The role of simulation on design and analysis of OMEGA experiments

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Contributors and collaborators

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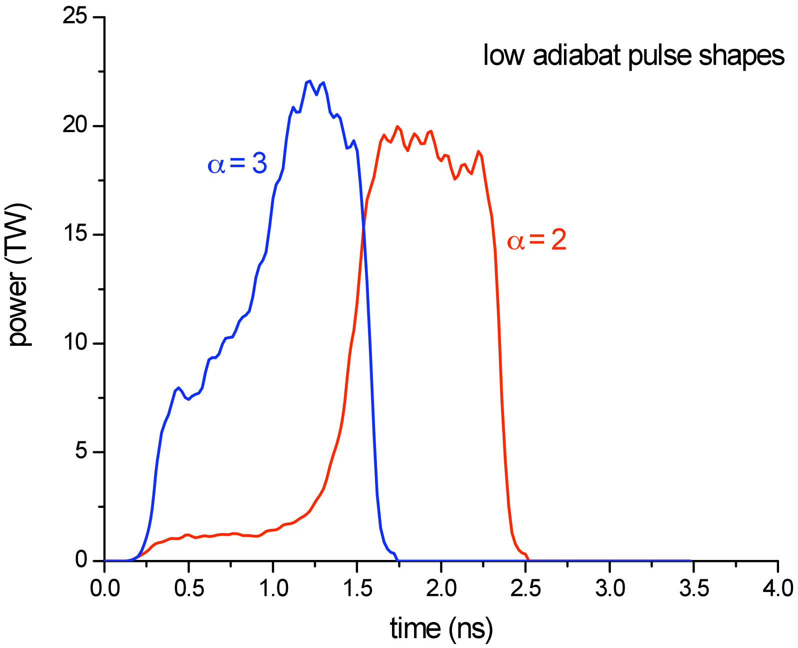
- R. Tommasini, N. Izumi, J. Koch, S. Glenzer (LLNL)
- J. Delettrez, F. Marshall, S. Regan, V. Smalyuk (LLE)
- R. Petrasso (MIT)
- P. Drake (UM)

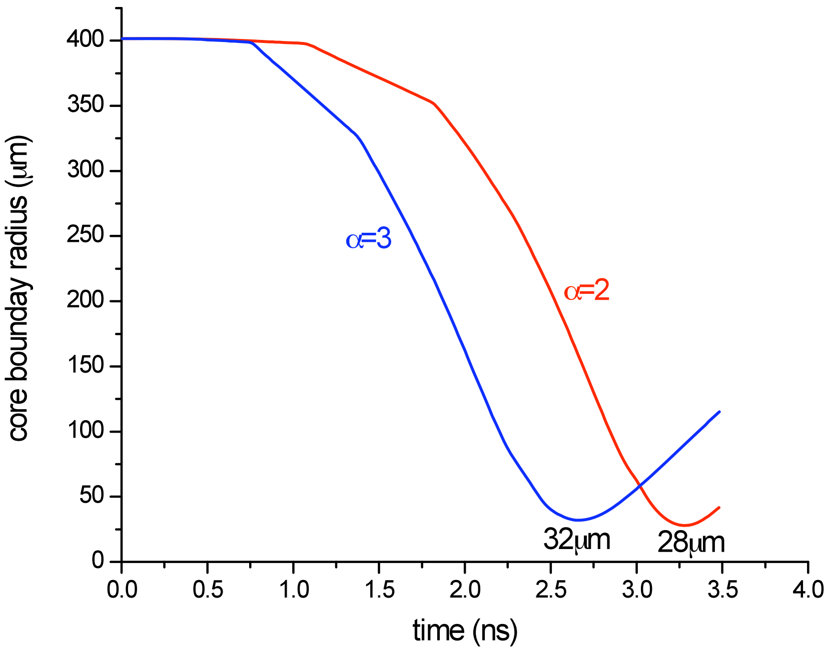
Outline

- Modeling and simulation plays a critical role in **both** the design and the data analysis of OMEGA experiments
- The scope of the science in OMEGA experiments is broad → so is the scope of theory/modeling and simulation methods employed
- Examples of modeling and simulation relevant for several OMEGA campaigns are used to illustrate these points
- These examples are drawn from a variety of cases involving:
  - hydrodynamics, and radiation-hydrodynamics,
  - atomic and radiation physics, and detailed spectra modeling,
  - x-ray emission and absorption spectroscopy,
  - generation and evolution of electric and magnetic fields,
  - x-ray Thomson scattering spectroscopy,
  - Compton scattering radiography,
  - PIC simulation of particle and atomic kinetics

LILAC 1D hydrodynamic simulations

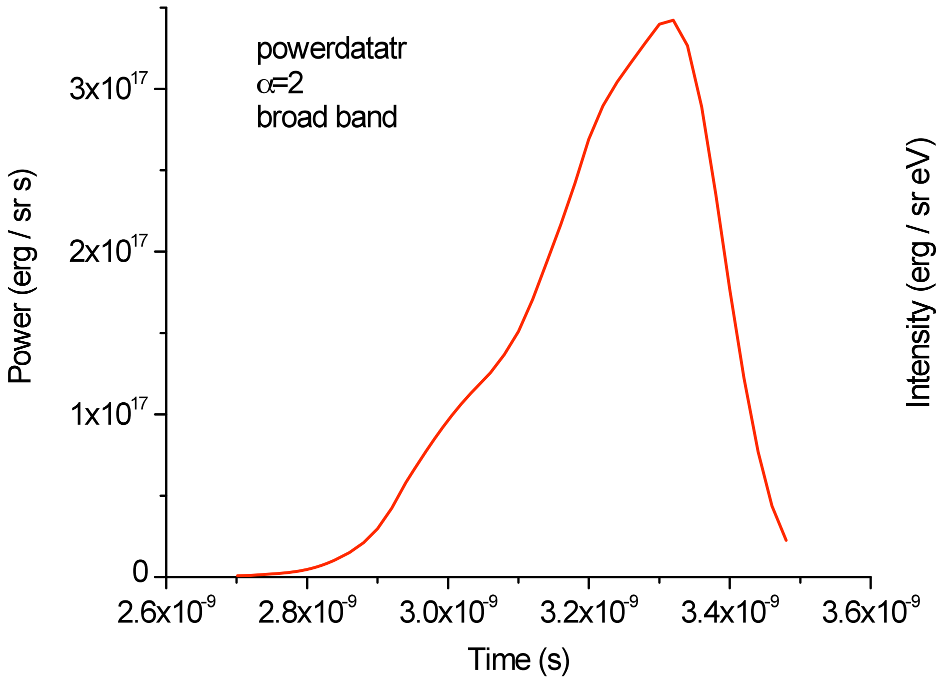
- LILAC 1D hydrodynamic simulations can provide the starting point for testing and modeling many OMEGA experiment ideas
- Lagrangian hydrodynamics, Te and Ti, realistic EOS, thermal transport, LTE or NLTE average-ion atomic and radiation physics, ray-tracing laser energy deposition, hot-electrons preheating, shock heating, particle yields
- Simulations can be done for testing and refining many experimental configurations, including OMEGA pulse shapes and target designs

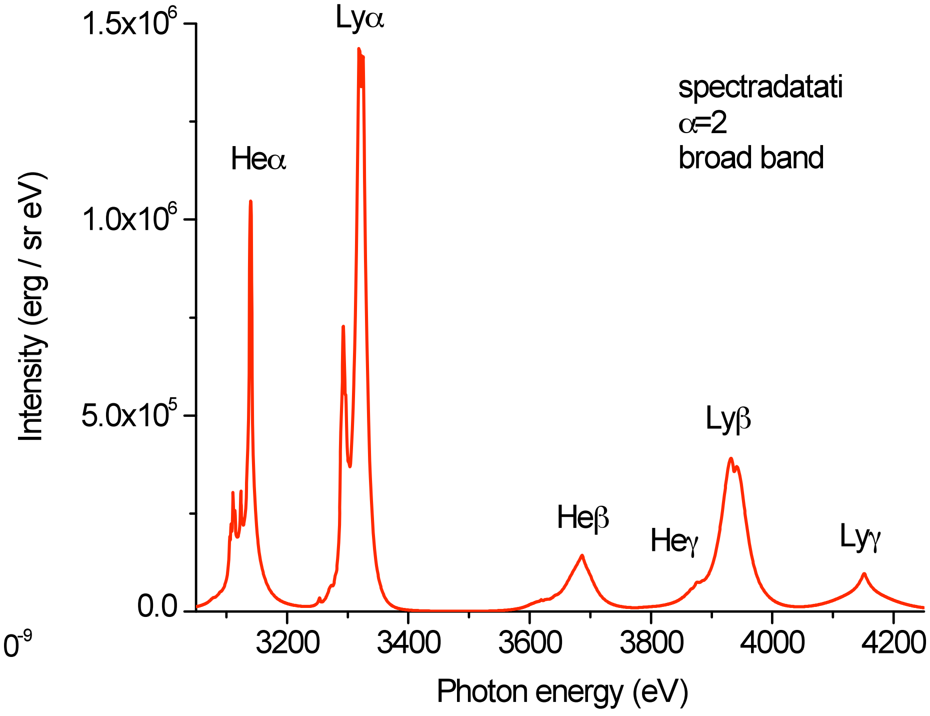




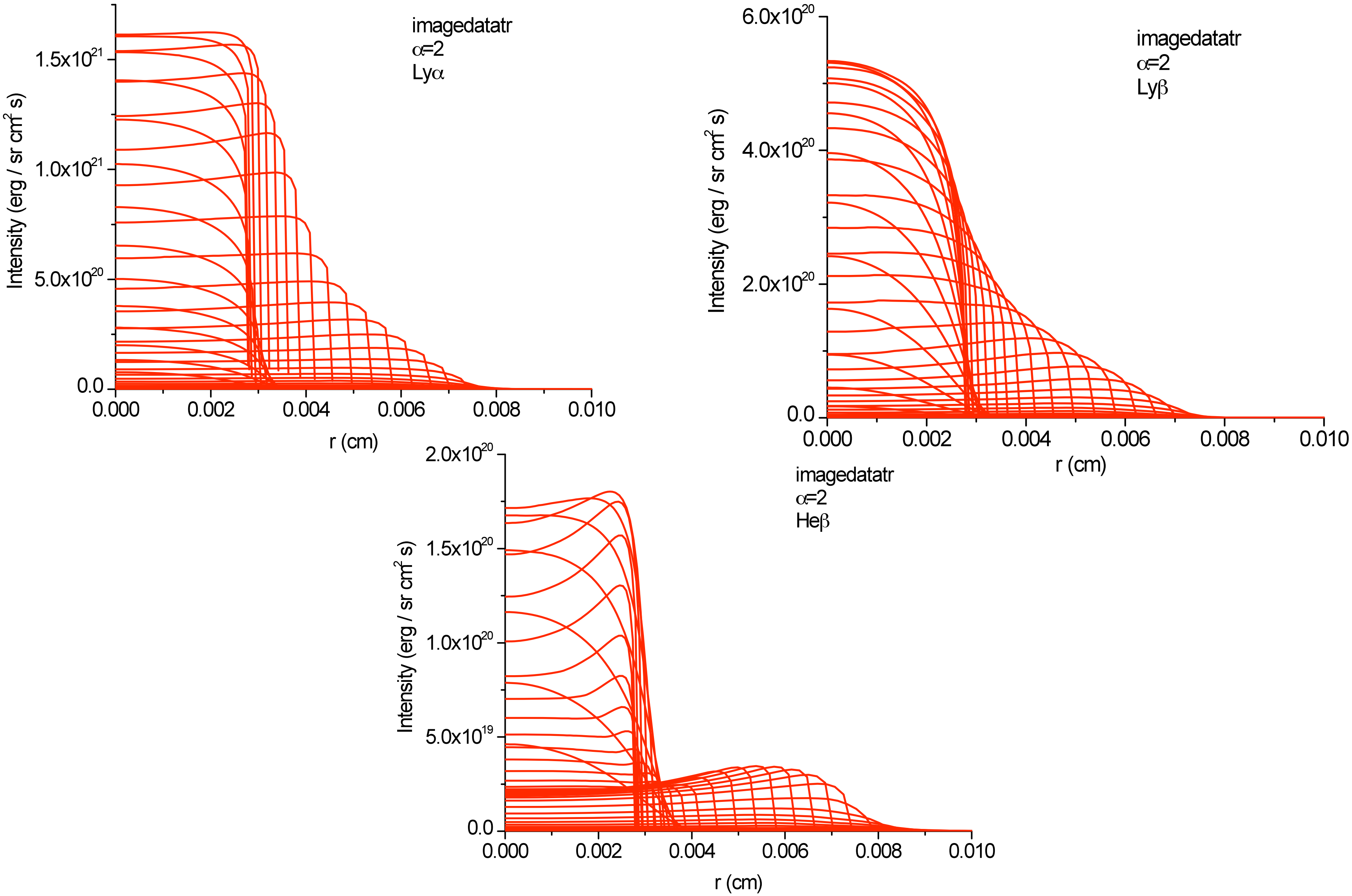
Time-history of argon K-shell line emission

- Post-processing of LILAC simulations with a detailed atomic and radiation physics model produces spectroscopic characteristics useful for setting up and modeling of spectroscopy diagnostics





Time-history of argon narrow-band image intensity profiles

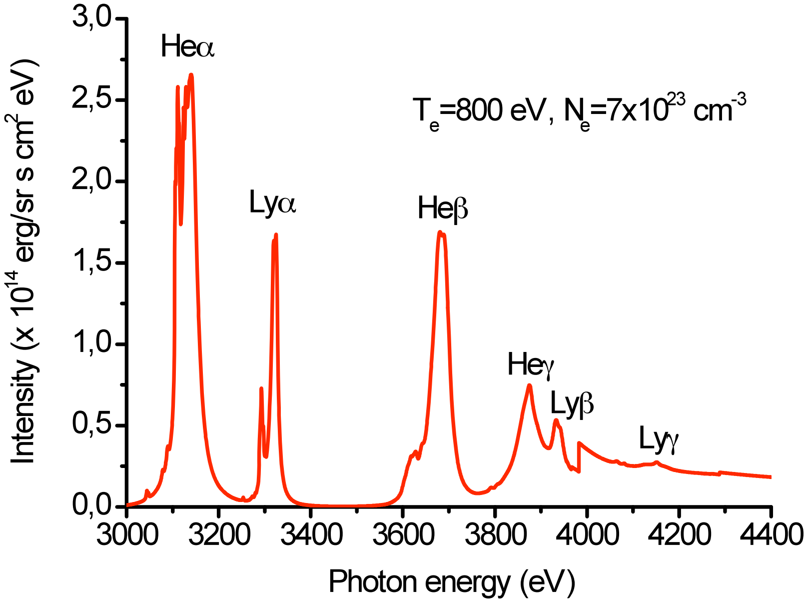


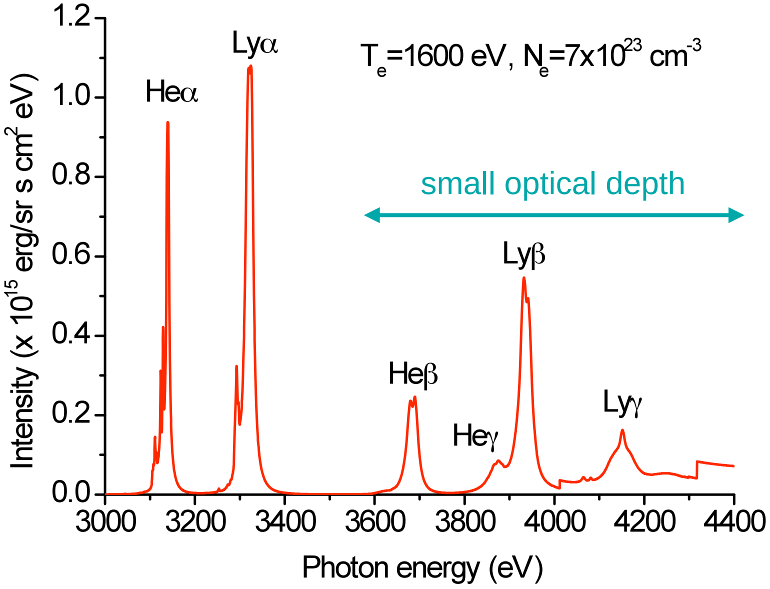
Modeling of X-ray emission from tracer elements

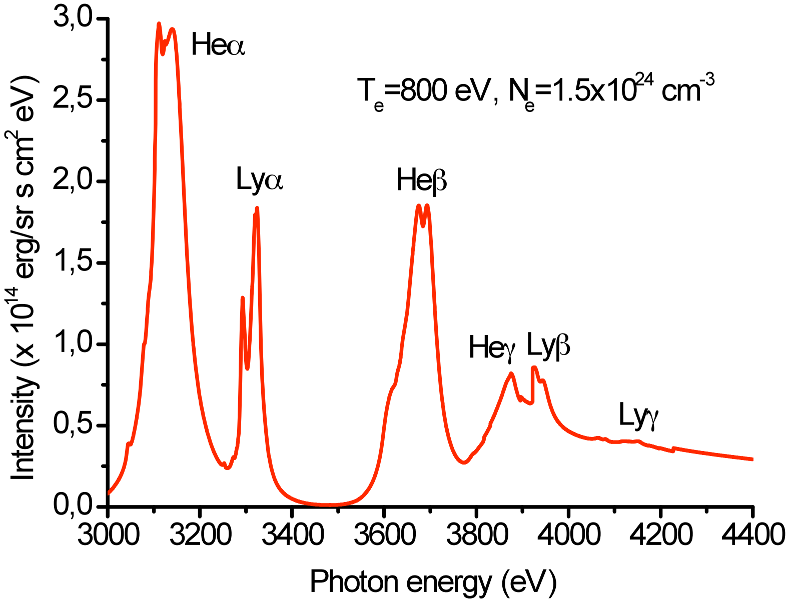
- Problem: mid-Z tracer element in high-energy density plasmas*
- Atomic structure to compute energy level structure and decay rates
- Atomic scattering to compute collision cross-sections and rates
- Radiation dependent rates, photoexcitation and photoionization
- Collisional-radiative atomic kinetics for atomic level populations and ionization balance
- Spectral line shapes: natural and Doppler broadening, and Stark broadening due to plasma microfields
- Radiation transport to calculate the emergent intensity distribution
- Important result: the intensity distribution of the tracer element is sensitive to the plasma electron temperature and density

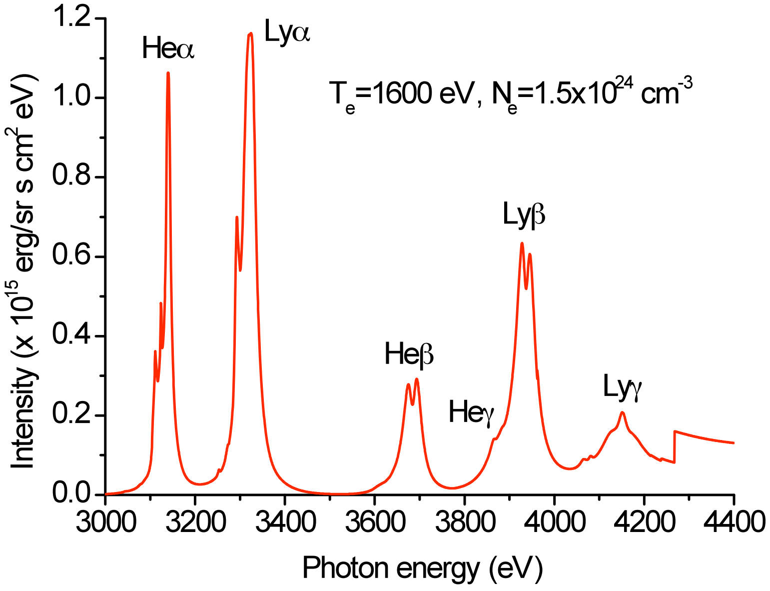
*I.Golovkin and R.C. Mancini, J. Quant. Spectrosc. Radiative Transfer **65**, 273 (2000).

Temperature & density dependence of Ar K-shell spectra



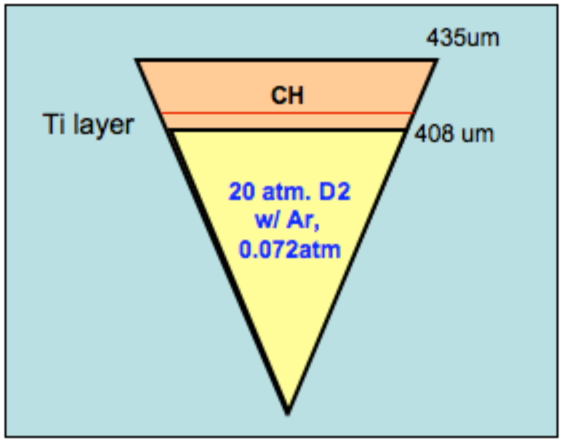


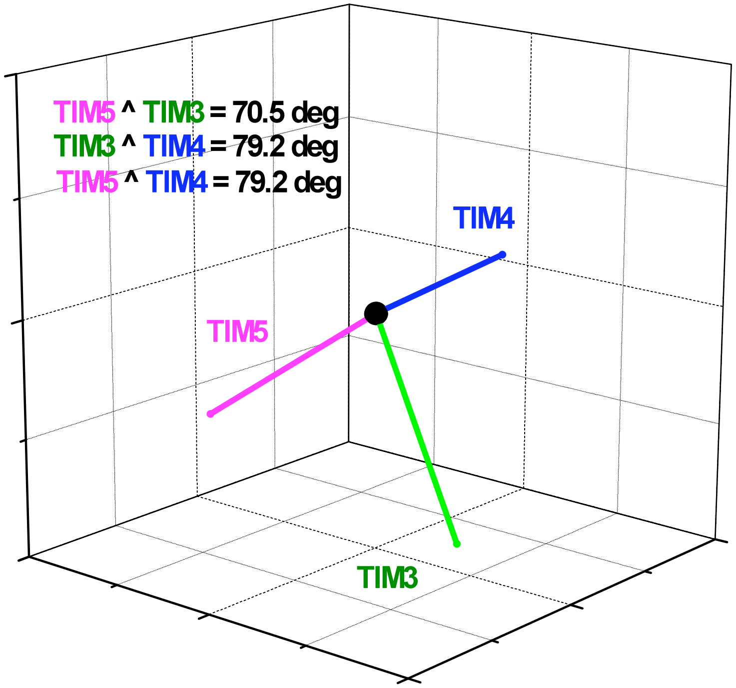




X-ray spectroscopy of direct-drive OMEGA implosions

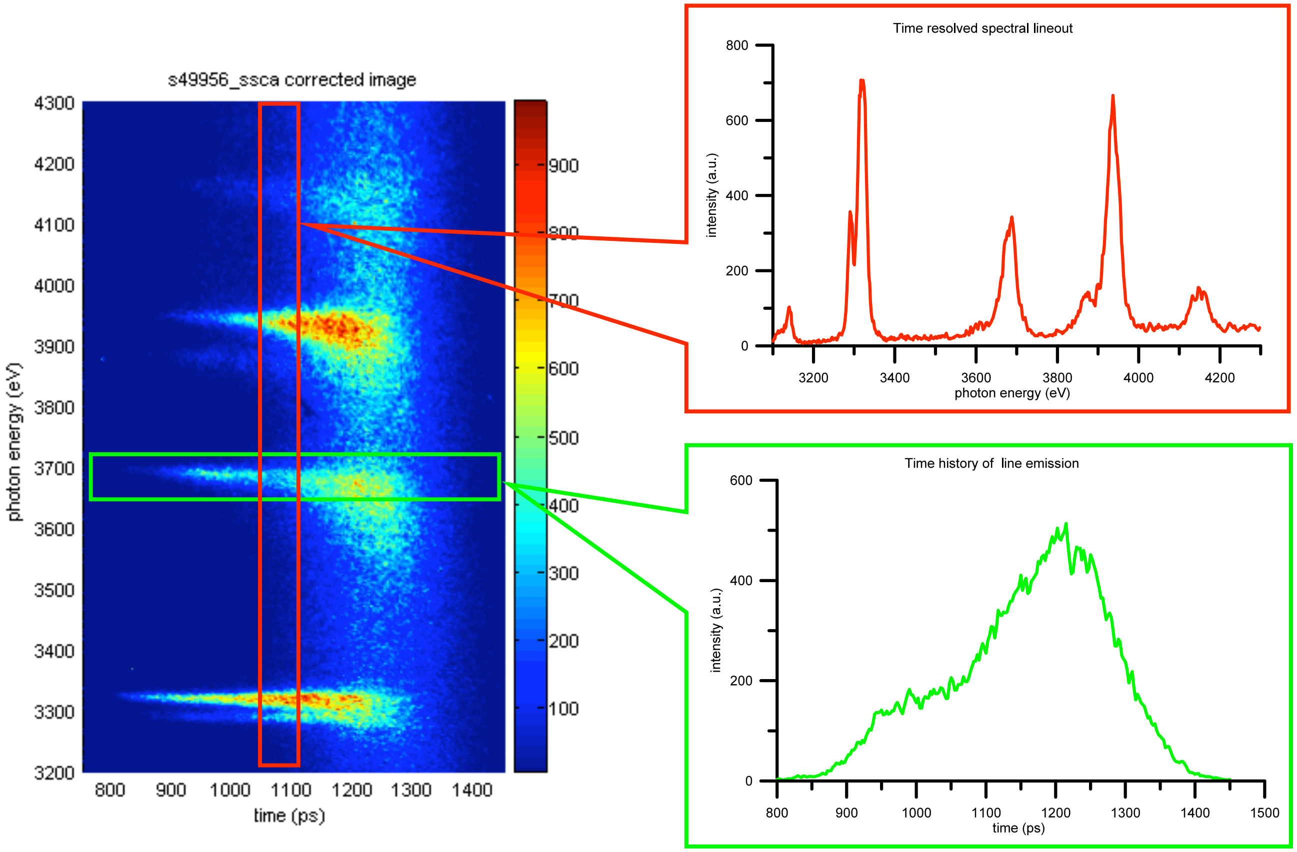
- Argon tracer added for core spectroscopic diagnostic of electron temperature and density
- Titanium-doped tracer layer added for diagnosis of un-ablated/compressed shell
- Three identical DDMMI
  - DDMMI = Direct-Drive Multi-Monochromatic x-ray Imager
  - Record gated narrow-band core image data (Δt ~50ps, Δx~10μm, E/ ΔE~150)
  - Three identical DDMMI were built and fielded along quasi-orthogonal directions (TIM3, TIM4, and TIM5)
  - Space-resolved spectra can also be extracted from data
- Two streaked x-ray crystal spectrometers
  - SSCA, high-speed (TIM1)
  - SSC1, low-speed (TIM2)





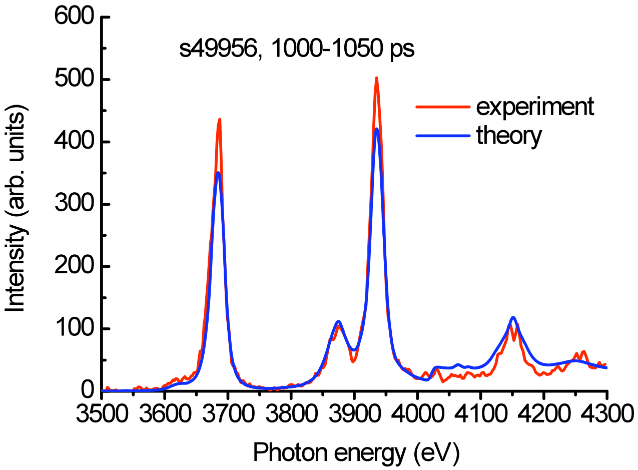
SSCA streaked x-ray crystal spectrometer

Vertical or horizontal lineouts yield spatially-integrated, time-resolved spectra or narrow-band time-histories, respectively

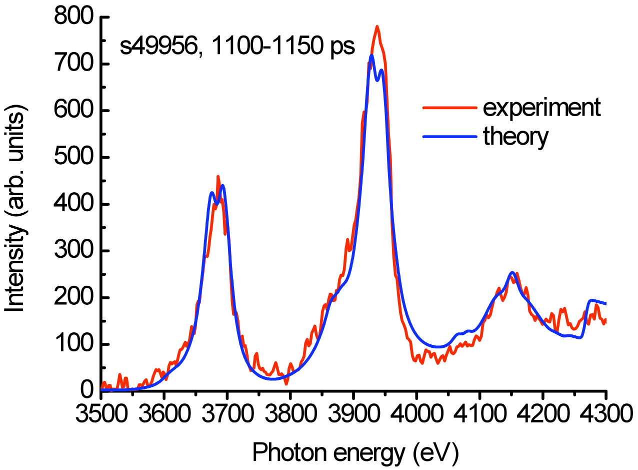


Synthetic spectra calculations produce good approximations to SSCA tracer spectra*

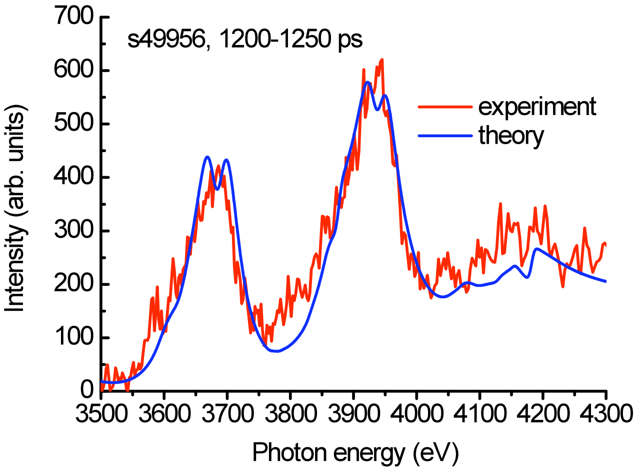
Te=1300 (+/-80) eV
Ne=5(+/-0.8) ×10^{23} cm^{-3}



Te=1450 (+/-80) eV
Ne=1.4 (+/-0.2) ×10^{24} cm^{-3}



Te=1270 (+/-100) eV
Ne=3.1 (+/-0.5) ×10^{24} cm^{-3}

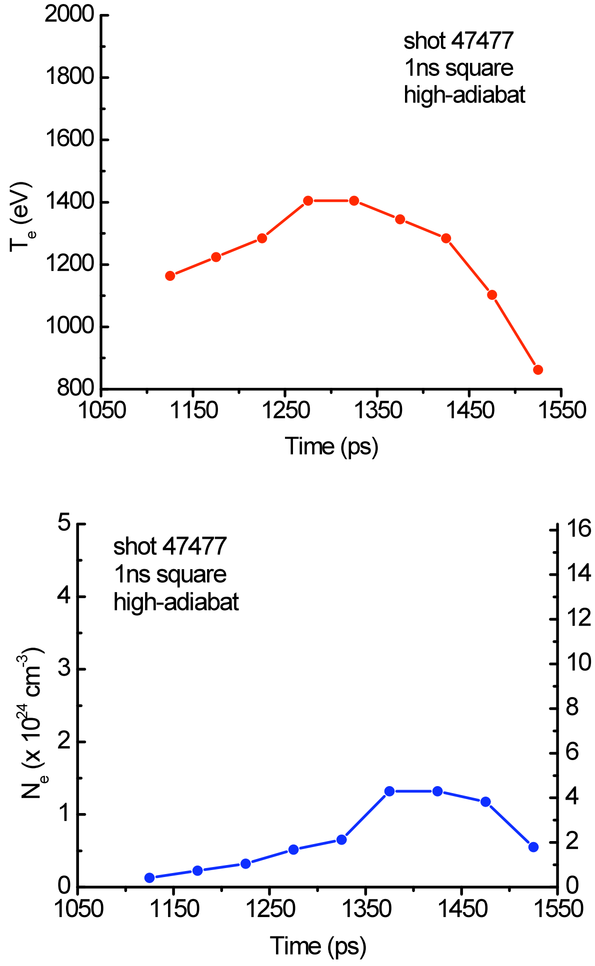


- Time-resolved (streaked) space-integrated spectra
- Instrumental broadening included, FWHM=9eV
- Each spectrum is representative of Δt=50ps
- Changes in plasma Te and Ne conditions are reflected in characteristic changes in the tracer spectra

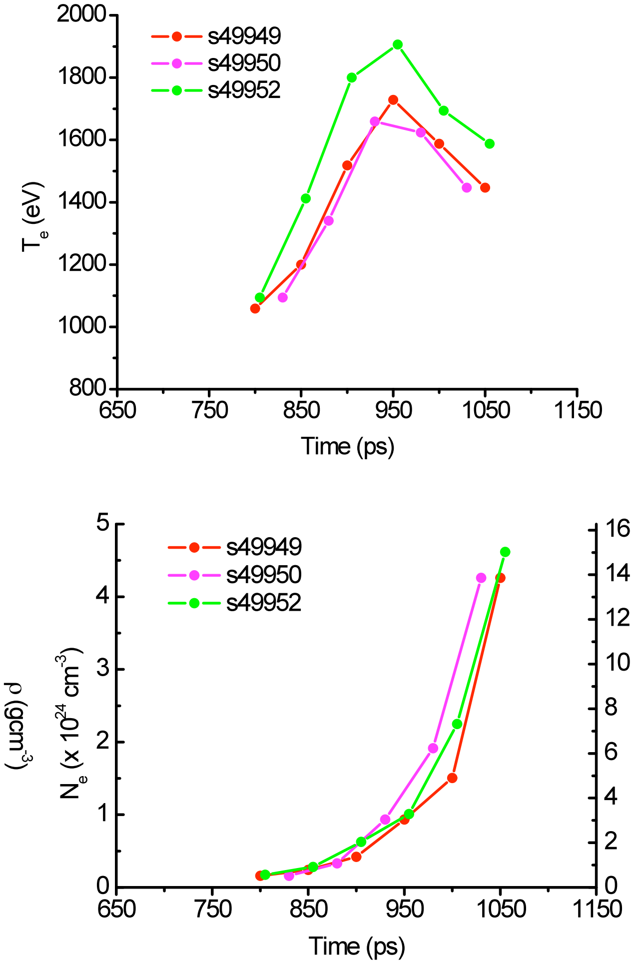
*R. Florido, T. Nagayama, R. Mancini, R. Tommasini, J. Delettrez, S. Regan, V. Smalyuk, R. Rodriguez and J. Gil, Rev. Sci. Instrum. **79**, 10E310 (2008)

Time-resolved spectroscopic analysis of OMEGA direct-drive implosions shows different hydrodynamic evolutions*

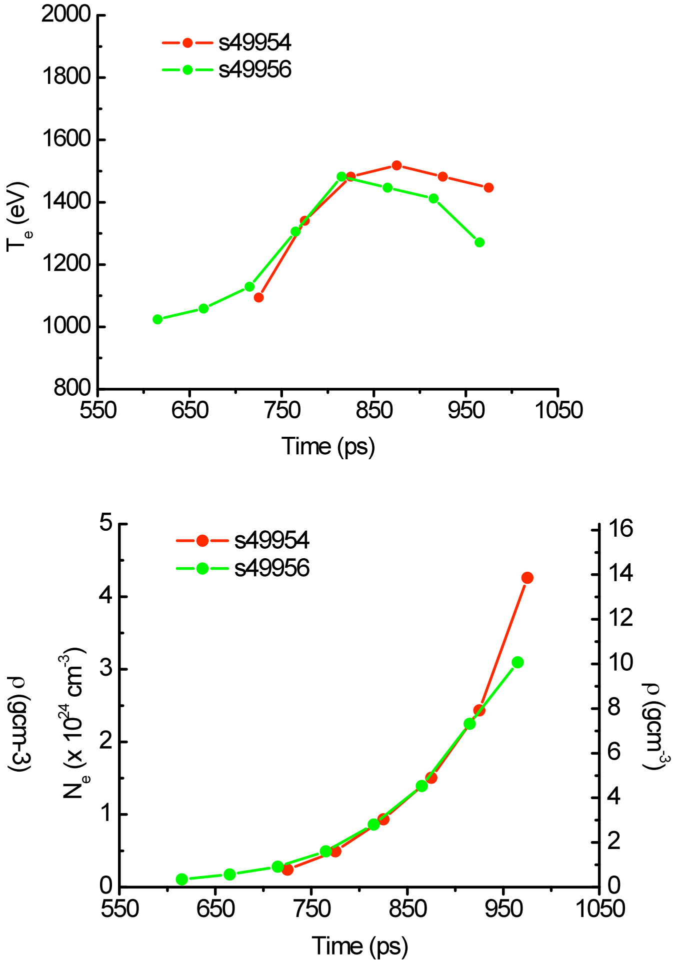
1ns square 23kJ



α3 low-adiabat 21.4kJ



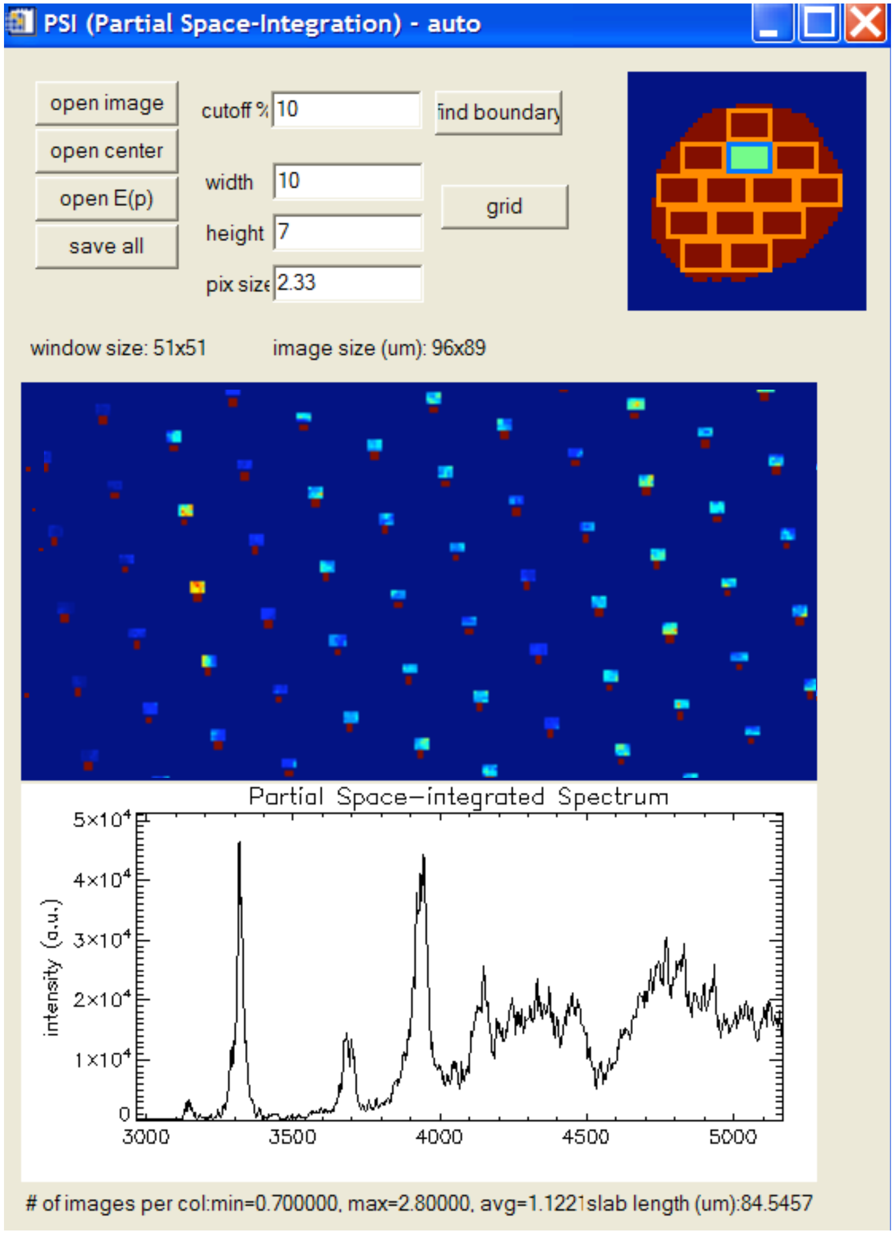
α2 low-adiabat 19kJ



*R.Florido, R.C. Mancini et al, in preparation for publication (2009)

Spatially-resolved spectra from spectrally-resolved pinhole core images*

- Space-integrated spectrum can be extracted from DDMMI data by summing up intensities vertically for each photon energy
- Space-resolved spectrum: select only a given spatial region of the image (same for all images) and compute spectra collecting contributions **ONLY** from this region
- **Important:** both Te and Ne are extracted from spectra analysis
- Limitations: space resolution, and signal-to-noise ratio



cutoff % 10

width 10

height 7

pix size 2.33

window size: 51x51

image size (um): 96x89

# of images per col:min=0.700000, max=2.80000, avg=1.1221slab length (um):84.5457

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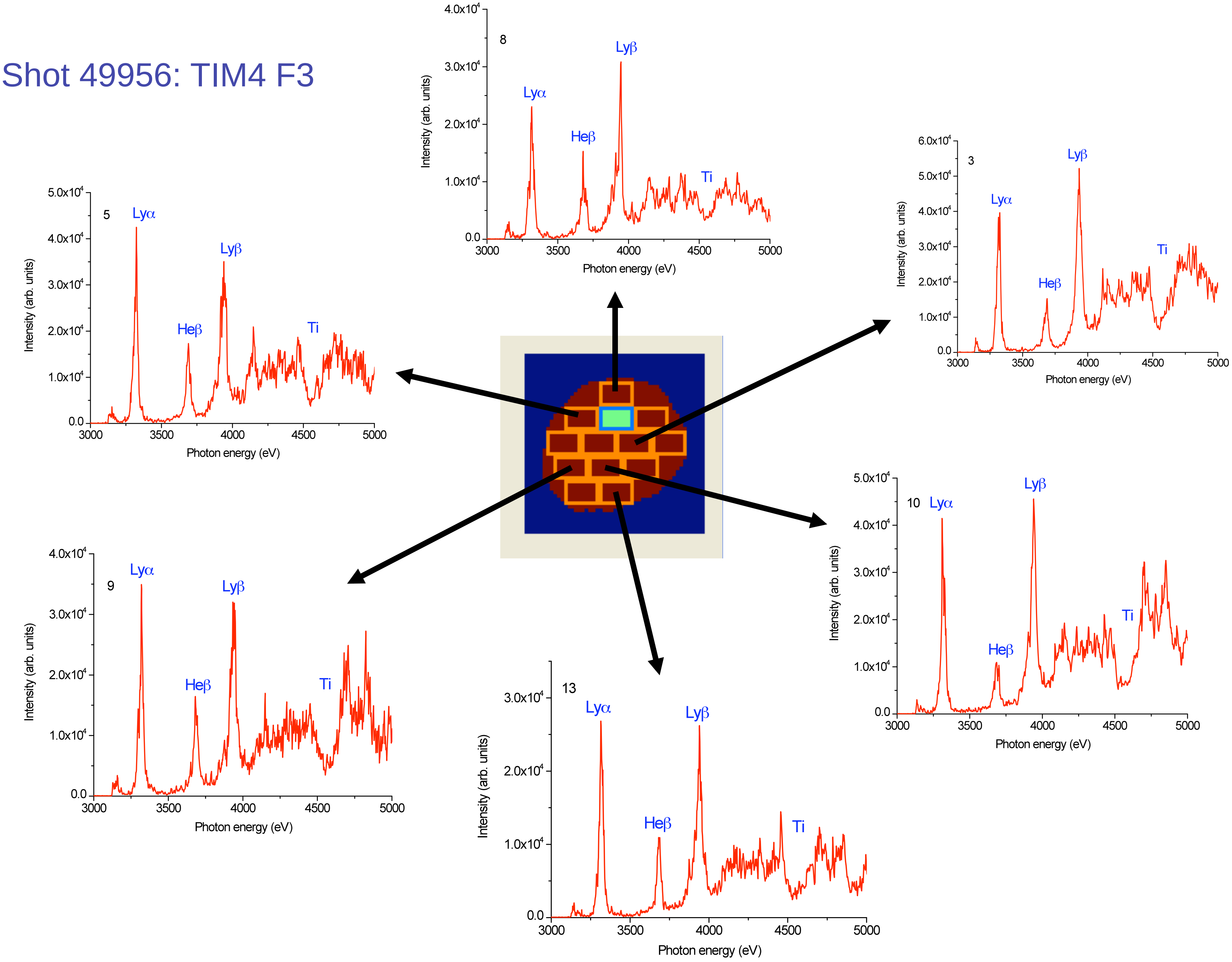
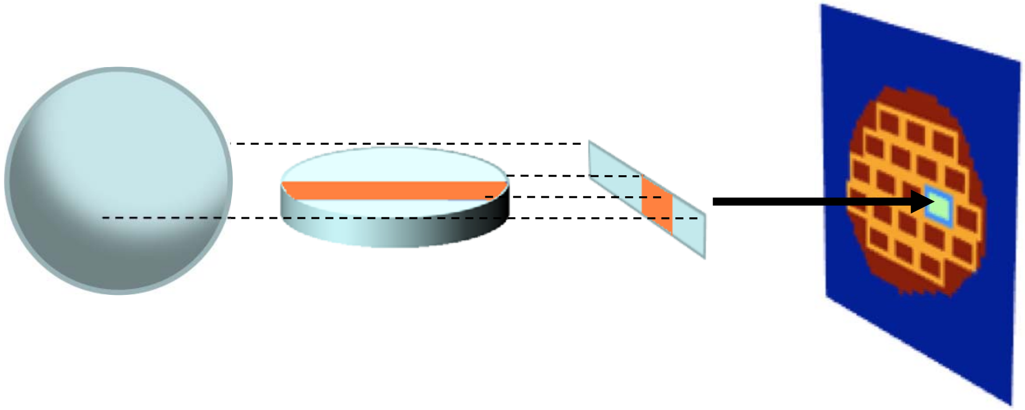
*R.C. Mancini et al, in preparation for publication (2009)

Shot 49956: TIM4 F3



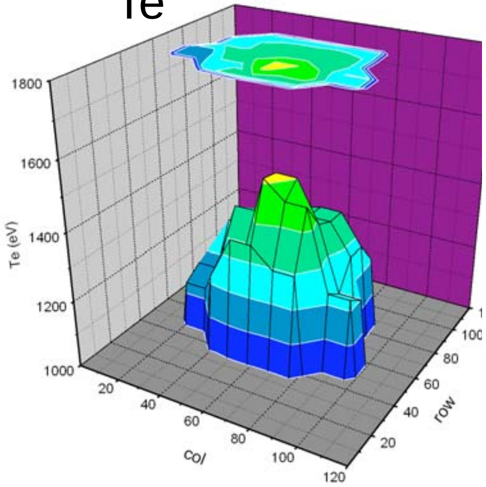
Simulation and analysis of space-resolved line spectra



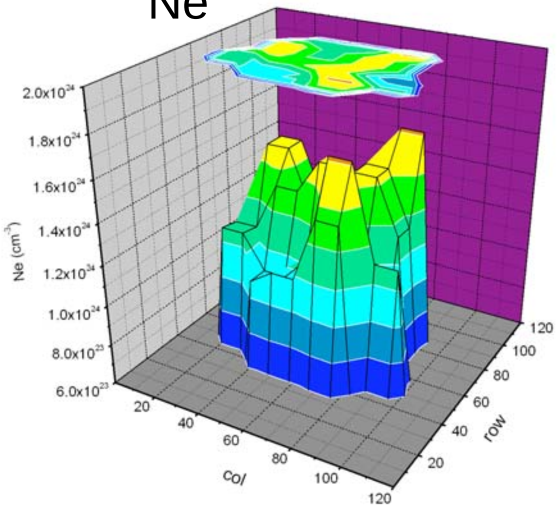
Each spatial region of the image represents a spatial integration over a slab in the core slice

Shot 49956, TIM4, F3: spatial profiles

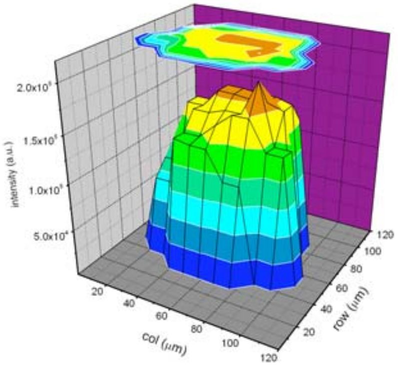
Te



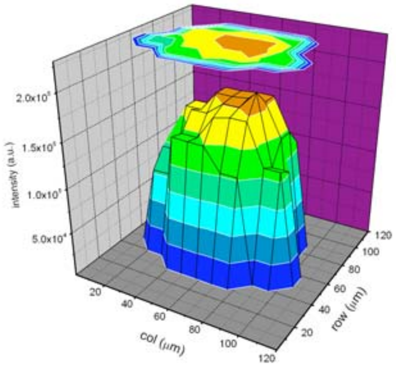
Ne



Lyβ exp



Lyβ model

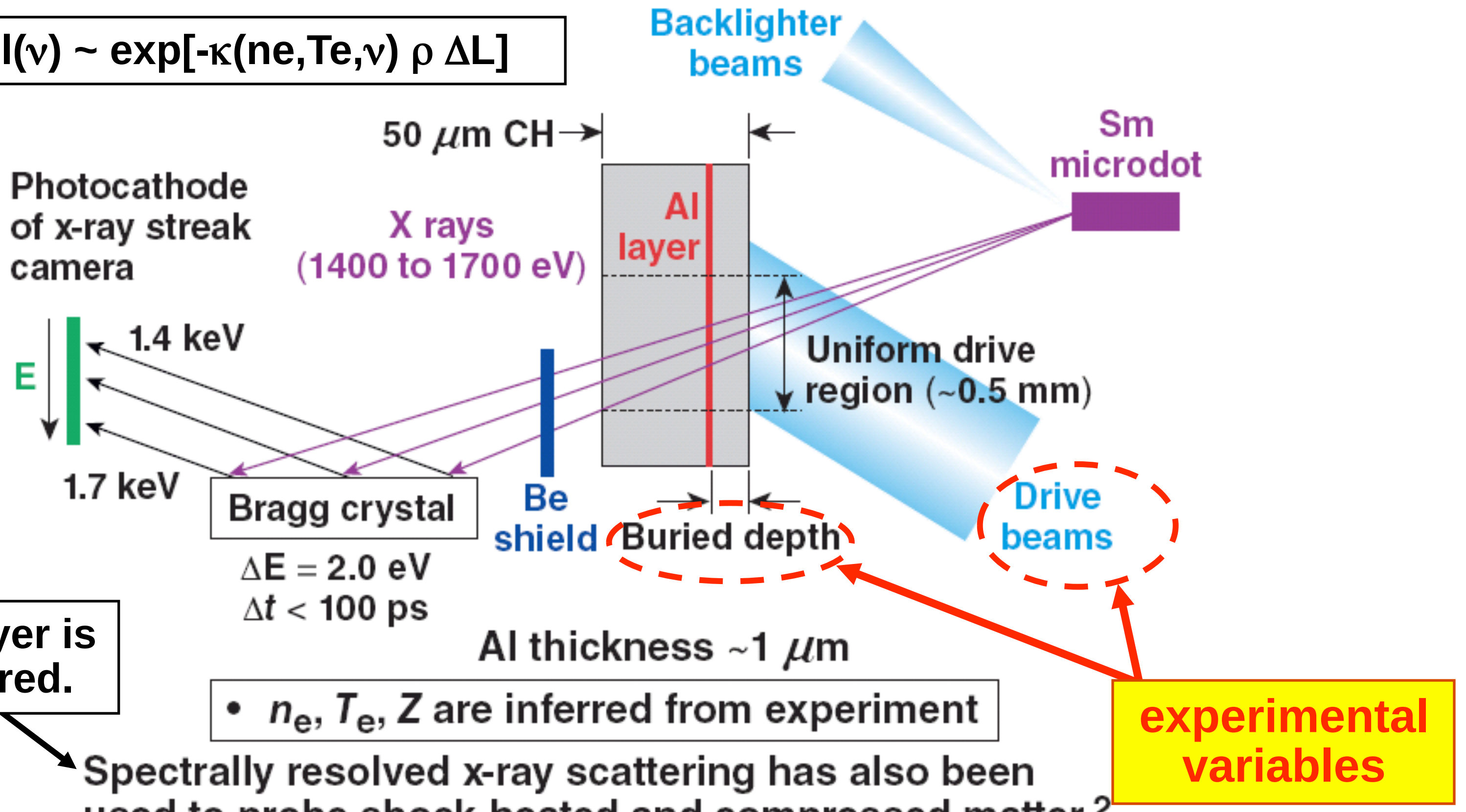


Consistency check: compute model image using Te and Ne spatial distributions from the analysis of space-resolved line spectra, and compare with experimental image

HEDP experiments were performed on OMEGA to create and probe matter compressed and heated by shock waves

Time-resolved Al 1*s*–2*p* absorption spectroscopy[1]

$T_{Al}(\nu) \sim \exp[-\kappa(ne,Te,\nu)\ \rho\ \Delta L]$



Al tracer layer is NOT required.

- n_e, T_e, Z are inferred from experiment

Spectrally resolved x-ray scattering has also been used to probe shock-heated and compressed matter.[2]

Slide credit: S. Regan

E16525a

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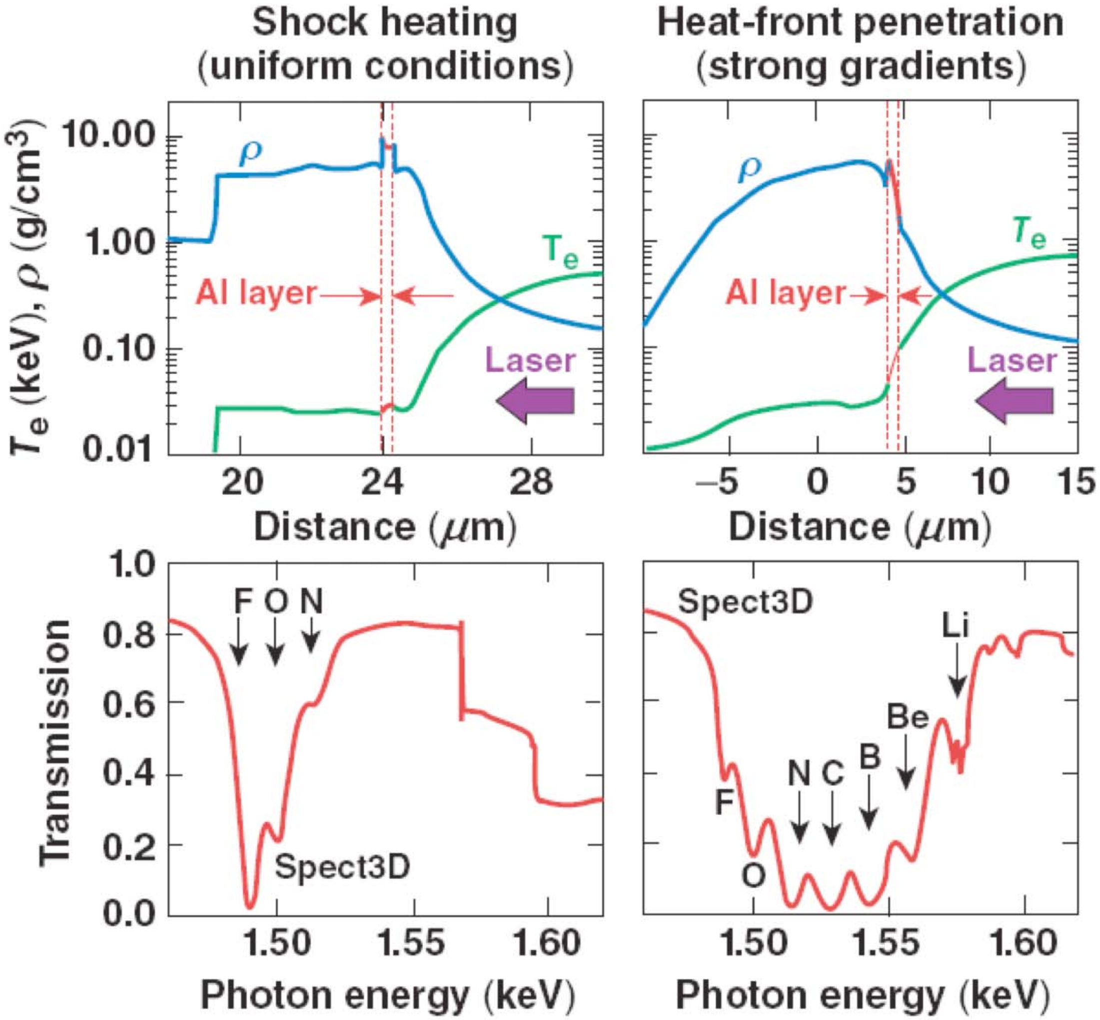
[1] Boehly et al., PRL 87, 145003 (2001); Sawada et al., submitted for publication.
[2] Sawada et al., Phys. Plasmas 14, 122703 (2007).

The shock wave creates uniform conditions in the Al layer, while the heat-front penetration creates strong gradients

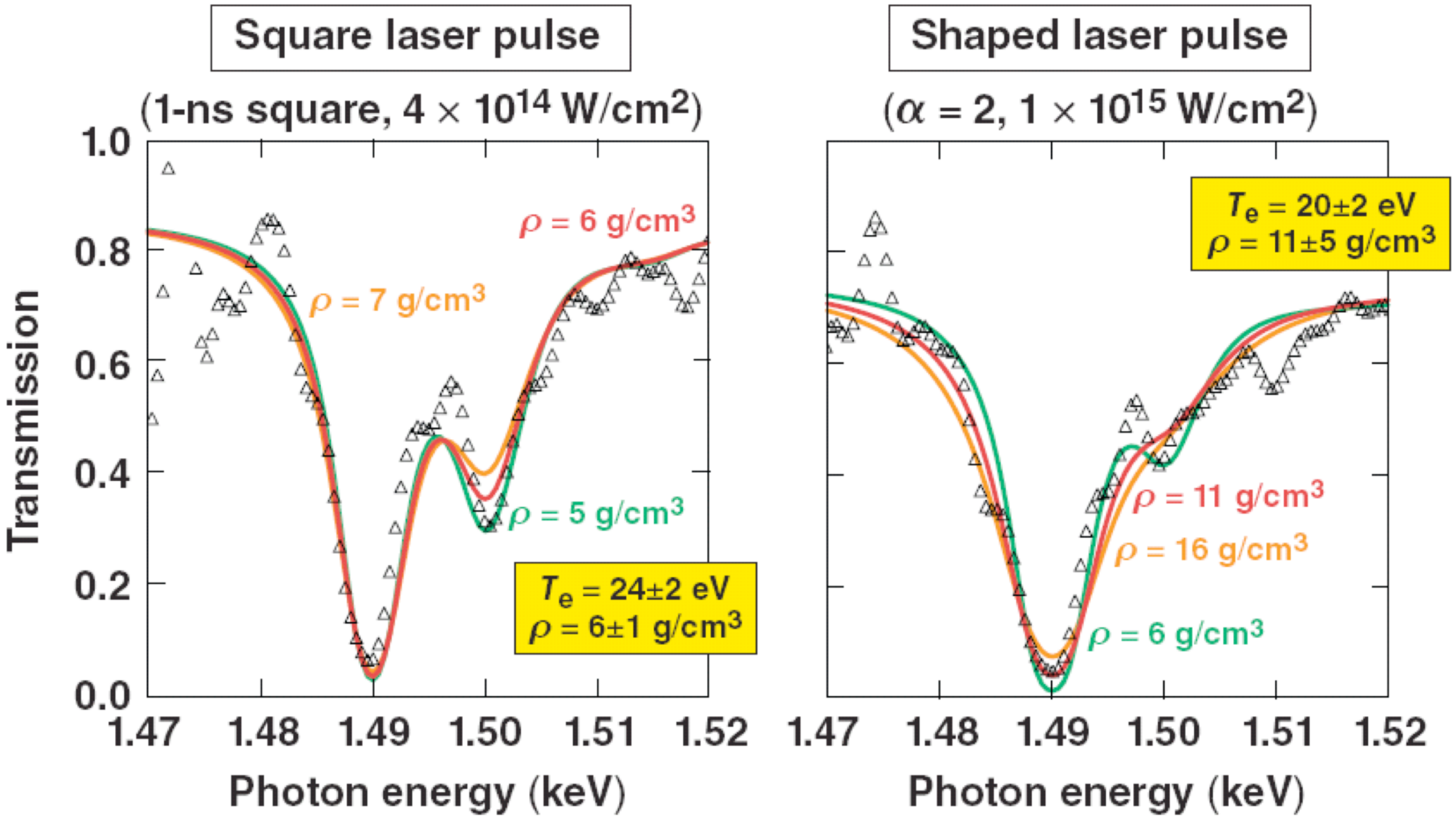
LILAC / Spect3D simulations



Slide credit: S. Regan

E16527

Higher compression is achieved with a shaped laser-pulse drive compared with the square pulse



T_e (*LILAC*) = 22 eV
ρ (*LILAC*) = 7.7 g/cm^3

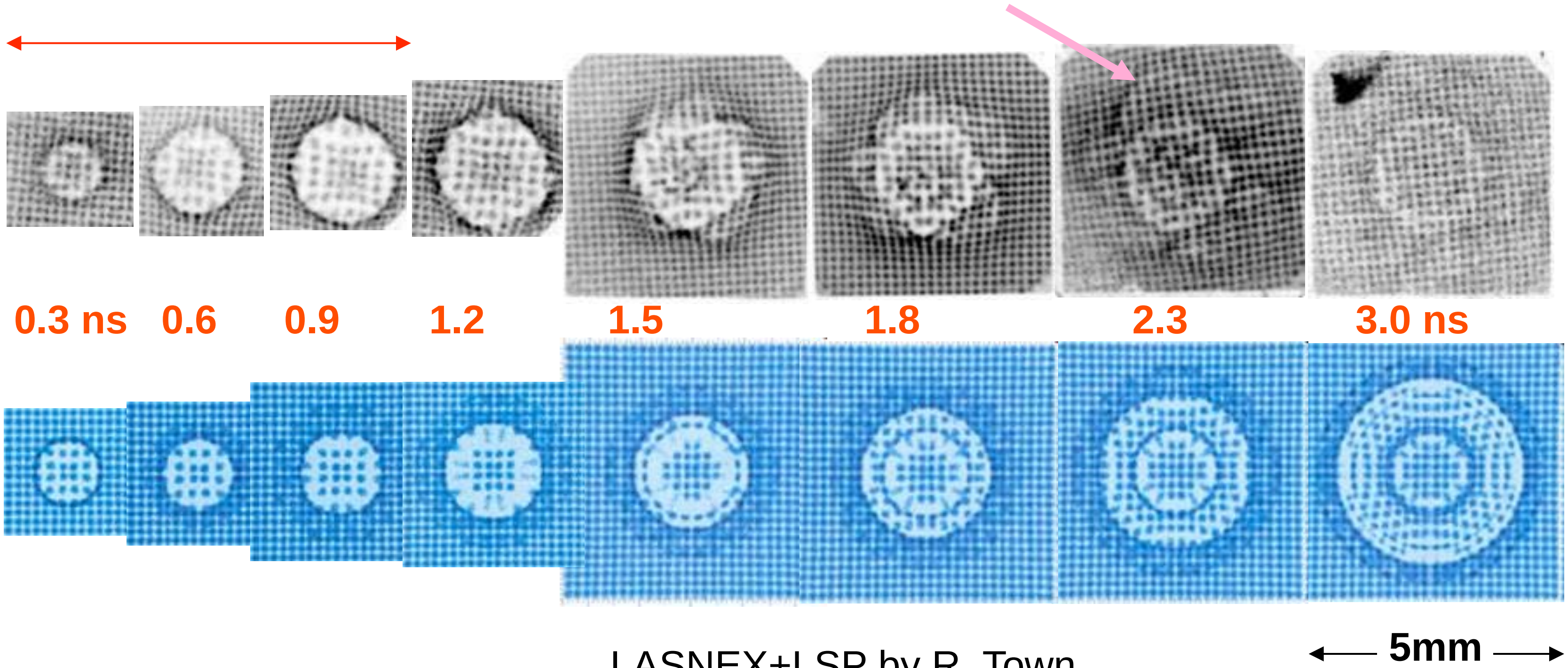
T_e (*LILAC*) = 20 eV
ρ (*LILAC*) = 13.5 g/cm^3

Slide credit: S. Regan

MG B-field generation, evolution & instabilities have been studied with 14.7-MeV-proton radiography at OMEGA*

Foil-illuminating laser on for 1 ns

3-D instability



0.3 ns 0.6 0.9 1.2 1.5 1.8 2.3 3.0 ns

LASNEX+LSP by R. Town

5mm

2-D code LASNEX produces credible simulations of hydro and fields while the laser is on, failing when 3-D instabilities appear.

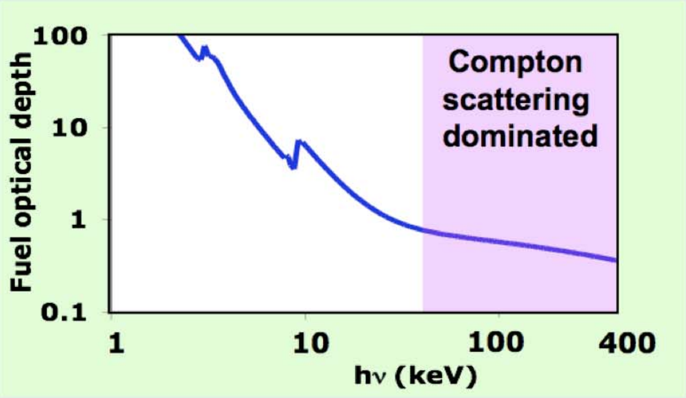
Slide credit: R. Petrasso

*C. K. Li *et al.*, PRL **99**, 015001 (2007)

ARC campaign: record Compton radiographs of OMEGA driven implosions using a μ-wire backlighter driven by OMEGA-EP at ARC relevant energies

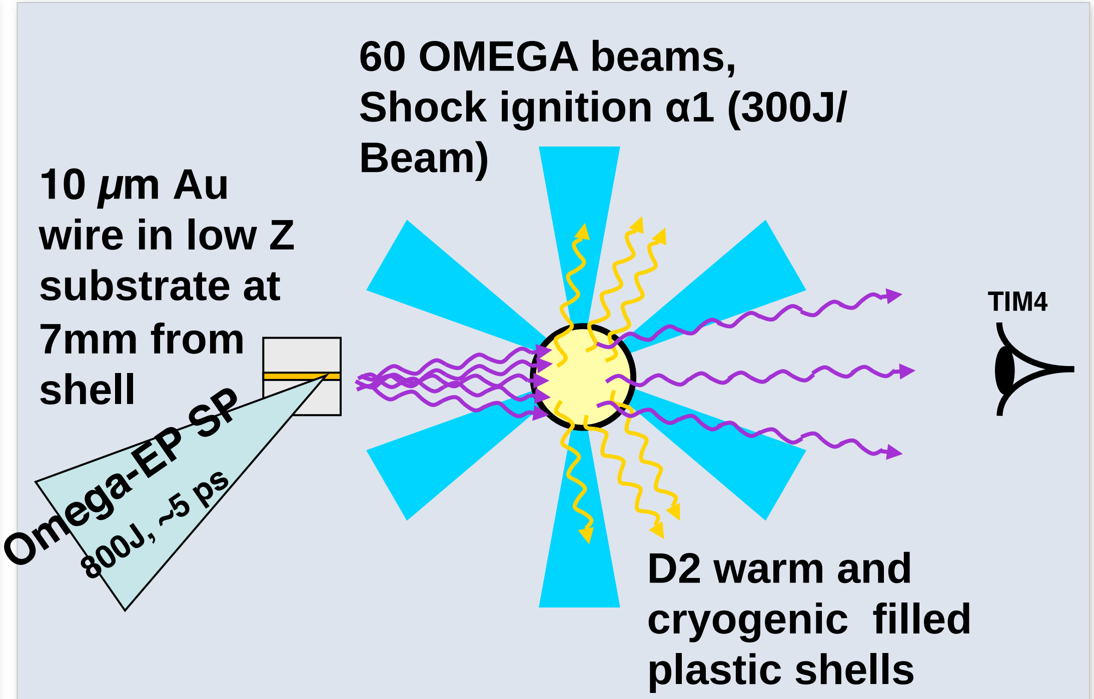
Compton Radiography

ARC will be used to generate a Bremsstrahlung backlighter that will produce radiographs of the imploding fuel during the National Ignition Campaign.



At hν>75keV, optical depth is nearly ideal (τ~1) to get good contrast, and scattering is largely independent of x-ray photon energy

Setup of CR campaigns on OMEGA

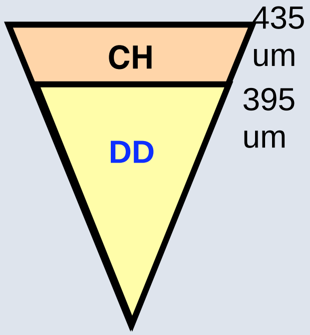


- **2D radiographs of high limb ρR imploding shells (up to 0.3 g/cm^2) will be recorded on imaging plates**
- **Bremsstrahlung spectra will be measured using step wedge filters coupled to imaging plates**

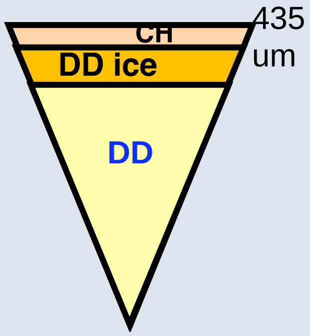
Slide credit: R. Tommasini

Modeling and simulation predict the expected ρR and the best timing of the backlighter to capture the radiograph at peak compression

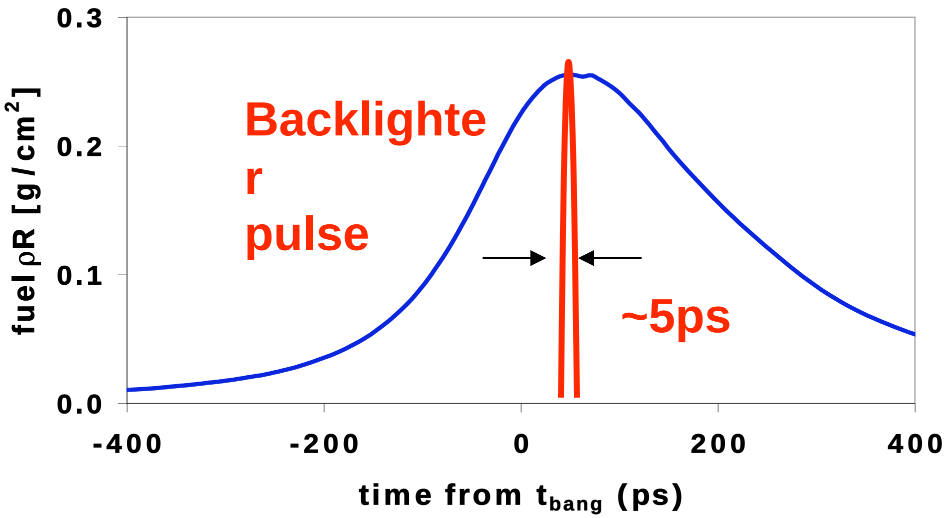
We will use warm and cryo DD fills



Warm plastic shell
Fill: DD, 8atm
870um OD
40um thick shell



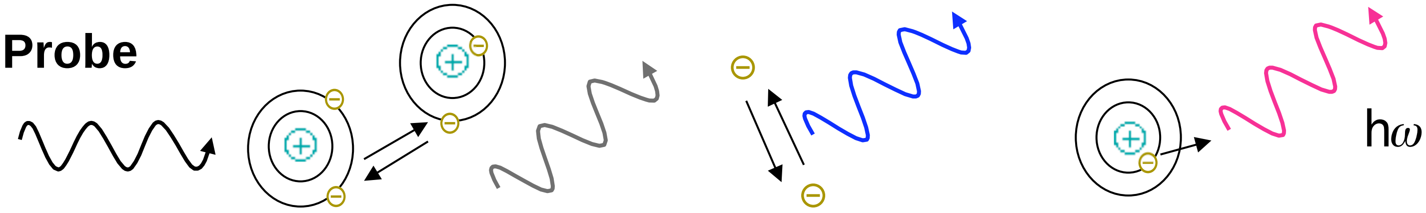
Cryogenic plastic shell
Fill: DD
870um OD
20um thick shell



Firing the backlighter slightly far from optimal values means insufficient ρR and contrast. Which translates in poor radiograph.

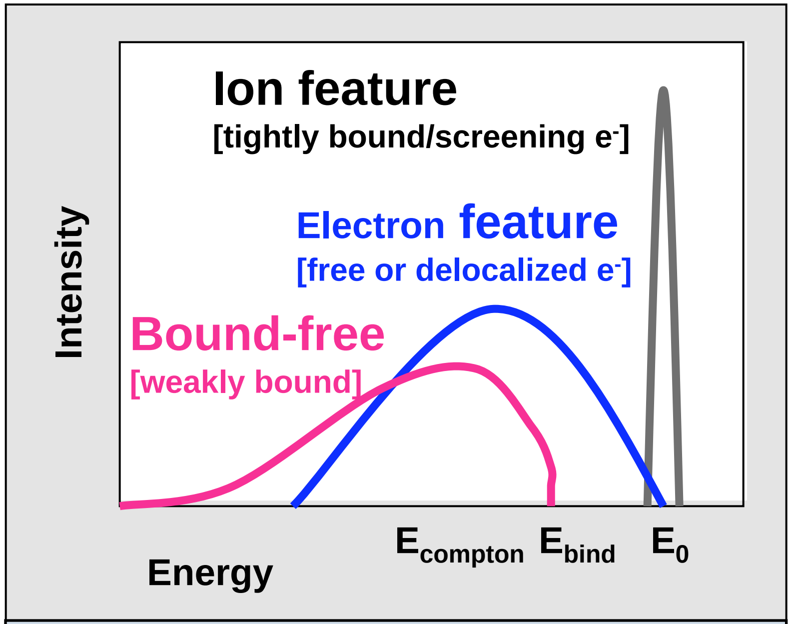
Slide credit: R. Tommasini

The theoretical form factor for x-ray scattering provides reliable plasma parameters for back scatter experiments



$$\hbar\omega = \hbar\omega_1 - \hbar\omega_0$$

$$S(k,\omega) = \underbrace{\left|f_I(k) + q(k)\right|^2 S_{ii}(k,\omega) +}_{\text{Ion feature}} \underbrace{Z_f S^0_{ee}(k,\omega)}_{\text{Electron feature}} \underbrace{+ Z_b \int \tilde{S}_{ce}(k,\omega-\omega')S_s(k,\omega')d\omega'}_{\text{Bound-free}}$$



Schematic Scattering spectrum

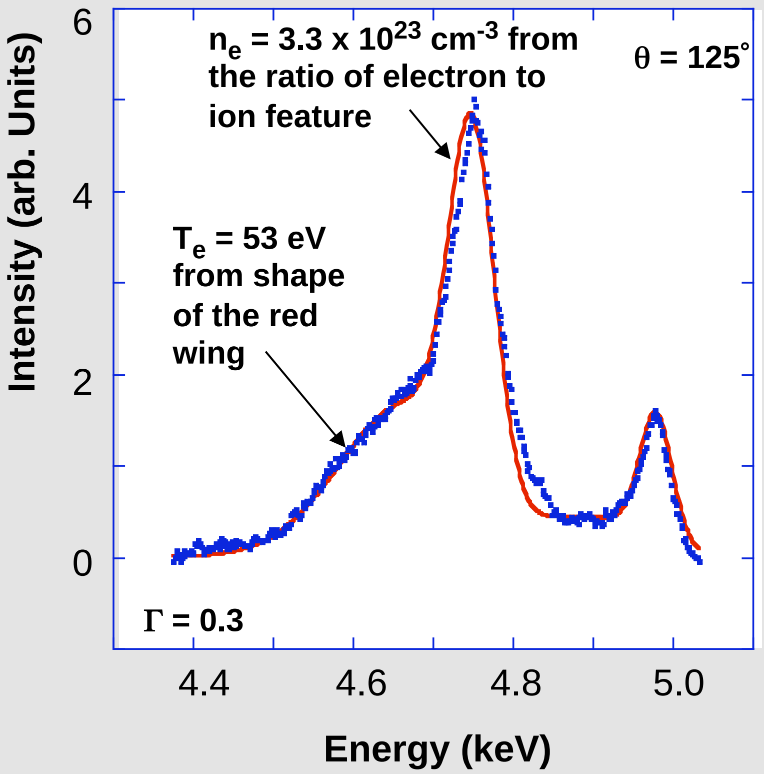
- Free or delocalized electrons result in the Compton down-shifted line, $Z_f\ S_{ee}\ (k,\omega)$
- Bound-free contribution also results into down-shifted spectrum
- $Z_b\ S_{ce}\ (k,\omega)$
- The momentum of bound e^- causes broadening
- The ion feature describes elastic scattering $S_{ii}(k,\omega)$
- In backscatter: theoretical approximations agree

Slide credit: S. Glenzer

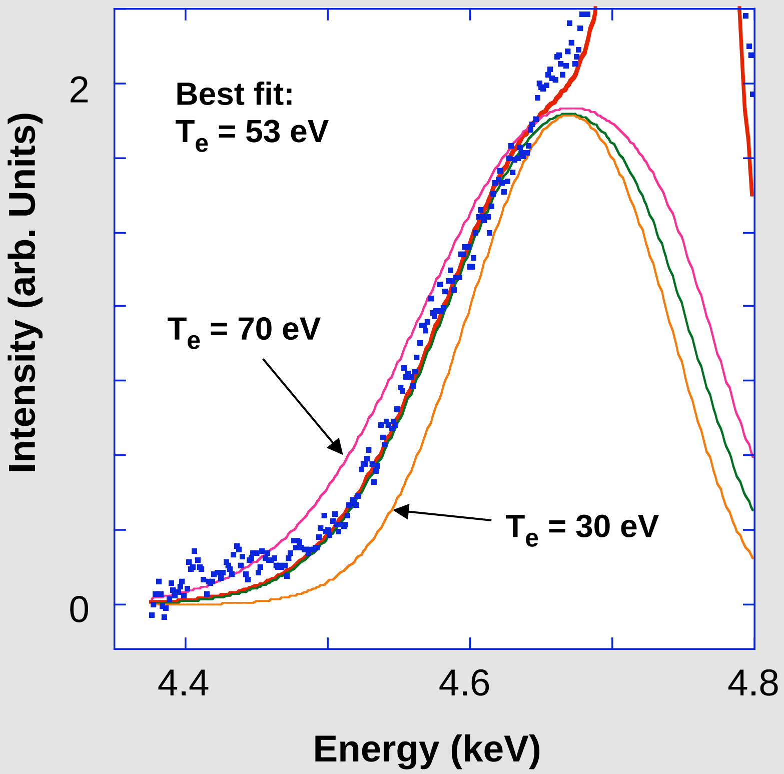
Chihara, PRE (2000), Gregori et al, PRE (2003)

X-ray scattering provides accurate temperature measurements in solid-density Be plasmas

X-ray scattering spectra provide accurate data on T_e and n_e



Comparison of experimental data with theoretical calculations for various T_e



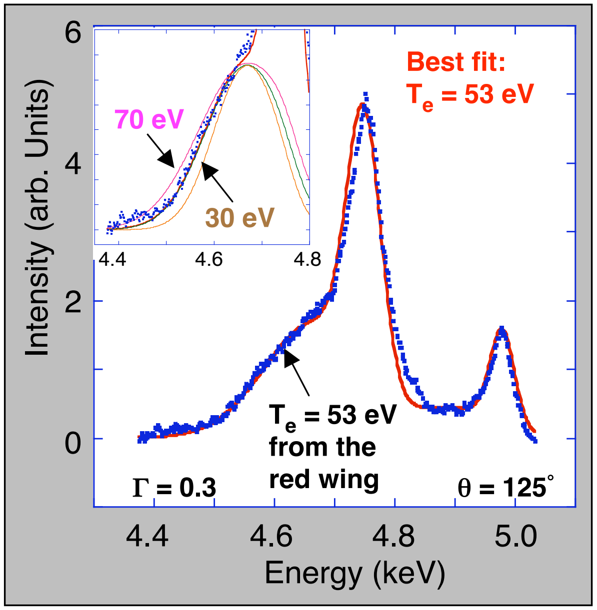
From the theoretical fit to the data:
T_e = 53 eV and Z_{free} = 3.1 corresponding to n_e = 3.8 x 10^{23} cm^{-3}

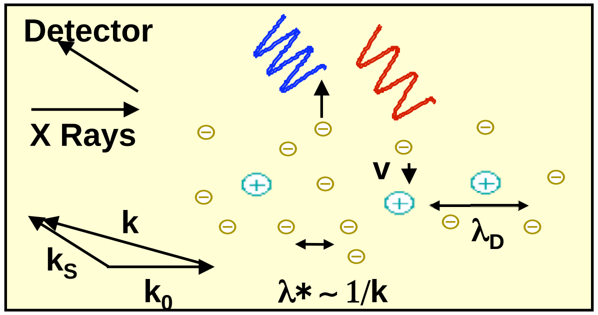
A sensitivity analysis shows that we can measure T_e with an error bar of ~15%

Slide credit: S. Glenzer

Back- and forward scattering have been demonstrated on OMEGA accurately characterizing solid-density plasmas

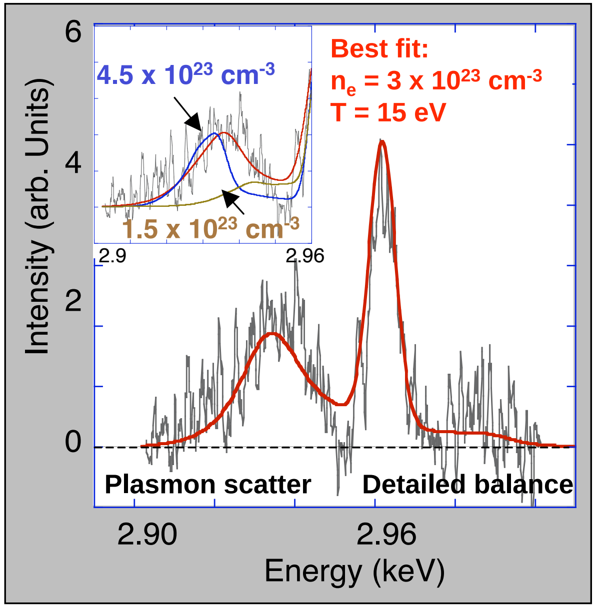
Compton (back-) scatter measures T_e from broadening

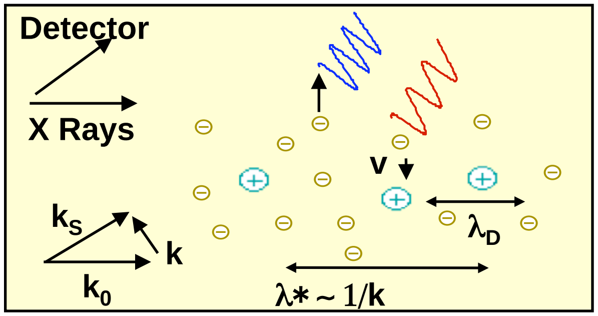




S. H. Glenzer et al., Phys. Rev. Lett. 90, 175002 (2003).

Forward scatter on Plasmons measures n_e from shift





S. H. Glenzer et al., Phys. Rev. Lett. 98, 065002 (2007).

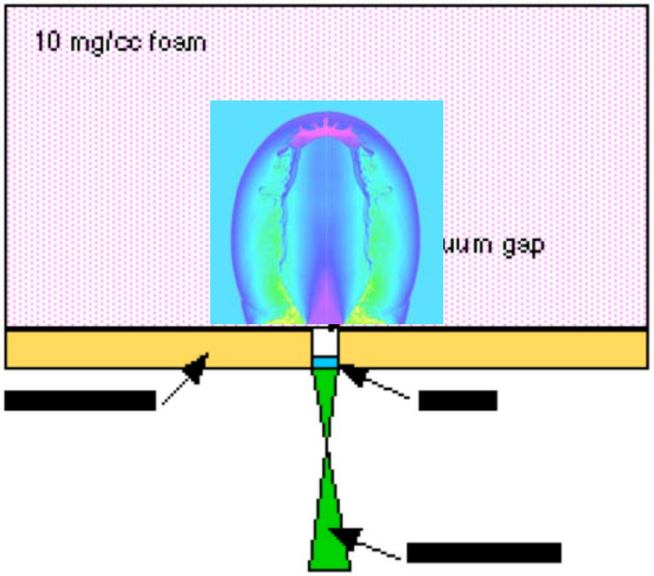
$$\lambda^* > \lambda_S \quad or \quad \alpha = \frac{\lambda^*}{\lambda_S} = \frac{k^{-1}}{\lambda_S} = \frac{\lambda_0}{4\pi\ \lambda_S\ \sin(\theta/2)} > 1$$

Slide credit: S. Glenzer

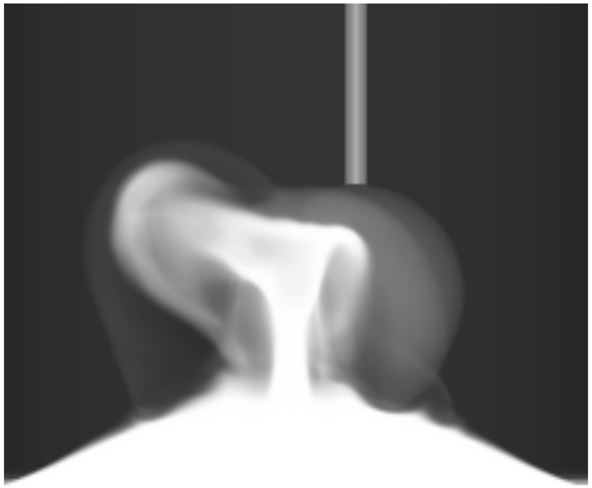
Simulation and design of radiation-hydrodynamics experiments

- 1D simulations are key first step in radiation-hydrodynamics experiment design
- Several 1D codes are available: HELIOS-CR, HYADES, MULTI, …
- Next step is 2D and 3D simulations
- Doing 2D and 3D simulations is much more involved than 1D modeling
  - Finding lab collaborators is good if you can do it
  - Don’t yet have an open community code for 2D and 3D simulations

Initial 2D Jet design work
Khokhlov, 2001

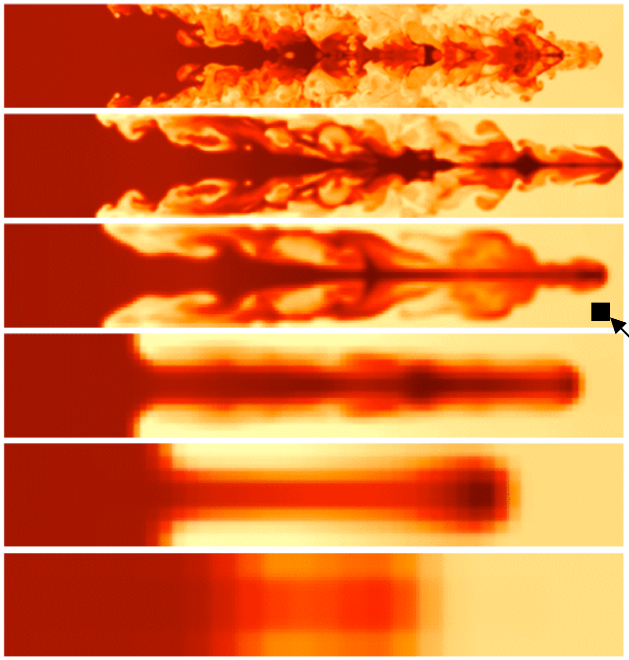


3D Simulations of follow-on jet/cloud experiments
Wilde, Coker, Rosen



Slide credit: P. Drake

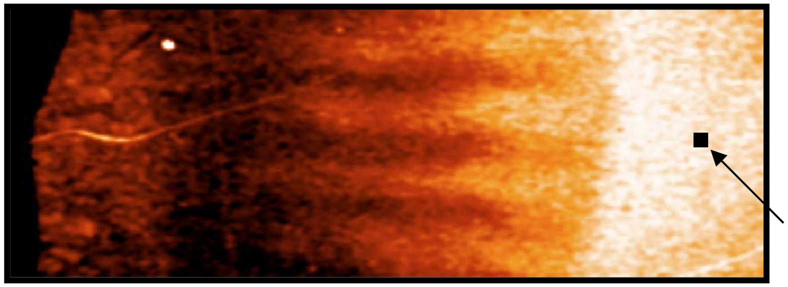
Beware: codes may not have the real physics and can produce misleading results



Calder et al., ApJSS 2002
Steady Rayleigh-Taylor
Variable resolution

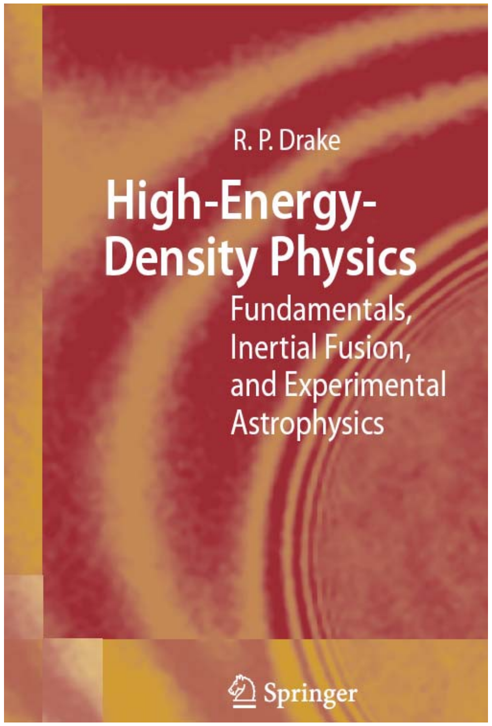
Experimental resolution

You need to learn enough physics and enough about the code to figure out when it might be lying to you



experimental resolution

Kuranz Omega Rayleigh-Taylor data: Spikes not lumpy as in simulation



R. P. Drake

High-Energy-Density Physics

Fundamentals, Inertial Fusion, and Experimental Astrophysics

Springer

Slide credit: P. Drake

Challenges in computational modeling of HEDLP/LPI

- Model requires to resolve extremely large density scales plasmas. (e.g.$10^{19} \sim 10^{26}$ cm^{-3} for LPI and transport in Fast Ignition)
- Model requires the Coulomb collision to simulate the energy transport and heating in HEDLP. (i.e. resistive effects, scattering)
- Model requires the dynamics ionization processes since the plasma electron density and the resistivity depend on the charge state inside the target. (e.g. ultra-fast heated thin metal target by LPI)
- Model should have a strict energy conservation to avoid the numerical heating/numerical ionization in HEDLP.

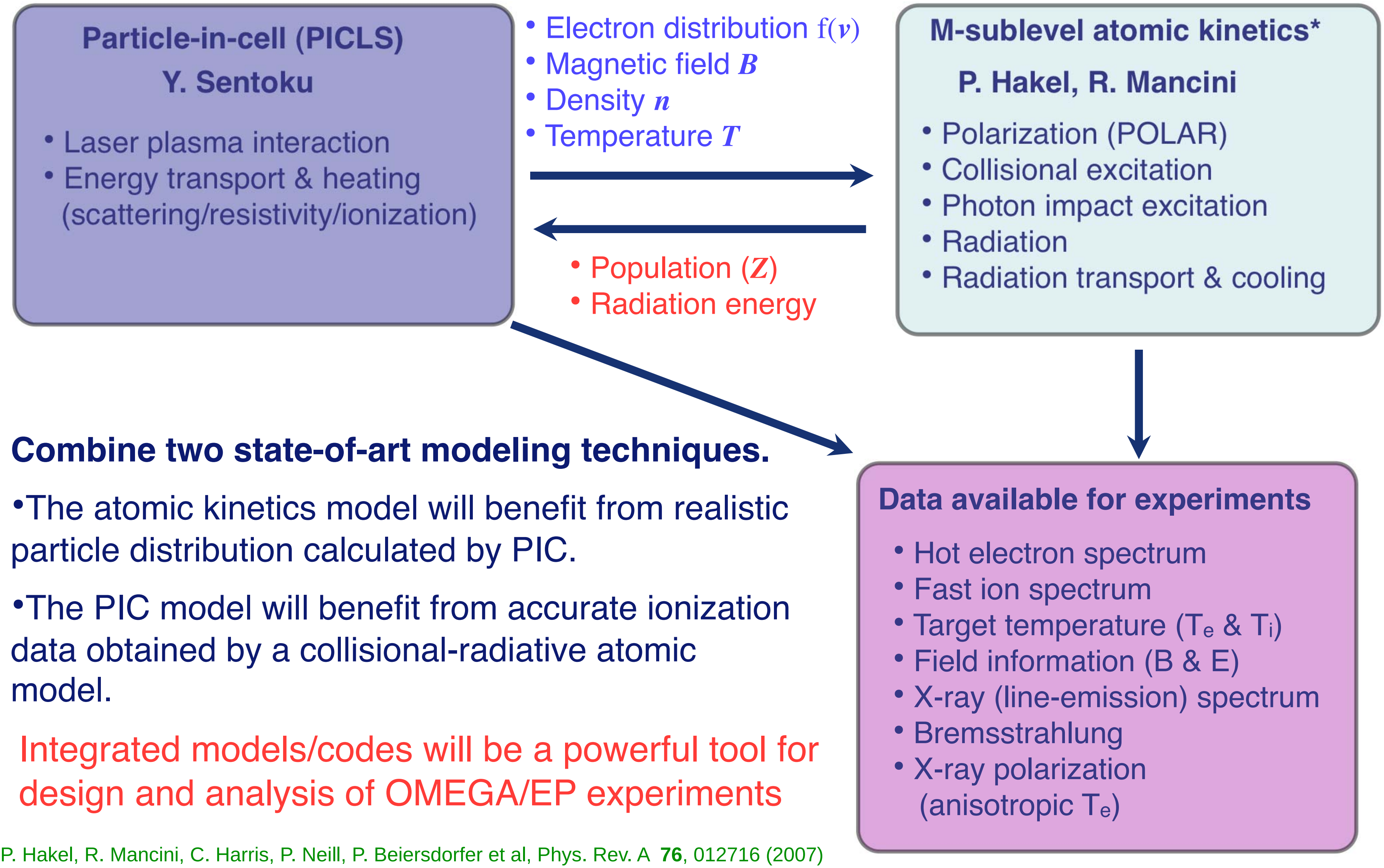
PICLS is a particle-in-cell simulation code, which is designed to solve the above issues, featuring the binary collisions among charged particles and the ionization processes.

"Numerical methods for particle simulations at extreme densities and temperatures"
Y. Sentoku and A. Kemp, Journal of Comp. Physics (2008)

Slide credit: Y. Sentoku

Integrated modeling and simulation project for HEDLP/LPI

- PIC simulation coupled to detailed atomic kinetics -



Particle-in-cell (PICLS)

Y. Sentoku

- Laser plasma interaction
- Energy transport & heating (scattering/resistivity/ionization)

- Electron distribution $f(\boldsymbol{v})$
- Magnetic field $\boldsymbol{B}$
- Density $\boldsymbol{n}$
- Temperature $\boldsymbol{T}$

M-sublevel atomic kinetics*

P. Hakel, R. Mancini

- Polarization (POLAR)
- Collisional excitation
- Photon impact excitation
- Radiation
- Radiation transport & cooling

- Population ($\boldsymbol{Z}$)
- Radiation energy

Data available for experiments

- Hot electron spectrum
- Fast ion spectrum
- Target temperature (T_e & T_i)
- Field information (B & E)
- X-ray (line-emission) spectrum
- Bremsstrahlung
- X-ray polarization (anisotropic T_e)

Combine two state-of-art modeling techniques.

•The atomic kinetics model will benefit from realistic particle distribution calculated by PIC.

•The PIC model will benefit from accurate ionization data obtained by a collisional-radiative atomic model.

Integrated models/codes will be a powerful tool for design and analysis of OMEGA/EP experiments

*P. Hakel, R. Mancini, C. Harris, P. Neill, P. Beiersdorfer et al, Phys. Rev. A **76**, 012716 (2007)

Conclusions

- Modeling and simulation plays a critical role in the design and analysis of OMEGA experiments
- The scope of the science in OMEGA experiments is broad → so is the scope of theory/modeling and simulation methods employed
- *For the graduate students: it will motivate you to review several of your core graduate courses … plus a few of the electives*
- Working with modeling/simulations and OMEGA experiments is a “two-way street”
- Modeling and simulation codes are “time-dependent” since they evolve as we use them to predict/explain new observations