A Spectroscopy Diagnostic of Plasma Gradients in ICF Imploded Cores

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Abstract

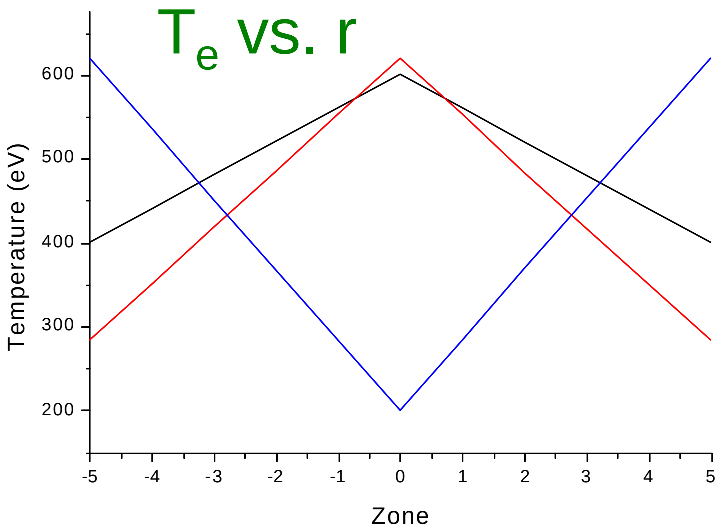
X-ray spectroscopy of laser-driven imploded ICF cores has proved to be a powerful diagnostic of spatially-averaged temperature and density plasma conditions at the collapse of ICF implosion experiments. Temperature and density time-histories can be extracted from the analysis of time-resolved X-ray line spectra using the temperature and density sensitivity of line intensities and Stark-broadened line shapes. The next step in the spectroscopy of imploded cores is the bracketing of core plasma gradients as a function of time. To this end, we discuss a spectroscopy diagnostic which is based on the self-consistent and simultaneous simulation and analysis of time-resolved X-ray line spectra and X-ray monochromatic images. Abel inversion of X-ray monochromatic images provide line emissivity spatial profiles; this information is critical for the determination of gradients in the core. We apply this technique to the analysis of data recorded in Ar-doped ICF implosion experiments driven with the GECCO XII laser system at Osaka University. In these experiments, time-resolved X-ray line spectra and X-ray monochromatic images were simultaneously recorded for the Ar Heβ and Lyβ spectral features. From the analysis of the data we can extract the time-history of temperature and density gradients in the core through the collapse of the implosion.

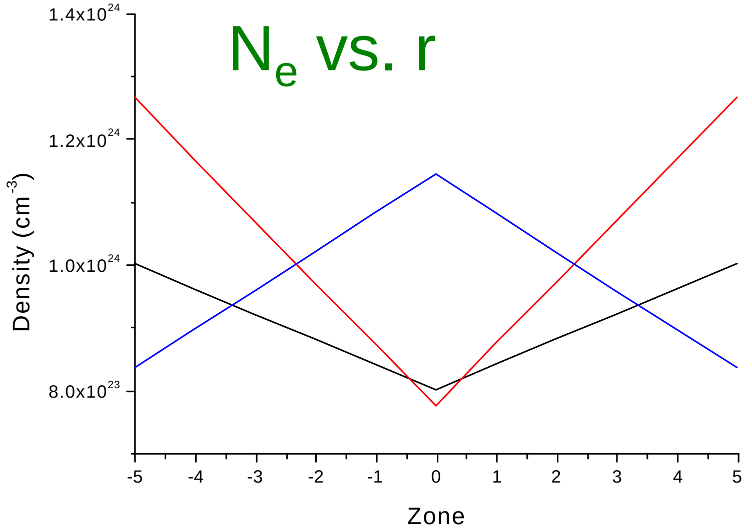
Motivation

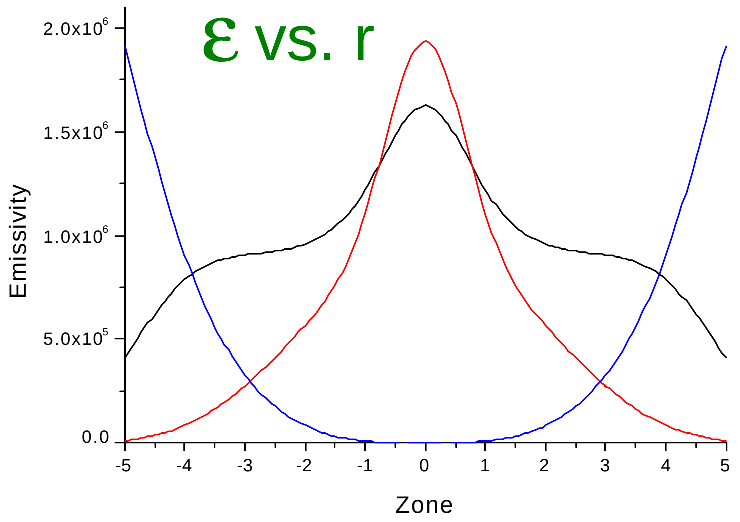
- Analysis of time-resolved Ar Heβ line spectra has been successfully employed to determine time-histories of core-averaged T_e and N_e in Ar-doped ICF implosions.
- The next step in the spectroscopic modeling of implosion core emission is the bracketing of the gradient structure as a function of time.
- Knowledge of core gradients will result in,
  - improved characterization of core plasma dynamics,
  - new data for detailed benchmarks of hydrodynamic codes.
- However, based only on the analysis of time-resolved, space-integrated spectra the determination of the gradients is ambiguous.
- A method for gradient determination based on the simultaneous and self-consistent simulation and analysis of time-resolved X-ray spectra and monochromatic X-ray images is presented.

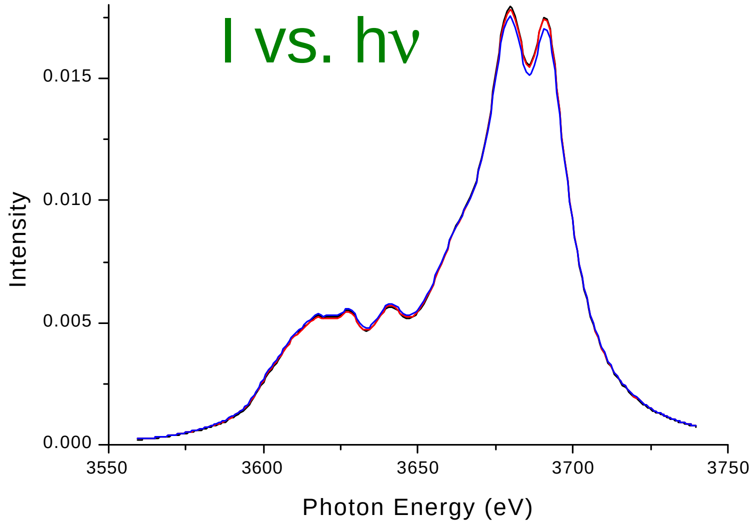
Spatially integrated spectra can not single out gradient

Different gradients relate to different emissivity spatial profiles

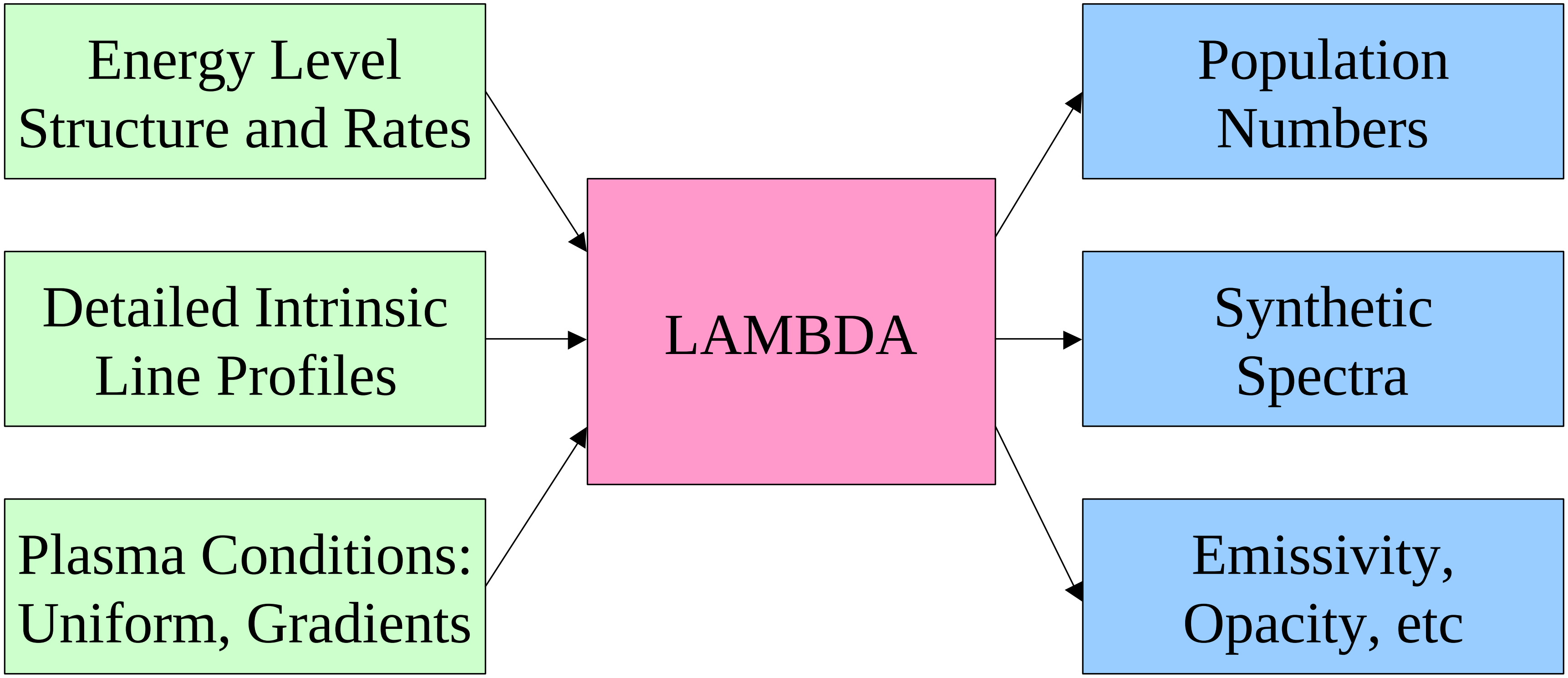








Model description



Energy Level Structure and Rates

Detailed Intrinsic Line Profiles

Plasma Conditions: Uniform, Gradients

LAMBDA

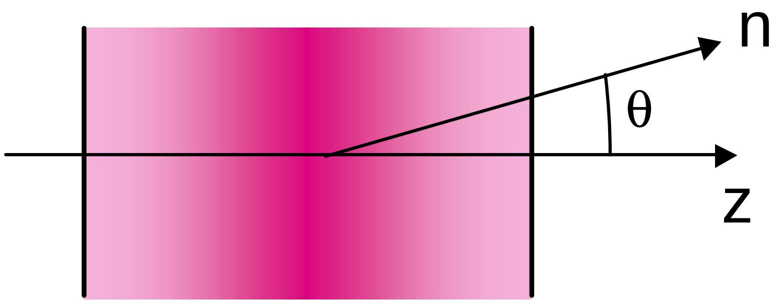
Population Numbers

Synthetic Spectra

Emissivity, Opacity, etc

Atomic kinetics and radiative transfer

NLTE radiation transport model requires self-consistent solution of:



- Transfer equation $$\mu \frac{dI_{\nu\mu j}(z)}{dz} = -\kappa_{\nu j}(z) I_{\nu\mu j}(z) + j_{\nu j}(z),\ \mu = \cos\theta$$

Emissivity $$j_{\nu j} = \sum_{i=1}^{n_l} \sum_{k<i} n_{ij} A_{ik} \varphi_{ik\nu} \frac{h\nu_{ik}^{0}}{4\pi}$$

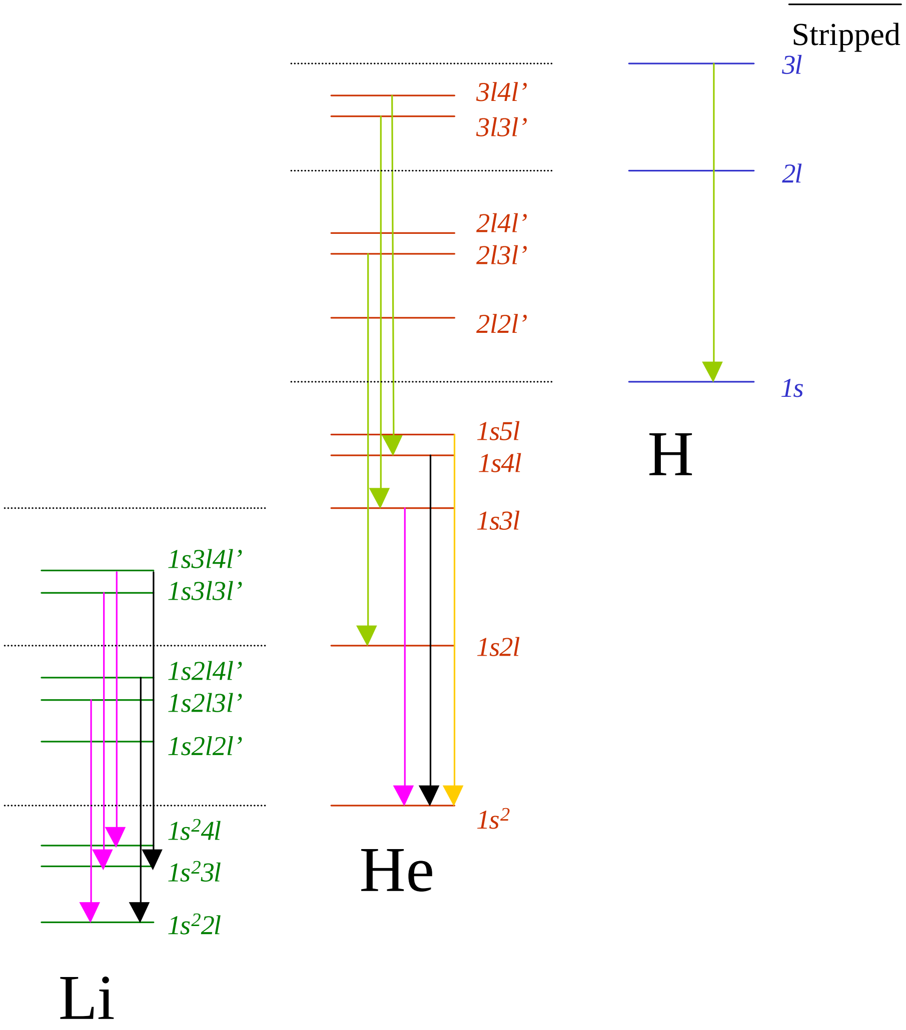
Opacity $$\kappa_{\nu j} = \sum_{i=1}^{n_l} \sum_{k>i} (n_{ij} B_{ik} - n_{kj} B_{ki}) \varphi_{ik\nu} \frac{h\nu_{ik}^{0}}{4\pi}$$

- Set of kinetic rate equations $$n_{ij} \sum_{k \neq i}^{n_l} P_{ikj} - \sum_{k \neq i}^{n_l} n_{kj} P_{ikj} = 0$$

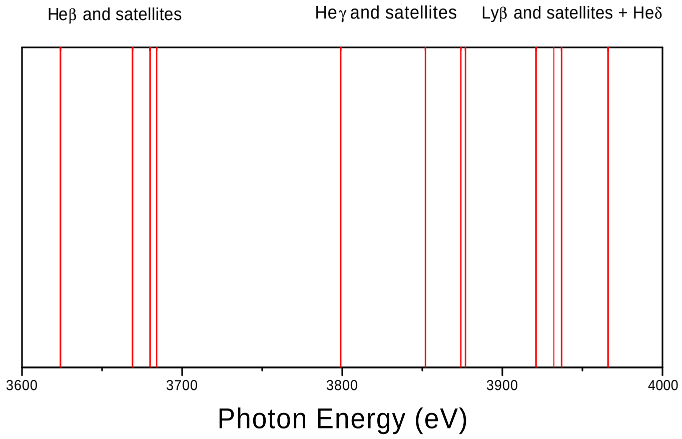
Rates include radiation dependent terms and therefore are coupled to the transfer equation.

- The problem is non-local and non-linear

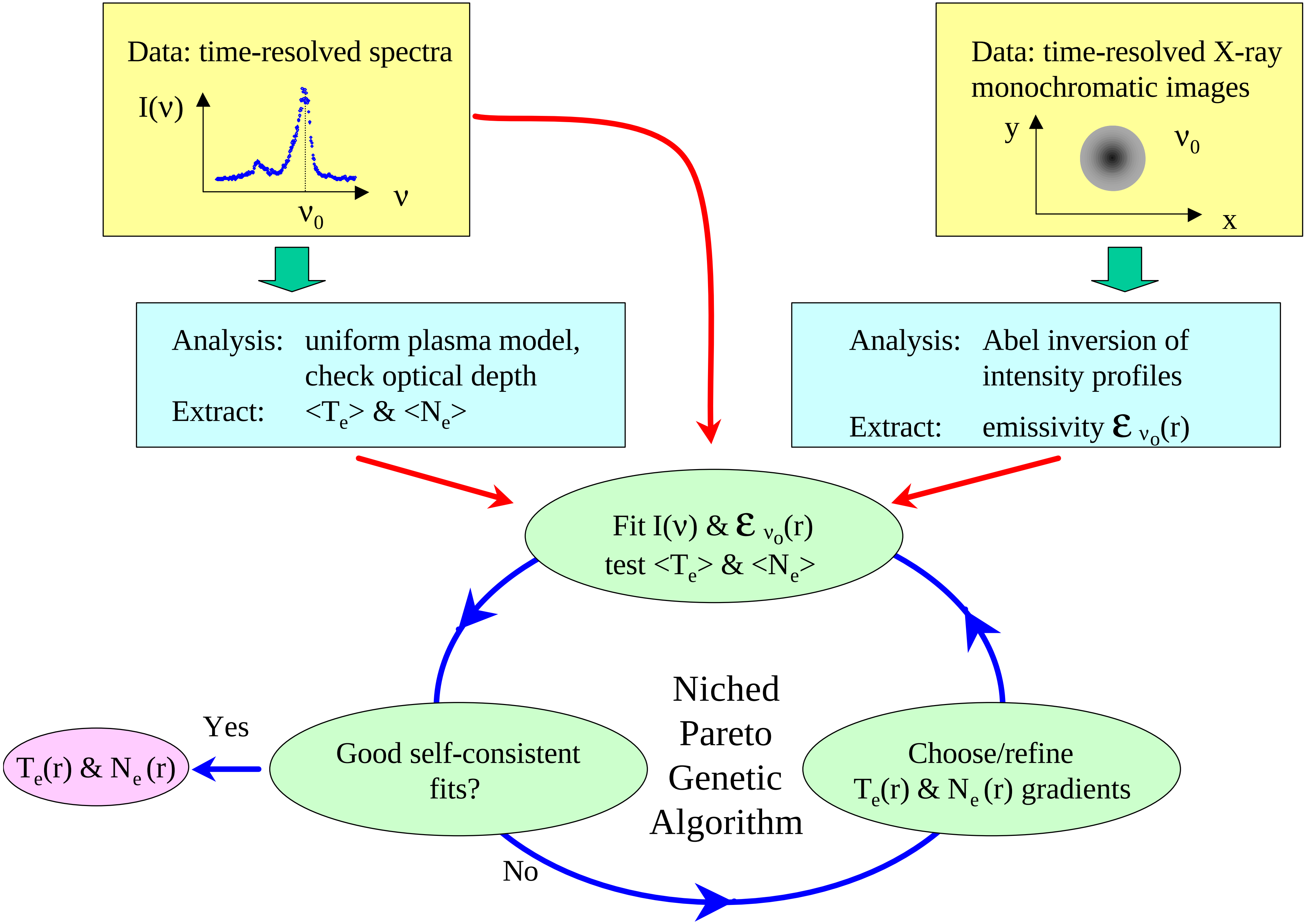
Energy levels and atomic processes



- Electron collisional excitation and de-excitation
- Electron collisional ionization and recombination
- Autoionization and electron capture
- Spontaneous radiative decay
- Photoexcitation
- Stimulated emission
- Radiative recombination



Atomic data have been calculated with the Los Alamos atomic structure and electron scattering codes: CATS, ACE, and GIPPER



Data: time-resolved spectra

Data: time-resolved X-ray monochromatic images

Analysis: uniform plasma model, check optical depth

Extract: $\langle T_e \rangle$ & $\langle N_e \rangle$

Analysis: Abel inversion of intensity profiles

Extract: emissivity $\varepsilon_{\nu_o}(r)$

Fit $I(\nu)$ & $\varepsilon_{\nu_o}(r)$

test $\langle T_e \rangle$ & $\langle N_e \rangle$

Niched Pareto Genetic Algorithm

Good self-consistent fits?

Yes

$T_e(r)$ & $N_e(r)$

No

Choose/refine $T_e(r)$ & $N_e(r)$ gradients

Search procedures

- Interactive search with a graphical user interface,
  - physics of the model,
  - sensitivity with respect to model parameters,
  - search might not be thorough enough,
  - unique solution?
  - difficult for complex models.

- Computer driven, automatized search procedure,
  - physics of the model,
  - sensitivity with respect to model parameters,
  - objective, systematic search,
  - helps to address uniqueness of solution issue,
  - can deal with complex non-linear models,
  - e.g. Genetic Algorithms.

Genetic Algorithms

Genetic Algorithms are search algorithms based on the mechanics of natural selection.

GA is different from conventional search procedures:

- GA works with binary encoded parameter sets (chromosomes),
- GA searches from a population of points,
- GA does not use derivatives or other auxiliary knowledge,
- GA uses probabilistic transition rules.

Simple genetic algorithm operators:

- Reproduction (selection) - choosing strings for reproduction according to their fitness,
- Crossover - exchanging genetic information between strings,
- Mutation - random flipping a bit in a chromosome.

Genetic algorithms perform well in finding solutions in a poorly understood search space.

Encoding and evaluation

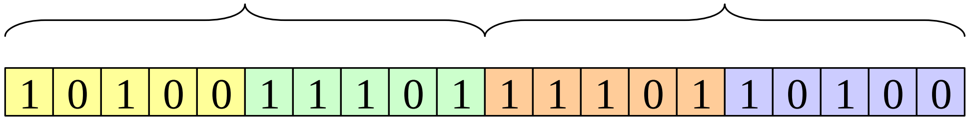
Parabolic Encoding

Temperature

$T(r) = a_1 r^2 + c_1$

Density

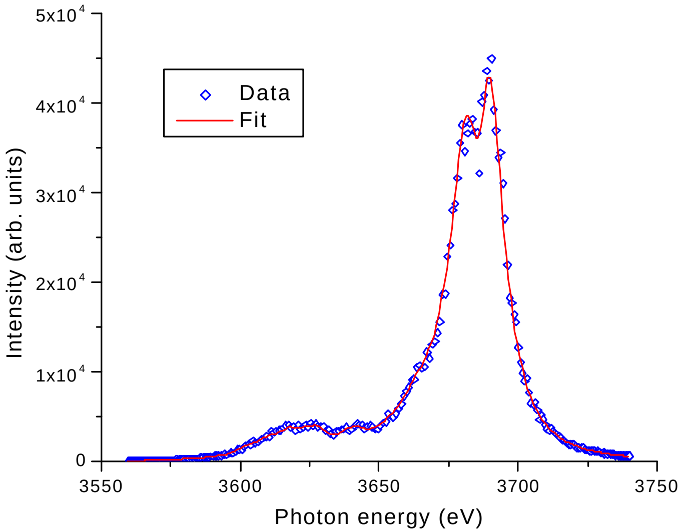
$N(r) = a_2 r^2 + c_2$



1 0 1 0 0 1 1 1 0 1 1 1 1 0 1 1 0 1 0 0

T(0) *T(R)* *N(0)* *N(R)*

[260 eV - 1500 eV] [$1.00\text{x}10^{23}$ cm^{-3} - $1.65\text{x}10^{24}$ cm^{-3}]



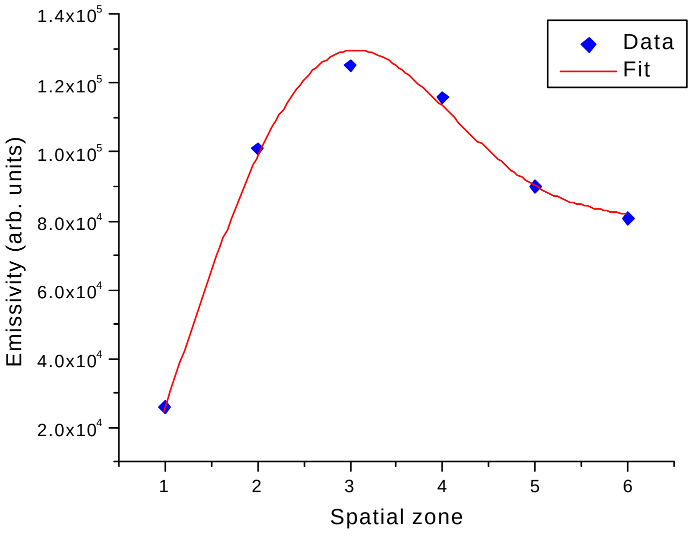
Evaluation

Spectrum

$$q_1^2 = \sum \left(I_{\exp} - I_{theor} \right)^2 \qquad \text{fitness}_1 = \frac{1}{q_1^2}$$

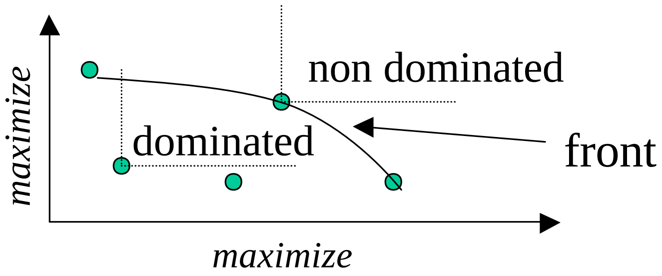
Emissivity

$$q_2^2 = \sum \left(E_{\exp} - E_{theor} \right)^2 \qquad \text{fitness}_2 = \frac{1}{q_2^2}$$



Niched Pareto Genetic Algorithm

Pareto Domination



Niched Pareto Genetic Algorithm* Implementation

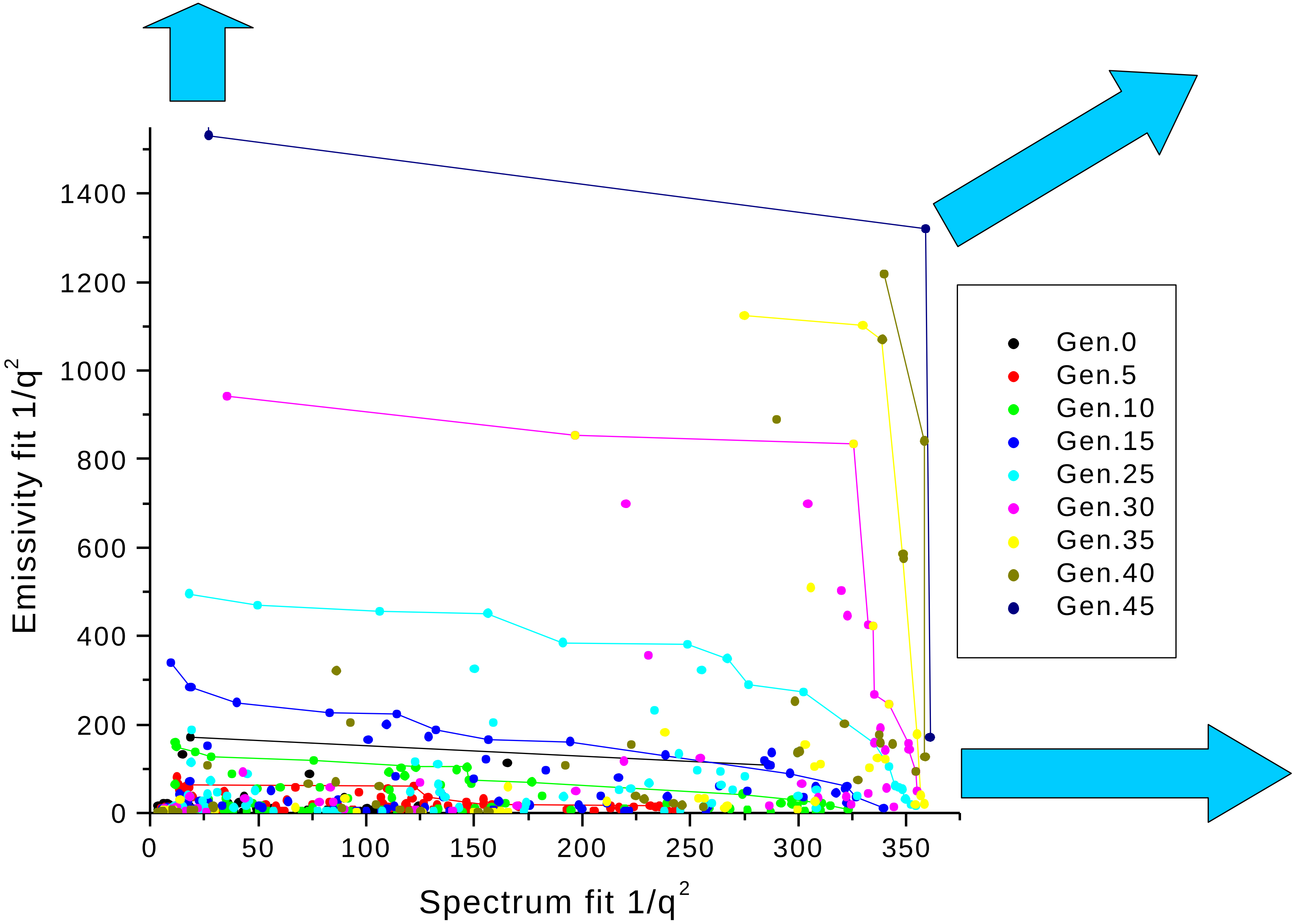
- Simultaneous spectrum and emissivity fit (multiple objectives)
- Tournament selection + elitist scheme
- Equivalence class phenotypic sharing
- Normalization of objective functions for each criterion
- Automatic niche size adjustment
- Uniform crossover
- Crossover probability: 0.95
- Mutation probability: 0.05

* *Multiobjective Optimization Using the Niched Pareto Genetic Algorithm*, J. Horn, N. Nafpliotis, IlliGAL Report No. 93005, July 1993

Analysis of synthetic data

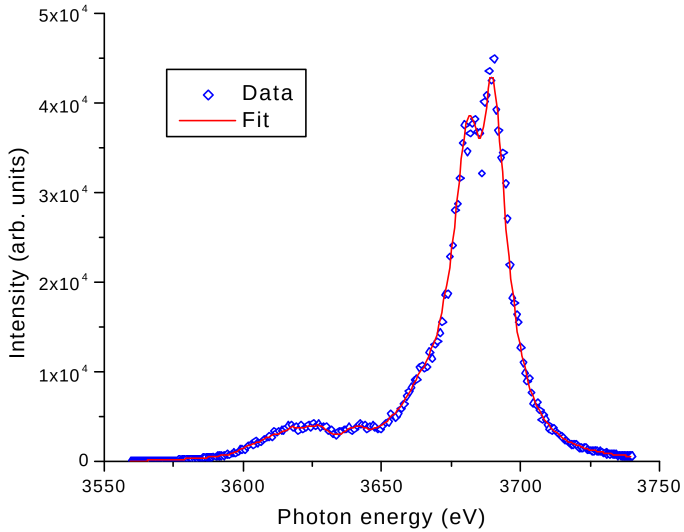
In order to study Niched Pareto Genetic Algorithm performance we consider the analysis of “synthetic data”. Noise was added to both emissivity and spectrum to simulate experimentally measured data. GA has been tuned to ensure fast and stable convergence.

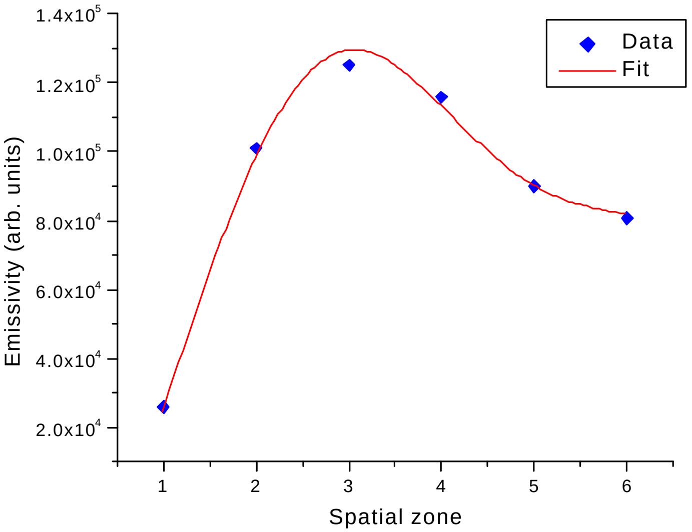
- At each generation an optimal parameter set is represented by a set of non-dominated solutions (Pareto front).
- Propagation of Pareto front indicates GA capability to drive the search for gradients that simultaneously fit emissivity and spectra.
- Solutions with good spectral fit / bad emissivity fit (bad spectral fit / good emissivity fit) are present, showing that satisfying either one of the criteria is not sufficient to correctly determine gradients.
- Plasma gradients in the vicinity of the solution should be similar. Analysis of this region may be used to study uniqueness and uncertainty of the solution.

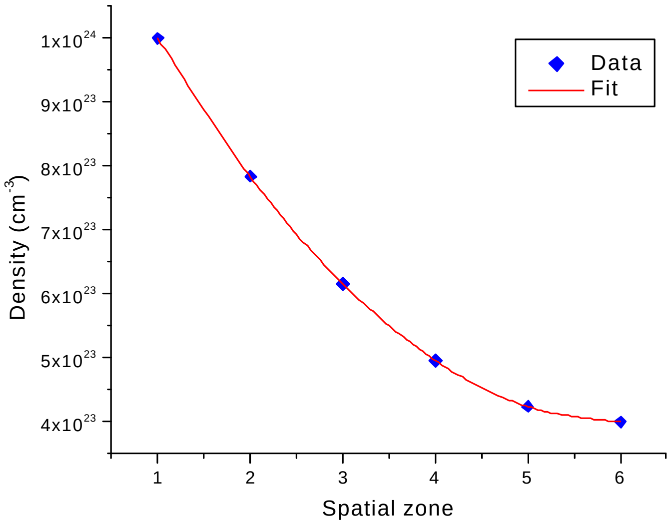


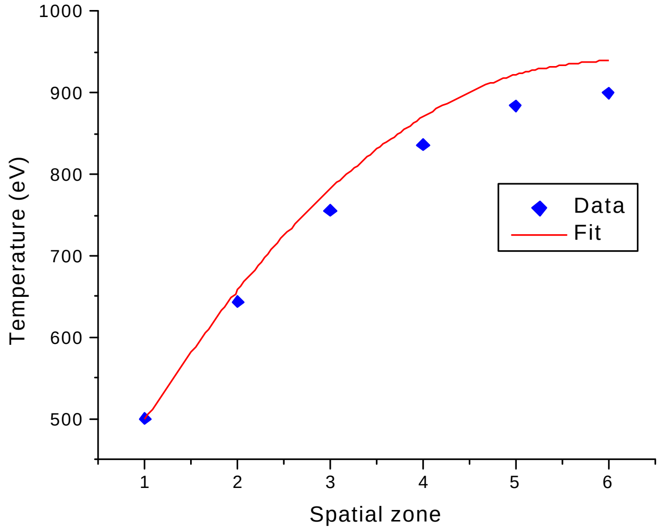
Propagation of Pareto optimal front during a niched Pareto genetic algorithm driven search of simultaneous fits to emissivity and spectrum

Good spectrum and emissivity fits

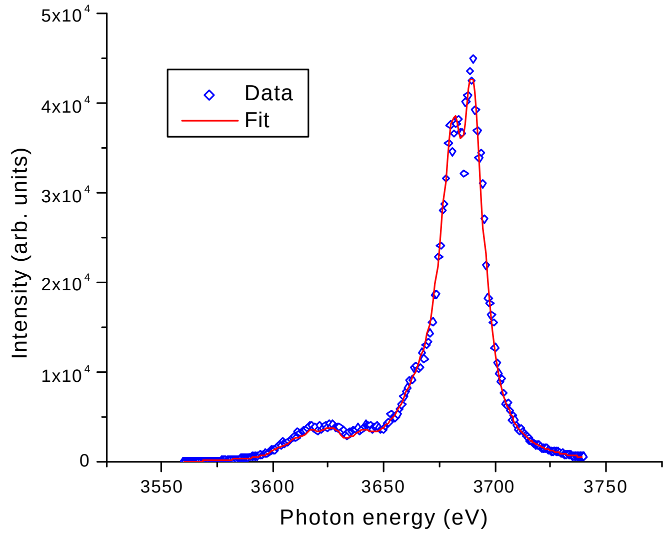


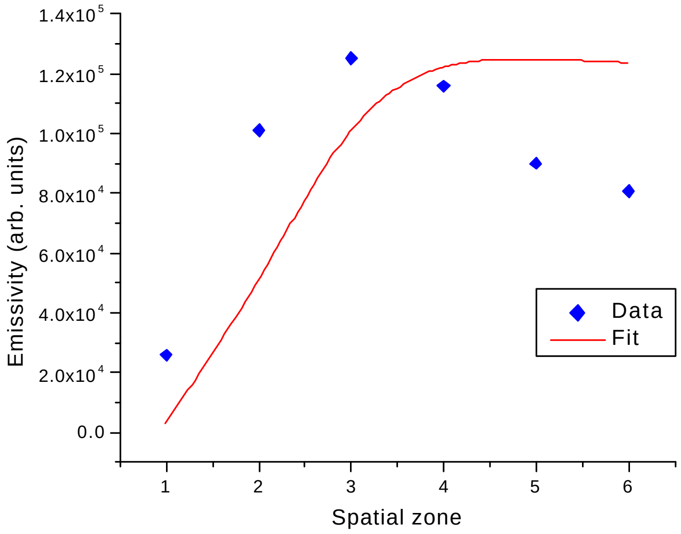


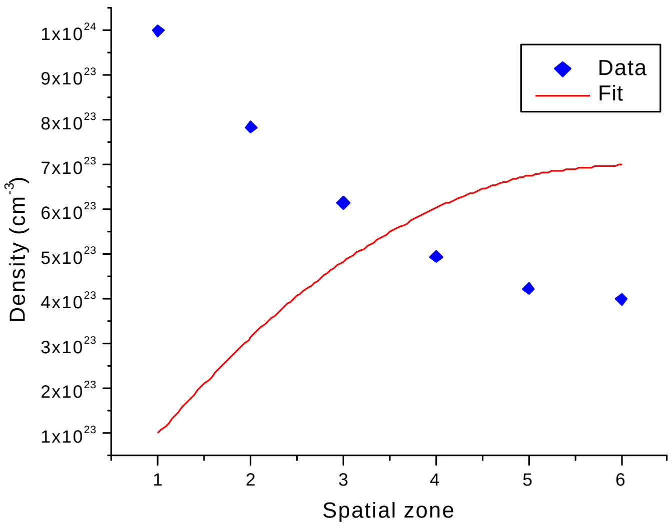


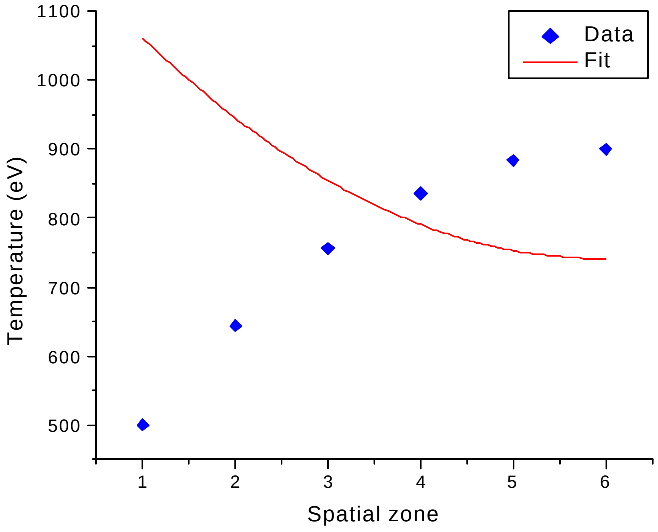


Good spectrum, bad emissivity fits

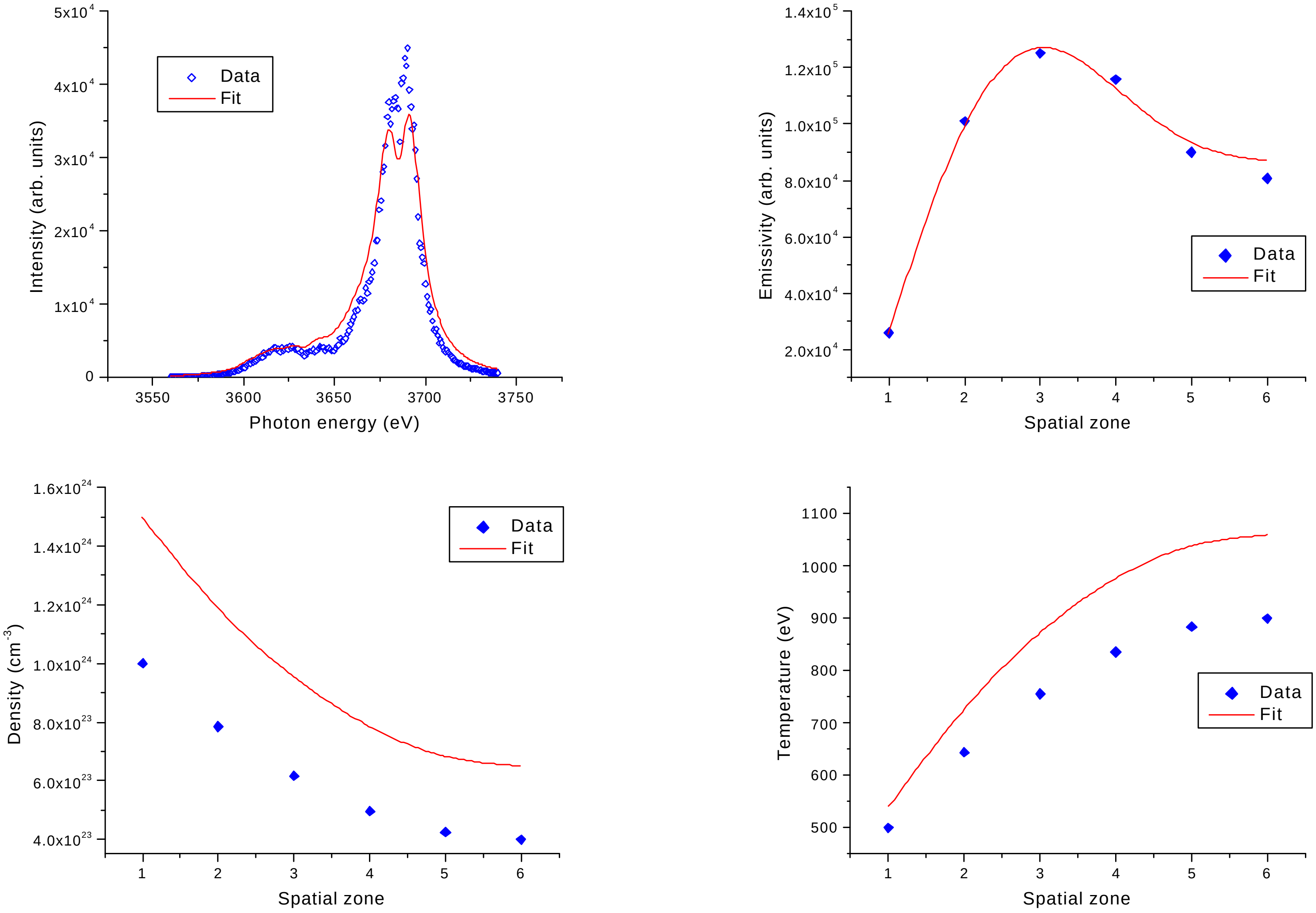






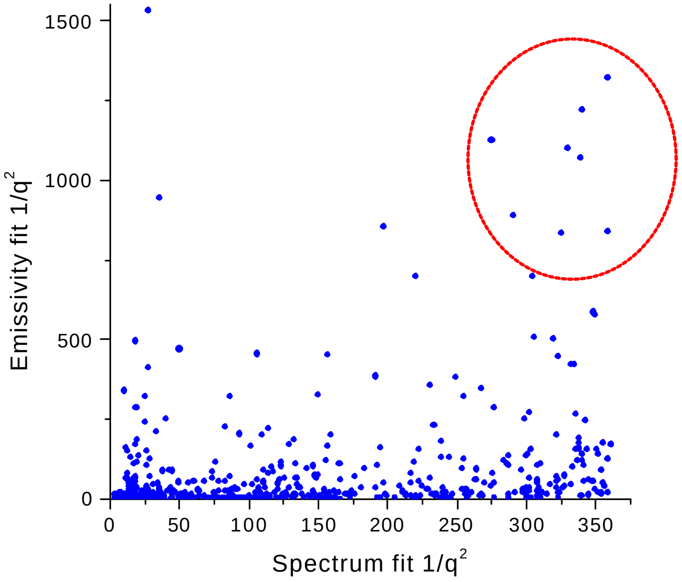


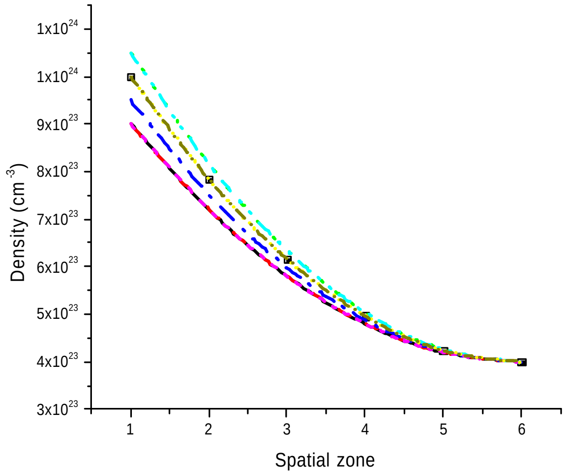
Bad spectrum, good emissivity fits

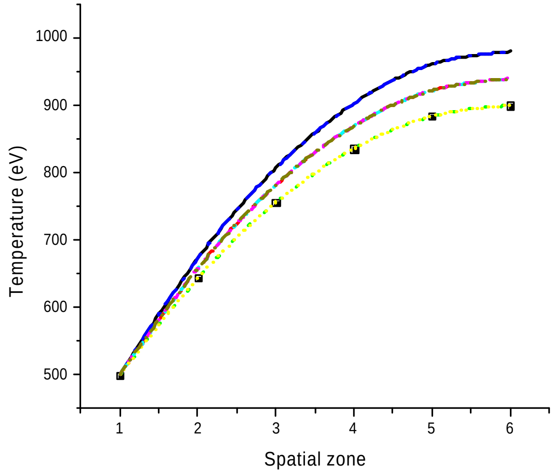


Uniqueness of the solution

Plasma gradients converge to a single solution that simultaneously fits emissivity and spectra (10% noise)







Gradient parameterization

It is important to know if the method can recover correct solution analyzing synthetic data calculated with more general gradients obtained from hydro simulations of plasma implosions. The problem arises because simple functions may not be capable of reproducing the gradients and will result in poor fits and wrong solutions. Therefore we need more flexible ways of gradient parameterization.

Parameterization and encoding

1. parabolic $(f(x) = ax^2+b)$,
2. bi-quadratic $(f(x) = ax^4+bx^2+c)$,
3. tabulated (each point in space is represented by a pair of temperature and density that can vary within the range of physically acceptable values),
4. tabulated with smoothness constrain (each point must not be very different from adjacent points),
5. tabulated with smoothness constrain, followed by a polynomial approximation.

Best performing parameterization

Tabulated With Smoothness Constrain, Followed by a Polynomial Approximation

- Each spatial zone in plasma is characterized by its density and temperature that can vary within a known range.
- Restrictions on the relative changes between adjacent points are used to prevent unrealistic behavior.
- Data points are fitted by a polynomial function.
- Temperature fitting function: bi-quadratic $(f(x) = ax^4+bx^2+c)$.
- Density fitting function: cubic $(f(x) = ax^3+bx^2+cx+d)$.

This parameterization combines flexibility of tabulated encoding with smoothness of functional dependence. The transformation is rather linear and does not make it more difficult for the algorithm to find the solution.

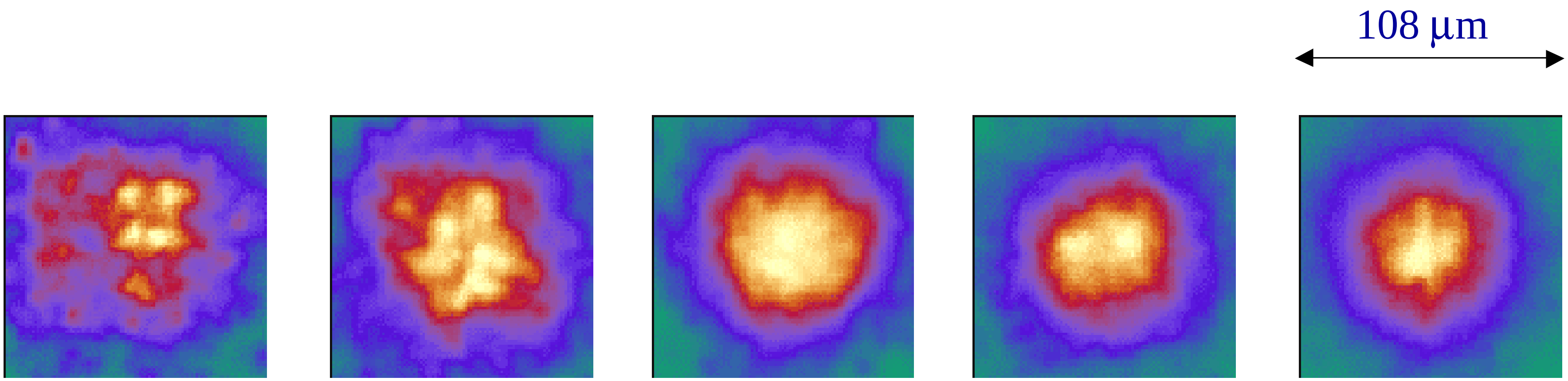
Laser-driven implosion experiments

- GEKKO XII laser system, Institute of Laser Engineering, Japan
- Laser shots 22091 and 22085, radial convergence ratio ~ 8
- PCL, 12 laser beams, λ=526 nm, square pulse τ=1.6 ns, E_T=2.55 kJ
- Plastic targets, 500 μm diameter, 8 μm wall thickness
- Filled with 30 atm of Deuterium and 0.075 atm of Ar
- Simultaneous, time-resolved X-ray monochromatic images & spectra,
  - XSS: time-resolved, spatially integrated X-ray spectra,
  - XMFC: time-resolved, monochromatic X-ray images,
  - data is illustrated for laser shot 22091

Time-resolved X-ray monochromatic images

Spatial emissivity profiles from intensity distributions

- GEKKO XII Shot 22091, balanced illumination case
- **XMFC**: **X**-ray **M**onochromatic **F**raming **C**amera
- Ar Heβ line, $h\nu=3680$ eV, $\Delta h\nu=19$ eV, $\Delta r=10$ μm, $\Delta t=40$ ps
- Five core images, 50 ps between frames



171-210 ps
a

221-260 ps
b

271-310 ps
c

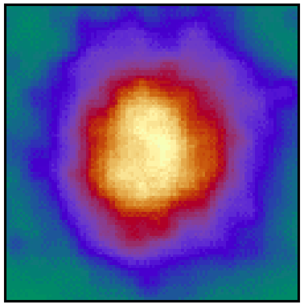
321-360 ps
d

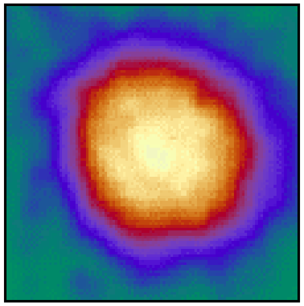
371-410 ps
e

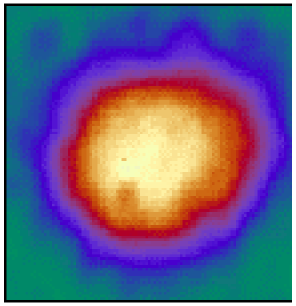
Time-resolved X-ray monochromatic images

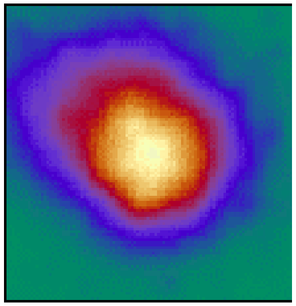
Spatial emissivity profiles from intensity distributions

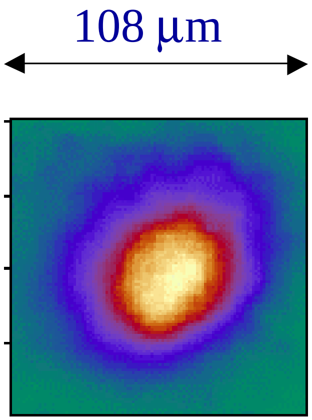
- GEKKO XII Shot 22091, balanced illumination case
- **XMFC**: **X**-ray **M**onochromatic **F**raming **C**amera
- Ar Lyβ line, $h\nu=3937$ eV, $\Delta h\nu=35$ eV, $\Delta r=10$ μm, $\Delta t=40$ ps
- Five core images, 50 ps between frames


121-160 ps


171-210 ps

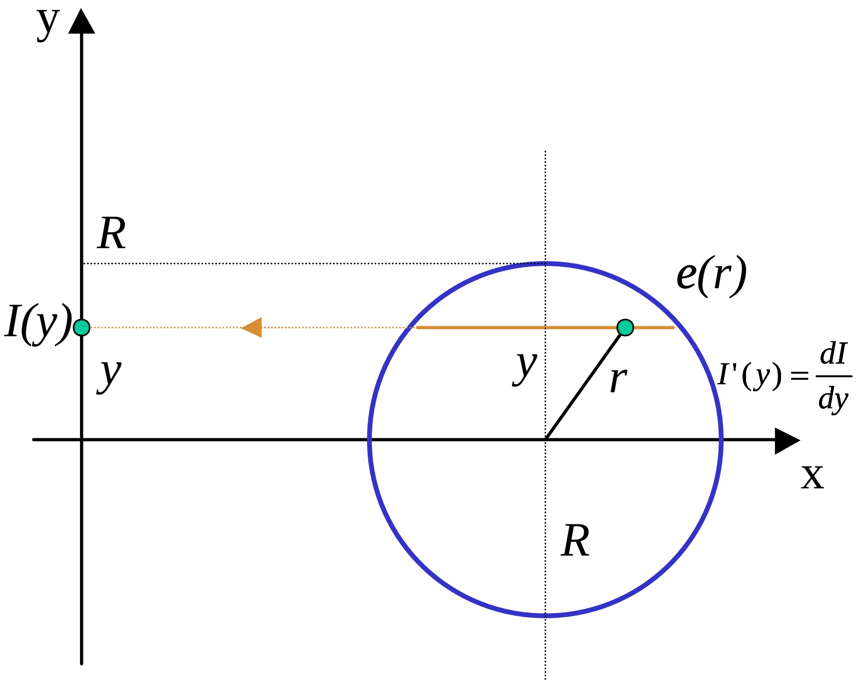

221-260 ps


271-310 ps



321-360 ps

Abel inversion



Intensity:

$$I(y) = 2\cdot\int_y^R \frac{e(r)rdr}{\sqrt{r^2-y^2}}$$

Emissivity:

$$e(r) = -\frac{1}{p}\cdot\int_r^R \frac{I'(y)dy}{\sqrt{y^2-r^2}}$$

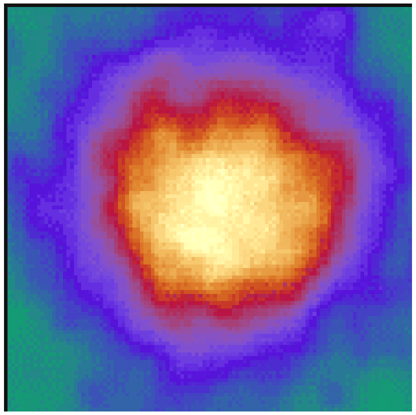
In the optically thin case *I(y)* is given by the line integral of *e(r)* along a chord of coordinate *y*.

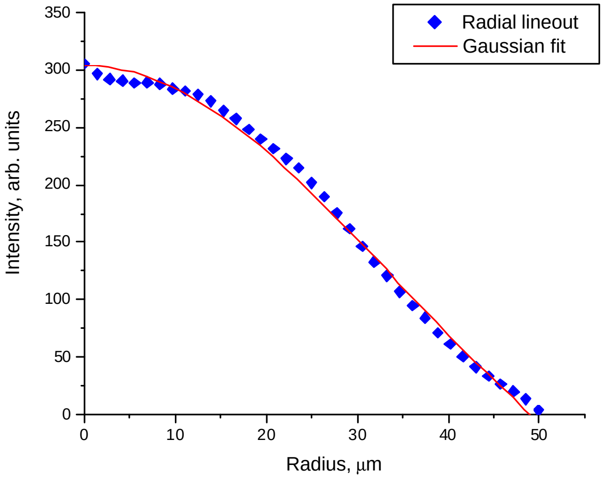
Then, the Abel inversion formally gives *e(r)* in terms of an integral of $I'(y) = \frac{dI}{dy}$

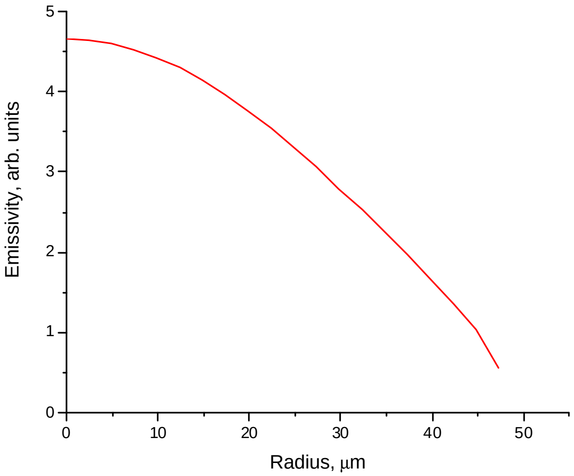
Monochromatic image analysis

From intensity profiles to emissivity profiles; time interval: 271 ps - 310 ps

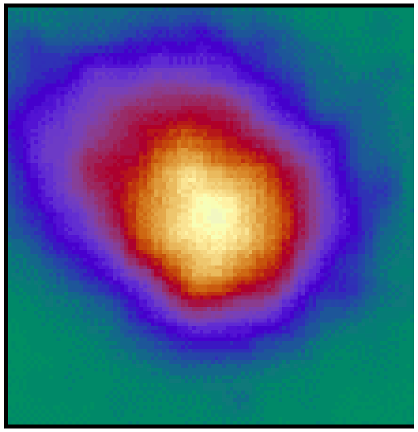
Heβ

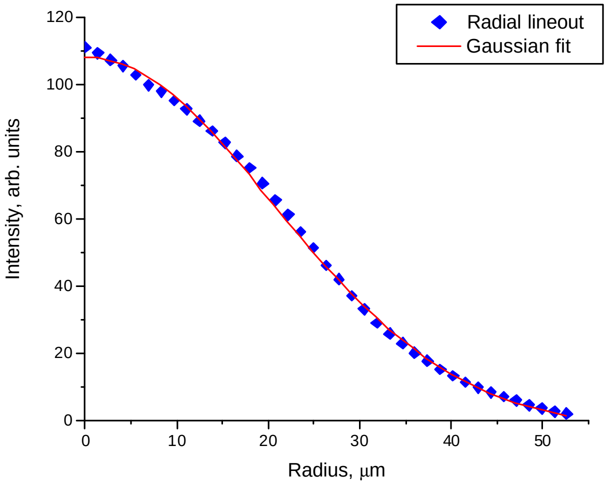


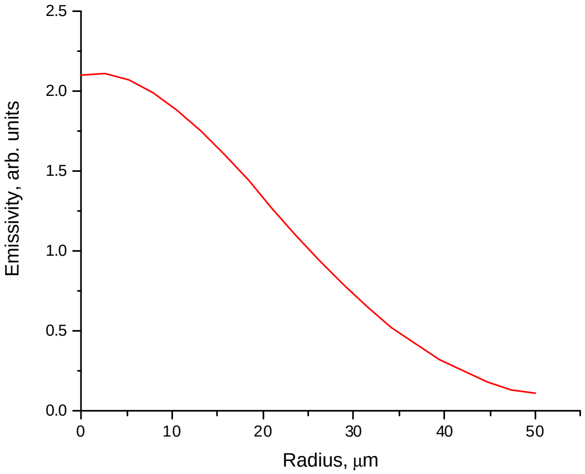




Lyβ



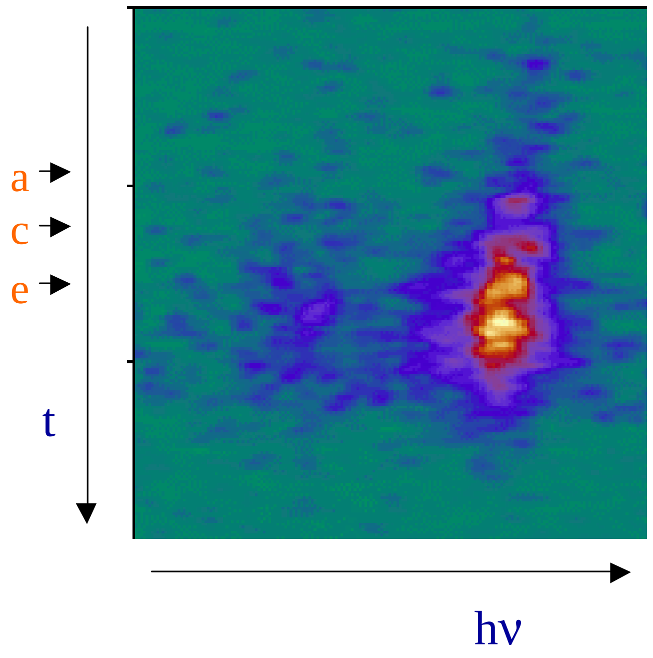




Time-resolved X-ray spectra

Ar Heβ $1s^1\ 3p^1 - 1s^2$ line and Li-like satellites

- GEKKO XII Shot 22091
- Ar Heβ line, hν=3680 eV, λ=3.369 A
- **XSS**: **X**-ray **S**treak **S**pectrograph
- Flat RbAP (100) crystal
- Resolution power λ/Δλ= 600
- Time resolution Δt=10 ps
- a, c & e: time-location of monochromatic images



Conclusions

- Simultaneous analysis of time-resolved X-ray spectra and monochromatic X-ray images can be used to determine plasma temperature and density gradients in the core.
- To a large degree these results are independent of hydrodynamic simulations.
- Niched Pareto Genetic Algorithm is capable of finding good fits to emissivities and spectra with the number of evaluations much smaller than the size of the search space.
- Tracing the Pareto optimal front helps to investigate the uniqueness of the solution.
- Work is in progress in the application of this method to data recorded in Ar-doped, ICF laser-driven implosions.