Time- and space-resolved diagnosis of Omega implosion cores

R. C. Mancini

Physics Department, University of Nevada, Reno

2015 National ICF Diagnostics Workshop, Los Alamos, NM, October 6 – 8, 2015

Students, post-doc, and collaborators

- P. Hakel (Ph.D. 2001, LANL), L. Welser-Sherrill (Ph.D. 2006, LANL), T. Nagayama (Ph.D. 2011, SNL),

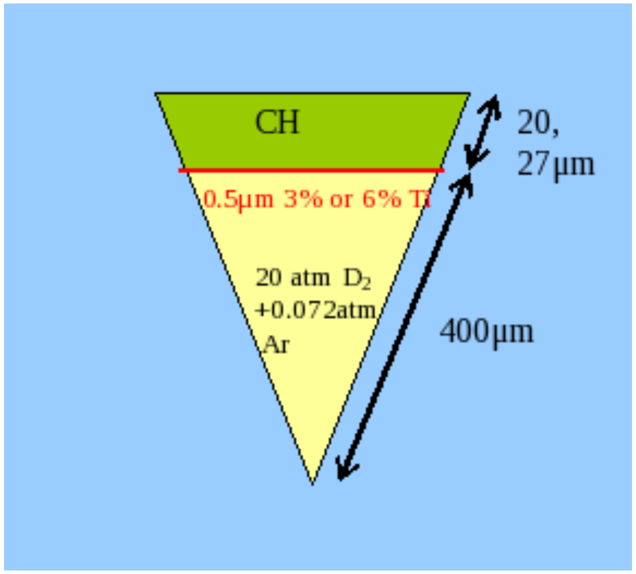
  H. Johns (Ph.D. 2013, LANL), T. Joshi (Ph.D. 2015, LANL)
- D. Mayes, D. Cliche, UNR
- R. Florido, ULPGC, Spain
- R. Tommasini, V. Smalyuk, LLNL
- S. Hsu, P. Bradley, J. Baumgaertel, J. Cobble,LANL
- J. A. Koch (NSTec)
- J. A. Delettrez, S. P. Regan, LLE, UR

Outline

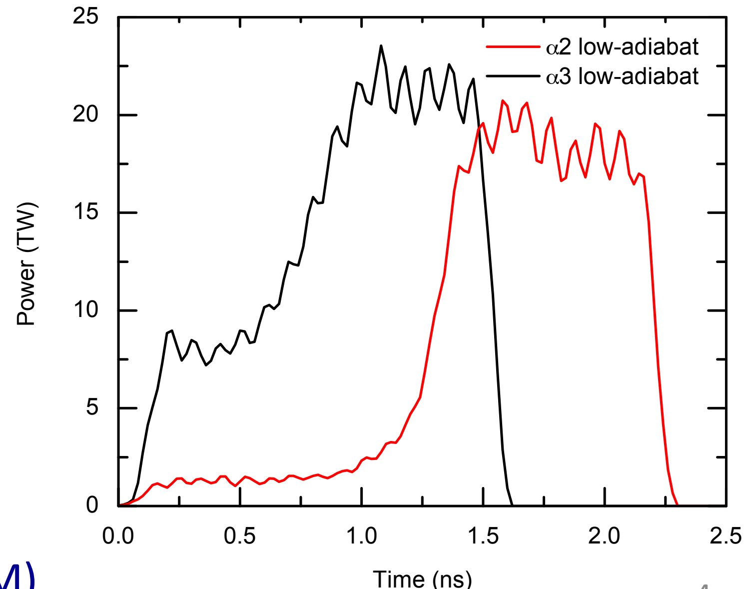
- X-ray spectroscopy has proven to be a powerful method to diagnose inertial confinement fusion (ICF) implosions
- Analysis of the emission/absorption spectrum from a suitable tracer element added to the core and/or shell permits the diagnosis of the plasma conditions under which the spectrum was formed
- The multi-monochromatic gated x-ray instrument MMI records arrays of spectrally resolved images
- MMI recorded data affords time, space and photon energy resolution of the implosion core
- We discuss analysis and results from direct-drive ICF implosion experiments performed at OMEGA
- In particular, the spatial distribution of temperature and density, and of a Ti tracer initially located on the inner surface of the shell

OMEGA direct-drive implosions

- Amount of Ar and Ti tracers has to be small:
  - Not to change the hydrodynamics
  - To keep the optical depth of the line transitions used for spectroscopic analysis small
  - **Ti-tracer: 3-6% atomic, 0.5µm thick on inner shell surface**
  - 5, 10 or 20 atmospheres of D_2 gas
  - Plastic shell thickness: 15, 20, 27 microns



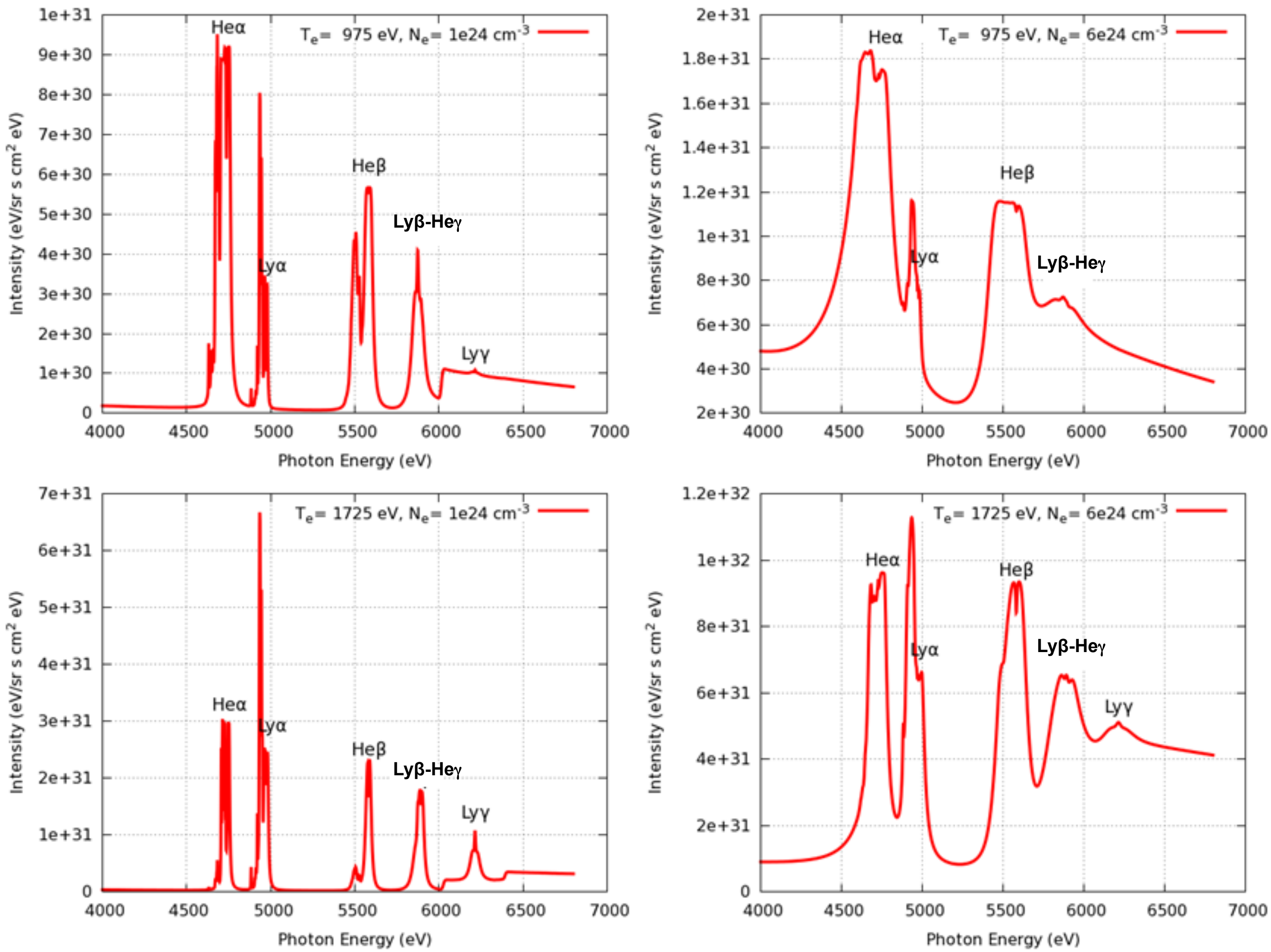
- Laser:
  - α2 and α3 low-adiabat pulse shapes
  - 60 beams, 20kJ to 23kJ UVOT
  - Smoothing: 2D-SSD/DPP-SG4/DPR



- Three x-ray spectrometers:
  - XRS1: crystal spectrometer (ADP)
  - SSCA: streaked, crystal spectrometer (RbAP)
  - MMI: multi-monochromatic x-ray imager (MLM)

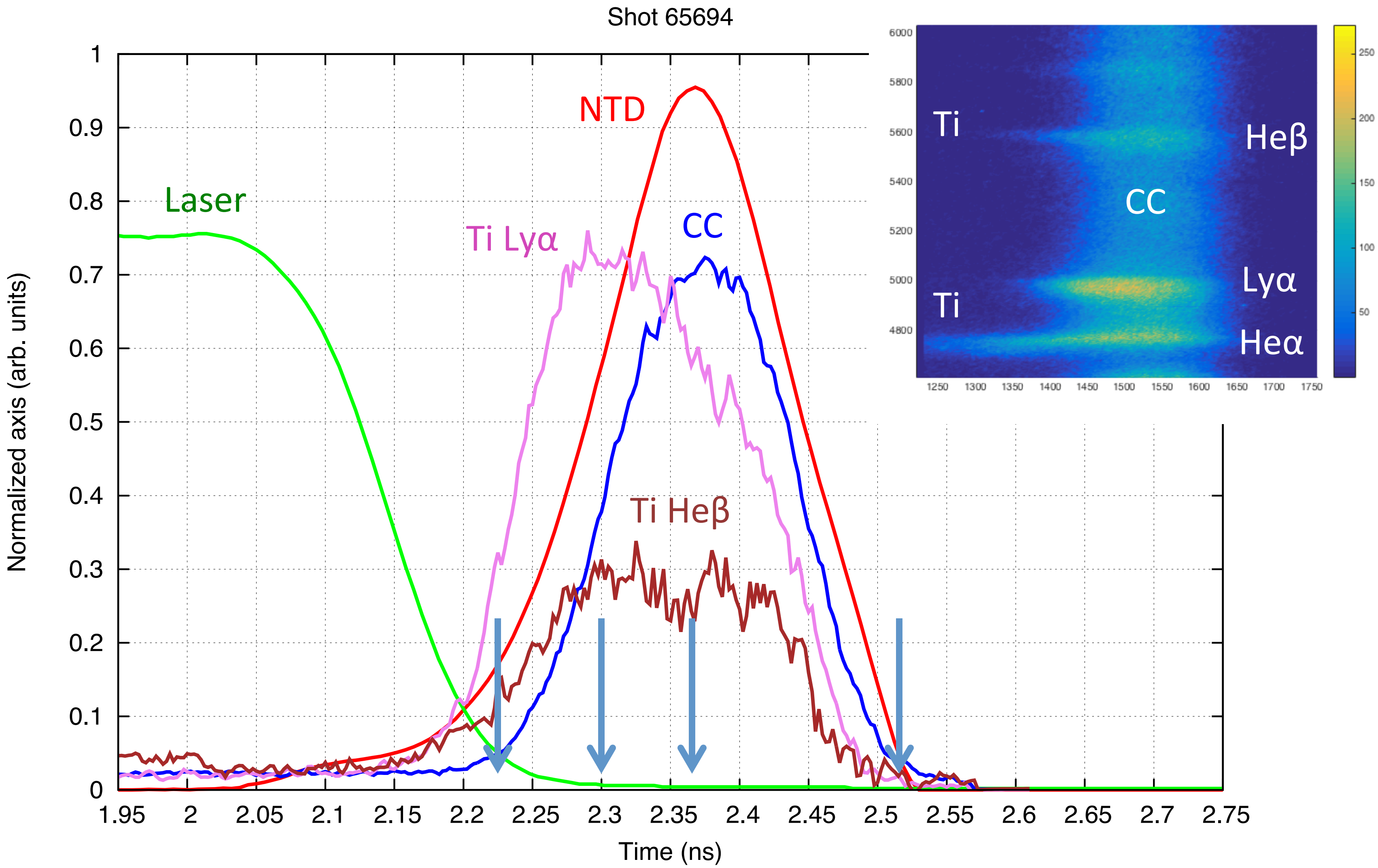
Titanium is a useful tracer to diagnose plasma conditions

T_e and N_e sensitivity through line intensities and Stark-broadened line shapes



Spectroscopic observations sample burning plasma

Consistent timing from three nominally identical shots: 65694, 65695 and 65696



Where is the Ti emission/absorption originating?

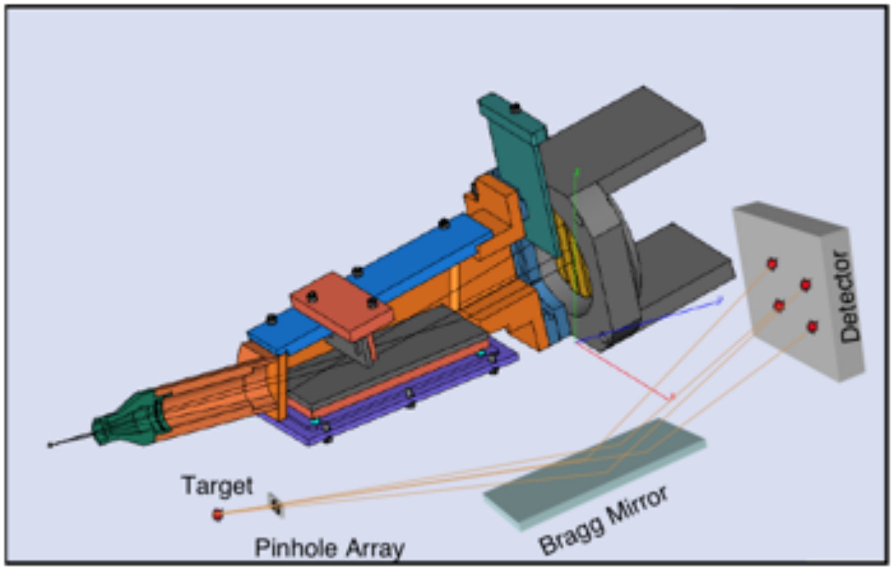
- Titanium spectra shows simultaneous emission and absorption
- Challenge: determine **both** the spatial distribution of tracer and implosion core conditions
- Unlike previous Ar core spectroscopy, the spatial distribution of the Ti tracer is unknown
- Streak data is time-resolved but space-integrated
- We address this issue using MMI data:
  - Titanium spatially resolved spectra from annular regions
- They can be extracted by processing the array of spectrally resolved images recorded with MMI[1,2,3]

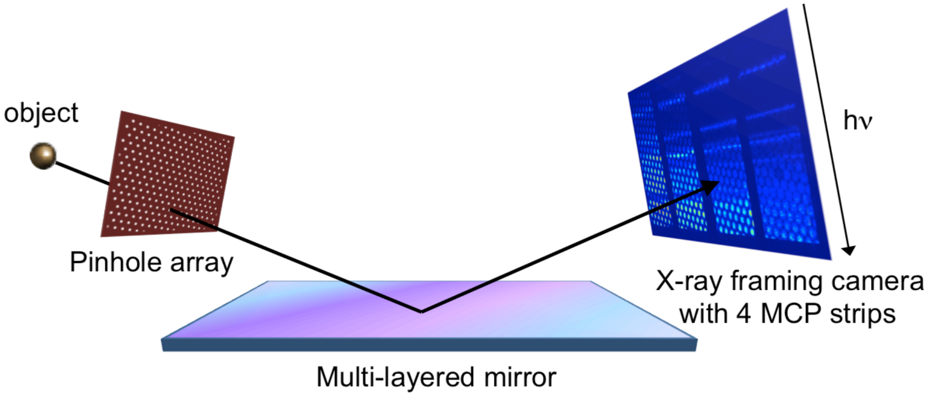
[1]T. Nagayama, R. C. Mancini, R.Florido, R. Tommasini, J. Koch, J. Delettrez, S. Regan, V. Smalyuk , J. Applied Physics **109**, 093303 (2011)
[2]T. Nagayama, R. C. Mancini, R.Florido, D. Mayes, R. Tommasini, J. Koch, J. Delettrez, S. Regan, V. Smalyuk , Phys. Plasmas **19**, 082705 (2012)
[3]T. Nagayama, R. C. Mancini, R.Florido, D. Mayes, R. Tommasini, J. Koch, J. Delettrez, S. Regan, V. Smalyuk , Phys. Plasmas **21**, 050702 (2014)

Spectrally resolved imaging with MMI

MMI ≡ multi-monochromatic x-ray imager[1-4]

- The OMEGA MMI was jointly developed by a UNR-LLNL collaboration as part of NLUF projects
- A pinhole-array coupled to a multi-layer Bragg mirror records arrays of gated, spectrally resolved images on a MCP based detector

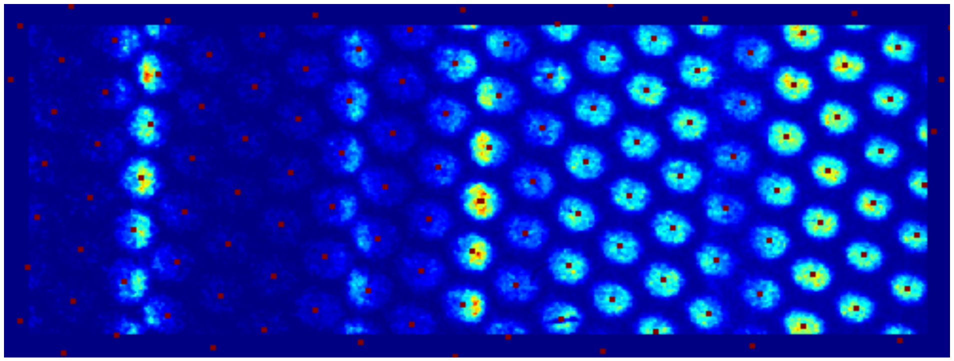




[1]L. Welser, R. C. Mancini, J. A. Koch, S. Dalhed, R. W. Lee, I. E. Golovkin, F. Marshall, J. Delettrez , L. Kelin, Rev. Sci. Instrum. **74**, 1951 (2003)
[2]J. A. Koch, T. W. Barbee, Jr., N. Izumi, R. Tommasini, R. C. Mancini, L. A. Welser,,F. J. Marshall, Rev. Sci. Instrum. **76**, 073708 (2005)
[3]R. Tommasini, J. Koch, N. Izumi, L. Welser, R. C. Mancini, J. Delettrez, S. Regan and V. Smalyuk, Rev. Sci. Instrum. **77**, 10E303 (2006)
[4]T. Nagayama, R. C. Mancini, R. Florido, R. Tommasini, J. Koch, J. Delettrez, S. P. Regan, V. Smalyuk, J. Applied Physics **109**, 093303 (2011)

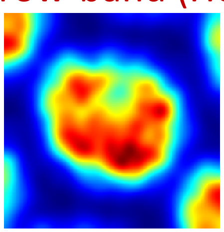
MMI records arrays of spectrally resolved images

- Resolution: $\Delta x \approx 10\ \mu m$, $E/\Delta E \approx 150$
- M = 8.1
- Frame separation: 100 ps

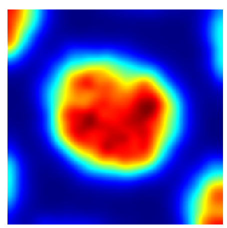


- MMI data are rich in information and can be processed to obtain[1,2]:

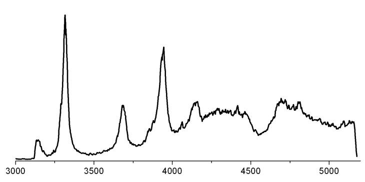
Narrow-band (Heβ)



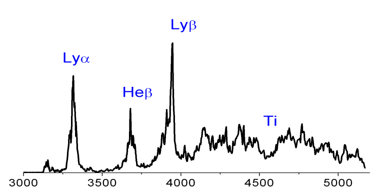
Broad-band

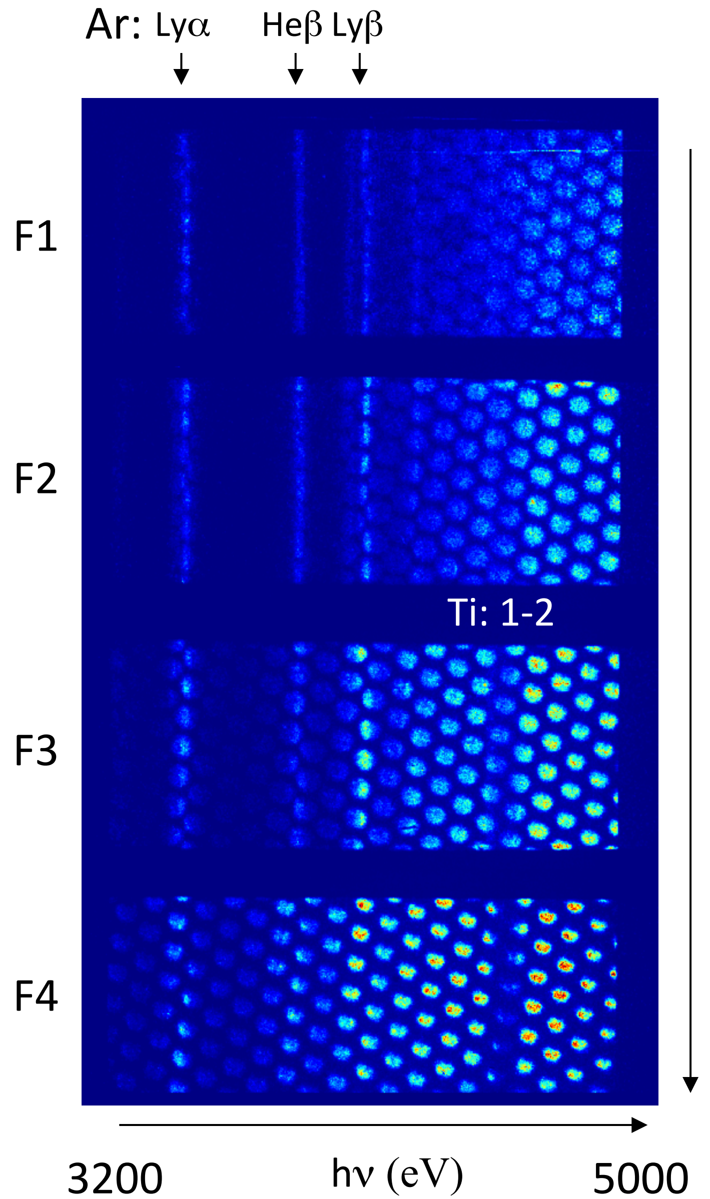


Space-integrated spectrum



Space-resolved spectrum





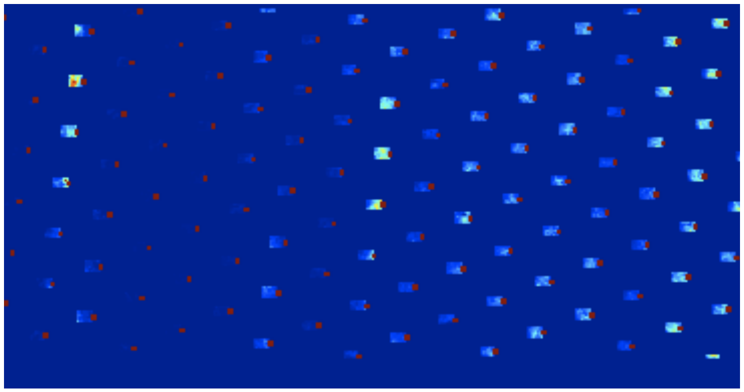
[1]T. Nagayama, R. C. Mancini, R. Florido, R. Tommasini, J. Koch, J. Delettrez, S. P. Regan, V. Smalyuk, J. Applied Physics **109**, 093303 (2011)

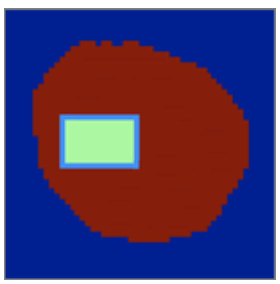
[2]R. C. Mancini, H. M. Johns, T. Joshi, D. Mayes, T. Nagayama, S. C. Hsu, J. Baumgaertel, J. Cobble et al, Phys. Plasmas **21**, 122704 (2014)

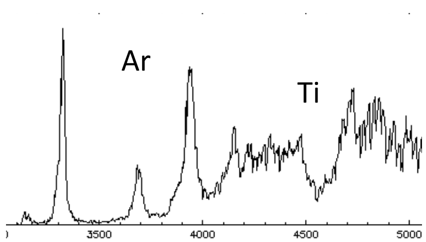
Spatially resolved spectra from spectrally resolved images

Contributions are taken **only** from a selected region of the image as a function of photon energy

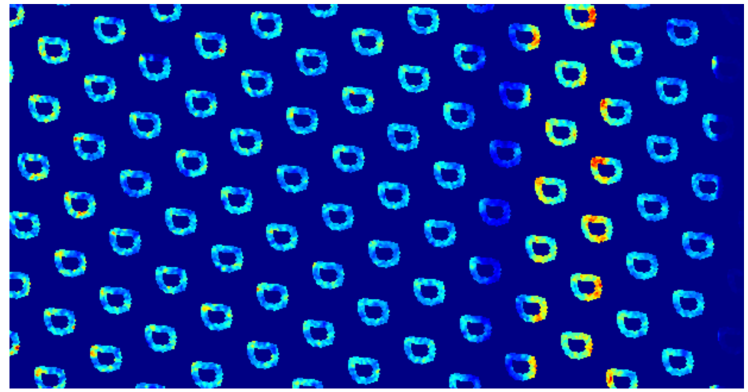
Rectangular regions

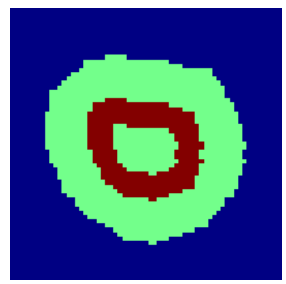


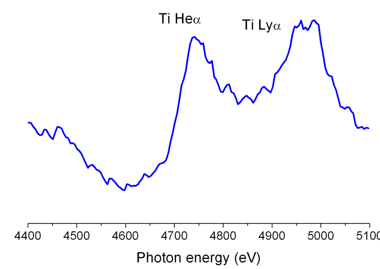




Annular regions







Relevant for polychromatic tomography[1], and extraction of areal-density maps[2]

Relevant for tracking tracer distribution and penetration into the core[3]

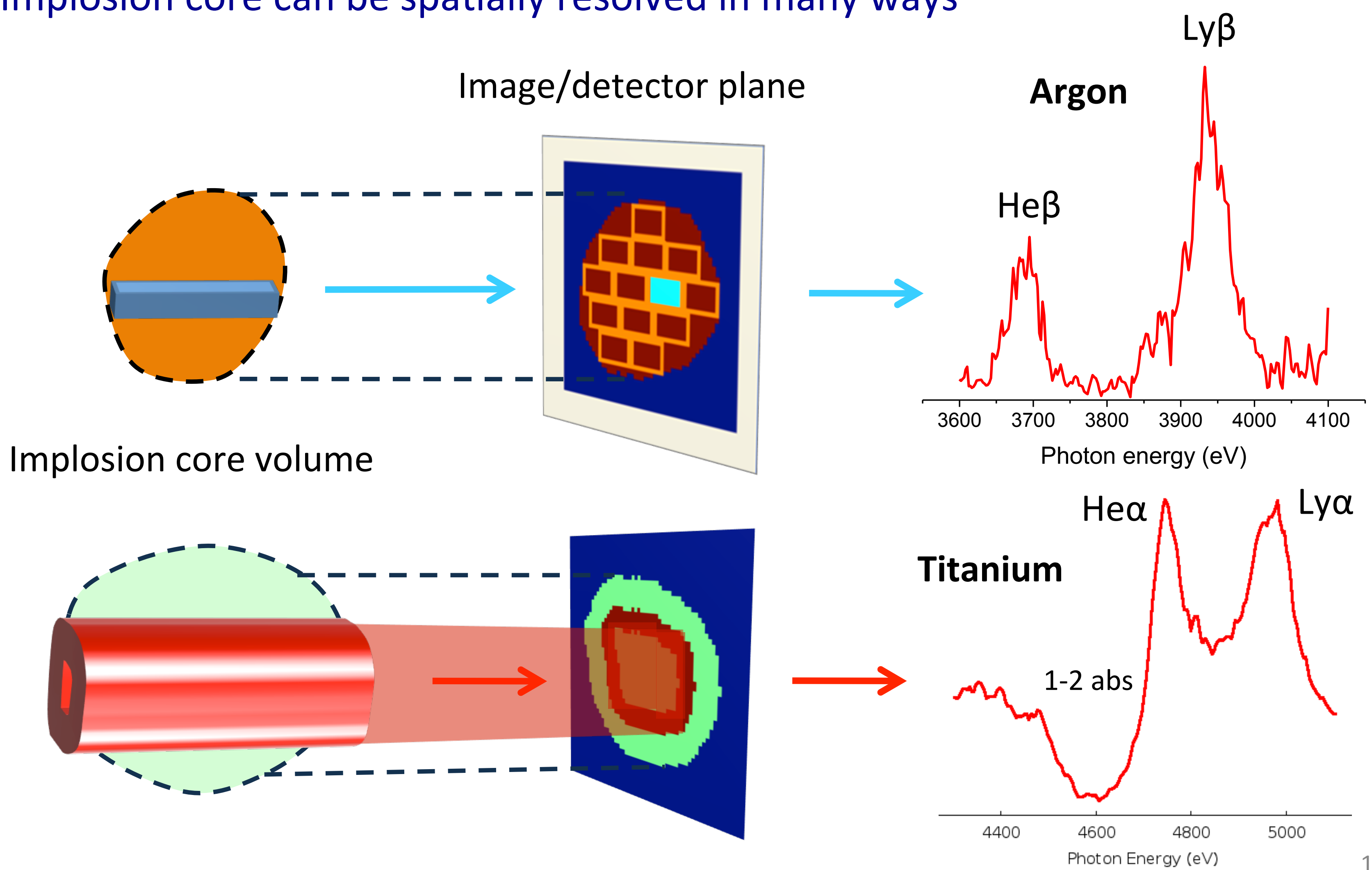
[1]T. Nagayama (Ph.D. dissertation UNR 2011); T. Nagayama, R. C. Mancini, R.Florido, D. Mayes et al , Phys. Plasmas **19**, 082705 (2012)

[2]H. M. Johns (Ph.D. dissertation UNR 2013); H. M. Johns, R. C. Mancini, P. Hakel, T. Nagayama et al, Phys. Plasmas **21**, 082711 (2014)

[3]T. Joshi et al, in preparation for publication

Interpretation of spatially resolved spectra

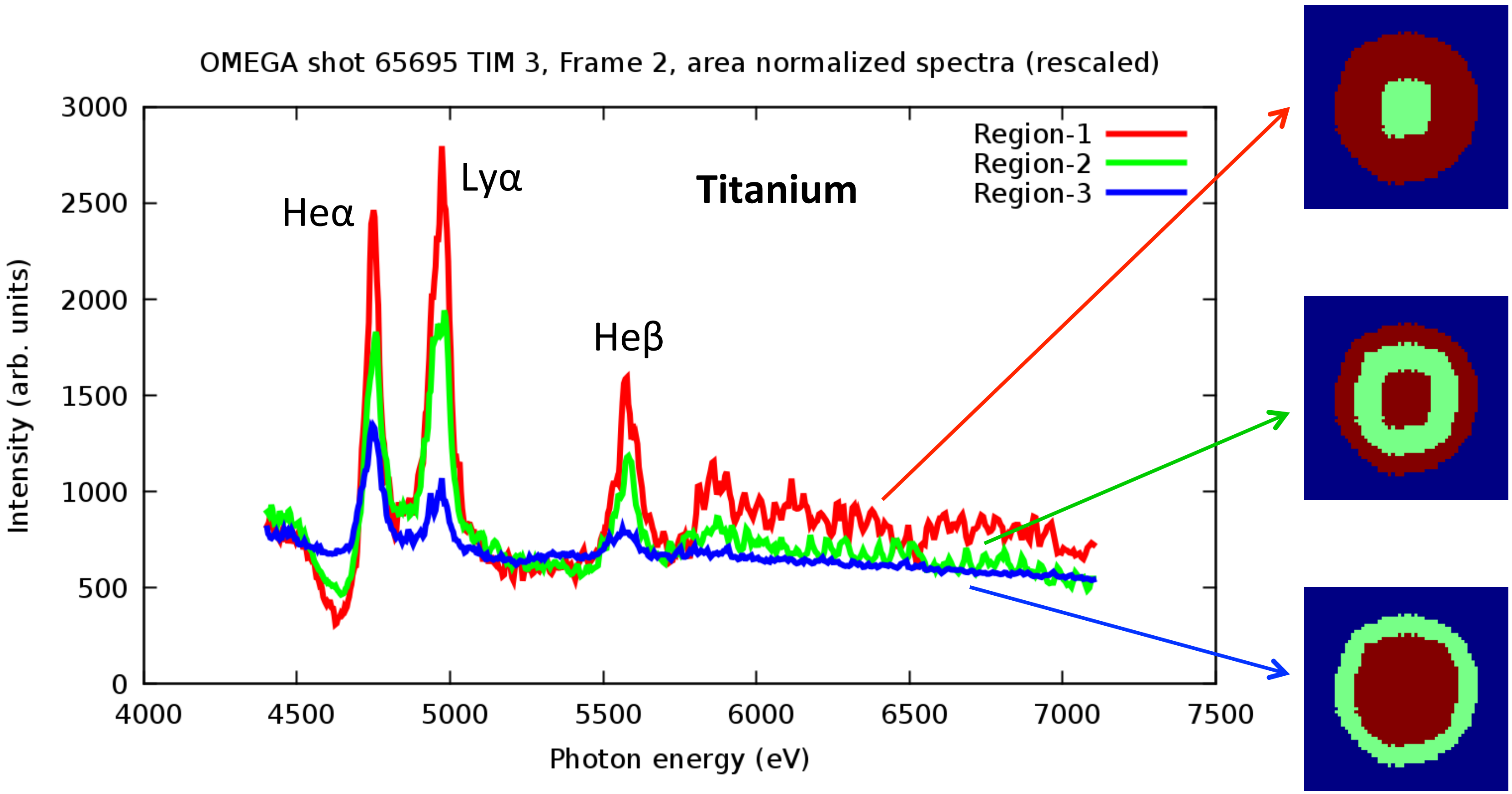
- The selection of image region defines the domain of integration in the core
- There is flexibility in the selection of the image region[1]
- Implosion core can be spatially resolved in many ways



1. T. Nagayama, R. C. Mancini, R. Florido, D. Mayes, R. Tommasini, J. Koch, J. Delettrez, S. Regan , V. Smalyuk, Phys. Plasmas **21**, 050702 (2014)

Annular spectra show characteristic intensity distributions

- The characteristics of the spectra reflect plasma conditions in different parts of the core, and provide an interpretation for the formation of the spectral features[1]
- They also provide direct evidence of Ti tracer penetration into the core



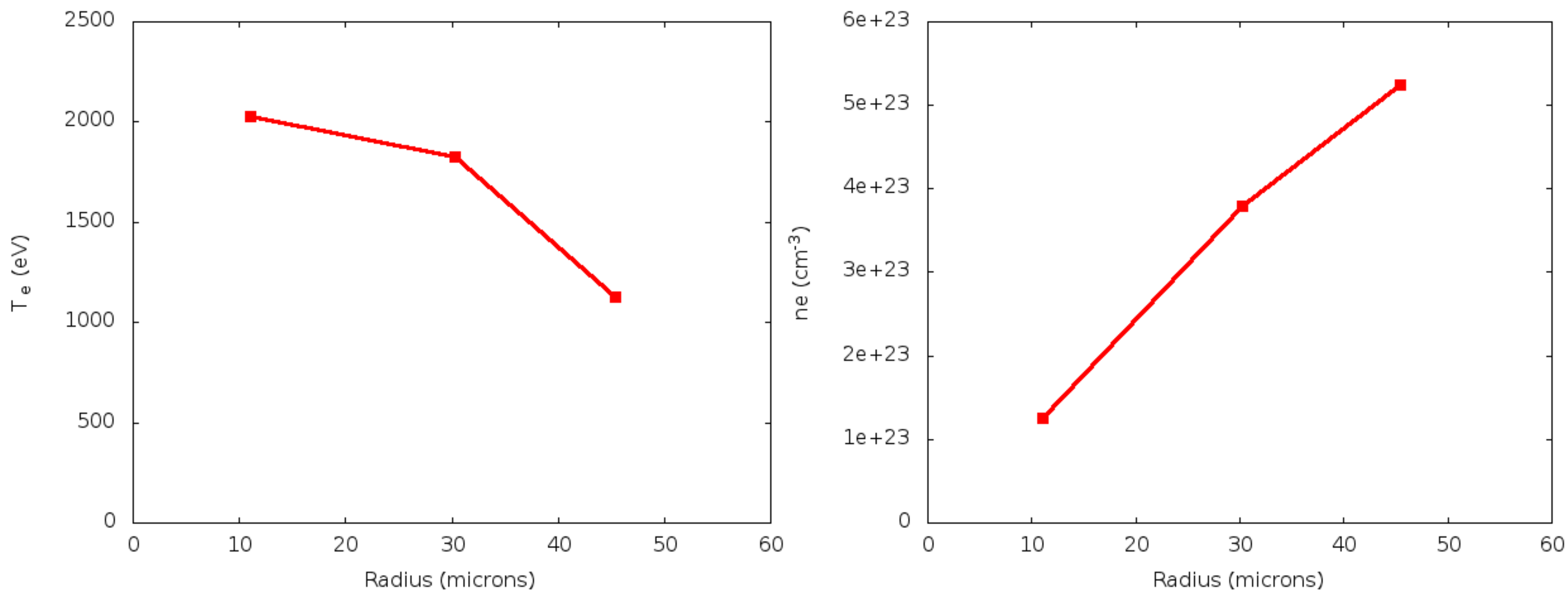
[1]T. Joshi et al, in preparation for publication

Analysis of annular spatially resolved spectra

- Electron temperature and density spatial distributions extracted from the analysis of the Ti spectra shows that the Ti tracer, initially located on the shell's inner surface, has moved deep into the core[1]
- Temperature uncertainty is ≈ 10%
- Density uncertainty is ≈ 15%

OMEGA shot 65695 TIM 3 Frame 2

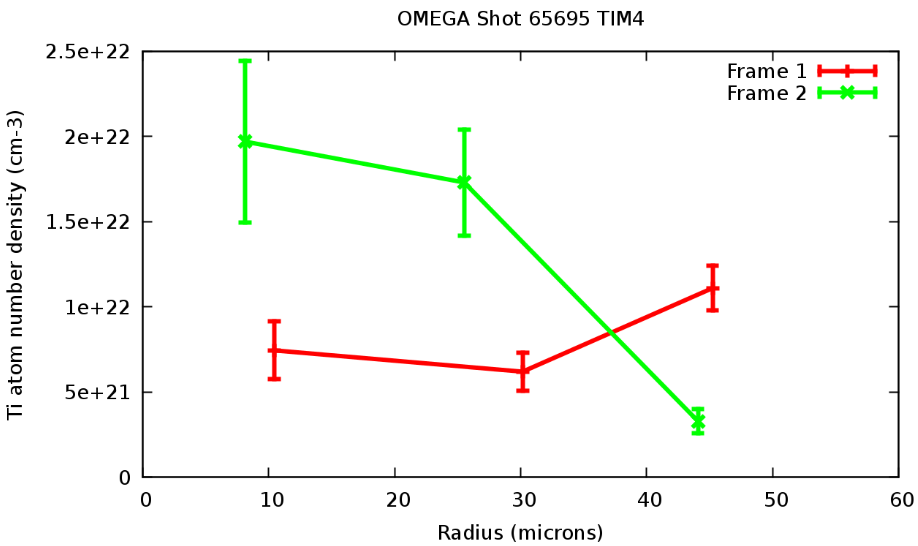
Laser pulse: α_2, shell thickness: 15 microns, filling pressure: 10 atm

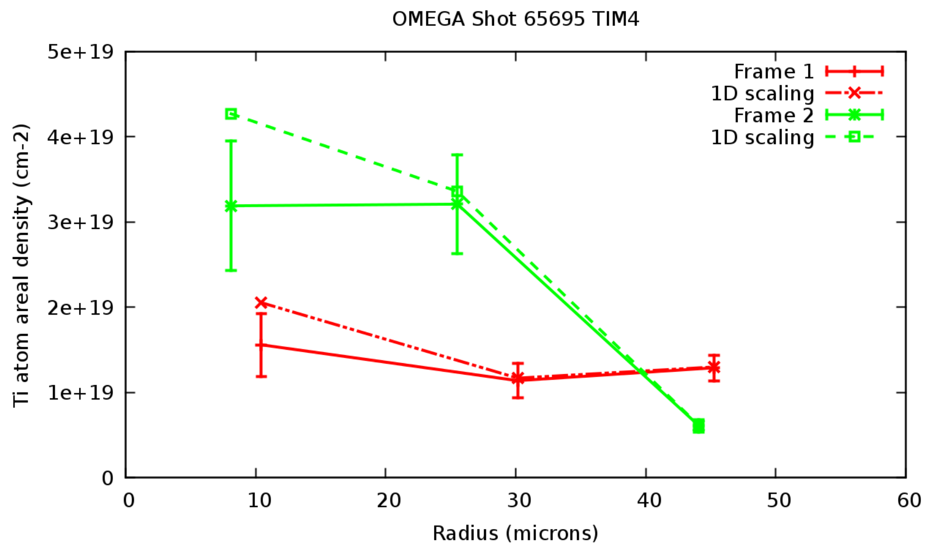


[1]T. Joshi et al, in preparation for publication

Time evolution of Ti penetration into the core

- Shot 65695: α2 pulse shape, ΔR=15μm, filling pressure=10atm
- Frame2 is approximately 80ps later than Frame 1



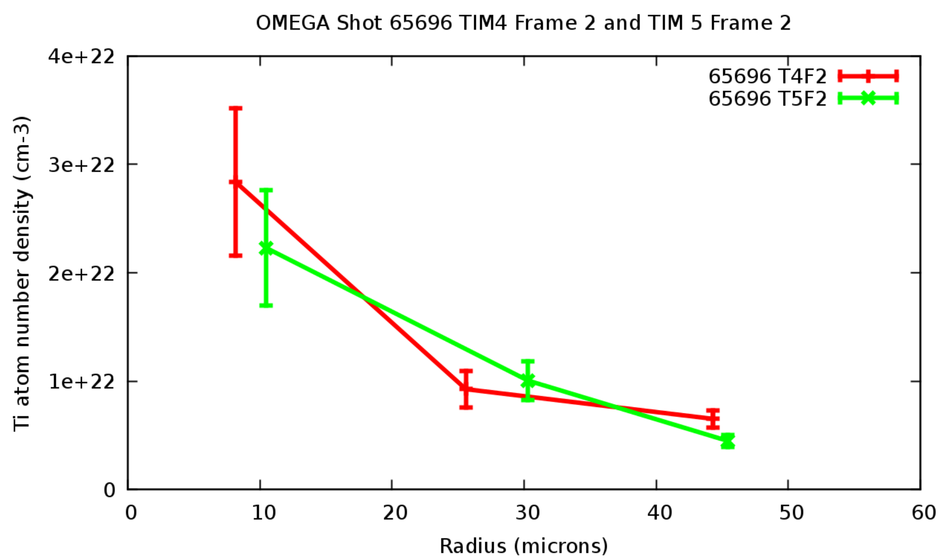


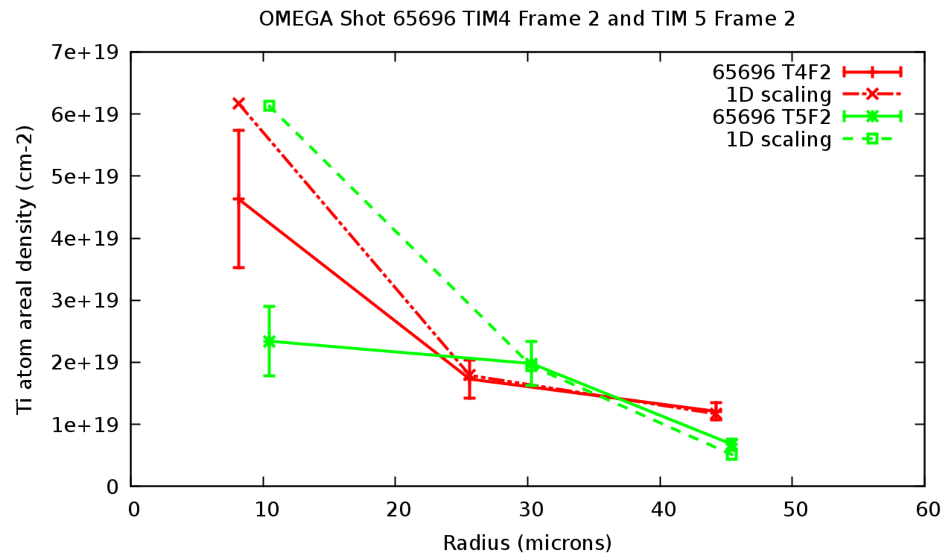
- The Ti atom number density profile evolves towards a centrally peaked distribution[1]
- This is in part due to a geometry effect
- 1D spherical geometry scaling: $(n_{Ti}\Delta r) = \frac{{R_0}^2}{R^2}(n_{Ti}\Delta r)_0$
- Middle and outer zones areal-densities compare well with 1D scaling
- Innermost zone areal-densities are smaller than 1D scaling by about 25%

[1]T. Joshi et al, in preparation for publication

Multiview observation of Ti penetration into the core

- Shot 65696: α2 pulse shape, ΔR=15μm, filling pressure=10atm
- Shots 65696 and 65695 are nominally identical
- TIM4 Frame 2 and TIM5 Frame 2 have approximately the same times
- TIM4/5 Frame 2 of 65696 is a little earlier than Frame 2 of 65695





- The MMI data of each TIM is independently analyzed
- A larger areal density difference relative to 1D scaling is observed along TIM5 compared to TIM4[1]
- Frames are characteristic of first half of and about burning-rate peak

[1]T. Joshi et al, in preparation for publication

Summary

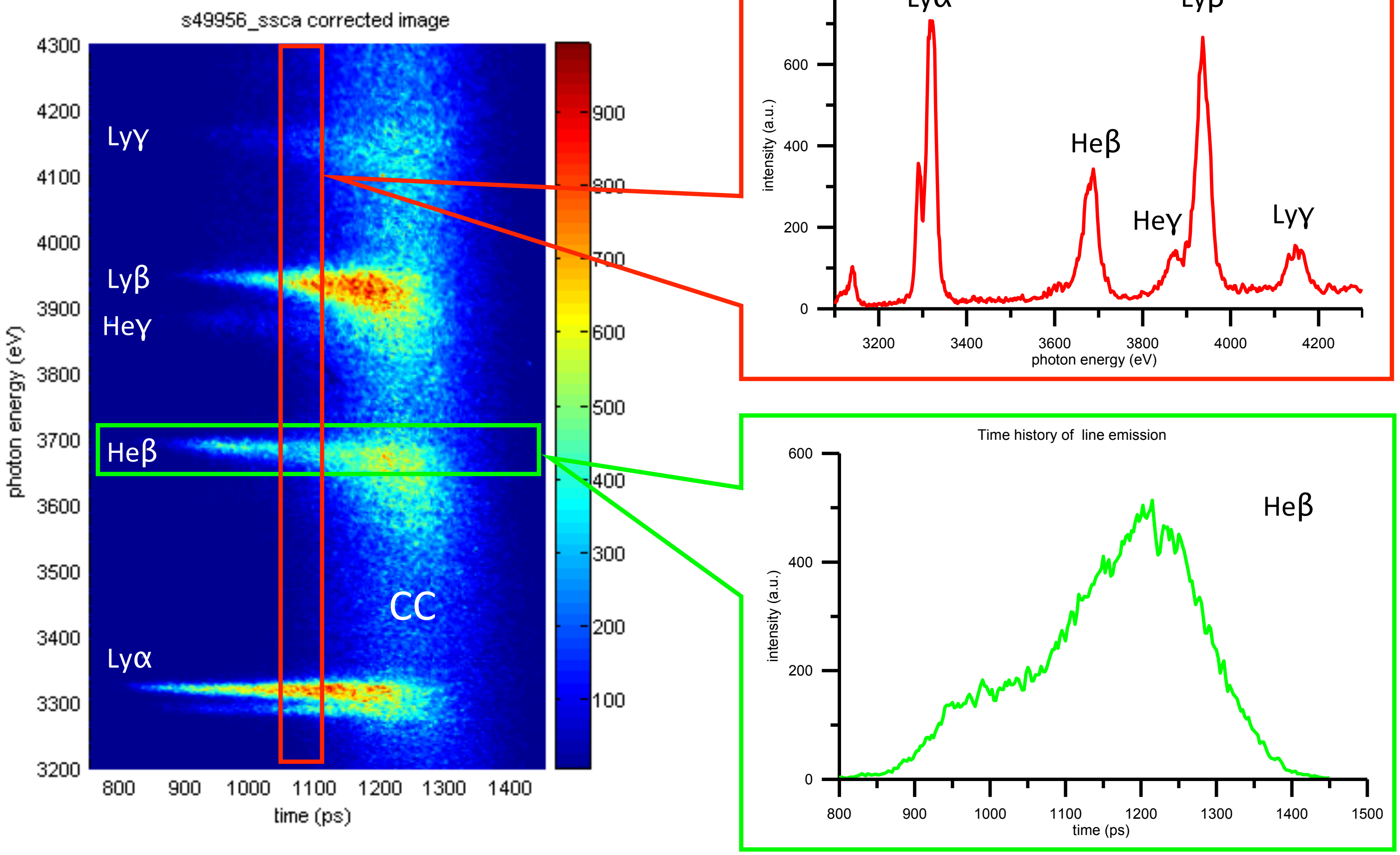
- In direct-drive implosions at OMEGA Ti was used as a spectroscopic tracer initially located in a thin layer of Ti-doped plastic on the inner surface of the shell.
- Gated spatially resolved data recorded with MMI provided key information to quantify the migration of Ti into the core.
- Forward reconstruction was applied to determine the spatial distribution of Ti atom number density and areal-density in the core using annular space-resolved spectra for the first time.
- The Ti tracer penetrates/migrates deep into the core during the deceleration and burning phases of the implosion, and the development of a centrally peaked distribution is observed.
- Approximately 85 percent of Ti-atoms are found in the emission region, and 15 percent in the absorption region for the case of 15μm thick plastic targets.
- Significant deviations from 1D scaling of the areal density were found in the innermost region of the core.

Work supported by DOE/NLUF Grants DE-NA0000859 and DE-NA0002267, and LLNL

Extra slides

Streaked spectrometer provides time histories

Streaked argon spectrum and compression continuum[1]



Time-resolved spectrum

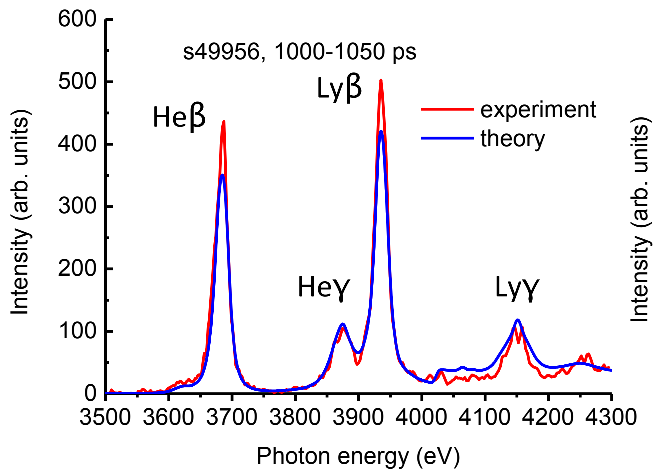
Time history of narrow-band

[1]R. Florido, R. C. Mancini, T. Nagayama, R. Tommasini, J. A. Delettrez, S. P. Regan, V. A. Smalyuk et al, High Energy Density Physics **6**, 70 (2010)

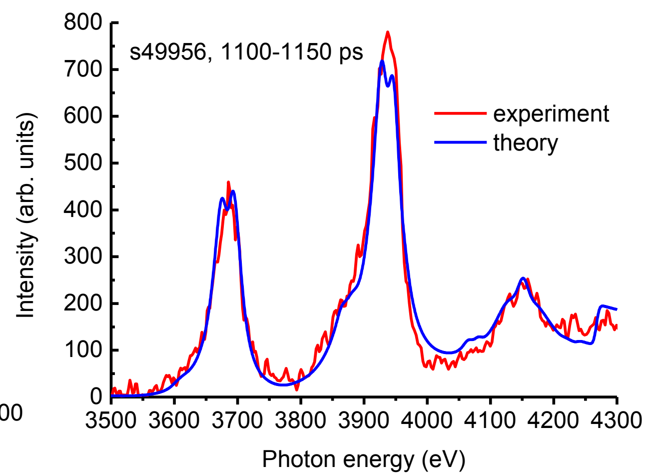
Theory produces good approximations to data

Spectroscopic analysis is based on argon β (1-3) and γ (1-4) lines[1]

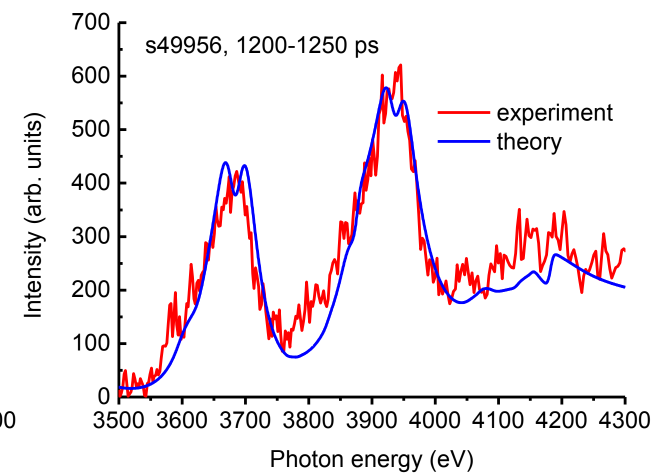
T_e=1300 ± 70 eV, n_e=5.0 ± 0.5 ×10^{23} cm^{-3}



T_e=1450 ± 80 eV, n_e=1.4 ± 0.2 ×10^{24} cm^{-3}



T_e=1270 ± 70 eV, n_e=3.1 ± 0.6 ×10^{24} cm^{-3}



- Instrumental broadening included, FWHM=9eV
- Each spectrum is representative of Δt=50ps
- Steady state approximation[2] good for $N_e > 1\times10^{22}$ cm^{-3}
- ρ [g/cm^3] ≈ 3.24×N_e [10^{24} cm^{-3}]
- Changes in plasma T_e and N_e conditions are reflected in characteristic changes in the argon tracer spectra

[1]R. Florido, R. C. Mancini, T. Nagayama, R. Tommasini, J. A. Delettrez, S. P. Regan, V. A. Smalyuk et al, High Energy Density Physics **6**, 70 (2010)
[2]R. Florido and R. C. Mancini, Journal of Physics B (submitted for publication)

Streaked data show simultaneous Ti line emission and absorption

Spatially integrated data do not reveal where emission/absorption is formed

He-like Ti Heβ

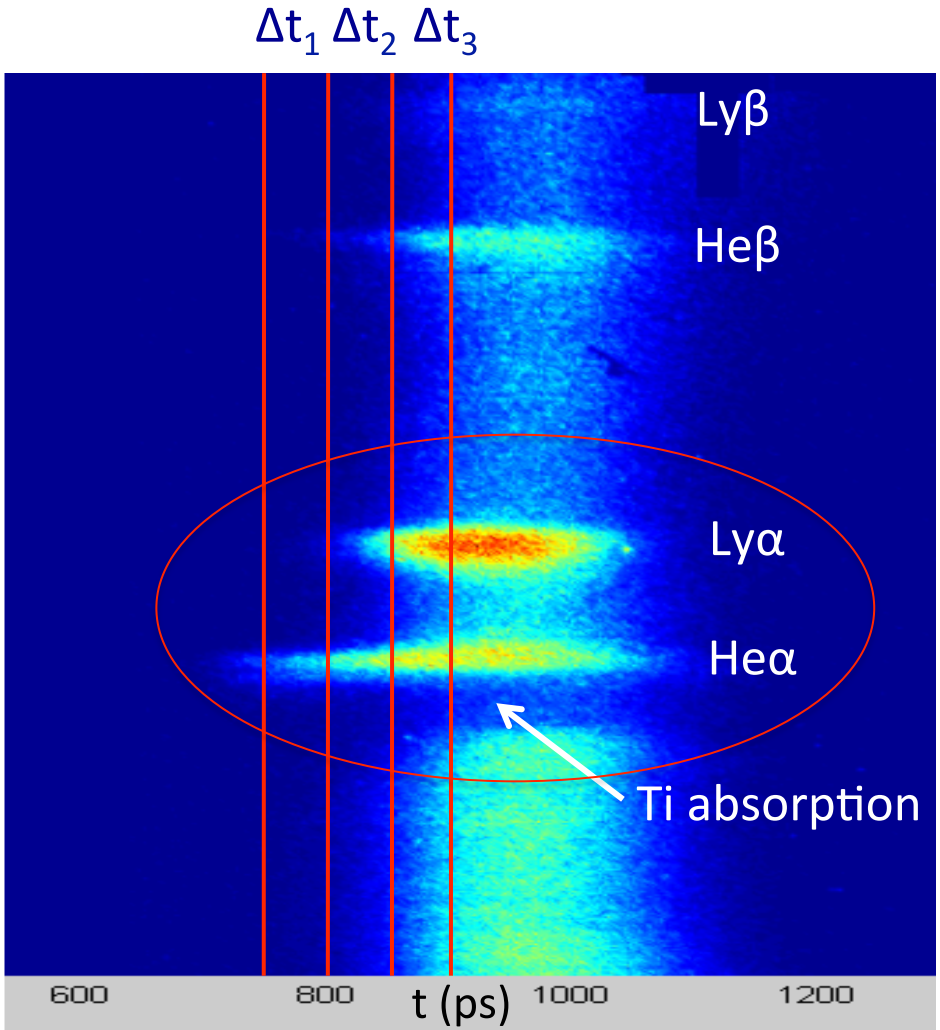
$1s^2\ ^1S_0 - 1s\ 3p\ ^1P_1$

$1s^2\ ^1S_0 - 1s\ 3p\ ^3P_1$

He-like Ti Heα

$1s^2\ ^1S_0 - 1s\ 2p\ ^1P_1$

$1s^2\ ^1S_0 - 1s\ 2p\ ^3P_1$



H-like Ti Lyβ

$1s\ ^2S_{1/2} - 3p\ ^2P_{1/2}$

$1s\ ^2S_{1/2} - 3p\ ^2P_{3/2}$

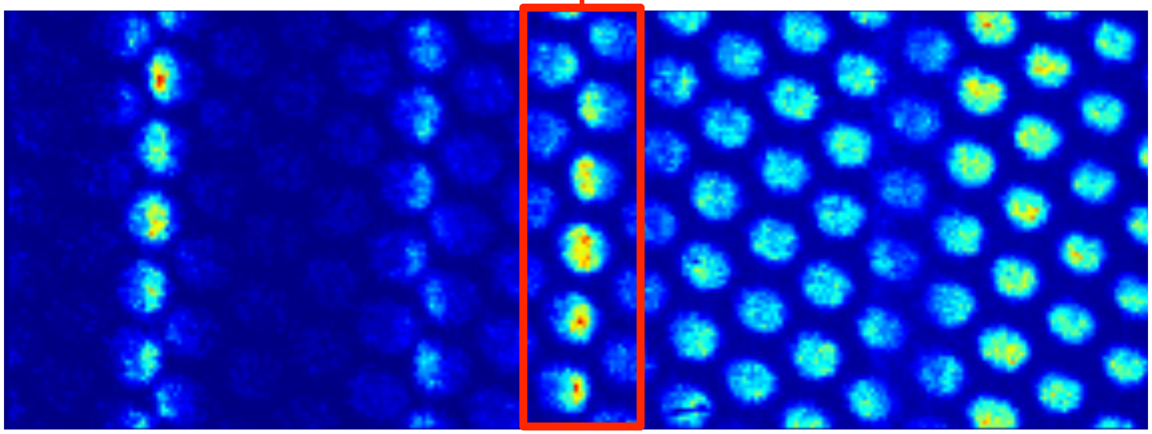
H-like Ti Lyα

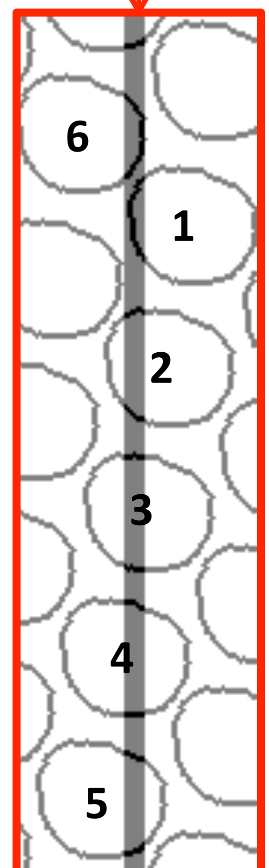
$1s\ ^2S_{1/2} - 2p\ ^2P_{1/2}$

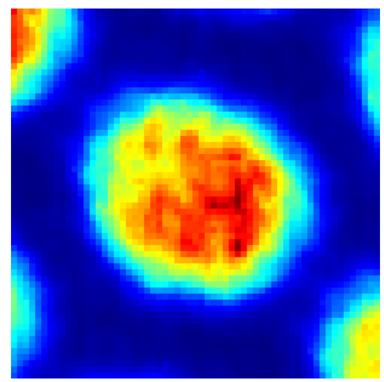
$1s\ ^2S_{1/2} - 2p\ ^2P_{3/2}$

n=1-2 transitions in
Li- through F-like Ti ions

Narrow-band image reconstruction







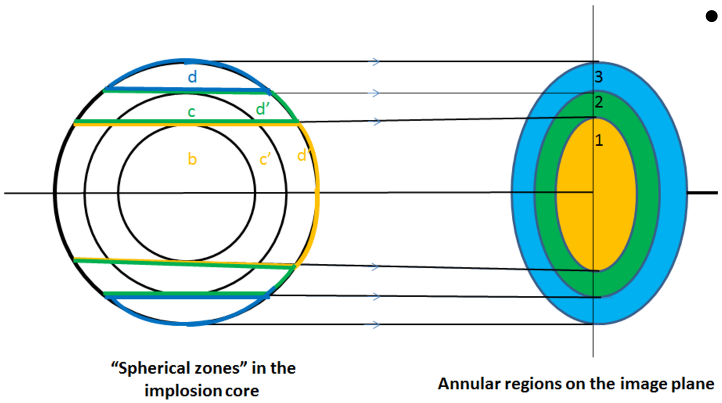
ΔE ≈ 68 eV

- For a given narrow-band range, pixels are collected from several spectrally-resolved images and reassembled in position to construct a new image of a given photon energy band[1,2]

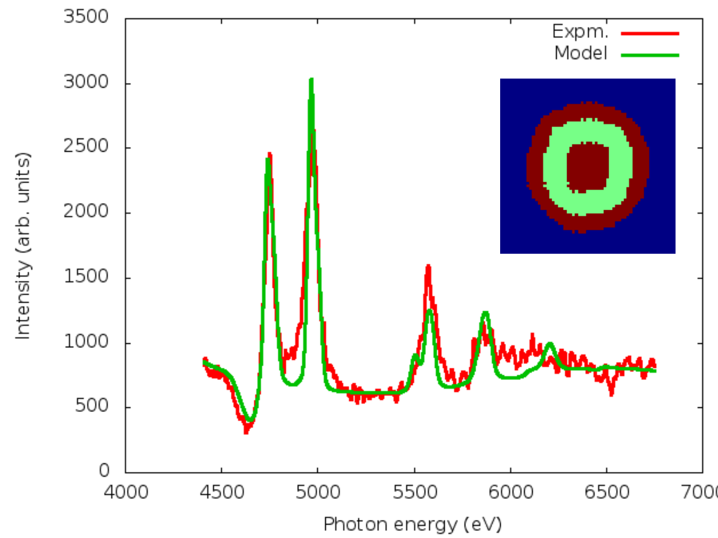
[1]N. Izumi, T. W. Barbee, J. A. Koch, R. C. Mancini and L. A. Welser, Rev. Sci. Instrum. **77**, 083504 (2006)
[2]T. Nagayama, R. C. Mancini, R. Florido, R. Tommasini, J. Koch, J. Delettrez, S. P. Regan, V. Smalyuk, J. Applied Physics **109**, 093303 (2011)

Spectroscopic analysis produces T_e and N_e in spherical zones

Challenge is to determine **both** plasma conditions **and** tracer distribution



- The number of **spherical zones** in object space (implosion core) is equal to the number of **annular regions** on the image plane



- Geometry details are taken from image annular regions
- The spectroscopic analysis considers outermost zone first and then gradually adds inner zones one-at-a-time
- Analysis is based on forward reconstruction of annular spatially resolved spectra, including the effect of an outer absorption zone
- Conditions in inner zones depend on outer zones
- Once the plasma conditions are known (T_e and N_e), the Ti atom number density is determined from total (photon energy integrated) line intensities
- Analysis is iterated for consistency and convergence