Observations of spatially-resolved line spectra in OMEGA direct-drive implosions

H. M. Johns[1], R. C. Mancini[1], T. Nagayama[1], P.Hakel[1], V. A. Smalyuk[2], S. P. Regan[2], J. Delettrez[2]

[1]Physics Department at University of Nevada, Reno College of Science: Reno, Nevada 89557
[2]Laboratory for Laser Energetics, University of Rochester: Rochester, New York 14623

Titanium spectral model

- Step 1: compute opacity and emissivity database with CRAK[1], using CATS[2] atomic data:

$$k_\nu(\mathbf{x},t,\mathbf{n},\nu)=\sum_i\left(\sum_{j<i}\left(N_jB_{ji}-N_iB_{ij}\right)\phi_{ij,\nu}\,\frac{h\nu_{ij}}{4\pi}\right)$$

- Database grid:
  - 31 Te x 51 Ne x 3601 eV
    - 20eV Te resolution (300 – 900eV)
    - $5.4\times10^{23}\,\mathrm{cm}^{-3}$ Ne resolution (3×10^{24} – $3\times10^{25}\,\mathrm{cm}^{-3}$)
    - 4460-4820eV, 0.1eV resolution
- Improvement:
  - addition of high-order satellite transitions with n = 3 spectator electrons

- Step 2: transport continuum radiation coming from the core through Ti-doped layer in the shell to compute absorption spectra to determine Ti areal density.
- Step 3: use data recorded from simultaneous views along several TIM's to construct a 3D map of areal density modulations for analysis and comparison with hydrodynamic simulations.

[1] P. Hakel, R. C. Mancini. U. Andiel, K. Eidmann, F. Pisani, G. Junkel_Vives and J. Abdallah, HEDP **5**, 35 (2009)

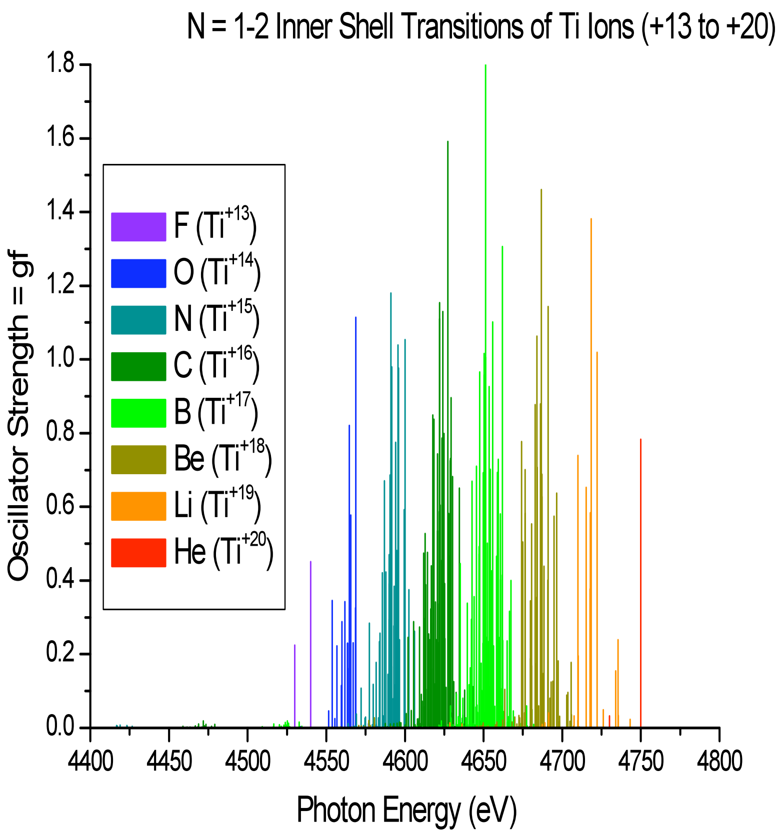
[2] Los Alamos National Laboratory, T-4 group atomic codes online: www.t4.lanl.gov (2007)

K-shell transitions included in the model

- K-Shell transitions of Ti^{+13} to Ti^{+20} ions
  - Transitions of the form:

$$1s^2 2s^n 2p^m \longrightarrow 1s^1 2s^n 2p^{m+1}$$

  - Final states are auto-ionizing excited states above the 1st ionization potential
    - Except for Ti^{+20} 1st excited state

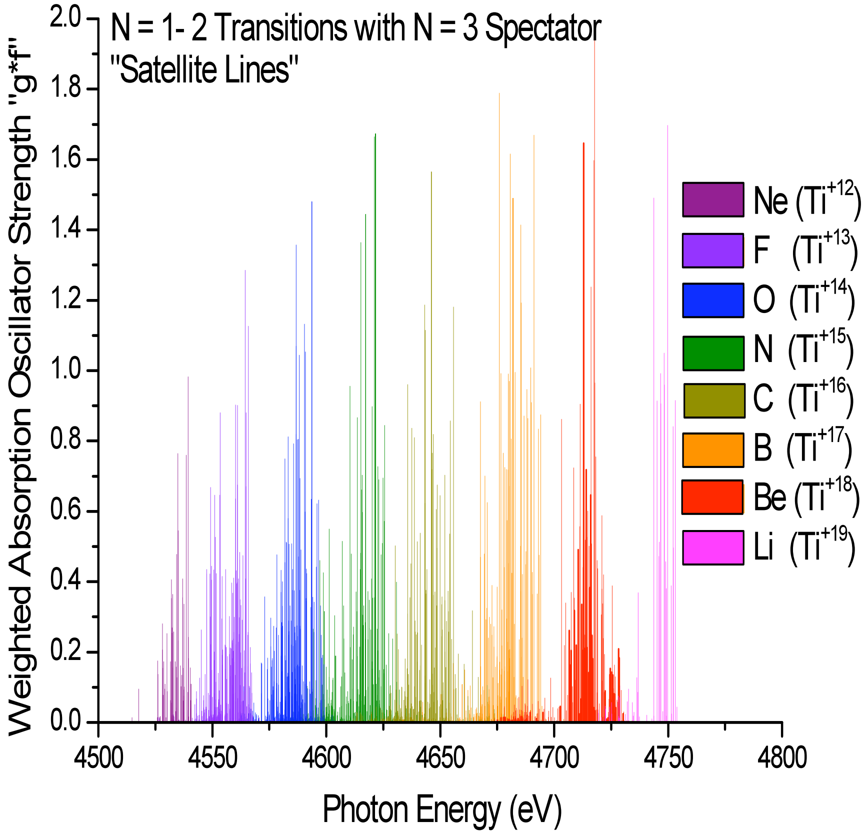


Additional satellite contributions

- K-shell transitions with n = 3 spectator electrons
  - Transitions of the form:

$$1s^2 2s^n 2p^m 3s \longrightarrow 1s^1 2s^n 2p^{m+1} 3s$$
$$1s^2 2s^n 2p^m 3p \longrightarrow 1s^1 2s^n 2p^{m+1} 3p$$
$$1s^2 2s^n 2p^m 3d \longrightarrow 1s^1 2s^n 2p^{m+1} 3d$$

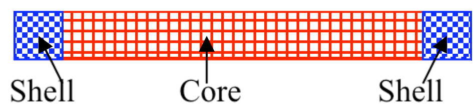
  - More complete accounting of ion populations
  - Satellite transitions are expected to be a significant source of broadening at late implosion times

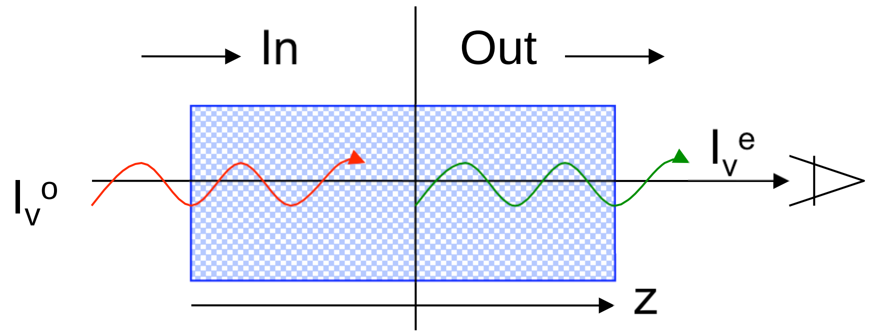


Radiation transport model

- The ends of each image chord sample information from the shell.
  - Each chord can be represented as a 1-d slab.
  - The observed Ti absorption I_v^e is fed by Bremsstrahlung emission from the core, I_v^o.

- We can calculate a synthetic spectrum I_v for any given Te and Ne values based on a database of photon-energy dependent emissivities and opacities, and an integral of the radiation transport equation along the chord of length z.



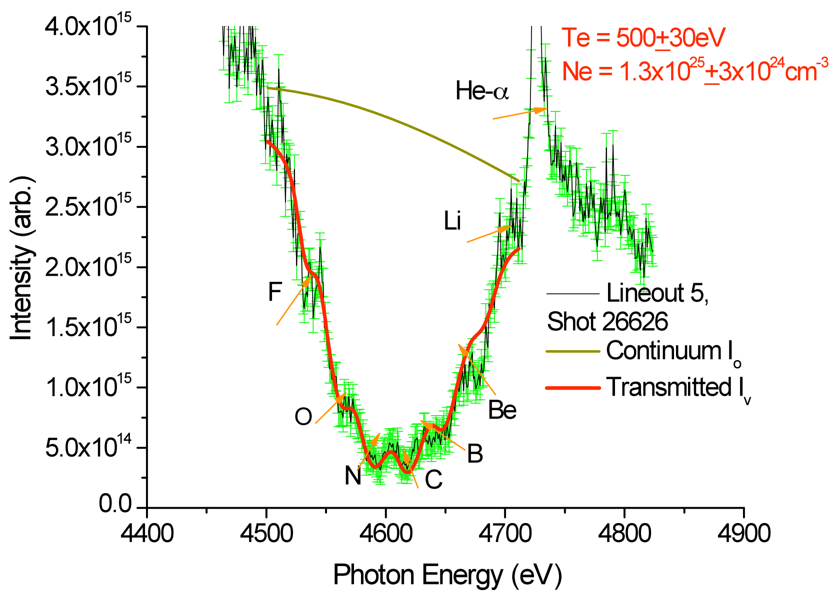


$$I_v = I_v^o e^{-\tau_v}$$

$$\tau_v = \frac{\pi e^2}{mc} f \Phi_v \rho r$$

Analysis of absorption spectrum

- Black trace: represents Ti absorption spectra from a lineout of OMEGA shot 26626[1], with standard deviations shown in green.
- Red trace: represents model approximation I_v
- Tan trace: is fit to continuum I_v^o determined from lineout.
- Typical range of χ^2 is 0.5 – 1.5.
- Analysis yields areal-density in the doped layer.
- However, if spectral resolution is sufficient, Te and Ne can also be extracted.



[1]V. A. Smalyuk, S. B. Dumanis, F. J. Marshall, J. A. Delettrez, D. D. Meyerhofer, S. P. Regan, T.C. Sangster and B. Yaakobi Phys. Plasmas **10**, 3 (2003)

Weighted least-squares minimization[1]

$$\chi^2(\rho r, Te, Ne) = \frac{1}{(N-M)} \sum_{\nu} \frac{1}{\sigma_\nu^{\;2}} \left[I_\nu^{Exp} - I_\nu^0 e^{-\tau_\nu(\rho r, Te, Ne)} \right]^2$$

Yields normalized χ^2

Weight by uncertainties in data points

Square of the difference between the experimental intensity and the model

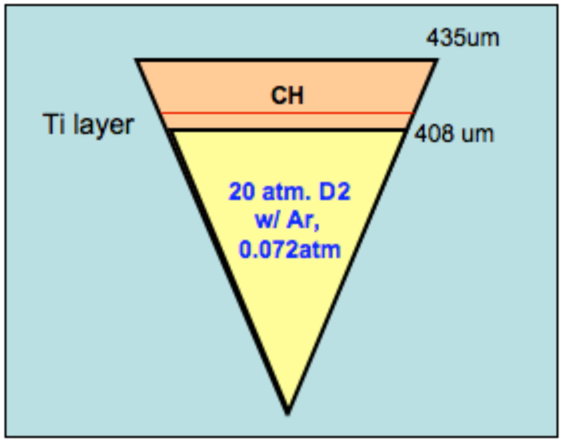
- X^2 will be calculated for each Te, Ne value in the database, but must be minimized with respect to ρr (the unknown) to obtain the best fit.

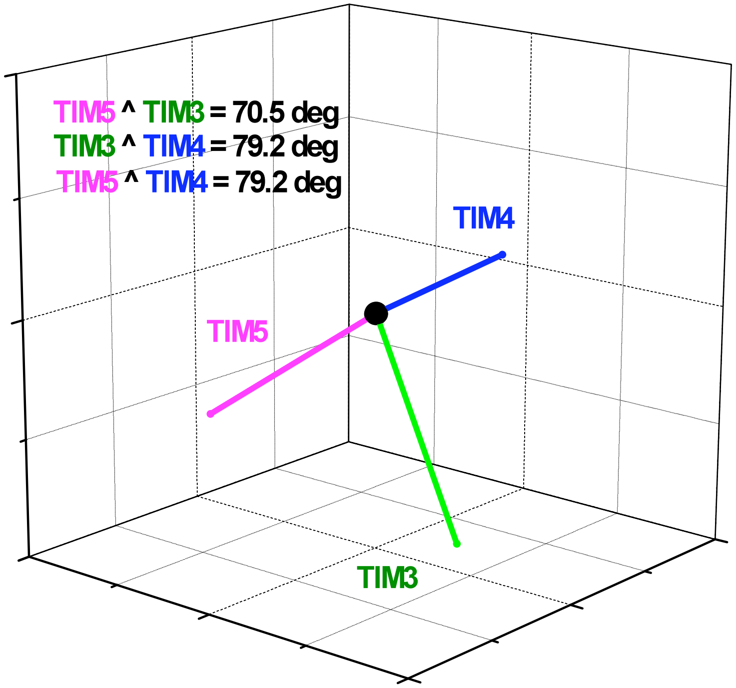
- Quantitative measure of goodness-of-fit:
  - $X^2 \sim 1$ the fit is within the uncertainties (“Good”)
  - $X^2 \ll 1$ the uncertainties are too high
  - $X^2 \gg 1$ the fit is outside the uncertainties (“Bad”)

[1]P.R. Bevington, D.K. Robinson, *Data Reduction and Error Analysis for the Physical Sciences*, 3rd ed. McGraw Hill: Boston, ©2003

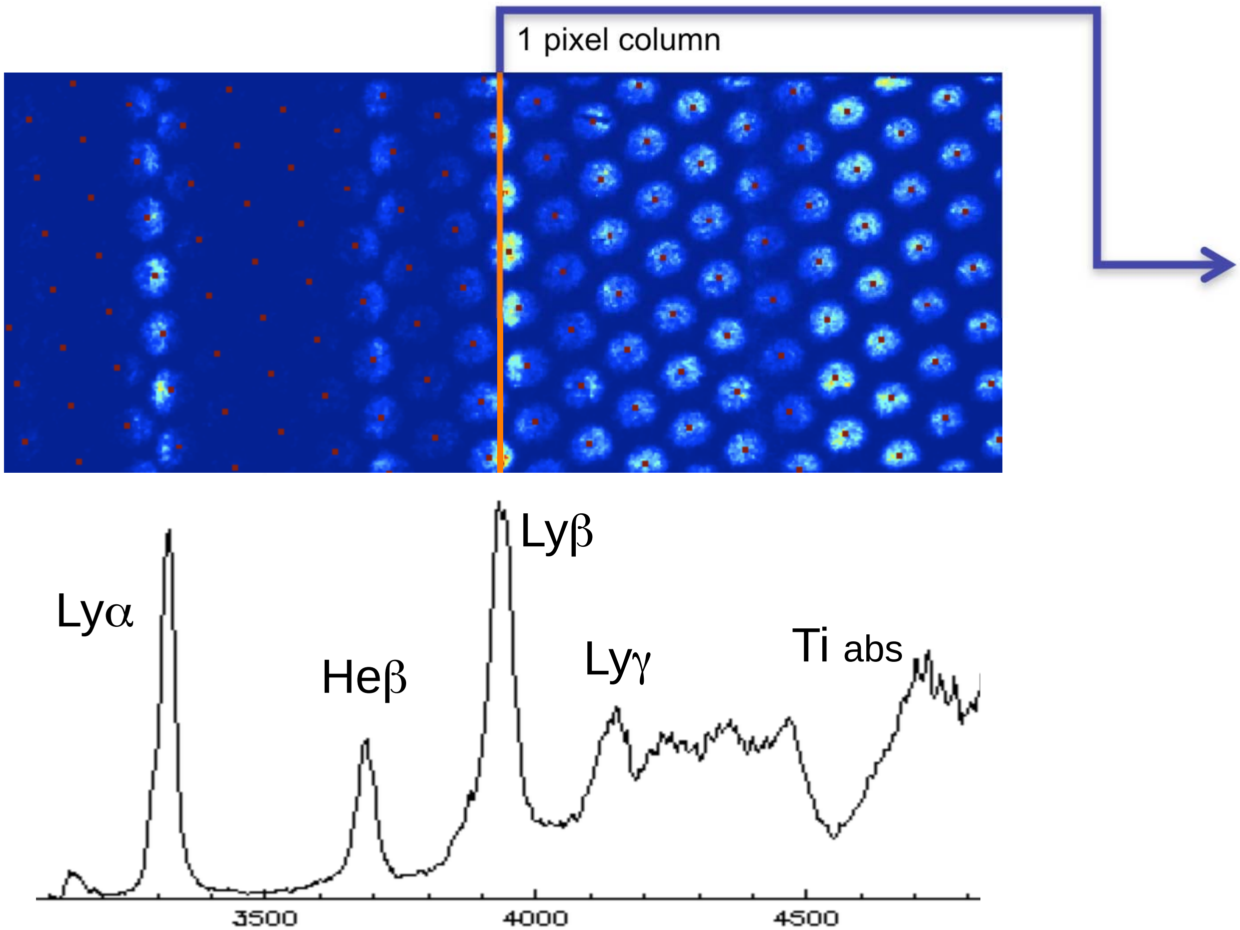
X-ray imaging of direct-drive OMEGA implosions

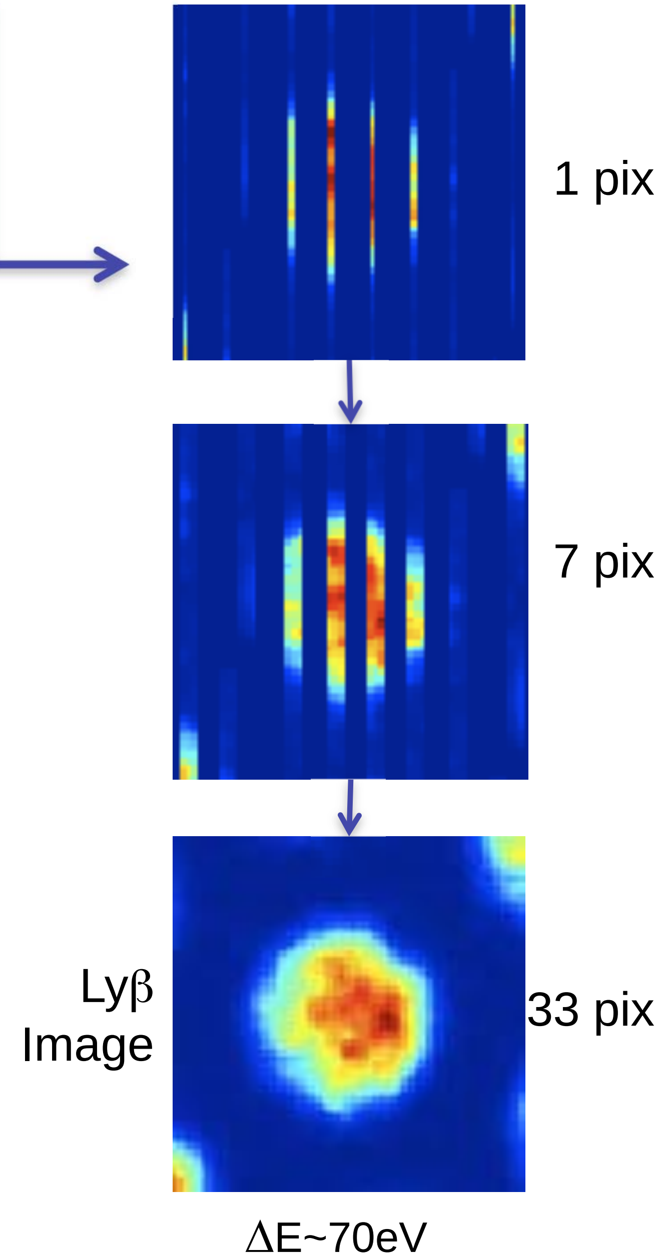
- Argon tracer added for core spectroscopic diagnostic of electron temperature and density
- Titanium-doped tracer layer added for diagnosis of un-ablated/compressed shell
- Three identical DDMMI
  - DDMMI = Direct-Drive Multi-Monochromatic x-ray Imager
  - Record gated narrow-band core image data (Δt ~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
  - SSC1, low-speed





MMI data processing: narrow-band image reconstruction

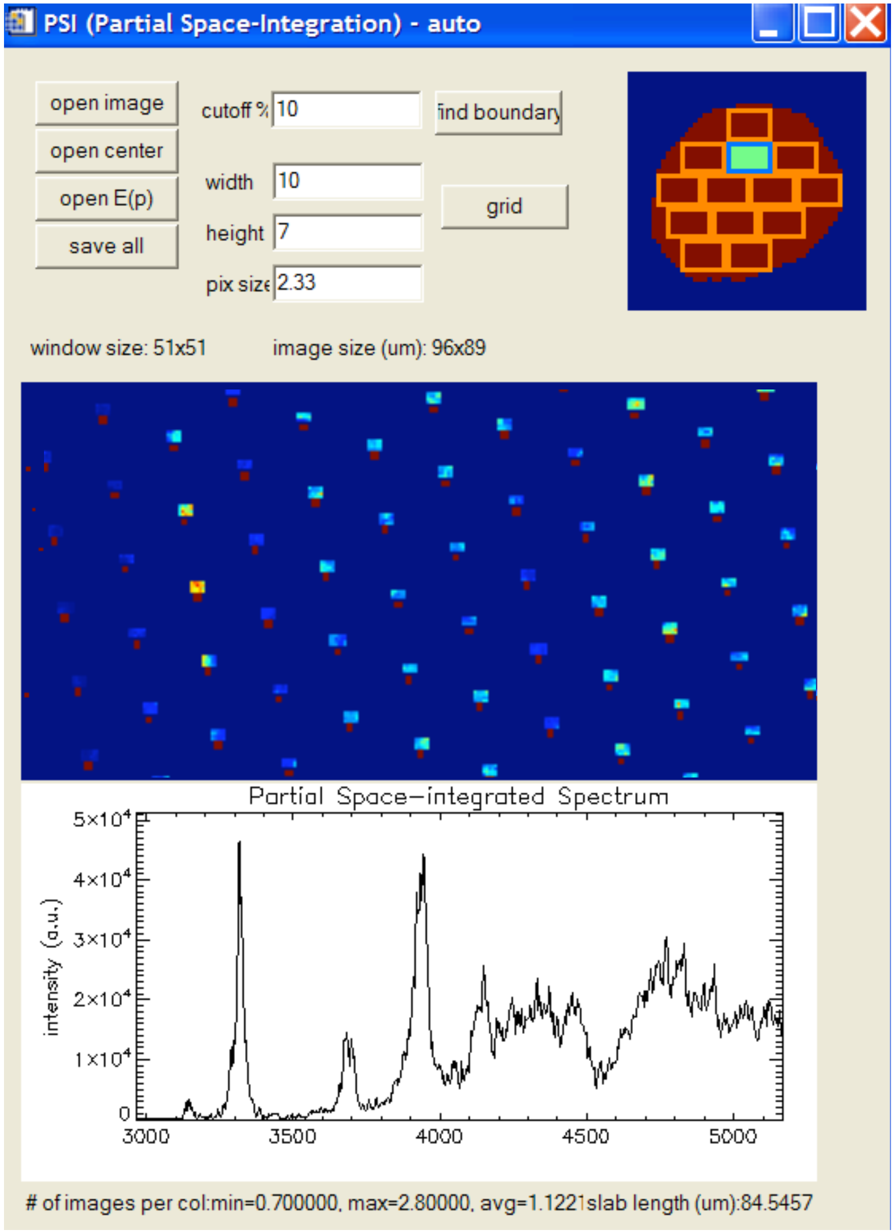




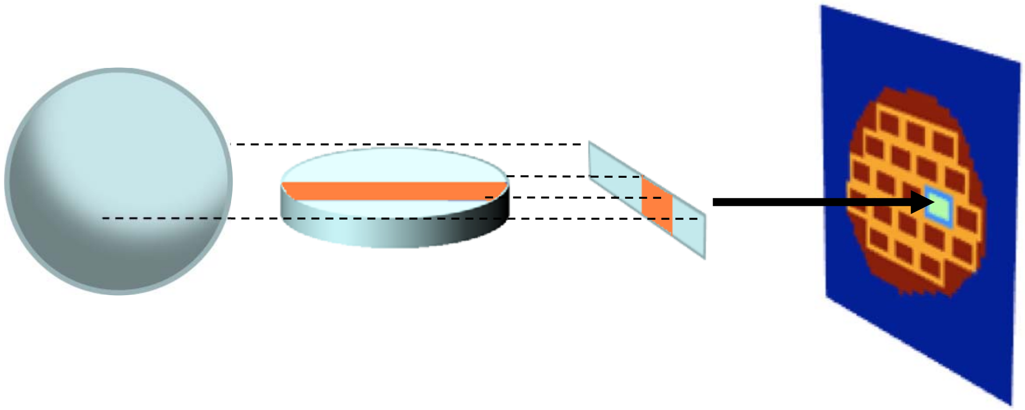
- For a given narrow band range, pixels are collected and reassembled into the local positions of the image with their nearest centers as their reference points
- Space-integrated spectrum can be computed by summing up intensities vertically for each photon energy

Spatially-resolved spectra from spectrally-resolved pinhole core images

- Space-integrated spectrum can be extracted from MMI 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



Integration domain of spatially-resolved spectra



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

- The domain of integration in the core of the spatially-resolved spectra is a chord of finite cross-section determined by the spatial-resolution of the MMI x-ray imager

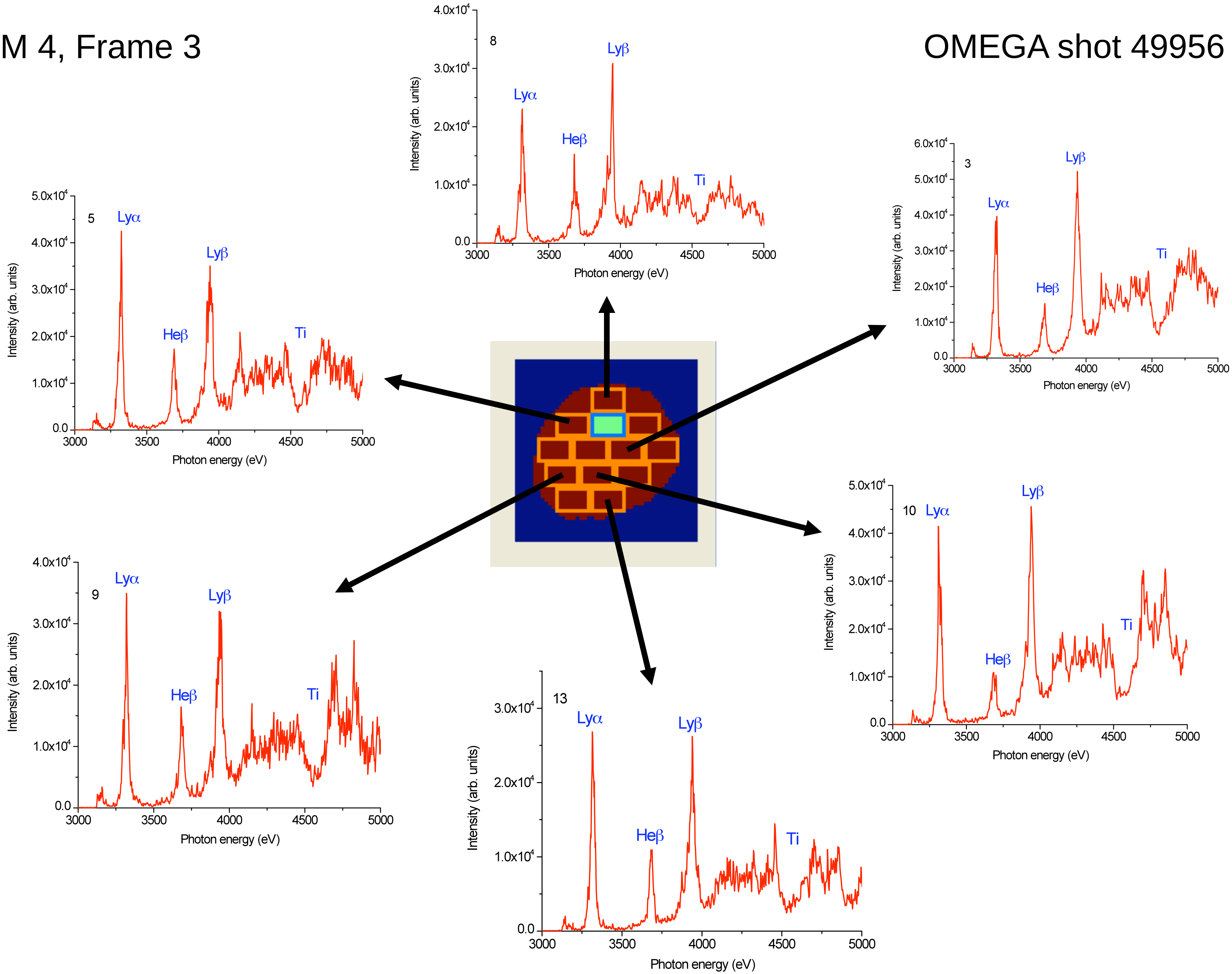
- In the schematic figure, this chord is indicated by an orange slab

- The spatially-resolved argon emission spectrum provides information about the spatial structure of the implosion core

- The spatially-resolved titanium absorption spectrum provides a map of the areal-density of the un-ablated plastic shell confining the core

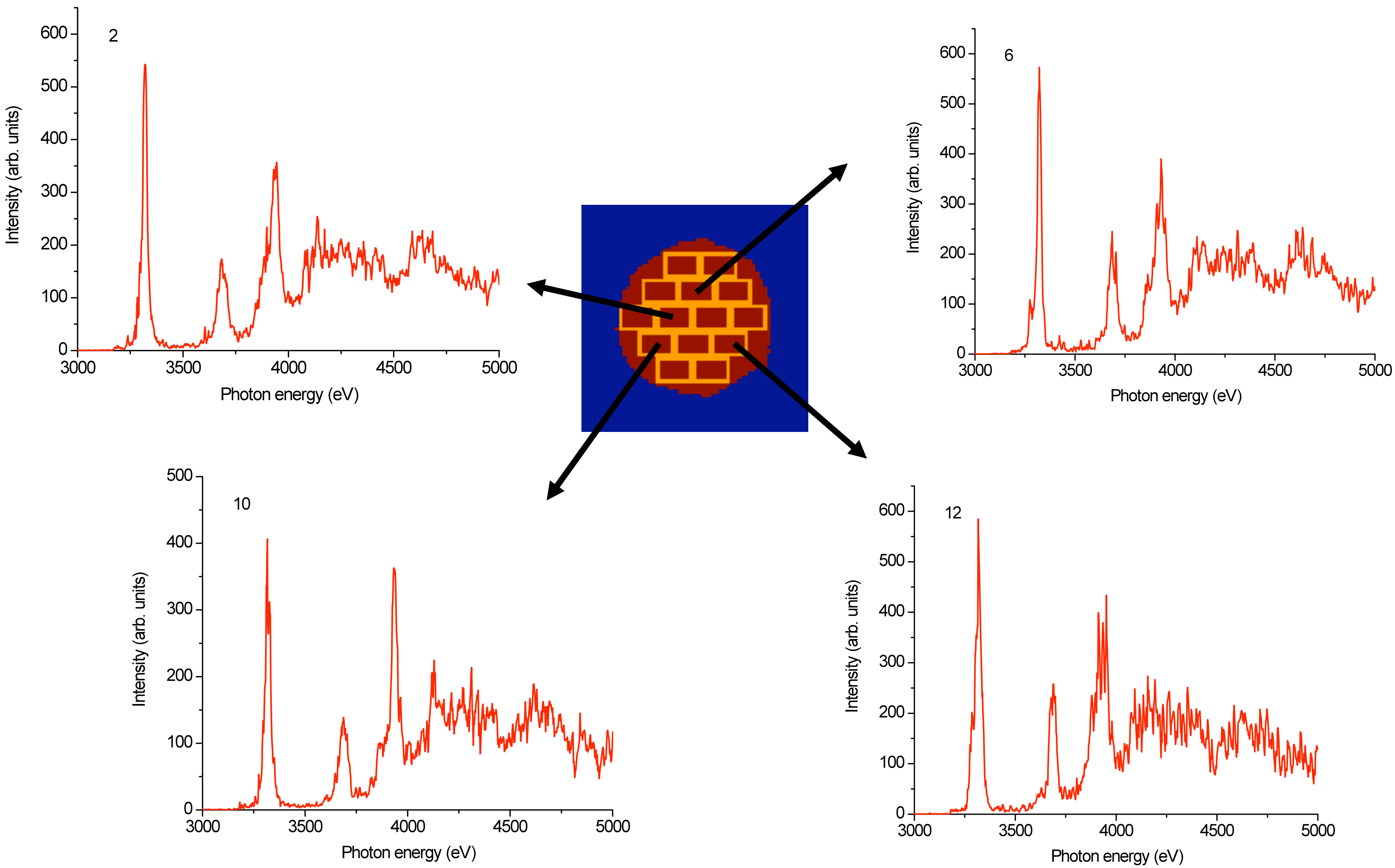
TIM 4, Frame 3

OMEGA shot 49956



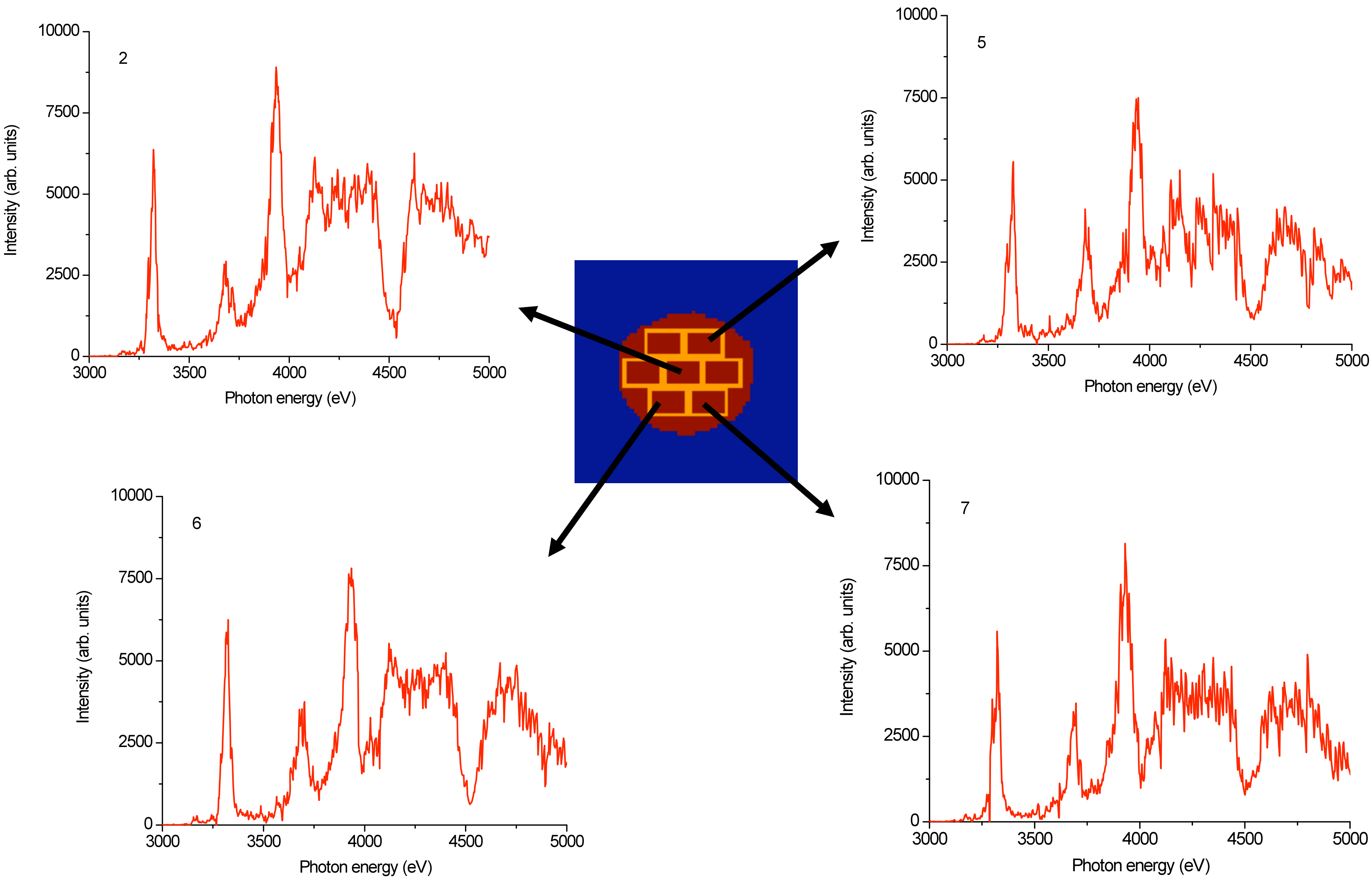
TIM 3, Frame 3

OMEGA shot 49956



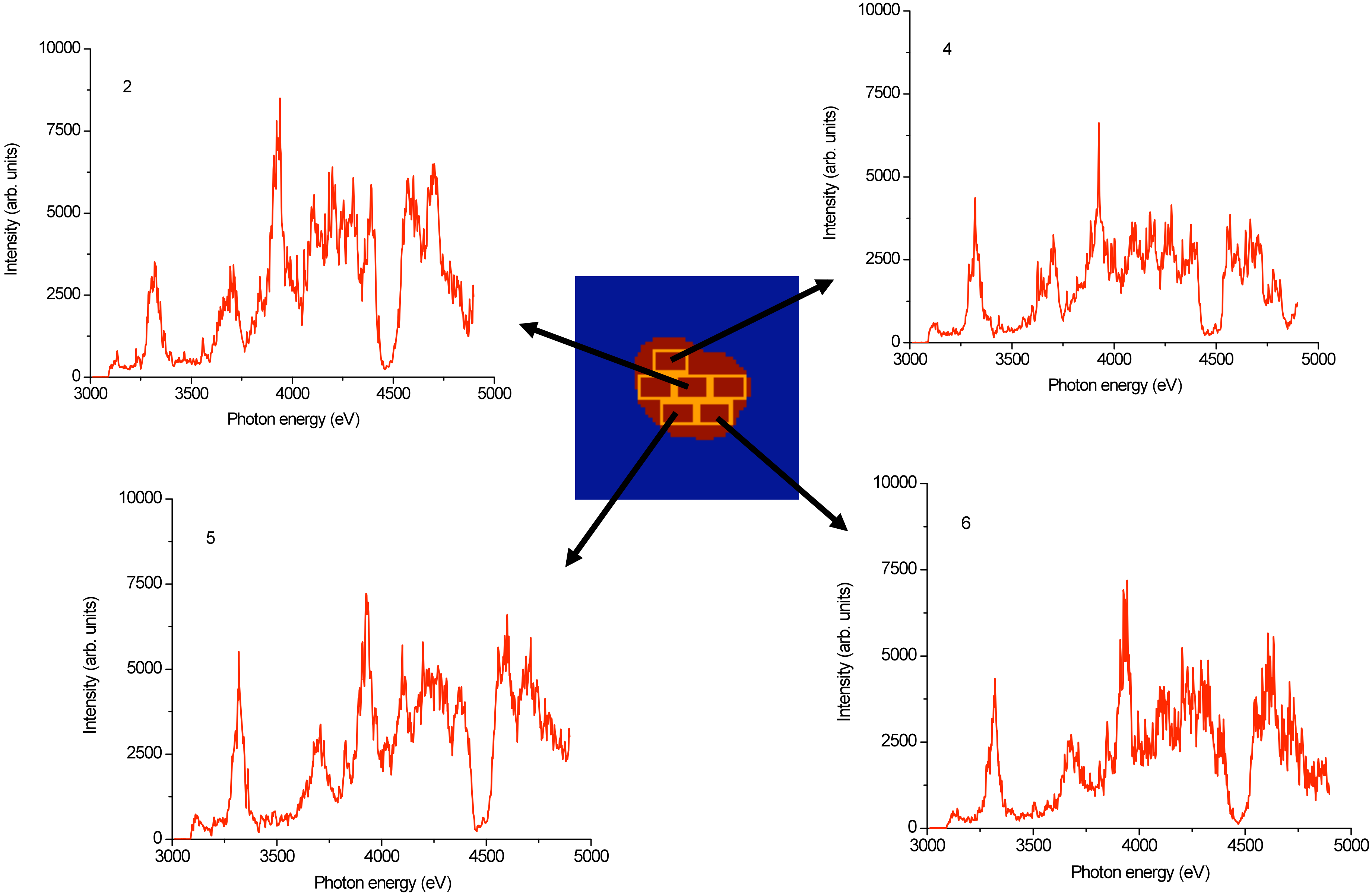
TIM 5, Frame 3

OMEGA shot 49956



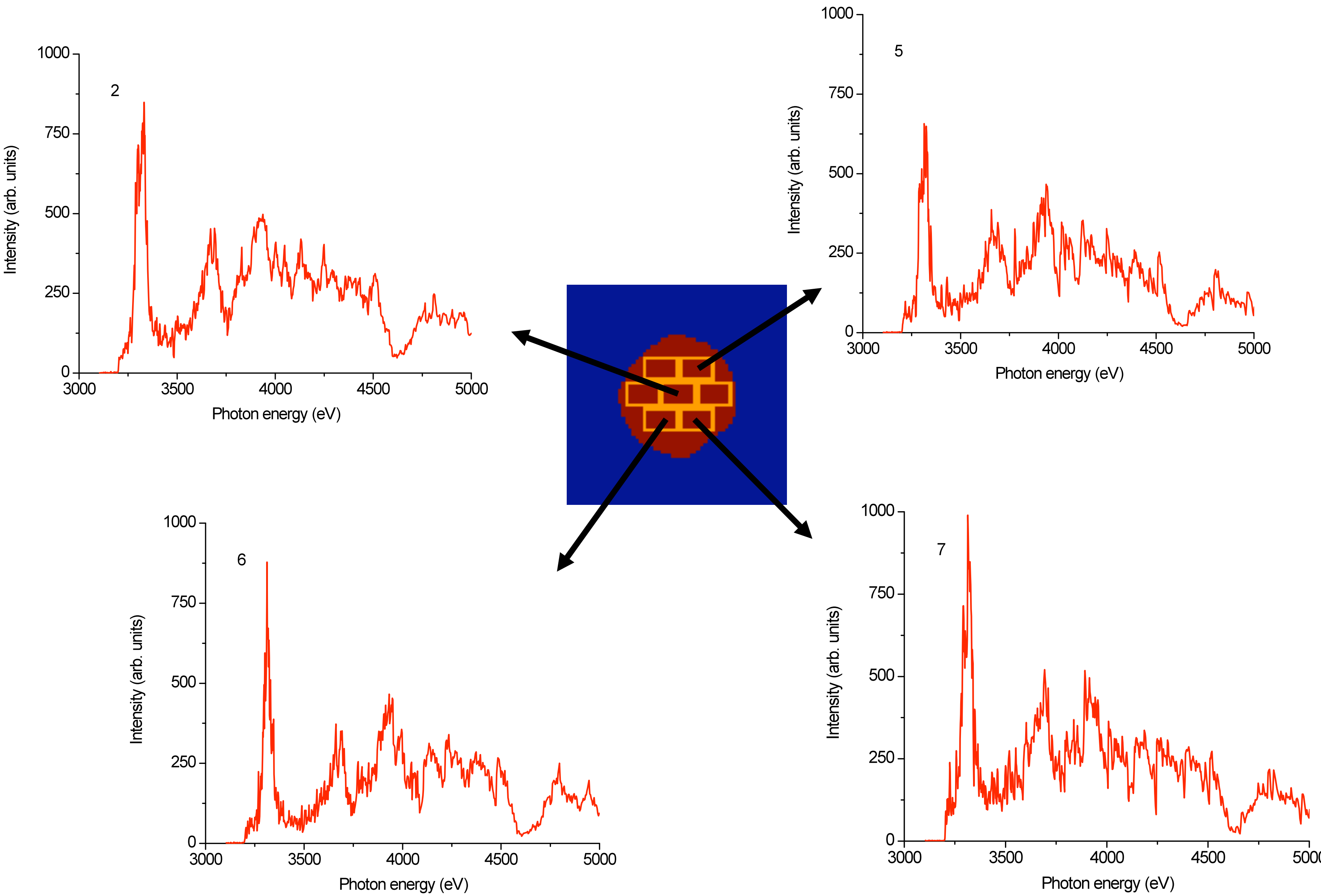
TIM 4, Frame 4

OMEGA shot 49956



TIM 3, Frame 4

OMEGA shot 49956



Conclusions

- We have discussed spectral lineouts from OMEGA shots with Ti-doped shells and Ar-doped cores.
- These lineouts are time- (gated) and spatially-resolved.
- Each lineout is produced by integrating small regions of the image that, in turn, correspond to integrations along chords in the implosion core.
- Lineouts show Ti absorption in the 4000-5000eV range with some He-α and Lyman-α emission features.
- A method for analyzing sets of spatially-resolved Ti absorption spectra for ρr determination, which can be used to determine 3D maps of ρr modulations in the imploded shell, has been discussed.
- Surface plots of ρr modulations can be compared with the results of 2D and 3D hydrodynamic simulations to be conducted later this year.

Work supported by DOE/NLUF Grant DE-FG52-07NA28062, and LLNL