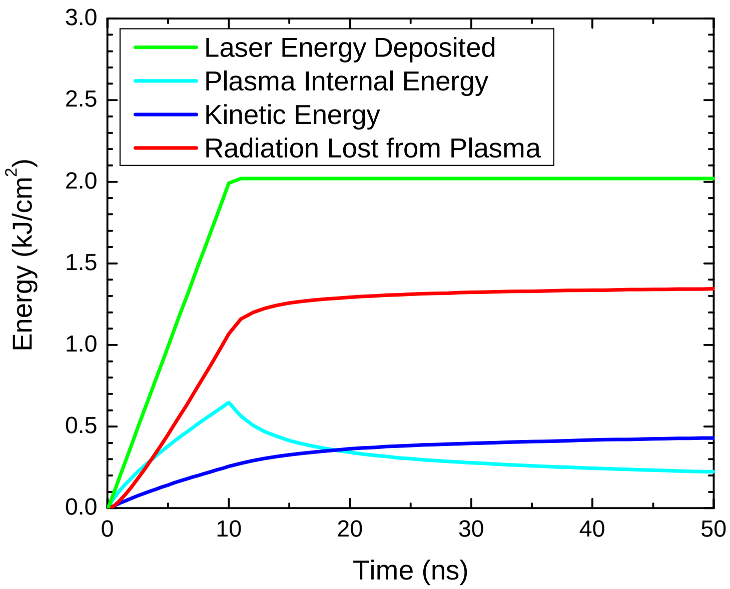
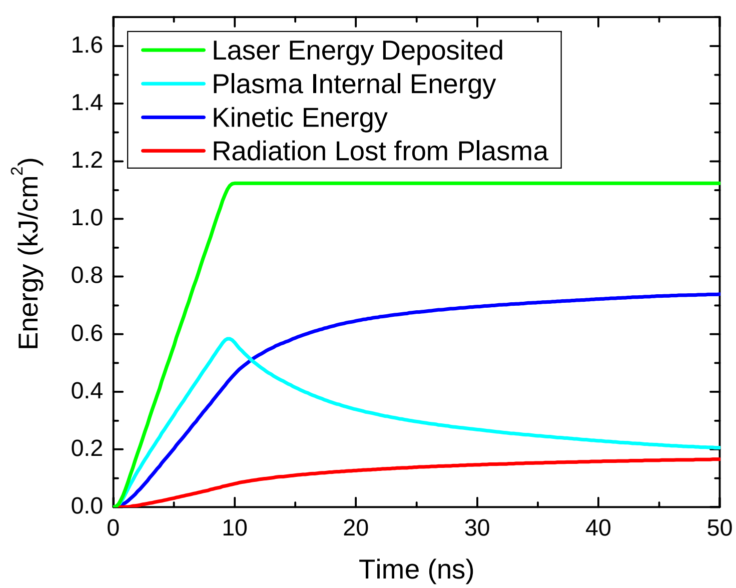
Comparison of HELIOS Energy Partitioning for Tin vs. Lithium

Planar Tin Calculation
0.355 µm, 0.2 TW/cm^2, 10 ns



Planar Lithium Calculation
0.355 µm, 0.125 TW/cm^2, 10 ns



For Lithium, of energy input by laser beam, by 50 nsec:

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

For Tin, the fraction of energy radiated away is significantly higher:

- ~ 21% is in fluid kinetic energy
- ~ 66% is radiated away from Tin plasma

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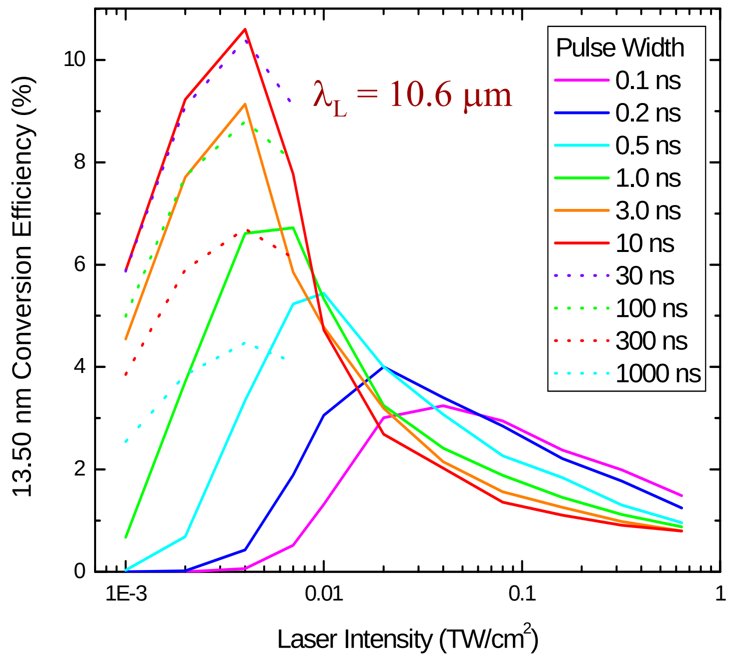
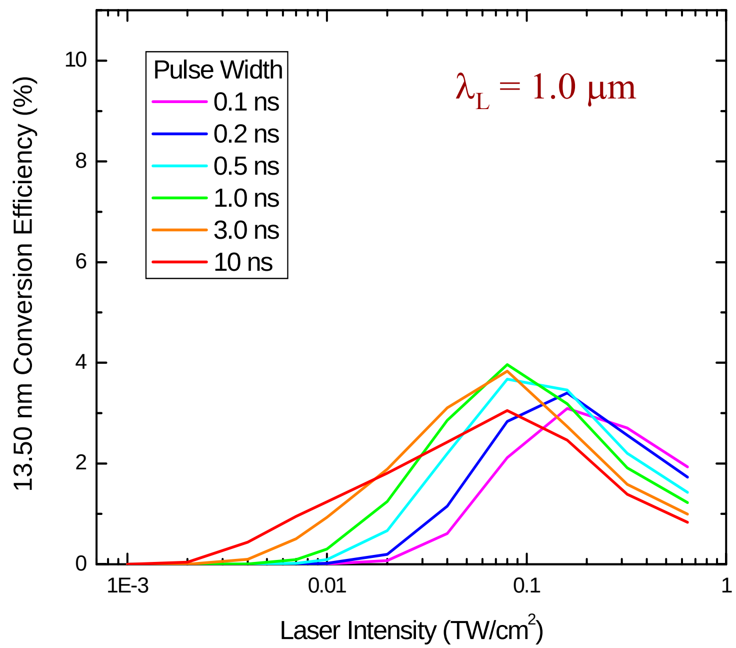
HELIOS Simulations of Tin LPPs Show High 13.5 nm Conversion Efficiencies (CEs) for 10.6 μm Lasers





Significantly higher 13.5 nm CEs (~10%) occur for λ_L = 10.6 μm laser beams.

This occurs at low laser powers (~ 4 x 10^9 W/cm^2), and is due to short laser penetration depths.

Utilizing an accurate atomic database is critical for predicting CEs in the 13.5 nm band (2% Gaussian FWHM).

It may be possible to further enhance the 13.5 nm CE using shaped laser pulses or different target geometries

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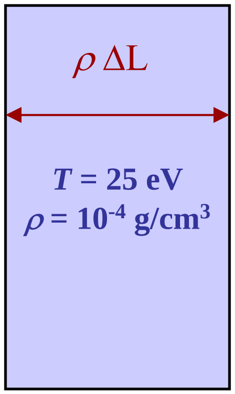
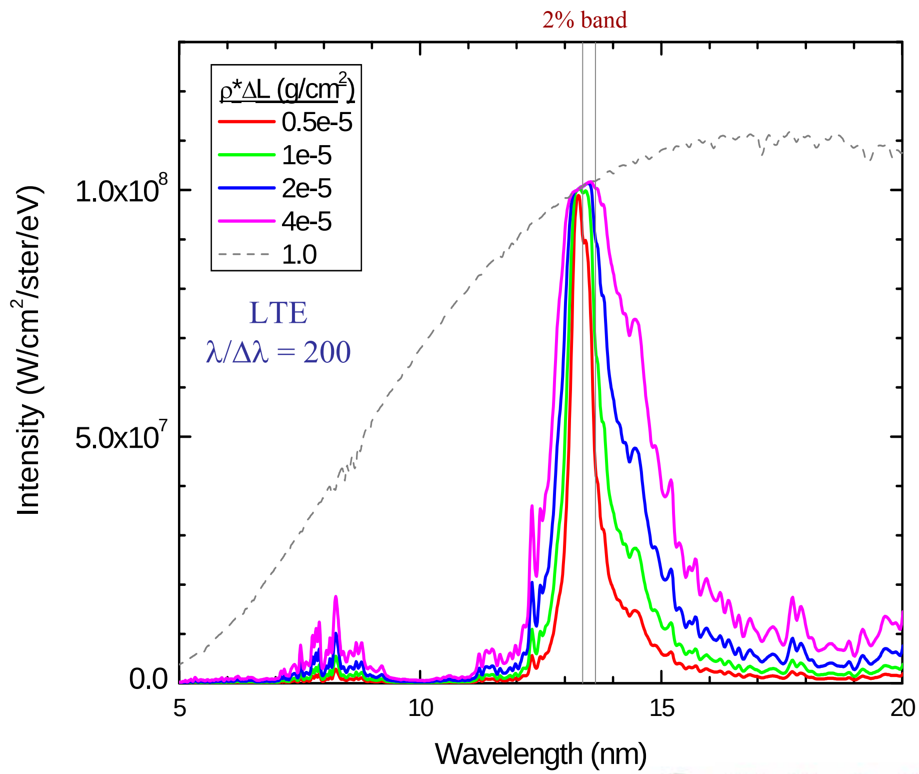
As Thickness of Hot Emitting Region of Tin Plasma Increases, More Out-of-Band Radiation is Produced



To assess effect of thickness of radiation layer on spectral emission, we performed **PrismSPECT** calculations for simple planar plasmas.

- Even for very thin plasmas, the intensity at 13.5 nm approaches blackbody limit.
- As plasma thickness increases, width of 13.5 nm feature increases, but additional radiation is emitted outside of 13.5 nm 2% band.



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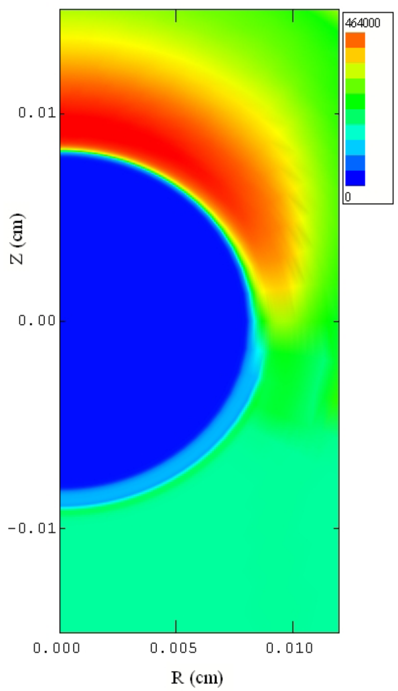
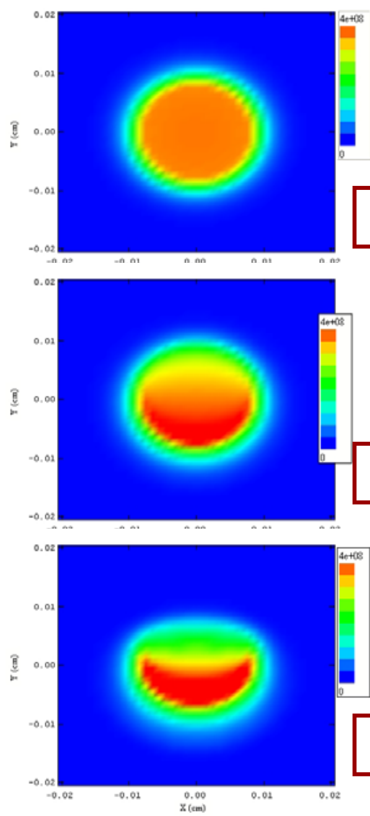
We Have Performed 2-D Radiation-Hydrodynamics Simulations To Investigate Angular Dependence of Radiation Emitted by Laser-Produced Plasmas

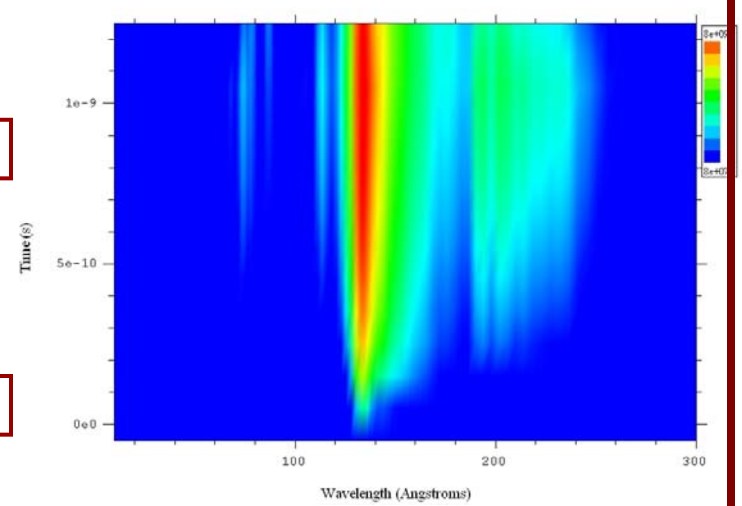
Example simulation: 160 µm-diameter Sn sphere illuminated on one side by a λ_L = 1.06 µm, P_L = 0.1 TW/cm^2, 1 ns laser pulse with 200 µm-diameter spot size.



Rad-hydro $T(r,z)$ at t = 1.0 ns



Framing camera images at t = 1.0 ns



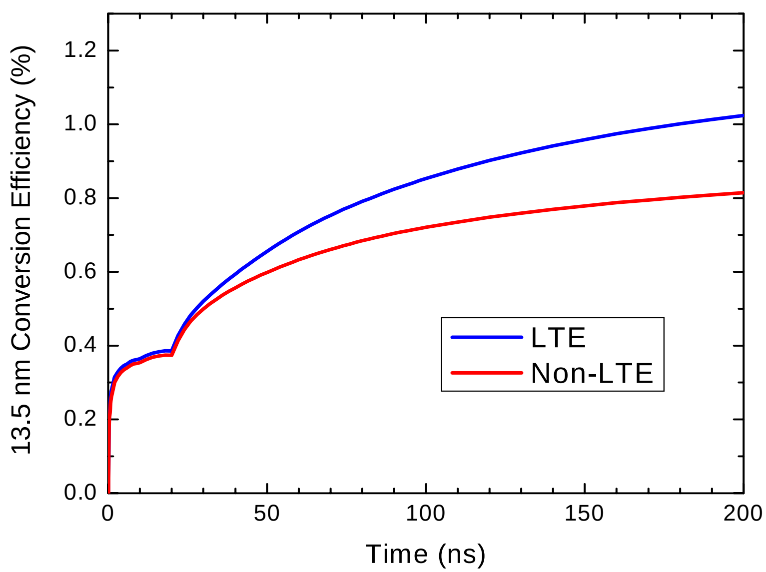
Streaked spectrum at θ_{Det} = 22 deg

Images and spectra generated by post-processing 2-D rad-hydro simulations with SPECT3D.

PRISM Computational Sciences, Inc.

Using HELIOS-CR, Non-LTE Atomic Rate Equations are Solved at Each Time Step in the Hydro Simulation

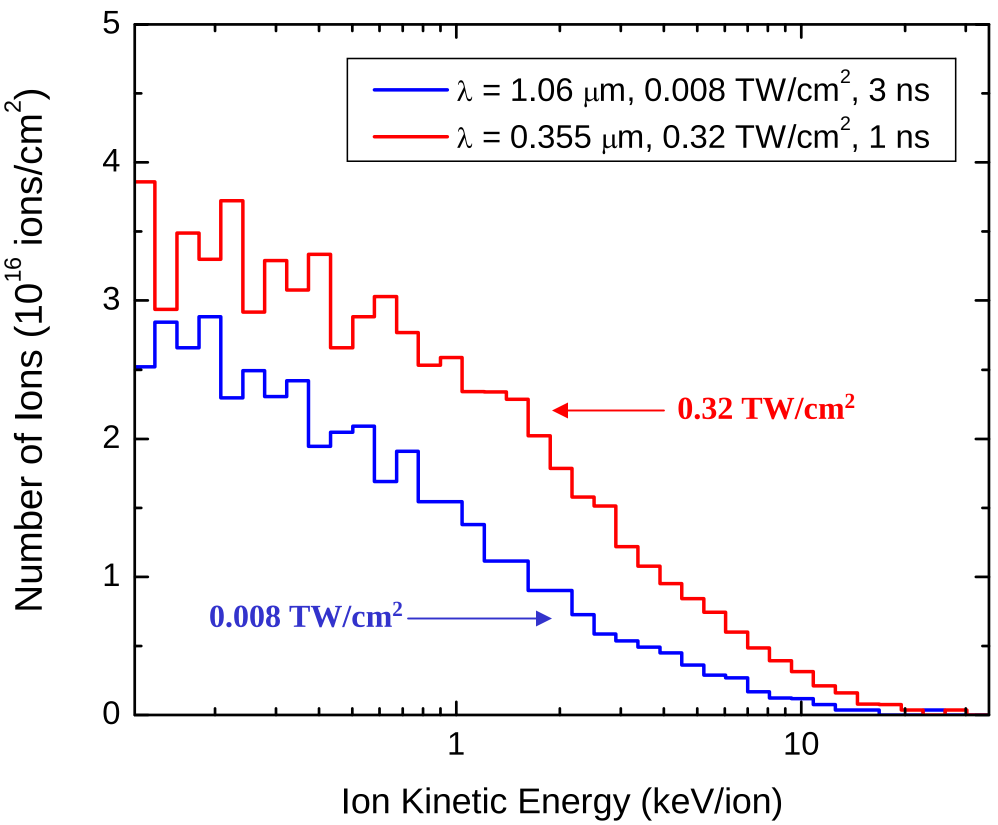
- Time-dependent ionization dynamics (including photoionization/photoexcitation rates) are computed inline for relatively simple atomic models ($\lesssim 10^3$ atomic levels).
- Example below shows time-dependent conversion efficiency (CE) for Lithium plasmas.



1.06 μm
0.1 TW/cm^2
20 ns

- Assumption of LTE tends to overestimate population of upper state of lithium Ly-α line.
- For calculations performed to date, deviations from LTE alter 13.5 nm CE by ~ 10 - 25%.

The Debris Ion Kinetic Energy Spectrum is Obtained from HELIOS Velocity Distributions at Late Times



This example shows more multi-keV Sn ions are produced in higher intensity case.

Summary

- Prism has developed a suite of well-tested, user-friendly simulation tools and atomic physics databases for studying plasma radiation sources. Our codes and data are being used at major commercial and government laboratories and universities in the U.S. and overseas.

- These simulation tools are being applied in the analysis of Lithium and Tin laser-produced plasma experimental data. Our codes are particularly well-suited for optimizing the EUV 13.5 nm band emission for different laser beam and target parameters.

- Simulated time-integrated spectra and 13.5 nm conversion efficiencies are in good agreement with data obtained in Lithium and Tin LPP experiments.

Our simulations suggest that for Tin targets irradiated by 10.6 μm laser beams, it may be possible to achieve very high 13.5 nm conversion efficiencies (~ 10%).

- In future work…
  - 2-D simulations are required to examine plume expansion effects, different target geometries, and the angular dependence of the 13.5 nm radiation into the collector optics.
  - Exploring the use of shaped laser pulses may lead to further enhancements in the 13.5 nm conversion efficiency.