3D spectroscopic analysis of temperature and density spatial distributions in OMEGA implosion cores

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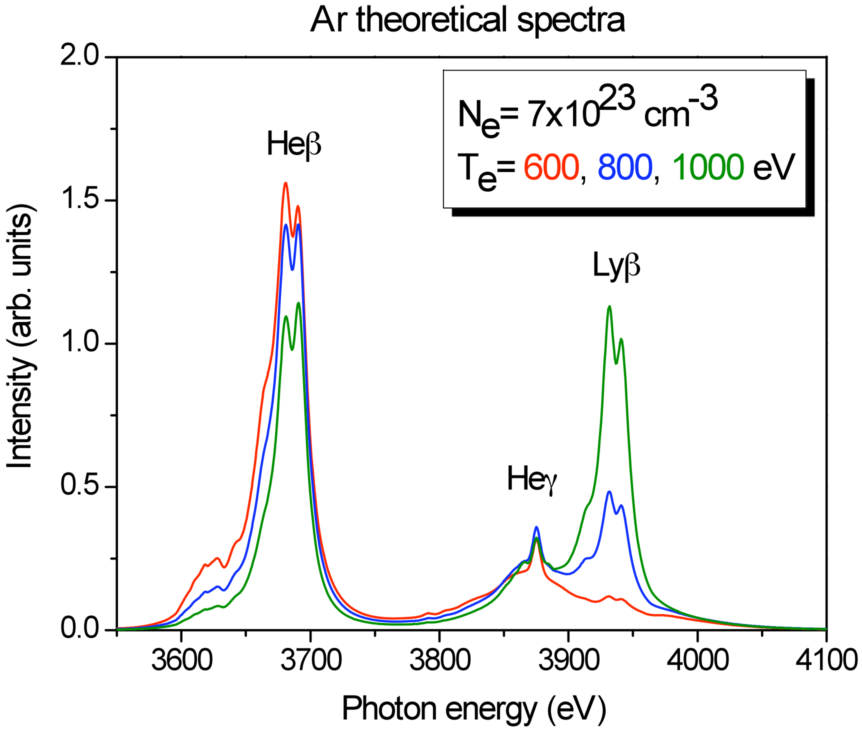
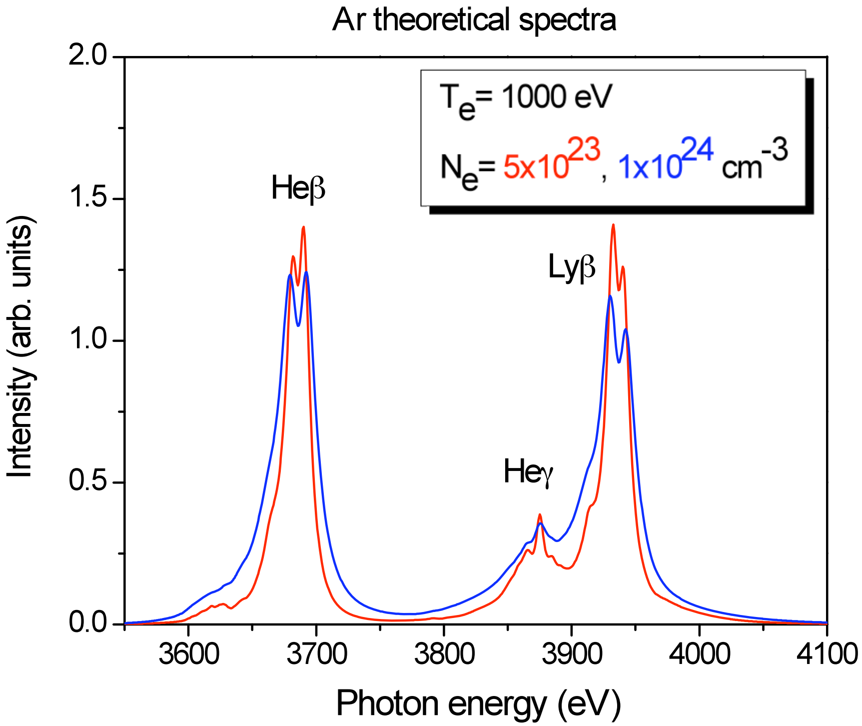
Theory: Spectroscopy

Ar K-shell emission spectrum depends on Te and Ne

In addition to fuel gas (D_2), we added very small amount of Ar in the ICF implosion core for diagnostic purposes





- Increasing electron temperature (Te) shifts the ionization balance up and results in increasing Lyβ and decreasing Heβ intensities, respectively.
- Energy levels of the radiator (Ar) are perturbed by the electric field of plasma ions and electrons (Stark effect). Higher electron density (Ne) results in more perturbation and spread in energy levels, and thus in broader profiles.

Theory: Physics Model

Physics model: Te, Ne dist → theoretical data

- How model works:

  Electron temperature (Te) and density (Ne) distributions in space are first converted to emissivity and opacity distributions in space, then radiation transport equations are numerically integrated to compute emergent intensity for a given photon energy and a given spatial point on an image plane

  → i) intensity image, ii) SIS, and iii) SRS can be computed

1. Te, Ne dist → emissivity and opacity distributions

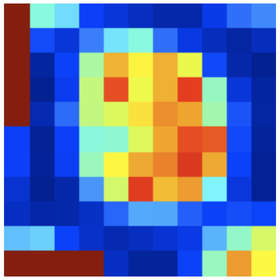
- Use pre-computed emissivity and opacity table as functions of Te, Ne, and photon energy

Atomic Kinetic Code	**Atomic Code**	**Opacity corrections to the population**	**Broadening Mechanisms**
LAMBDA	CATS, ACE, GIPPER	Radiation transport equations and CRE are solved simultaneously and self-consistently	• Detailed Stark broadening line shape • Doppler broadening • Natural broadening
ABAKO	FAC	Approximated with escape factor	

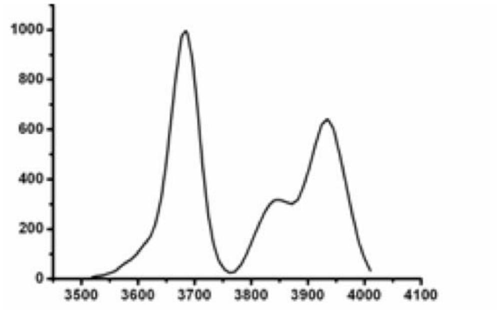
2. Radiation Transport

$$\frac{dI_\nu}{dx} = \varepsilon_\nu - I_\nu \kappa_\nu \quad \Rightarrow \quad I_\nu = \int_{rear}^{front} \varepsilon(x) e^{-\tau(x)} dx$$

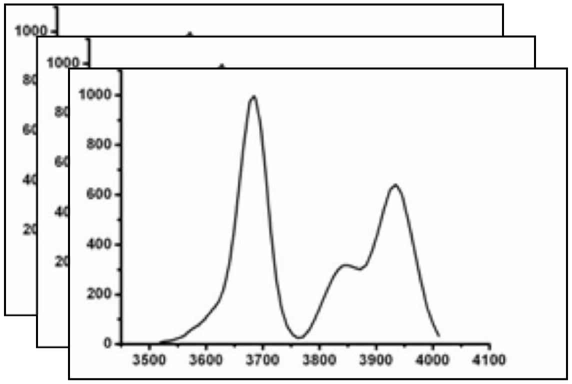
i) Intensity images



ii) Space-integrated spectrum (SIS)



iii) Space-resolved spectra (SRS)



Theory: Search and Reconstruction Method

SR method + physics model: Exp Data → Te, Ne dist

The physics model is embedded into a search and reconstruction method to find Te and Ne distributions from the experimental data. The search and reconstruction method has two steps: initialization and finalization

Initialization

There are two options for the initialization

1. Pareto genetic algorithms
    - Genetic algorithms (GA) are robust search algorithms inspired by evolutionary biology
    - Pareto genetic algorithms (PGA) are GA for multi-objective problems
    - Find a solution by exploring only a fraction of the (parameter) search space
    - Search from a population of solutions called generations
    - Unbiased initial generation: computed with a random number generator

      → One can test uniqueness

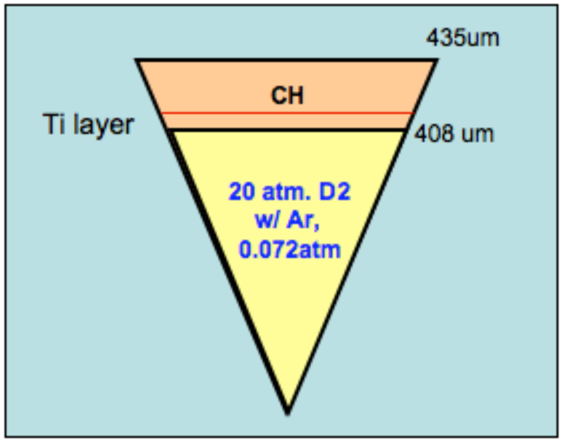
3. Uniform model approximation
    - Estimate the space-averaged Te and Ne by analyzing the space-integrated spectra recorded from three lines of sight
    - Initialize the volume with the uniform Te and Ne

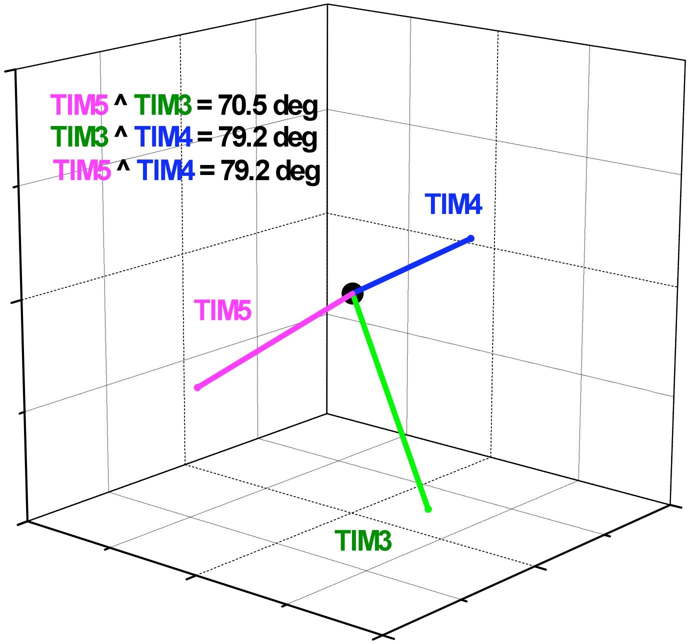
Finalization

- Levenberg-Marquardt non-linear least-squares minimization method
    - Uses initial parameter guess from PGA
    - Refine a given set of good initial parameters to the optimal set

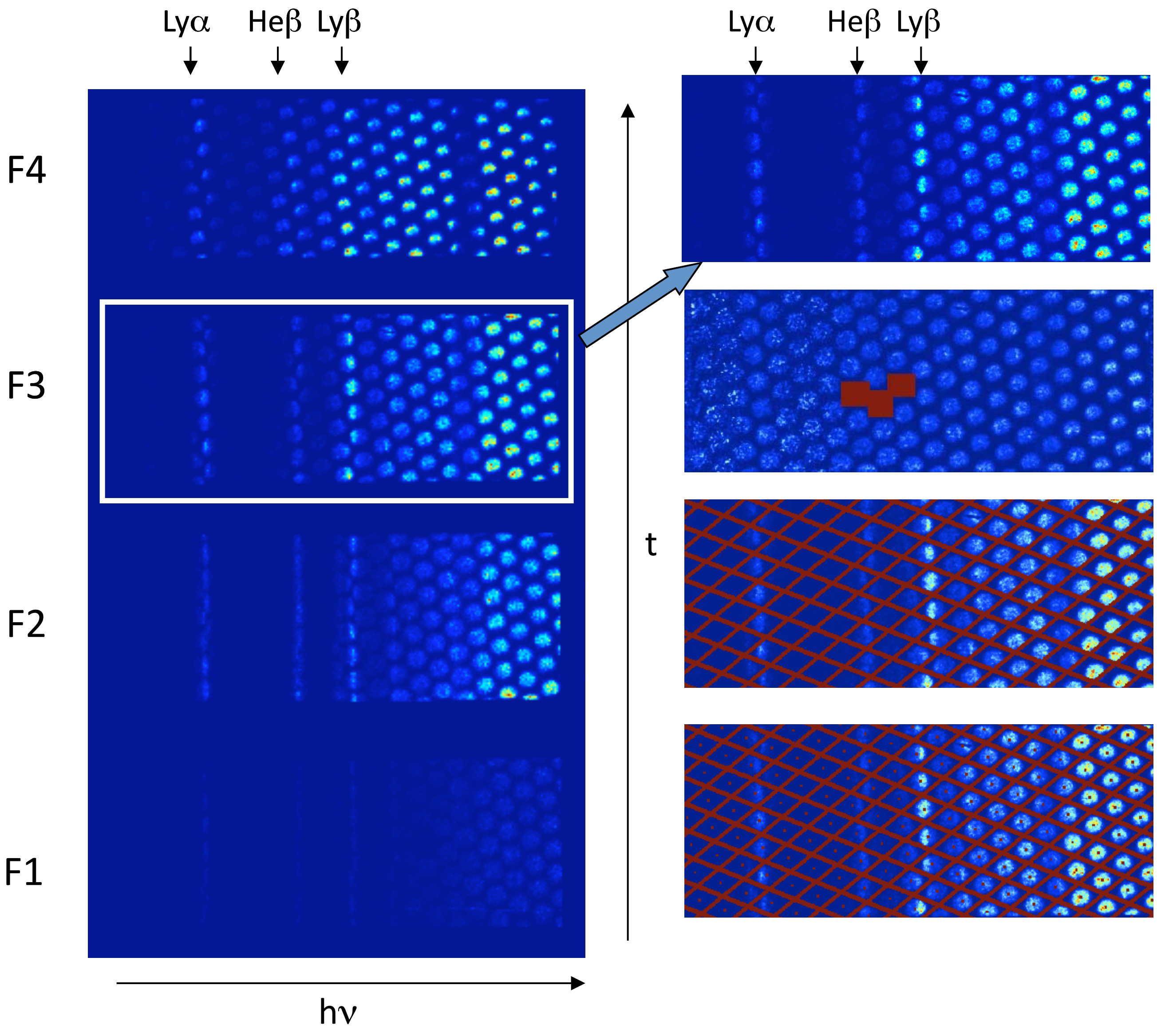
Experiment details

- Record argon K-shell x-ray spectra and narrow-band x-ray images for core spatial structure analysis of direct-drive implosions
  - Gated narrow-band x-ray images along three quasi-orthogonal directions:
    - DDMMIa/b/c: TIM5/XRFC1, TIM3/XRFC2, and TIM4/XRFC3
  - Streaked x-ray line spectrum: TIM2/SSC1, TIM1/SSCA
  - Gated narrow-band x-ray imager: SXRFC: TIM6/XRFC4
- Pulse shapes: SG1018, LA1501, LA2201
- D_2-filled/Ar-doped, 20 atm/0.072 atm
- Plastic shells, 400 µm/427 µm, 27 µm, with Ti-doped layer.
- Primary diagnostics:
  - DDMMIa/b/c mounted on TIM5/3/4, gated x-ray images, identical instruments
  - SXRFC mounted on TIM6, gated x-ray images, with alternative collimator and pinhole-array plates
  - SSC1/SSCA mounted on TIM2/1, streaked x-ray line spectra



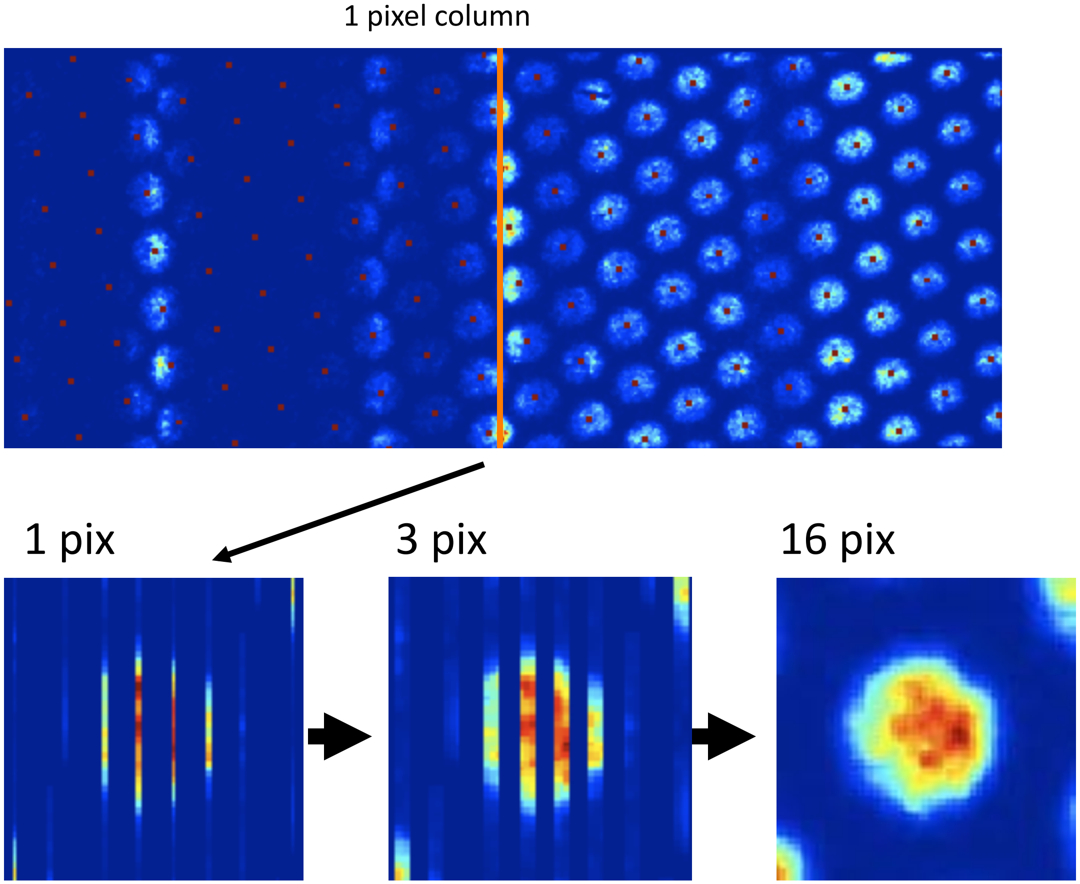


Frame selection and center finding



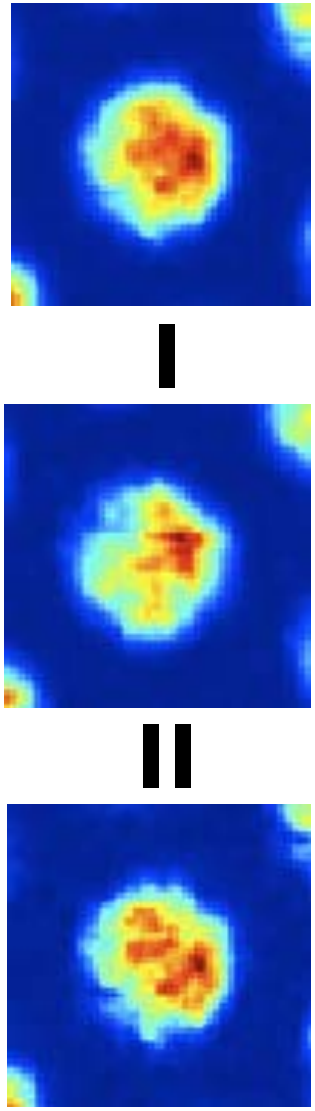
1. Select one frame
2. Remove spectral content ("flatten" the image)
3. Select three adjacent images, and find their intensity weighted centers → initial parameter's estimate
4. Based on the initial estimation draw a grid through the regions in-between images (i.e. "avoid images")
5. Optimize the parameters of the grid using Powell's method
6. Centers of diamond-shaped boxes define the centers of images

Narrow-band image reconstruction



- Using the centers of sub-images as reference points, portions of several sub-images can be reassembled into local position of the core image
- Combining vertical portions of a given photon energy bandwidth permits the reconstruction of a core image for that bandwidth.

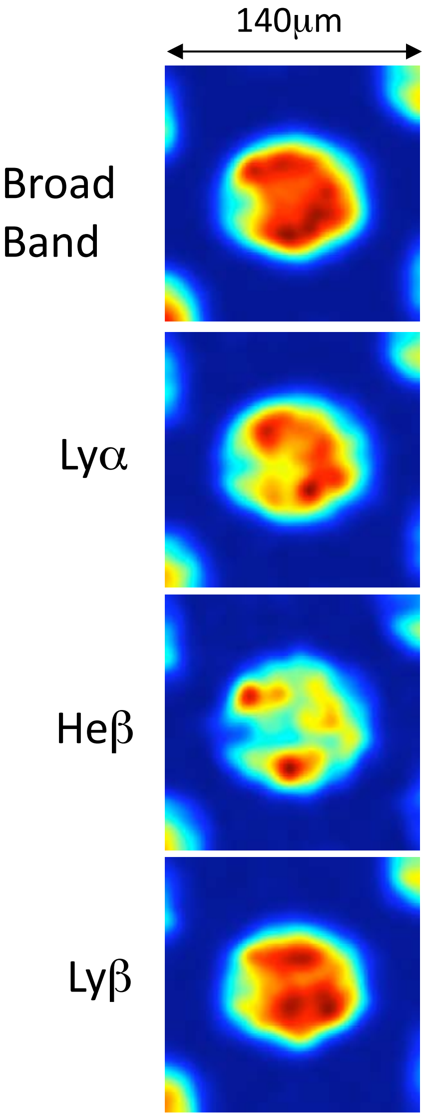
Continuum Removal

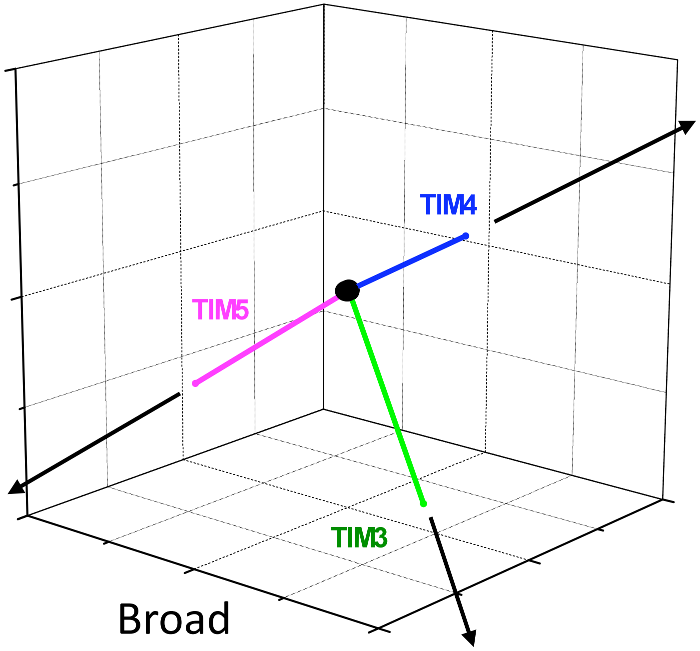


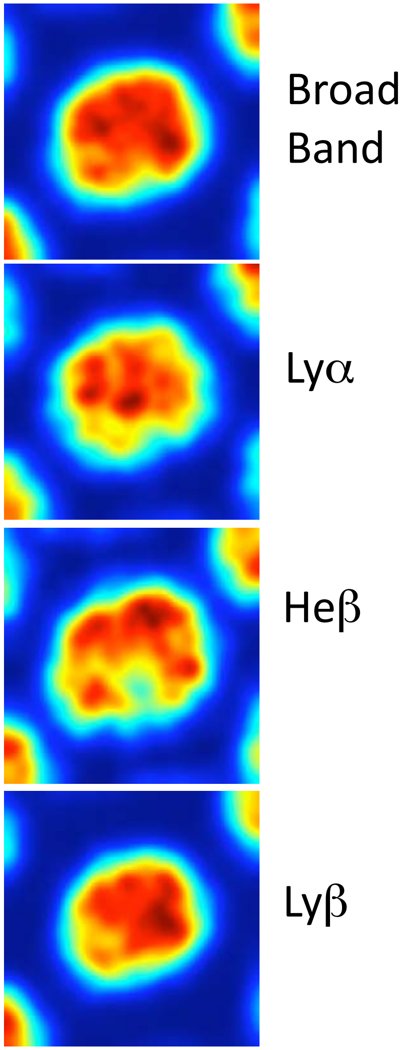
Data Processing: Ar Line Images (Frame 3)

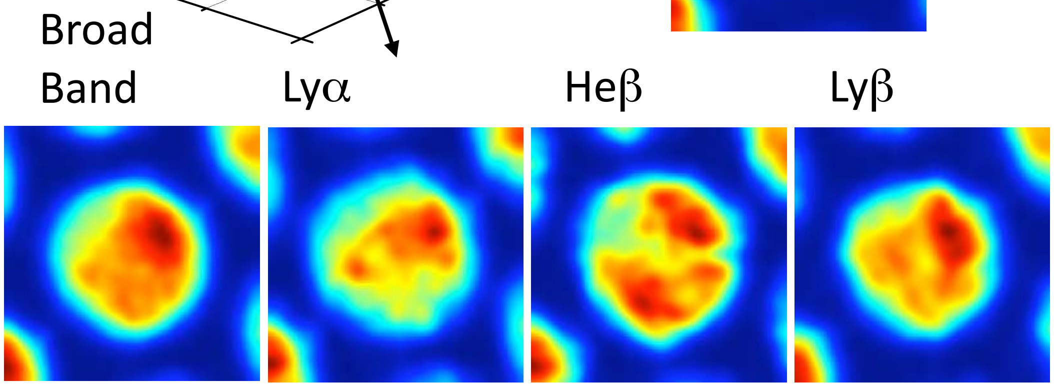
Gated narrow-band core images based on argon spectral features

OMEGA shot 49956, frame 3





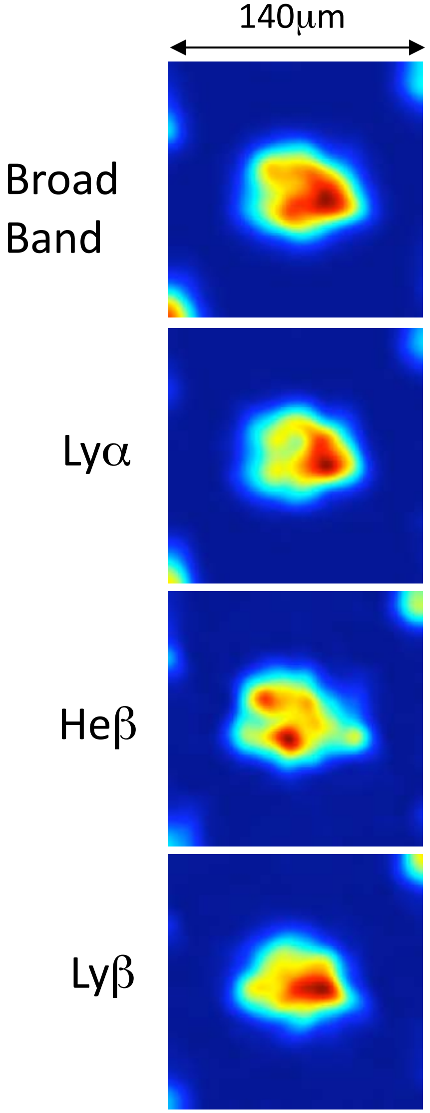


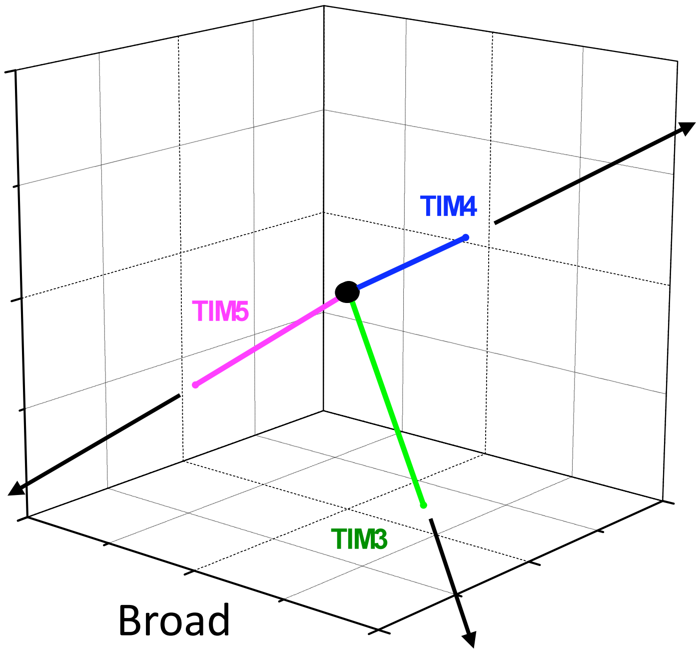


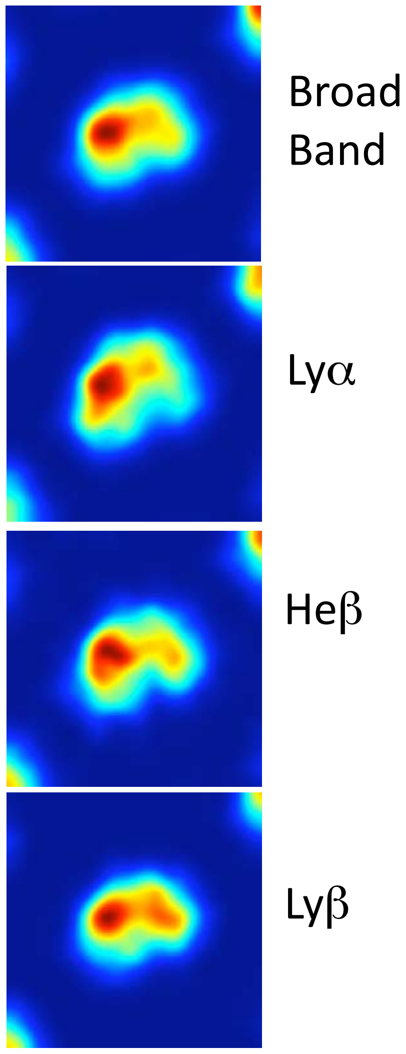
Data Processing: Ar Line Images (Frame 4)

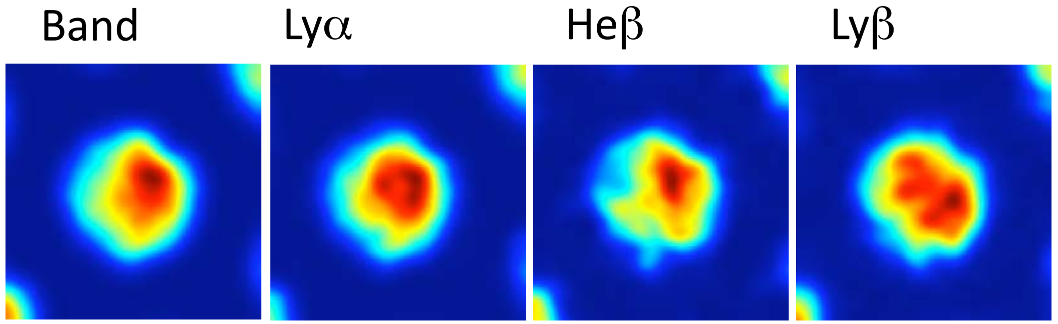
Gated narrow-band core images based on argon spectral features

OMEGA shot 49956, frame 4



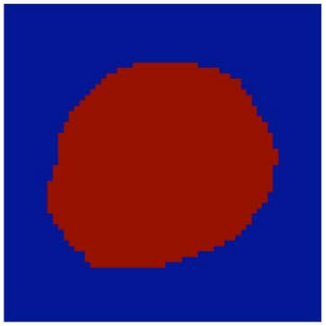






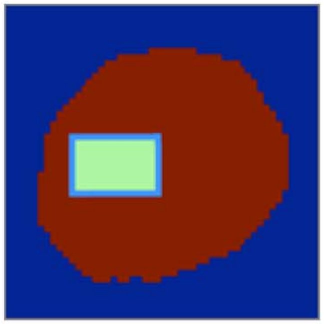
Data Processing: Space-integrated/resolved Spectrum

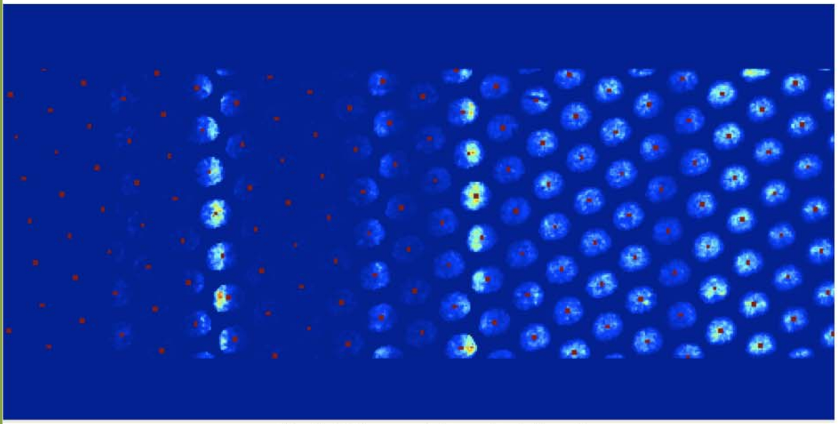
Space-integrated and space-resolved spectra

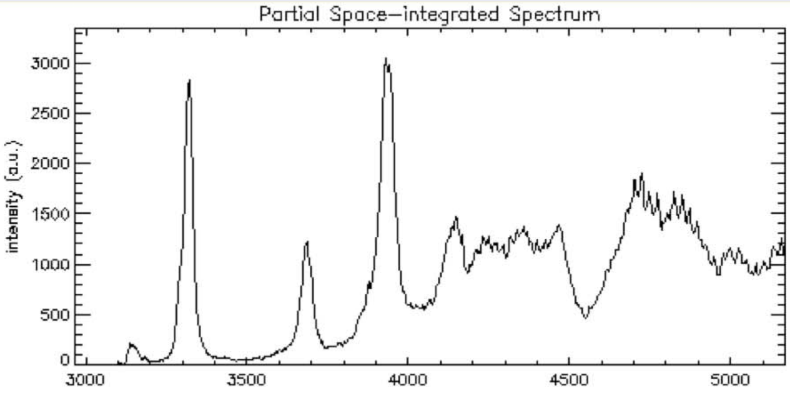


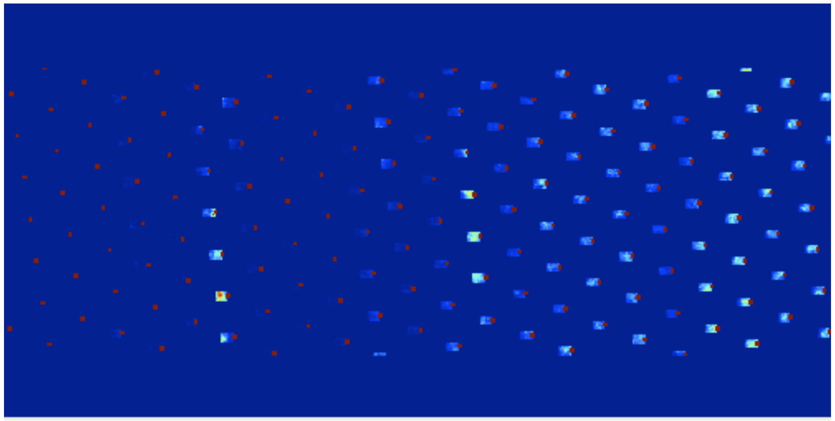
- Space-integrated spectrum (SIS) can be computed by summing up all pixels vertically
- What if we pick up the contributions only from a selected region of the core image?

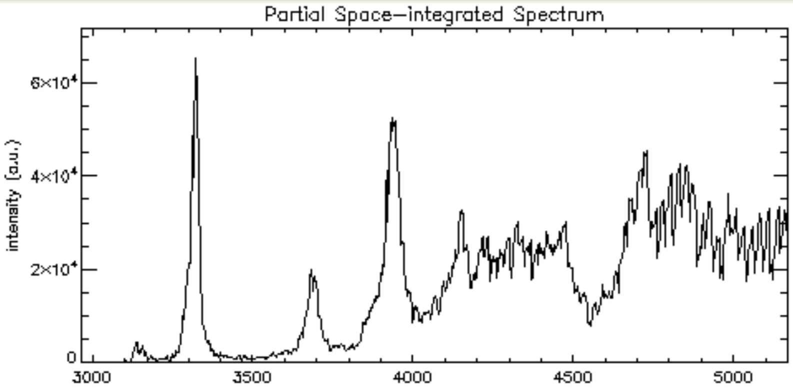
  → Space-Resolved Spectra (SRS)





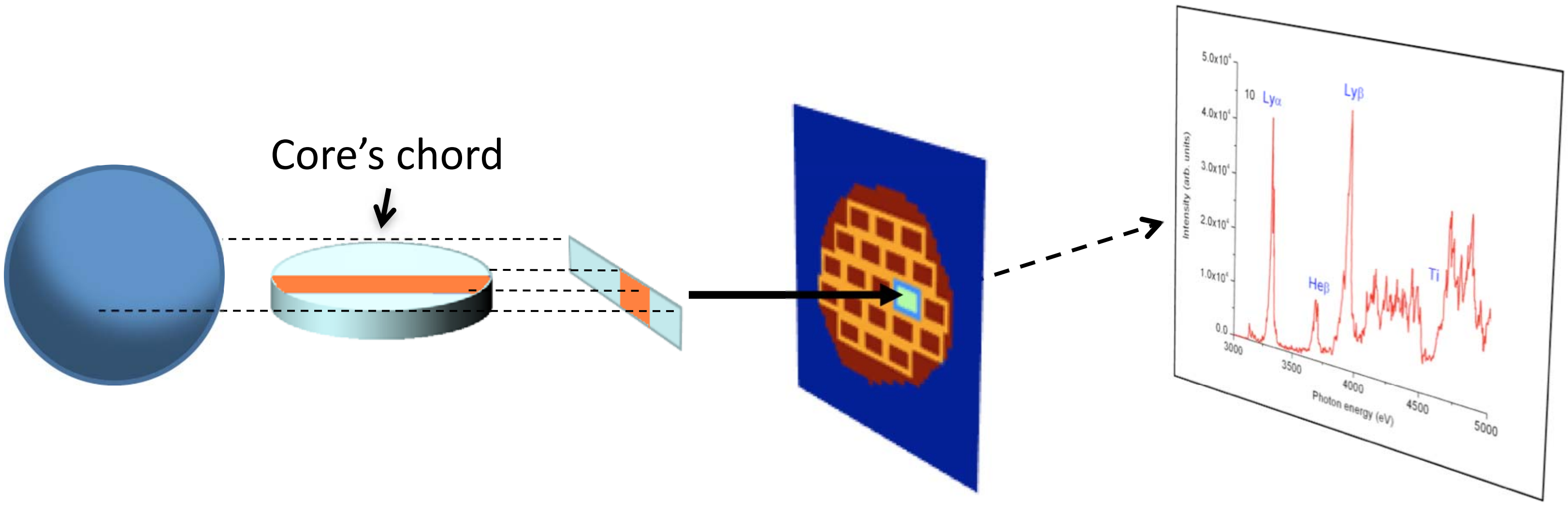






Data Processing: Domain of Integration

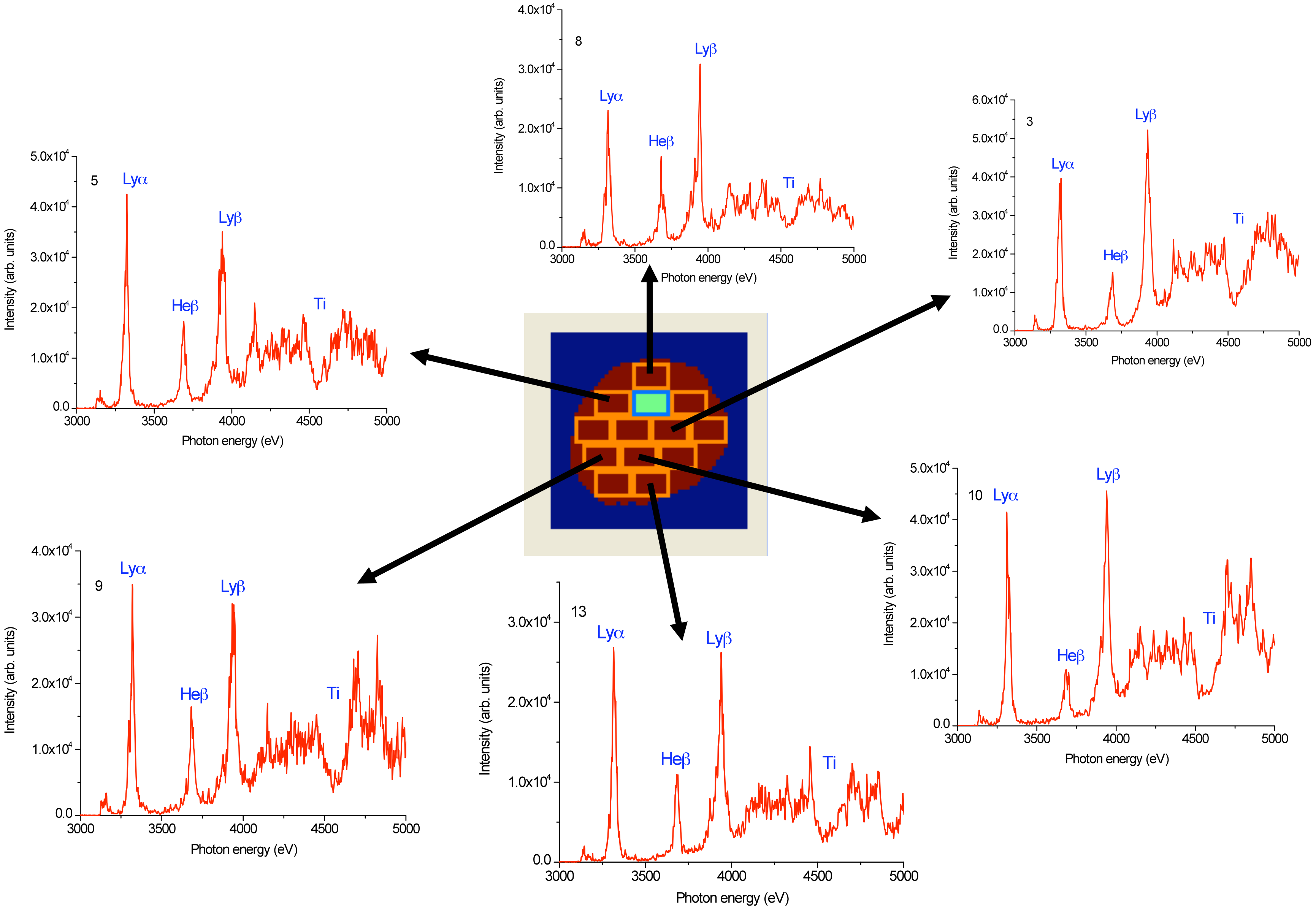
Domain of integration of space-resolved spectra



- Each spatial region of the image corresponds to a slab in the core and the associated space-resolve spectra
- Each slab length is estimated based on the volume determination

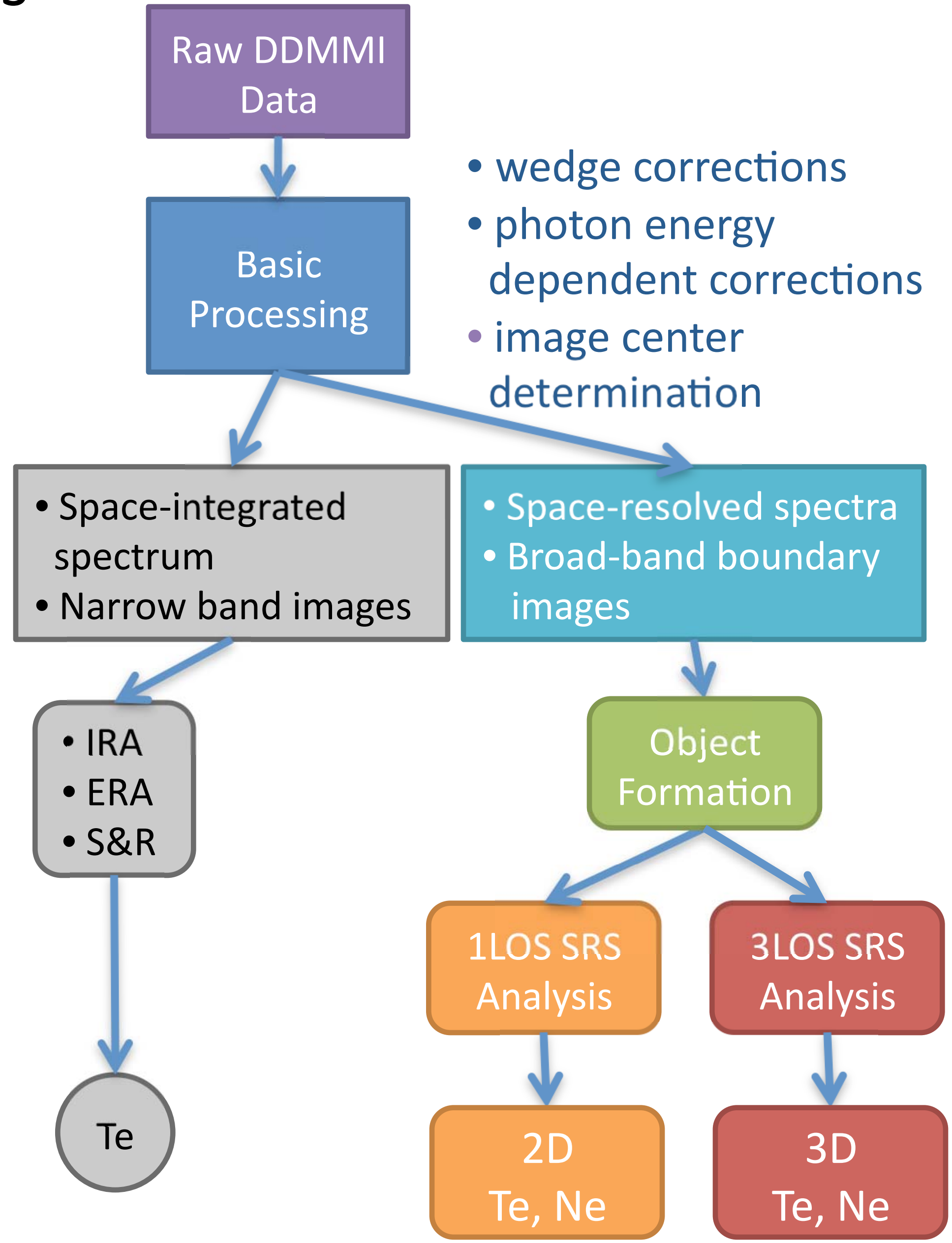
Data Processing: Space-resolved Spectra

Set of space-resolved spectra



Roadmap of analysis

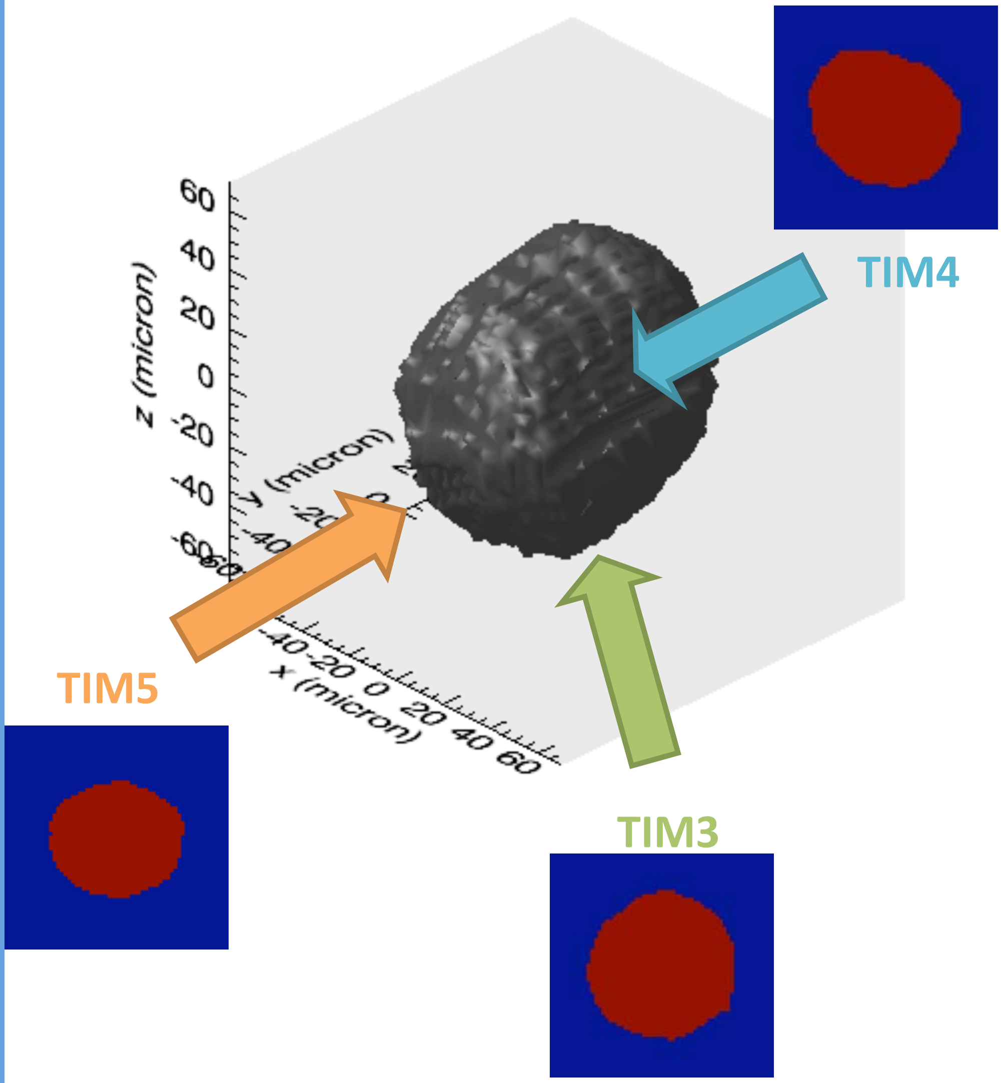
- Experiment using DDMMI
- Basic data processing
- Data extraction
  - Space-integrated spectrum
  - Narrow-band images
  - Space-resolved spectra
  - Broad-band boundary image
- Object formation
- Data analysis
  - 1LOS SRS Analysis
  - 3LOS SRS Analysis



Different types of analysis methods

	Name of Analysis	**Geometry/ symmetry**	**Opacity assumption**	**Input**	**Output**
1D	Uniform Model	Uniform sphere or slab	Thick	Space-integrated spectrum (SIS)	Space-averaged Te and Ne
	IRA	N/A	Thin	Heb, Lyb images	Chord-averaged Te dist. on the image plane
	ERA	Spherical symmetry	Thin	Heb, Lyb images	1D radial gradient of Te
	S&R	Collection of core slices with local axial symmetry	Thick	SIS, Heb, Lyb images	Quasi-3D Te and Ne dist. in the core
	1LOS SRS Analysis	Collections of uniform slabs	Thick	SRS from 1 TIM	Chord-averaged Te and Ne dist. on image plane
3D	3LOS SRS Analysis	General	Thick	SRS from 3 TIMs	3D Te and Ne dist. in the core

Volume determination (OMEGA s49956 frame 3)

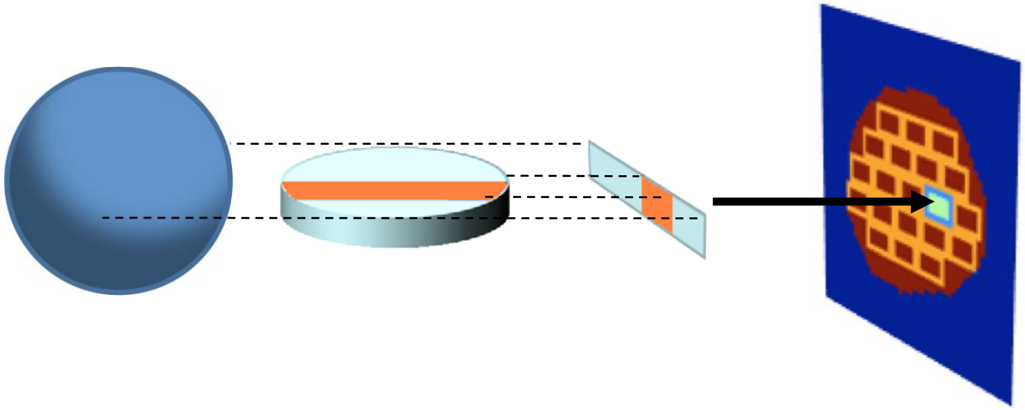


1. Extract a broad-band boundary image from each line of sight
2. Project the boundary images towards the origin from each TIM
3. The intersection of the three projections defines the upper bound volume of the implosion core
4. Unnaturally elongated portions of the volume are truncated based on an upper bound radius

	TIM3	TIM4	TIM5
θ	142.62	63.44	100.81
ϕ	342	342	270

Images after the object formation:

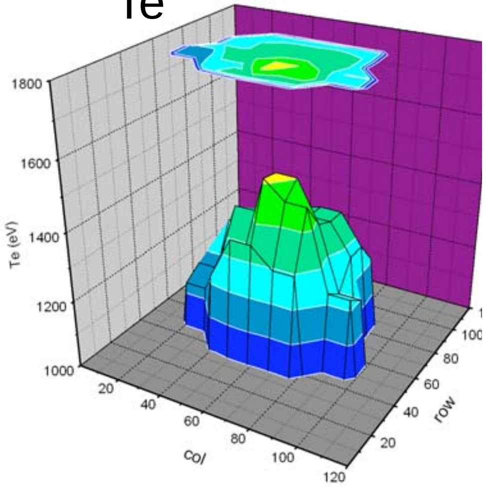
Simulation and analysis of space-resolved line spectra



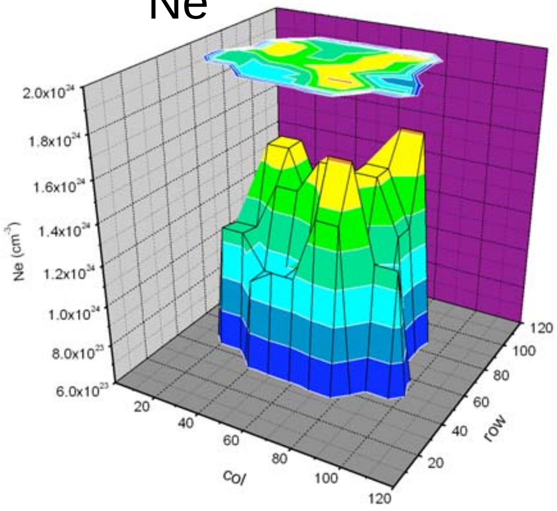
Each spatial region of the image represents a spatial integration over a slab in the core slice

Shot 49956, TIM4, F3: spatial profiles

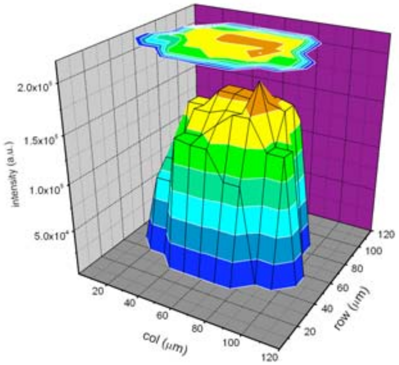
Te



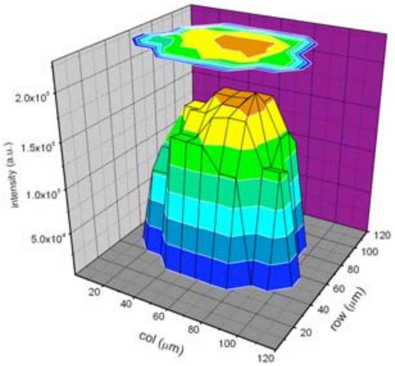
Ne



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

Conclusions

- Four major components of this research: 1) experiments at OMEGA, 2) image data processing, 3) atomic and radiation physics modeling, and 4) data analysis
- We recorded spectrally resolved core image data from three quasi-orthogonal lines of sight simultaneously using identical DDMMI instruments
- From each DDMMI data, we extracted:
  - Narrow-band/broad-band intensity images
  - Space-integrated spectrum (SIS)
  - A set of space-resolved spectra (SRS)
- With the search and reconstruction method, we extracted Te and Ne distribution that reproduces all the extracted space-resolved spectra simultaneously and self-consistently
- Three dimensional determination of temperature and density spatial distributions is important for implosion core diagnostics, and for benchmarking hydrodynamic simulation codes

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