Reconstruction and Analysis of Temperature and Density Spatial Profiles from Inertial Confinement Fusion Implosion Cores

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- J. Bailey, G. Rochau, SNL

Motivation

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- Temperature and density spatial profiles are important for efficient burning of the fuel in Inertial Confinement Fusion (ICF) implosion cores.
- Also relevant for benchmarking large-scale ICF radiation-hydrodynamic simulation codes.
- How can we extract this information from data recorded in ICF implosion experiments?
- Diagnostics: mostly particle and radiation based.
- **Focus:** x-ray spectroscopy of doped implosion cores.
- **Idea:** add a tracer amount of dopant (e.g. Ar, Kr, Xe) to the fuel, record its x-ray line emission, and perform data analysis.
- **Useful property:** x-ray line emission from ions in plasmas is sensitive to the plasma environmental conditions.

Three main, general ideas

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- Theory and modeling of x-ray line formation in plasmas:
  - atomic processes and kinetics,
  - detailed Stark-broadened spectral line shapes,
  - spectroscopic quality radiation transport.
- Instrumentation and spectroscopic data:
  - Multi-Monochromatic-Imager (MMI) x-ray imager
  - TREX slit spectrometer
- Data analysis methods:
  - need to solve an inversion problem,
  - quasi-analytic methods,
  - multi-objective search & reconstruction, genetic algorithms,
  - analysis of spatially-resolved line spectra.

Argon line spectrum has many bright features

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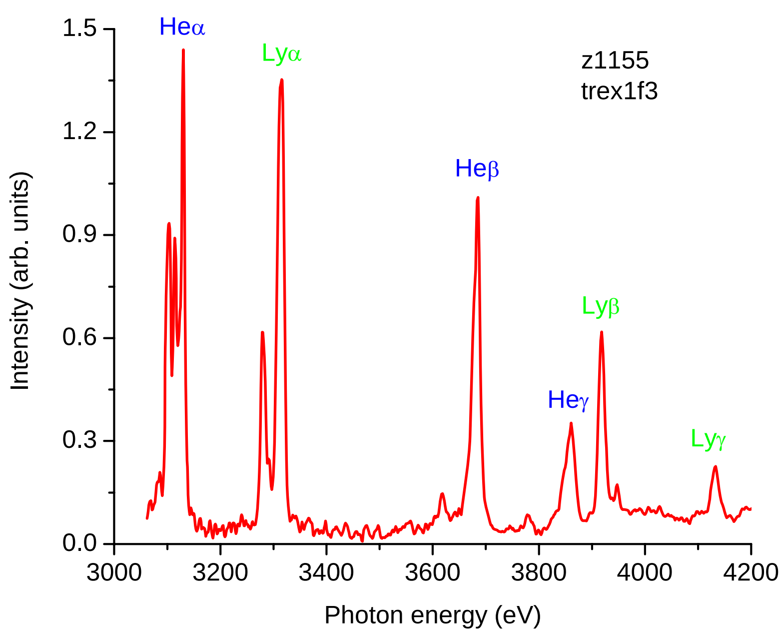
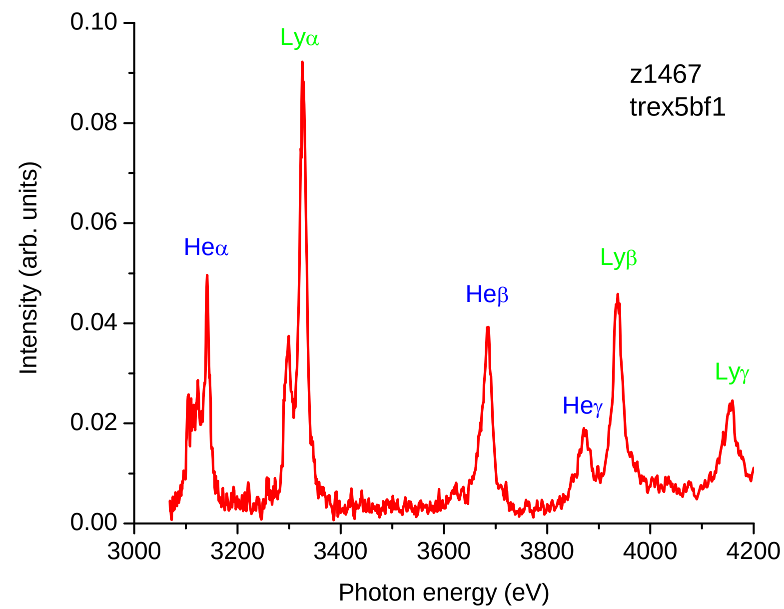
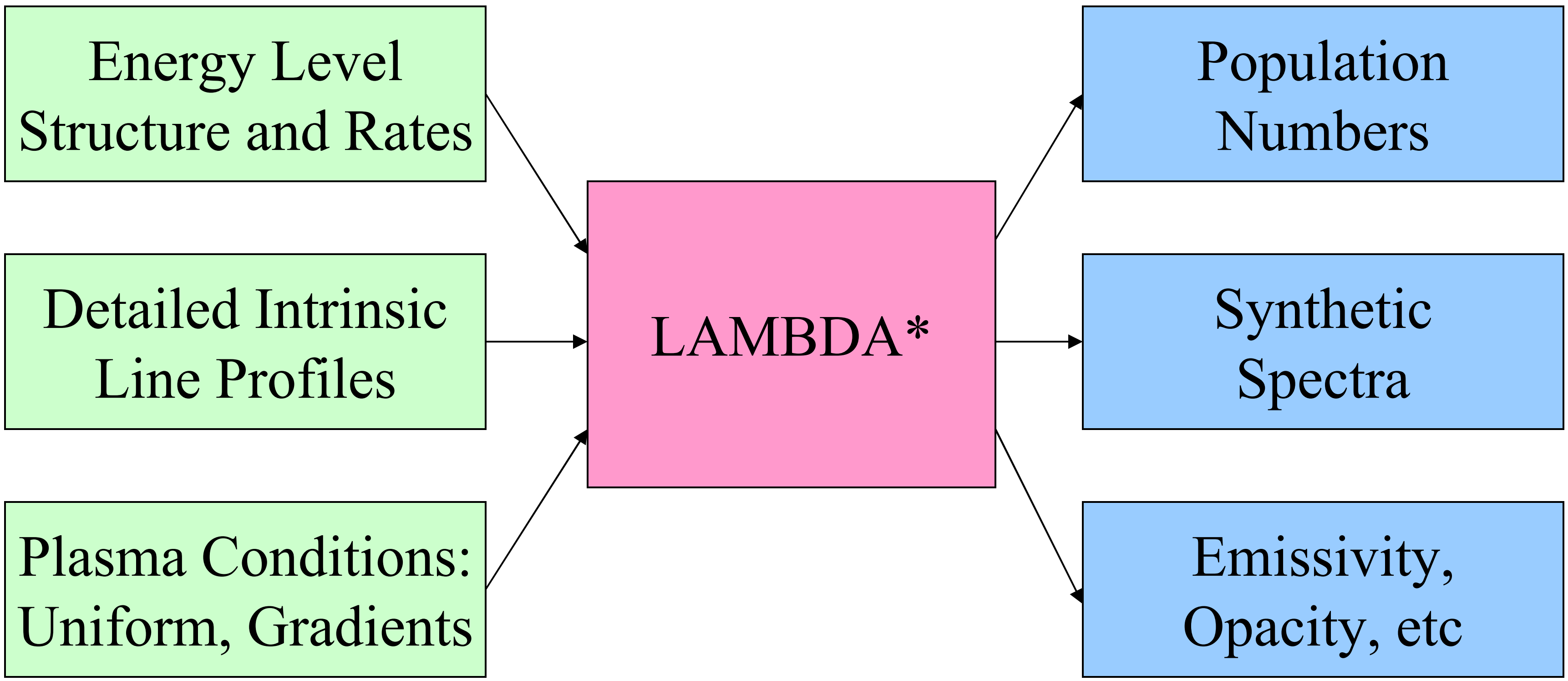




- Space-integrated, time-resolved lineouts.
- Several helium and Lyman lines are observed.
- Li- and He-like satellite lines are also observed.
- Several methods have been developed & applied to analyze these spectra.*

*T. Burris-Mog, R. Mancini, J. Bailey, G. Chandler, G. Rochau, G. Dunham, P. Lake, K. Peterson, S. Slutz, T. Mehlhorn, I. Golovkin and J. MacFarlane, J. Quant. Spectrosc. Radiat. Transfer **99**, 120 (2006).

Spectral model description



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

Temperature & density dependence of Ar line spectrum*

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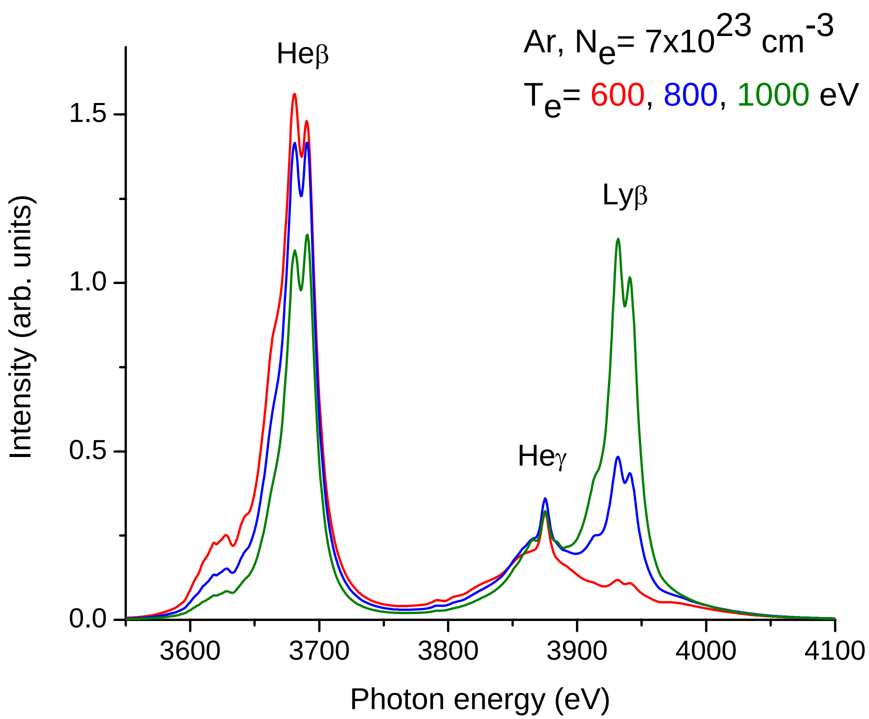

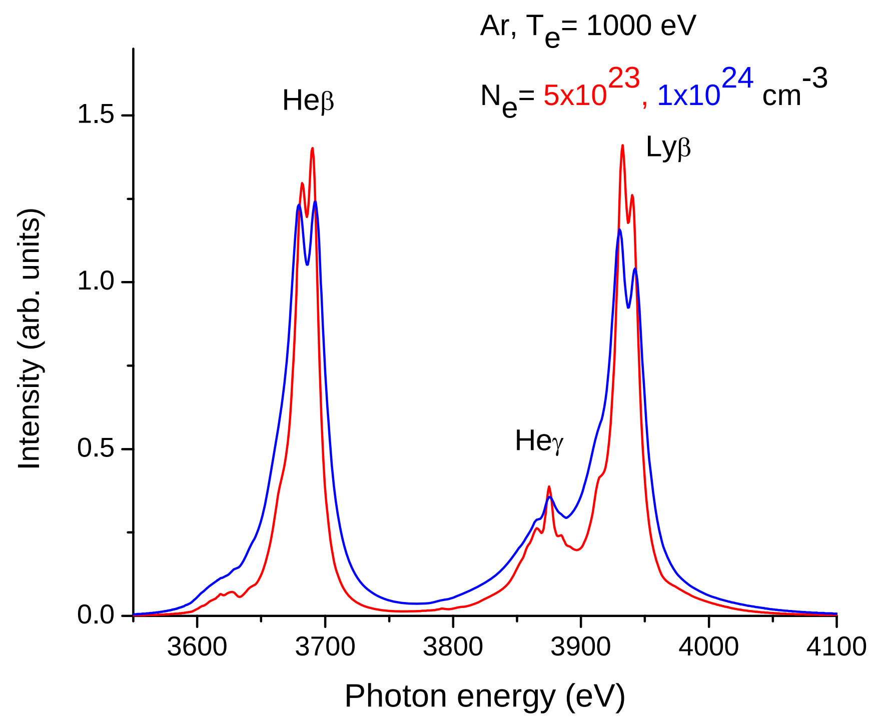

- Core filling conditions can be adjusted so that the argon x-ray line spectrum in the 3500 eV – 4100 eV range has small optical depth.

*L.A. Welser, R.C. Mancini, J.A. Koch, N. Izumi, H. Dalhed, H. Scott, T.W. Barbee, Jr., R.W. Lee, I.E. Golovkin, F. Marshall, J. Delettrez and L. Klein, J. Quant. Spectrosc. Radiat. Transfer **81**, 487 (2003)

Multi-Monochromatic Imager (MMI): narrow-band x-ray images

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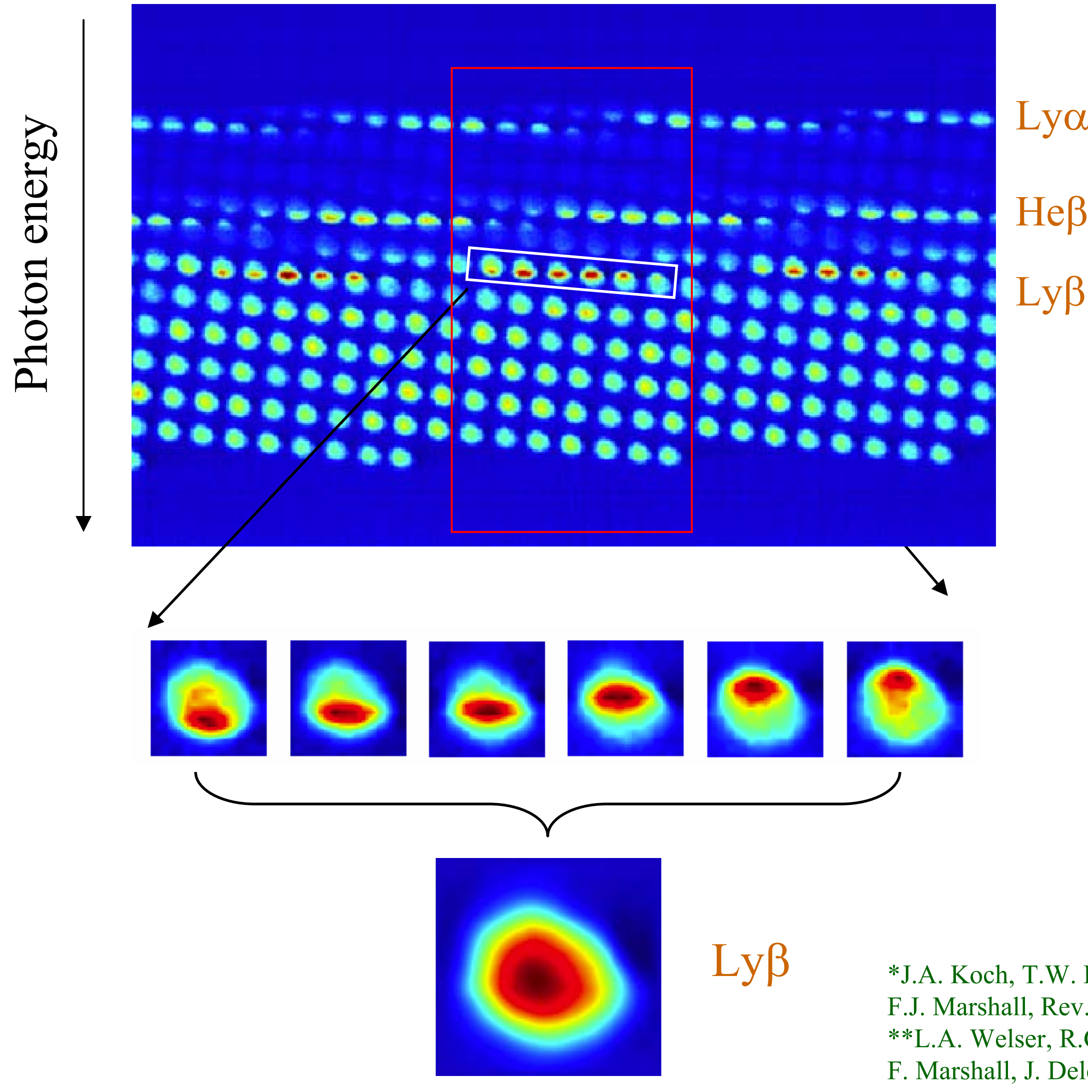
OMEGA Shot 26787

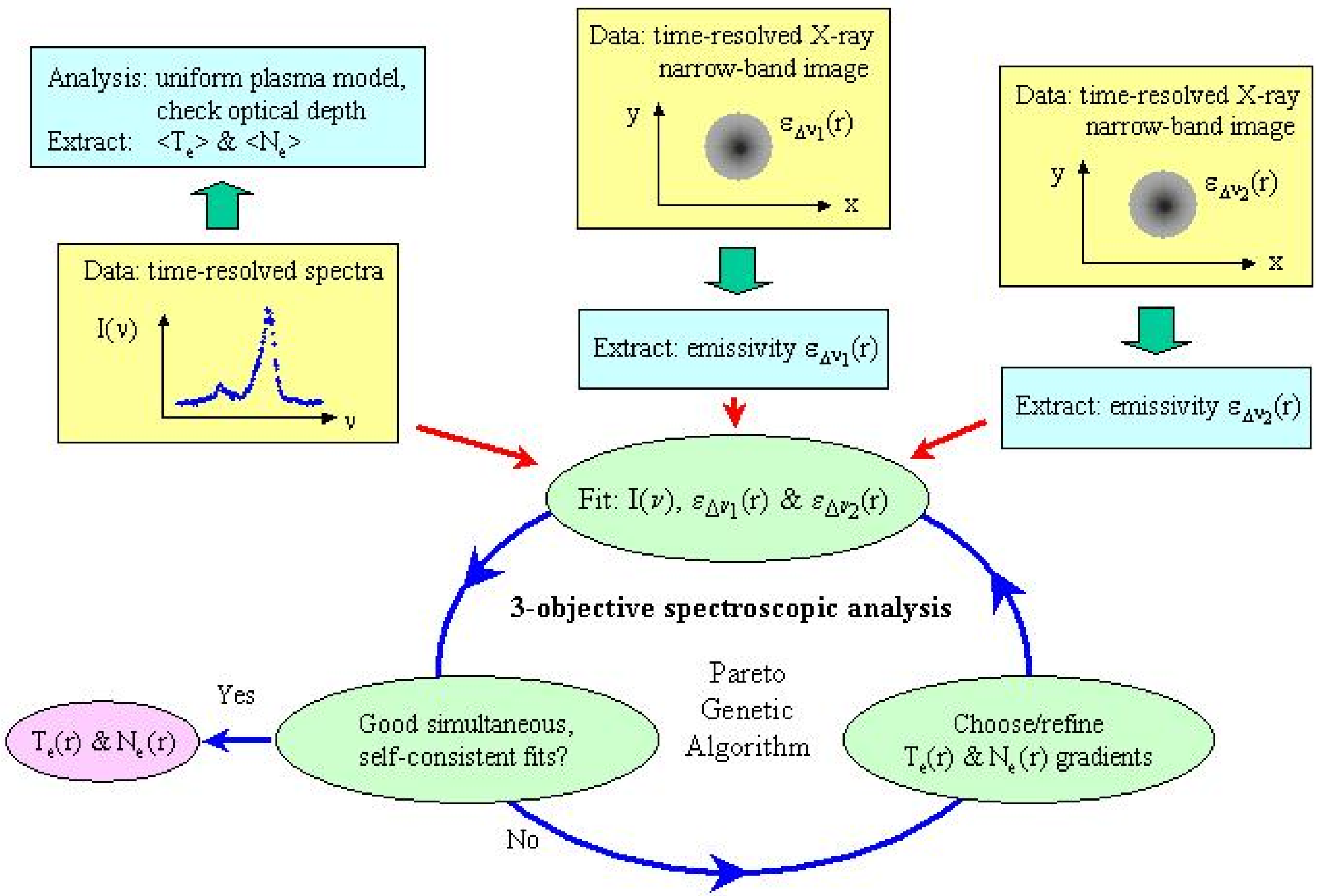


- MMI* uses a target-mounted pinhole array and flat multi-layer mirror Bragg reflector to provide numerous narrow-band images spanning the ≈ 3-5 keV photon energy range.
- Records time-integrated and gated data.
- Pinhole diameter is 5-10 μm.
- Each image spans ≈ 75 eV along spectral dispersion axis**, and the spatial resolution is ≈ 7-10 μm.

*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)

L.A. Welser, R.C. Mancini, J.A. Koch, S. Dalhed, R.W. Lee, I.E. Golovkin, F. Marshall, J. Delettrez and L. Klein, Rev. Sci. Instrum. **74, 1951 (2003)

PGA-driven multi-objective data analysis: 3-objective case*



*L.A. Welser, R.C. Mancini, J.A. Koch, N. Izumi, S.J. Louis, I.E. Golovkin, T.W. Barbee, Jr., S.W. Haan, J.A. Delettrez, F.J. Marshall, S.P. Regan, V. Smalyuk, D.A. Haynes, Jr., J. Quant. Spectrosc. Radiat. Transfer **99**, 649 (2006)

Temperature maps show changes depending on drive symmetry

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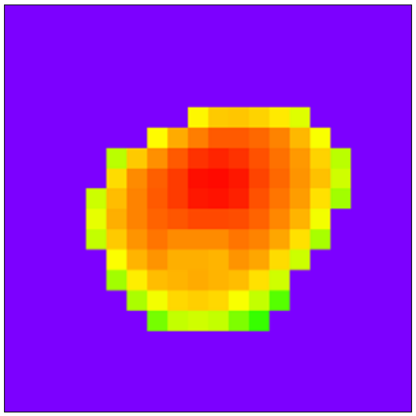
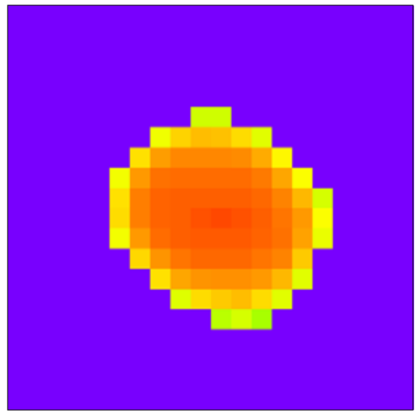
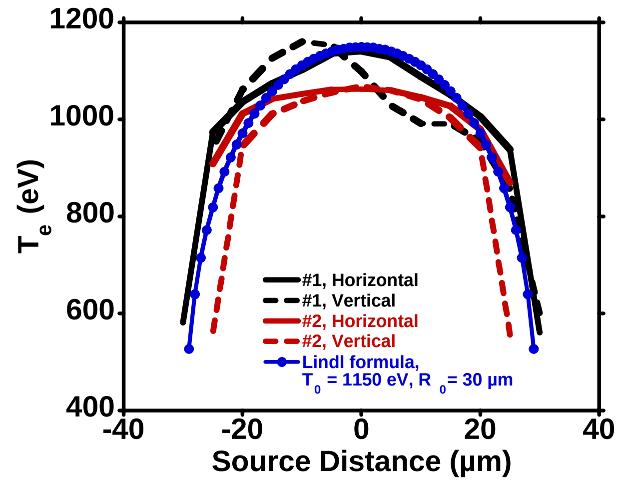
(a) Round #1

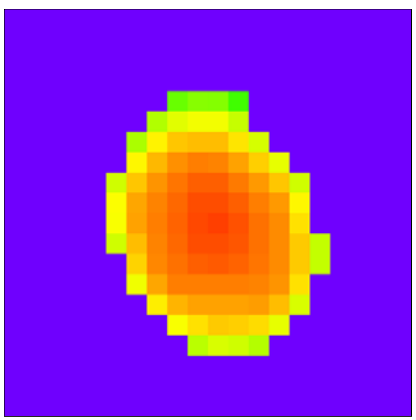


(b) Round #2

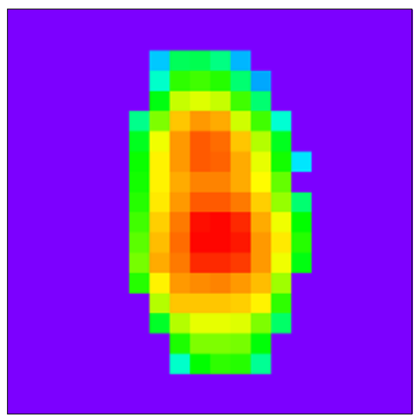


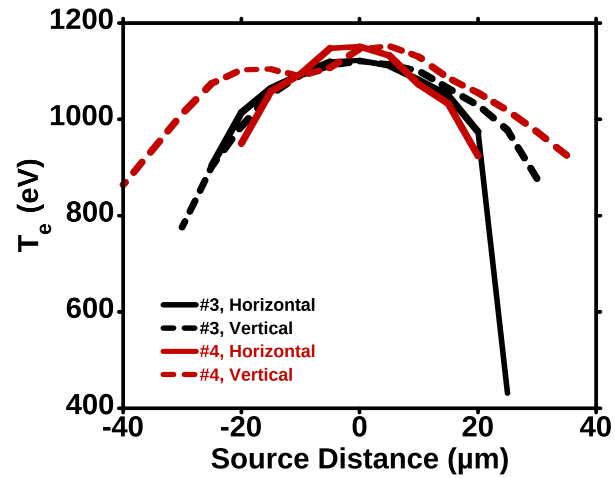


(d) Sausage #1



(e) Sausage #2





- Two-lobed temperature profile appears for “highly-sausaged” implosions

Scaled density maps show similar structure

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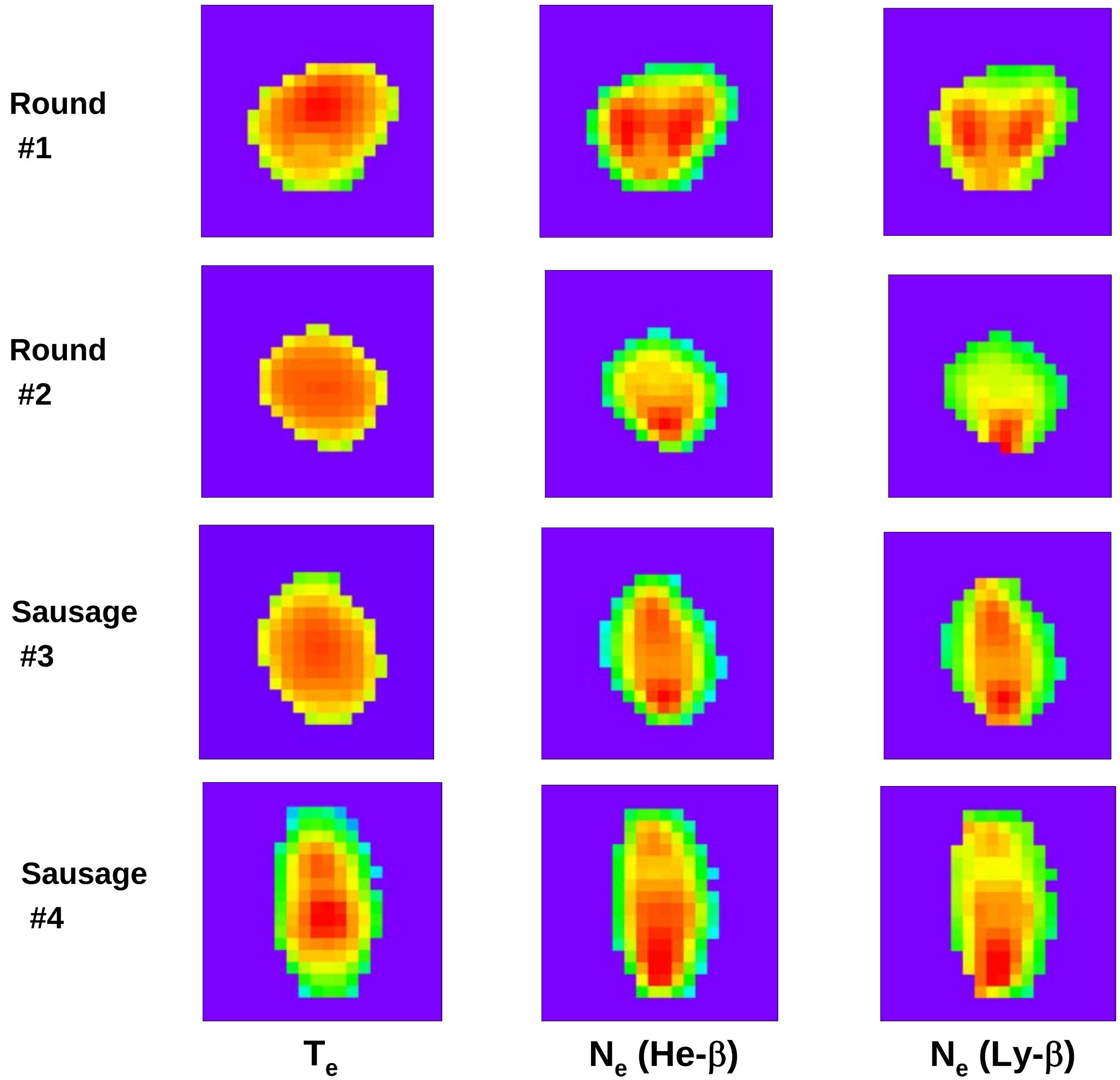

Analysis of gated data: quasi-3D spatial-structure

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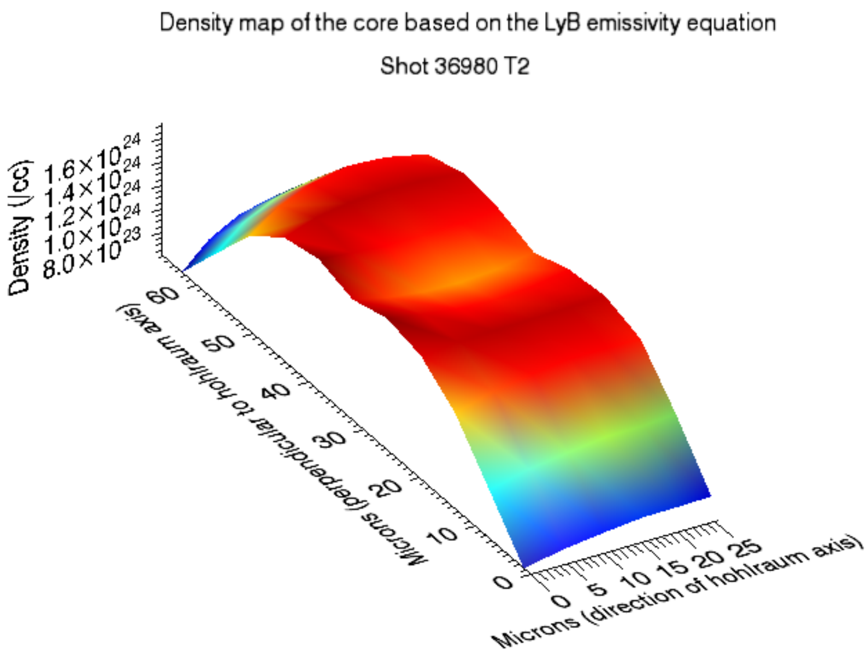
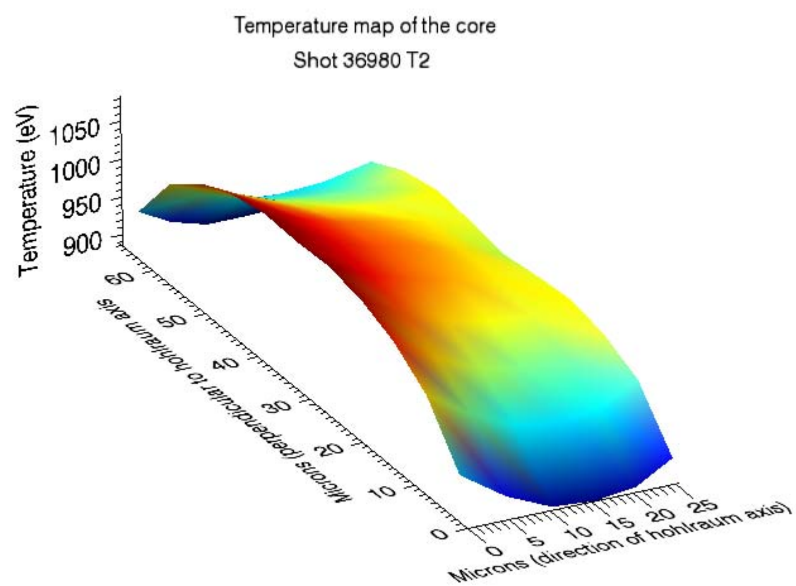
- OMEGA shot 36980, temperature and density spatial structure:
  - quasi-3d temperature and density maps extracted from the analysis of argon Heβ and Lyβ core image data.





- With additional image data, fuel-shell mixing information can also be extracted.

TREX slit spectrometer data*

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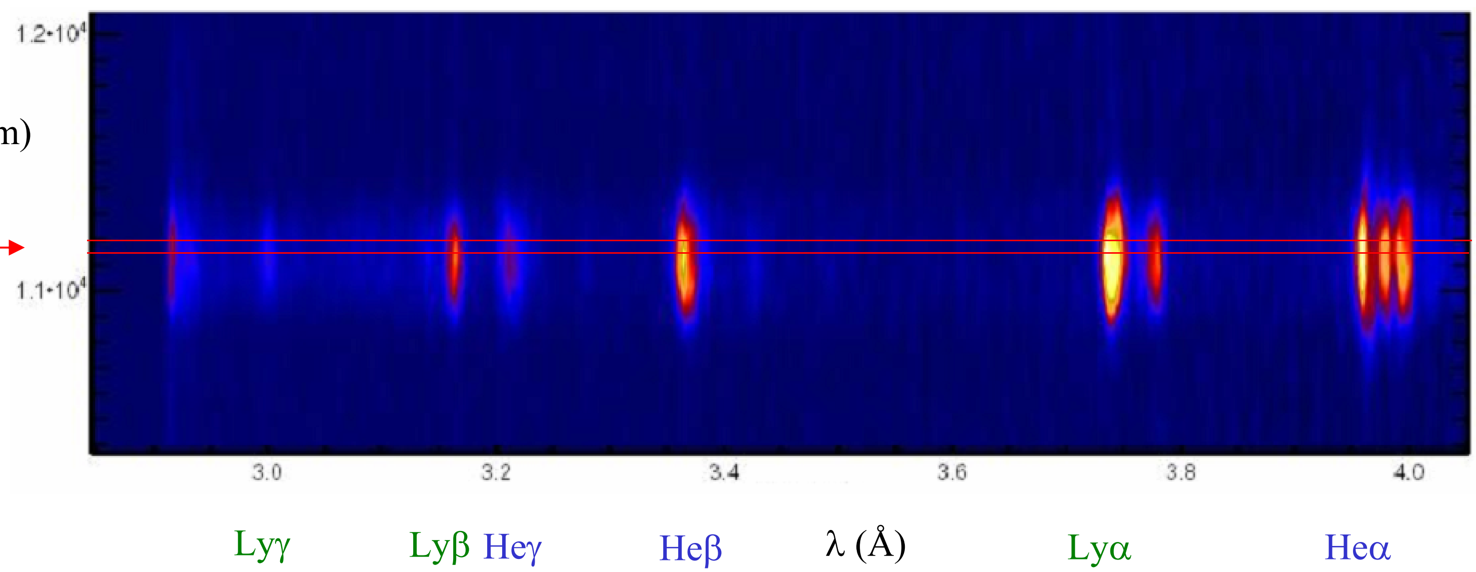
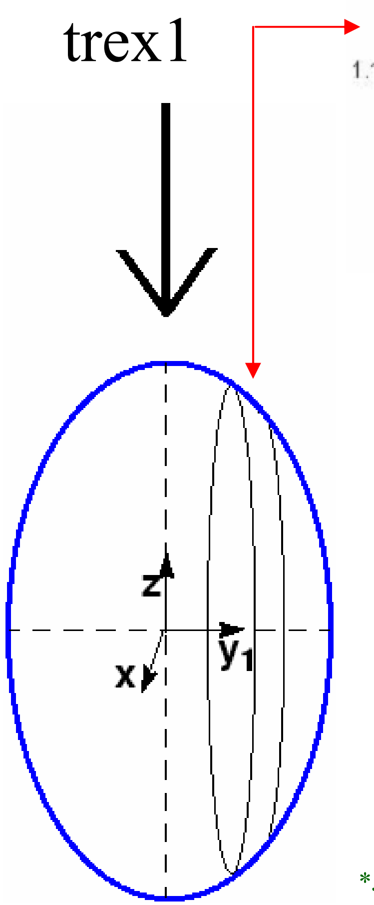
z1155 trex1f3





- 2 mm / 50 microns, 20 atm D2 / 0.085 atm Ar
- Gated image data shows space-resolved spectra recorded by the trex1 instrument.
- Slit oriented along the x axis, space-resolved along y axis.
- Each space-resolved lineout represents a spatial integration over a core slice.

*J. Bailey, G. Chandler, S. Slutz, I. Golovkin, P. Lake, J. MacFarlane, R. Mancini, T. BUrris-Mog, G. Cooper, R. Leeper, T. Mehlhorn, T. Moore, T. Nash, D. Nielsen, C. Ruiz, D. Schroen, W. Varnum, Phys. Rev. Letters **92**, 085002 (2004)

Core-slice based spatial structure

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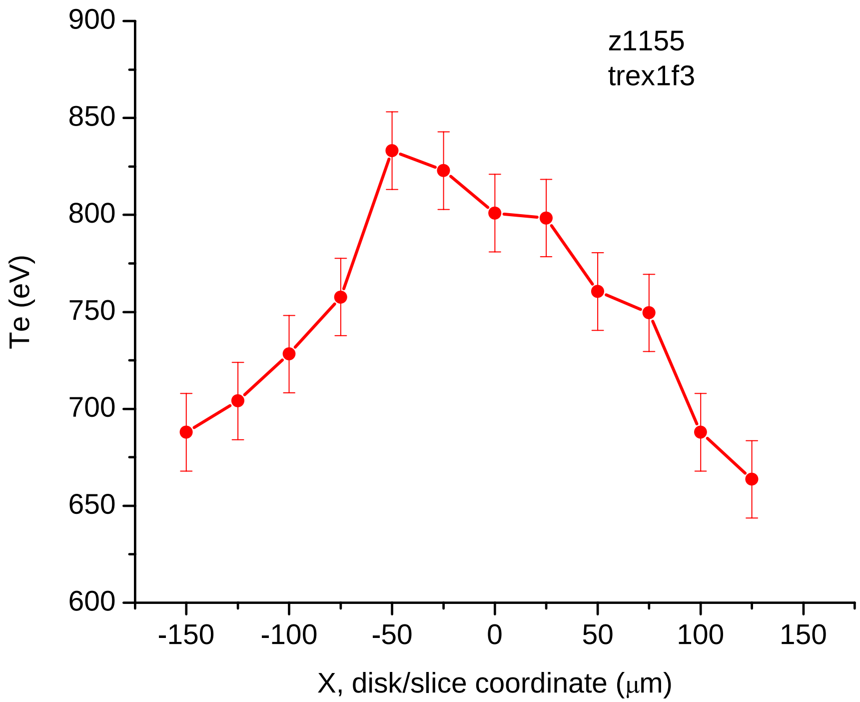
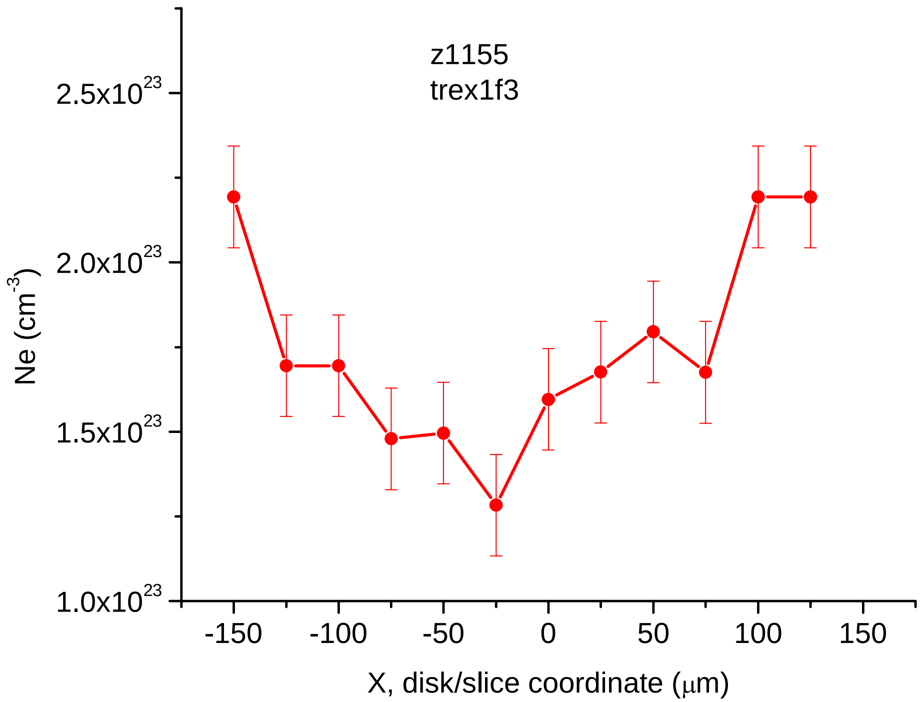
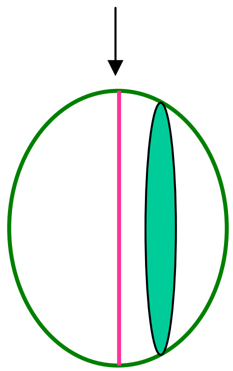




- Trex1: LOS parallel to z-pinch axis.
- Perform analysis on each lineout.
- Consistency check: two alternative sets of lineouts.
- Note: Ne gradient ≈ N_D gradient = Cρ, ρ: mass gradient.



TREX slit spectrometer data

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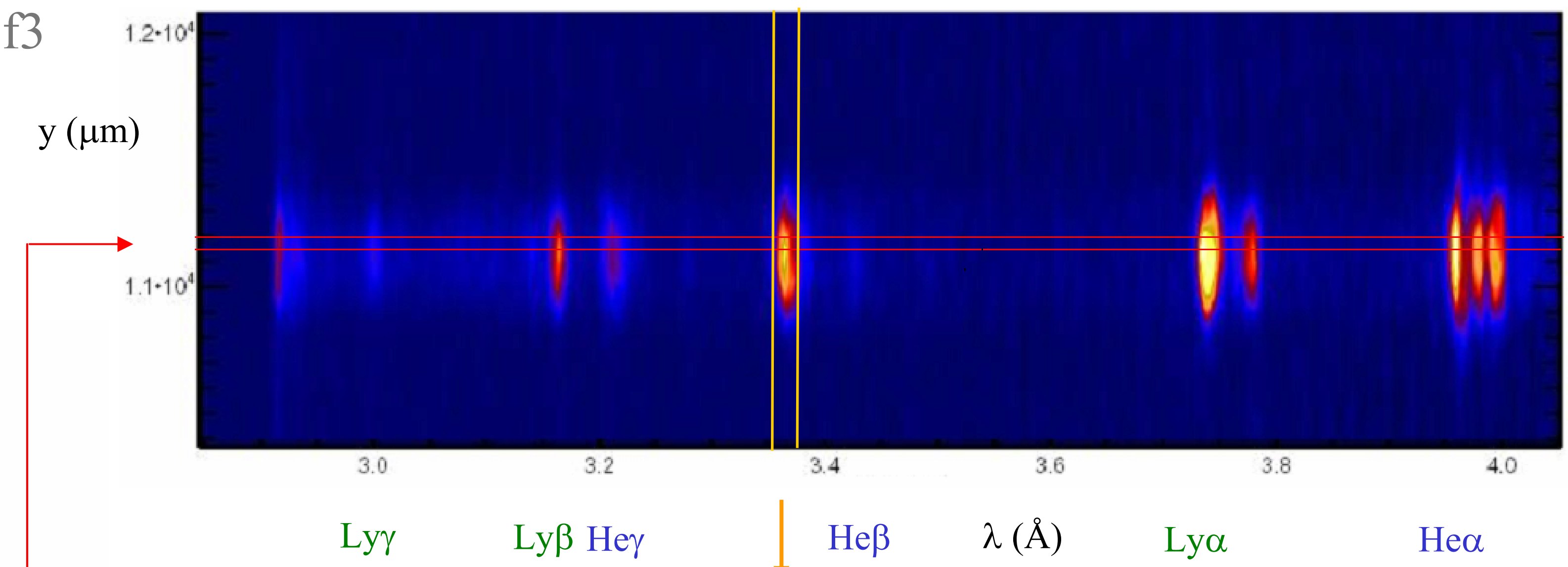
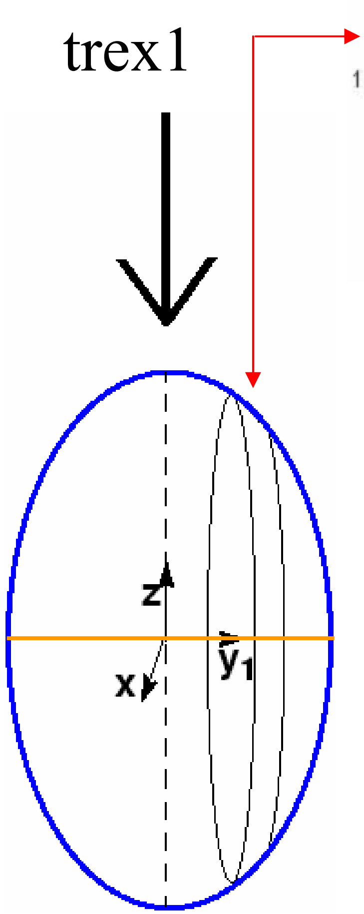
z1155 trex1f3





- Bright traces are slit images of implosion core at different photon energies.
- Vertical lineouts are narrow-band photon-energy intensity profiles on image plane.
- They represent space-integration over core slices resolved along a direction (y-axis) perpendicular to slit orientation (x-axis).
- Nearby continuum intensity profile can be subtracted.

Core slit image inversion

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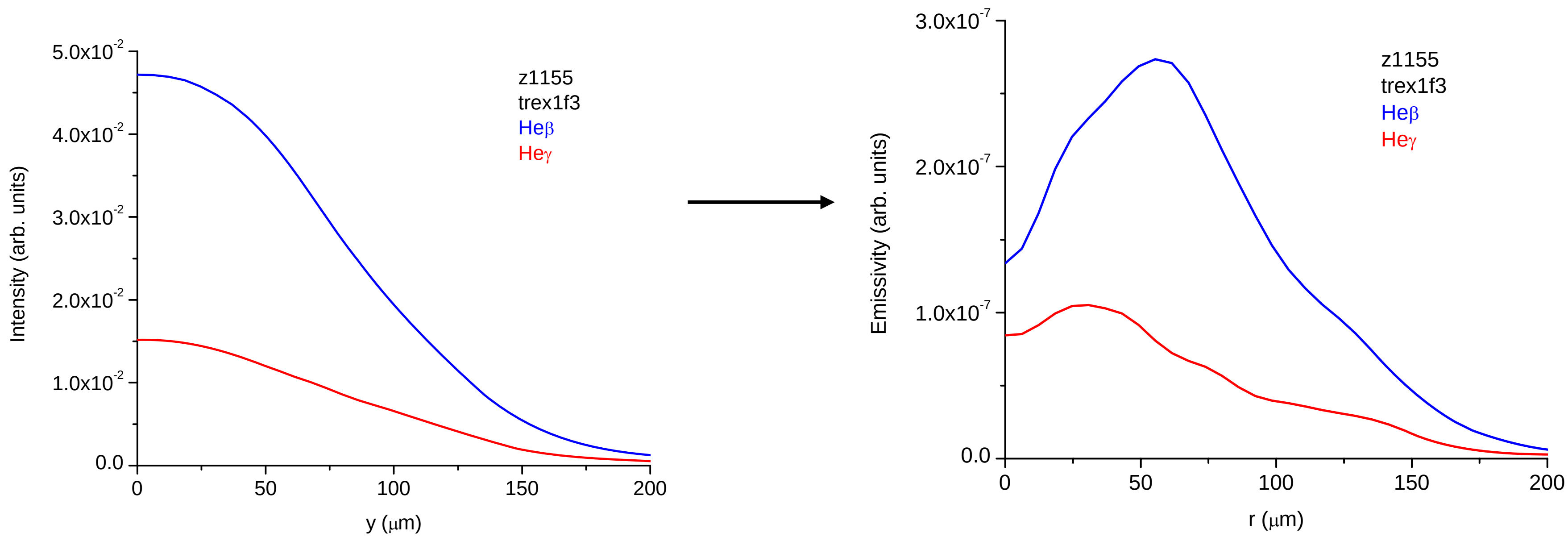

- Slit image intensity distributions can be inverted to produce emissivity spatial profiles in the core.
- Approximation: optically thin.
- Special case of Radon transform: spherical symmetry.*

*J. Radon, Leipzig, Math.-Phys. Kl. **69**, 262 (1917); S.R. Deans *The Radon transform and some of its applications*, Pub. J. Wiley & Sons (New York, 1983)

Conclusions

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- The determination of ICF implosion core spatial structure is important for efficient fuel burning, and for detailed studies and benchmarking of ICF hydrodynamic codes.
- Analysis methods are based on detailed analysis of imaged x-ray line emission from dopant elements in the implosion core.
- We have discussed three main ideas,
  - theory and modeling of dopant x-ray line emission,
  - imaging instrumentation and spectroscopic data,
  - data analysis methods.

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