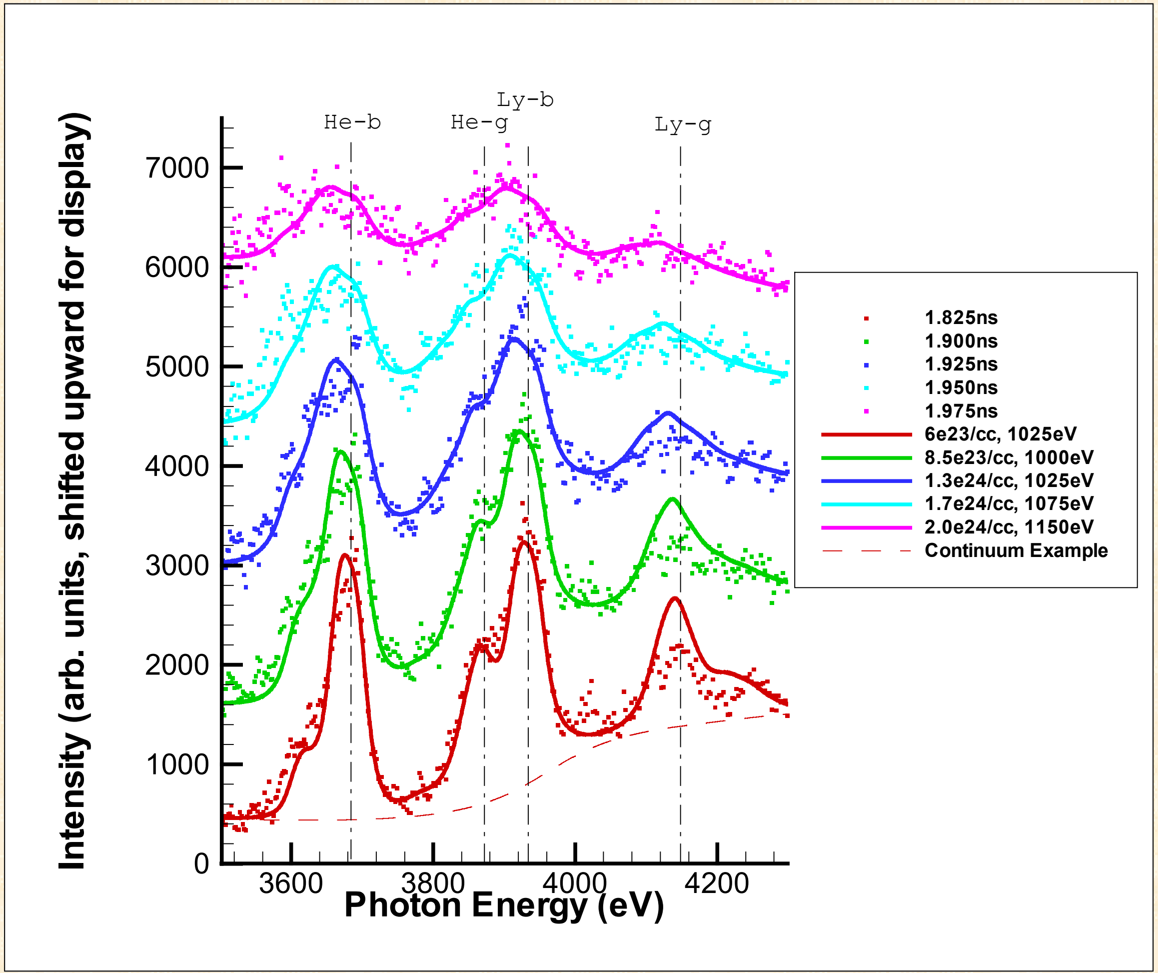
ArFIT: A detailed model of Ar K-shell emission from high energy density plasmas



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Abstract

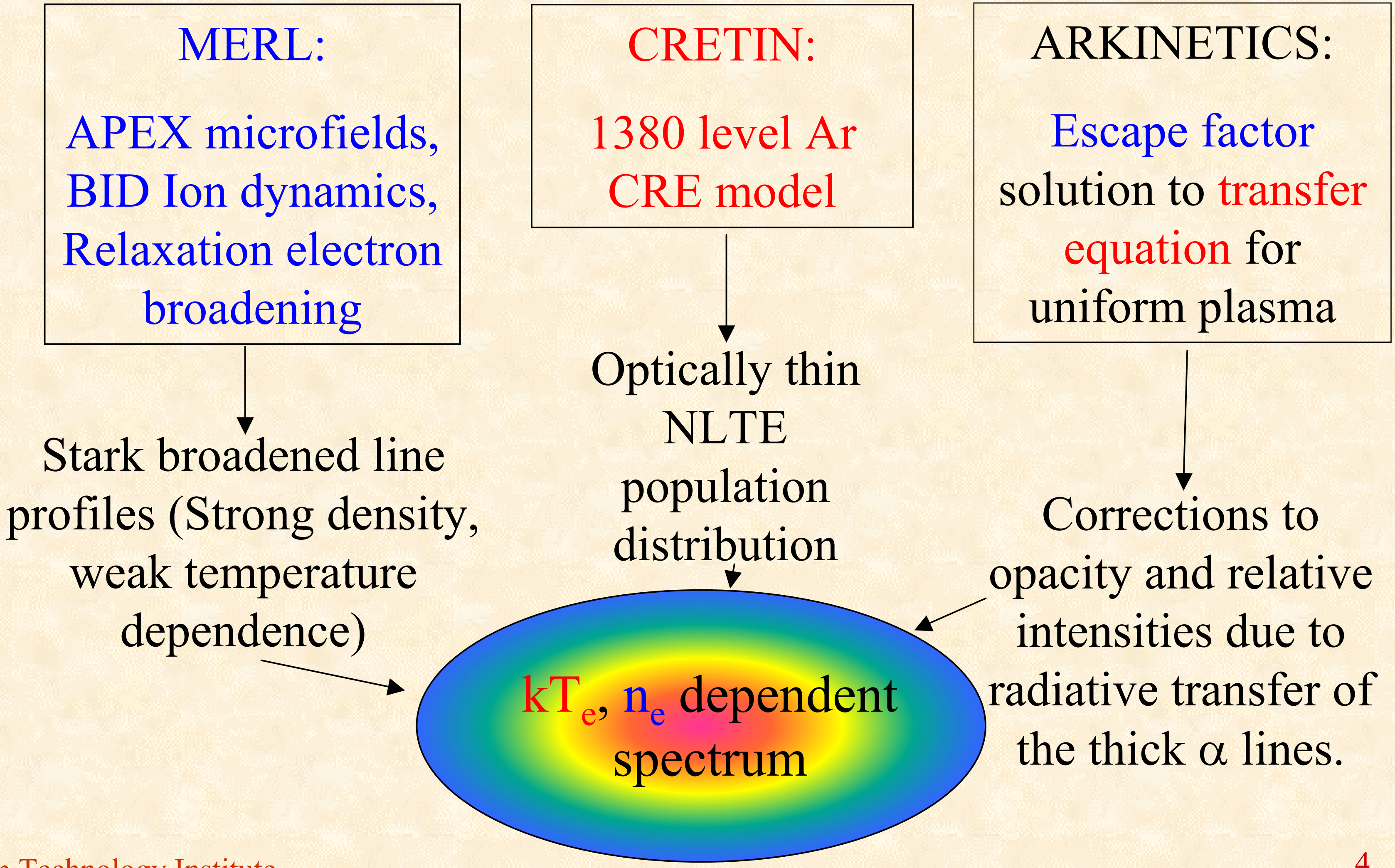
Ar K-shell spectroscopy has long provided a valuable tool for the diagnosis of high energy density plasmas such as those found in the imploded core of laser-driven microballoon implosions [see, e.g., D. A. Haynes, Jr., et al., Phys. Rev. E. 53, 1042 (1996) and references therein, I. E. Golovkin, et al., First International Conference on Inertial Fusion Sciences and Applications, Elsevier, p. 1123 (1999) and references therein]. The Stark broadening of optically thin resonance lines provides a strongly density dependent spectral feature. The relative intensities of the resonance lines or of resonance lines and their associated satellites depend on both temperature and density, and thus, in conjunction with a density inference from the lineshapes these ratios provide a temperature inference. In this presentation, details of ArFIT, a suite of codes which generates density and temperature dependent Ar K-shell spectra will be discussed. Recent advances in the model will be detailed, including the contribution of bound-free edges perturbed by the dense plasma environment. The practical implications of the main approximation in ArFIT, that the emitting plasma is homogeneous, will be explored by using ArFIT to analyze synthetic spectra obtained by post-processing BUCKY radiative-hydrodynamic simulations of typical Ar-doped DD filled microballoon implosions currently being conducted on the Omega laser.

Summary/Outline

ArFIT provides a highly detailed model of Ar K-shell emission from hot, dense plasmas. This model is useful for the extraction of time-dependent emissivity- averages of electron temperature and density from Ar-doped cores of ICF relevant implosions.

- Stark Broadened Lineshapes
- NLTE populations
- Corrections for Radiative Transfer
  - Intensities and lineshapes
- Example of analysis
- Continuum Edges
- Uniform core approximation effect for optically thin lines

Schematic of ArFIT data generation/ Approximations



MERL:

APEX microfields, BID Ion dynamics, Relaxation electron broadening

Stark broadened line profiles (Strong density, weak temperature dependence)

CRETIN:

1380 level Ar CRE model

Optically thin NLTE population distribution

ARKINETICS:

Escape factor solution to transfer equation for uniform plasma

Corrections to opacity and relative intensities due to radiative transfer of the thick α lines.

kT_e, n_e dependent spectrum

Stark broadened line profiles are generated using MERL, a multi-electron radiator line broadening code.

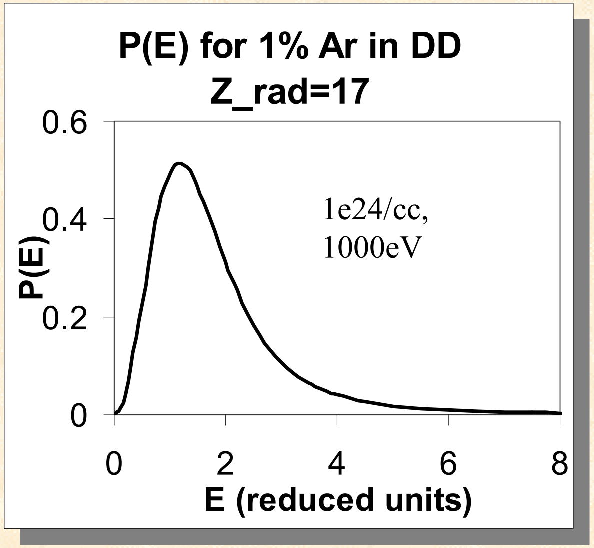
$$I(\omega) = \frac{4\omega^4}{3c^3}\underbrace{\int_0^\infty dE\; P(E)}\, J(\omega;E)$$

Lineshape

Average weighted by ion microfield distribution function

Electron-broadened lineshape emitted by a radiator experiencing a static ion microfield *E*

- APEX microfield
- BID Ion Dynamics
- Two full-coulomb formulations of electron broadening: all-order semi-classical, 2nd order quantum mechanical



$$J(\omega;\vec{E}) = -\frac{1}{\pi}\mathrm{Re}\,\mathrm{Tr}_{r}\left[\vec{d}\bullet R(\omega;\vec{E})\rho_r\vec{d}\right]$$

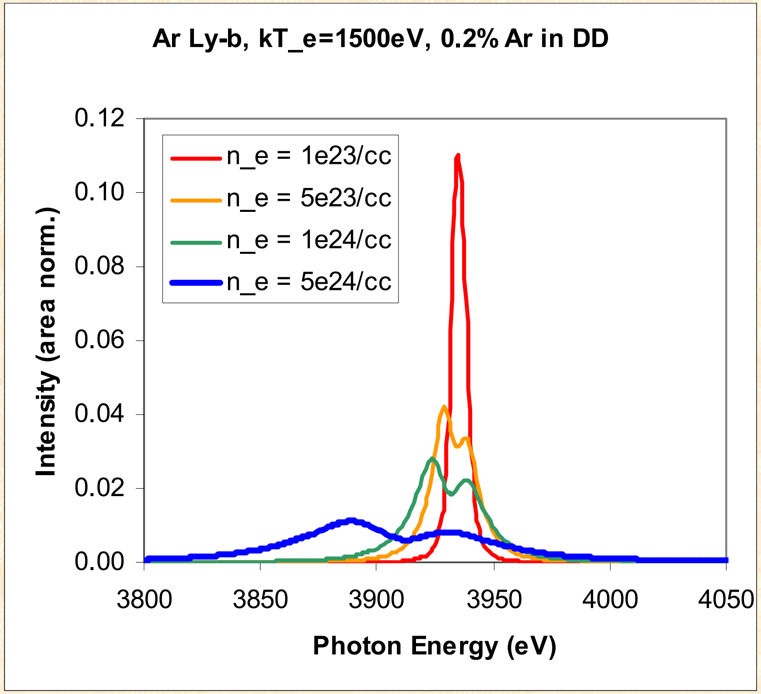
$$R(\omega;E) = \frac{1}{\Delta\omega - L_{i,r}(E) - \underbrace{B - M(\Delta\omega)}}$$

Ion microfield splitting

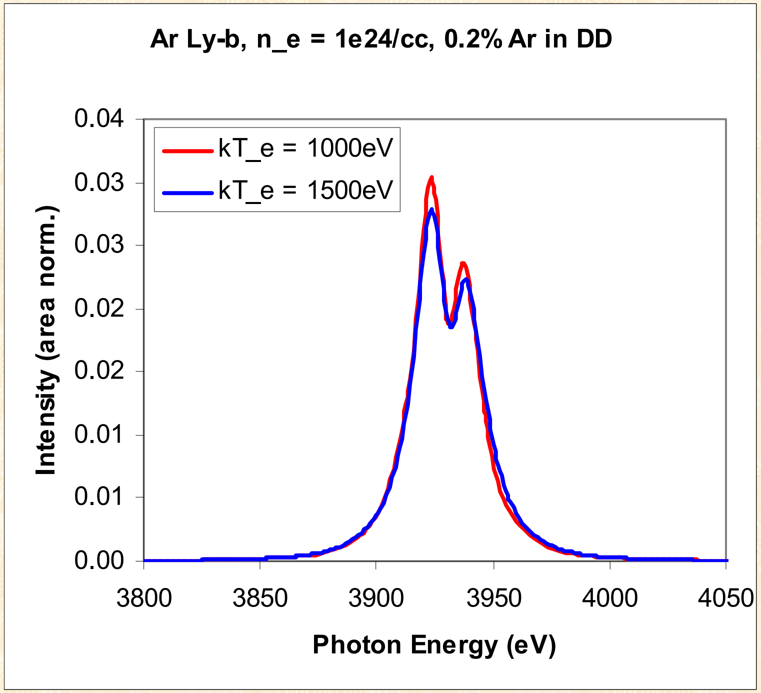
Plasma electron-radiator interaction

For the conditions found in current ICF implosions, optically thin Stark broadened Ar K-shell lines are strongly density sensitive, and relatively insensitive to temperature

Strong Density Dependence



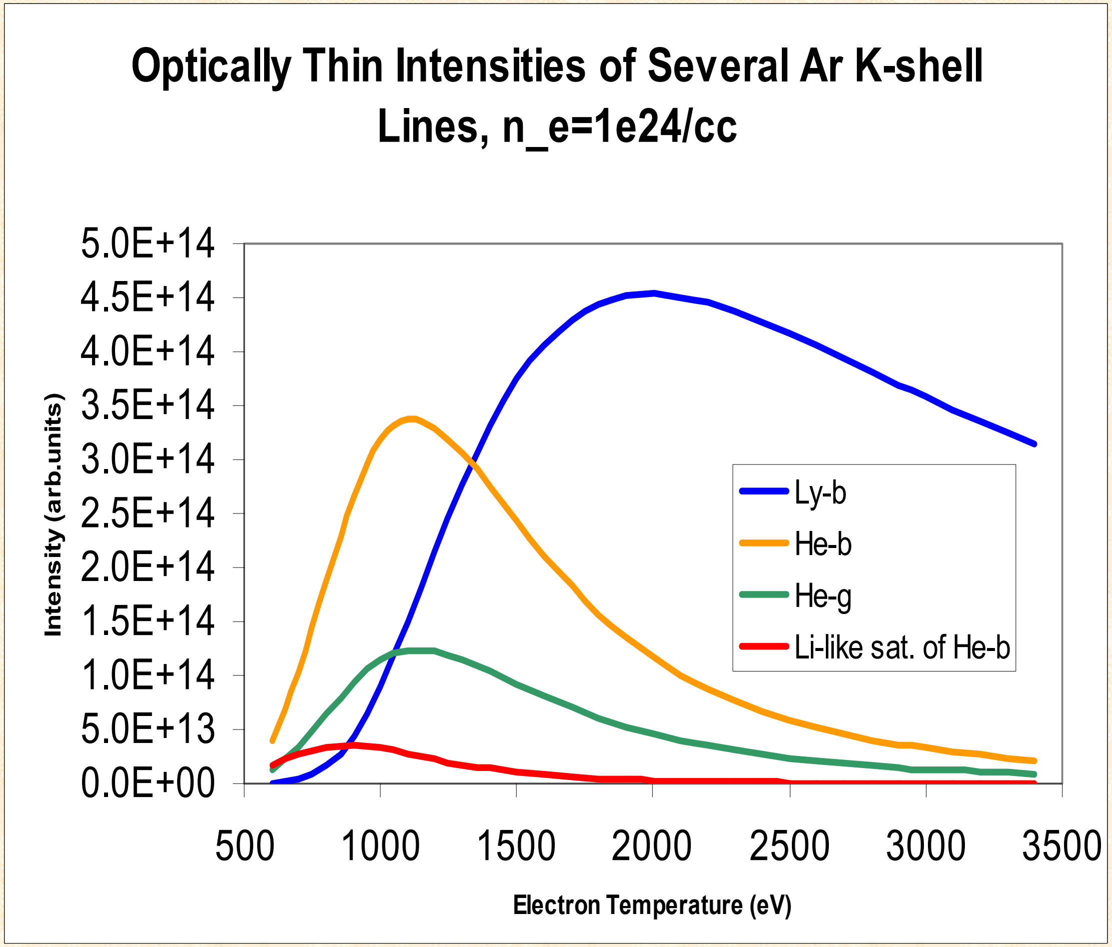
Weak Temperature Dependence



A 1380 level CRE model for K-shell Ar, with sufficient doubly excited states to account for all important L-shell satellite lines is solved using CRETIN in optically thin mode

- The strongly varying ratio of the Ly-b and He-b is the most useful for inferring core temperatures above 1.5keV.

- Below 1keV, the ration of the He-b line to its satellites is more useful for temperature inference



To account for the effect of the transfer of the optically thick α lines, ArFIT uses a reduced Ar K shell CRE model modified by escape factors calculated for the Stark broadened lineshapes.

The effect of the radiative transfer of the α lines is to drive the ionization balance towards more highly stripped ionization stages. This effect depends both on temperature (through the kinetics) and density (through the kinetics and the lineshapes used for the escape factors).

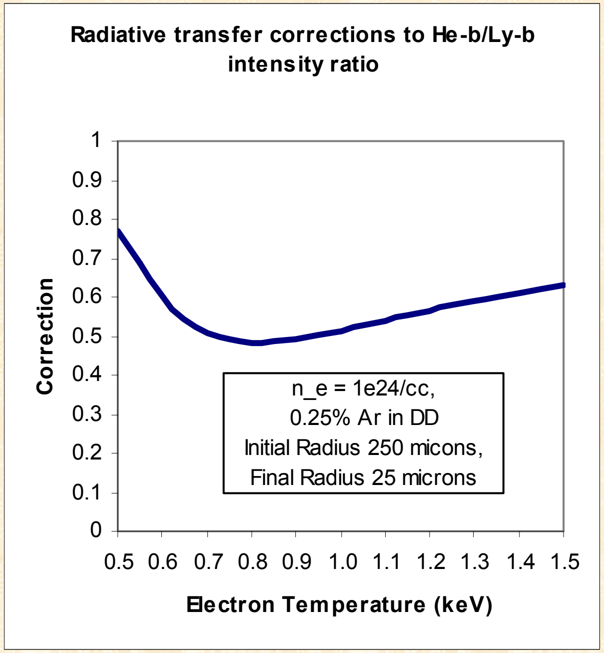
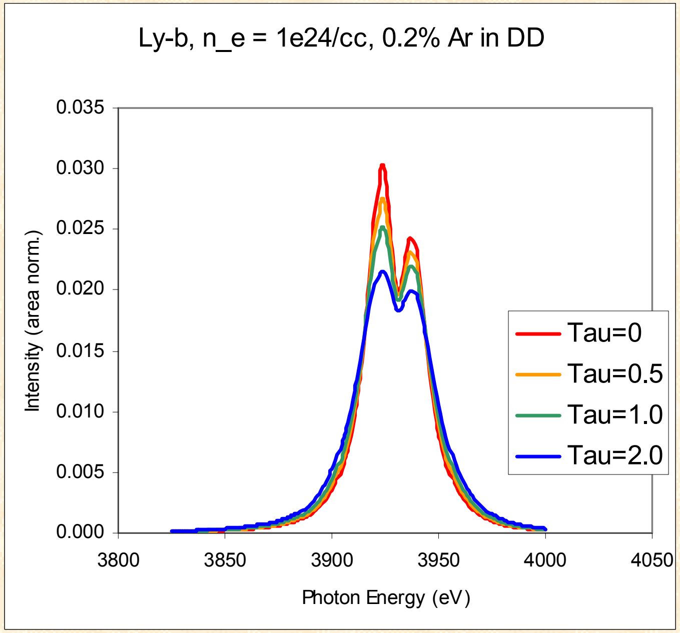

Radiative transfer corrections to He-b/Ly-b intensity ratio

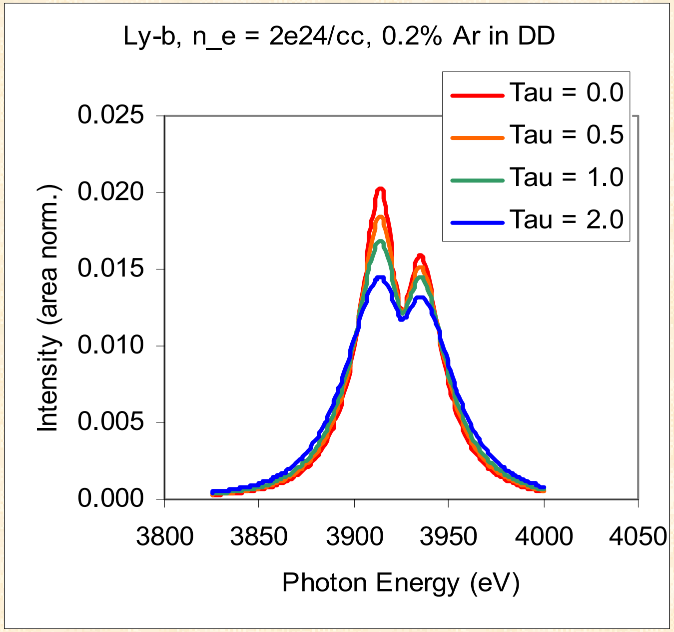
Table: corrections to populations and intensity ratios for a 0.2% Ar in 15 Atm DD capsule implosion

	1e24/cc	2e24/cc	2e24/cc	2e24/cc	4e24/cc
	1.5keV	1.5keV	2keV	2.5keV	2.5keV
Bare	1.35	1.14	1.14	1.07	1.07
1s	0.91	0.85	0.86	0.85	0.86
$1s^2$	0.70	0.77	0.77	0.82	0.81
Heb/Lyb	0.69	0.77	0.77	0.81	0.82

Radiative transfer also modifies the observed lineshape, though the effect for the optically thin ($\tau_0<1$) lines used for analysis small compared with that of Stark Broadening.

$$I_\nu = B_\nu\left(1-e^{-\tau_\nu}\right);\ \tau_\nu = \frac{\pi e^2}{mc}\bar{f}\, I_o\left(\nu; n_e, kT_e\right)\left(\rho\, r\right)_{\text{lower state}}$$

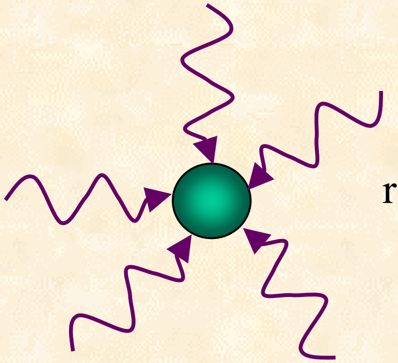

Ly-b, n_e = 1e24/cc, 0.2% Ar in DD


Ly-b, n_e = 2e24/cc, 0.2% Ar in DD

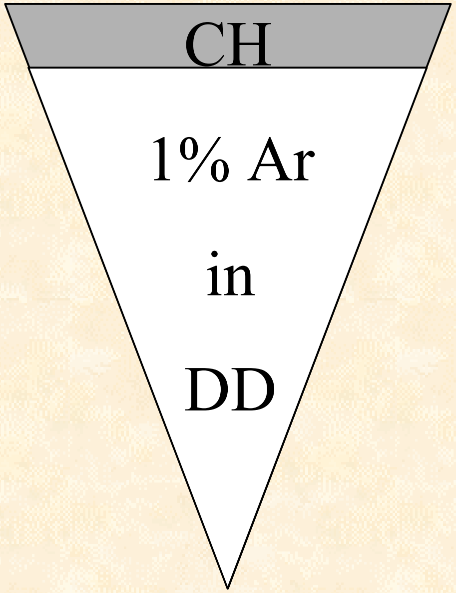
If this broadening effect were to be neglected, the density inference from spectral analysis would be too high, though by less than 20% for the conditions of recent OMEGA experiments.

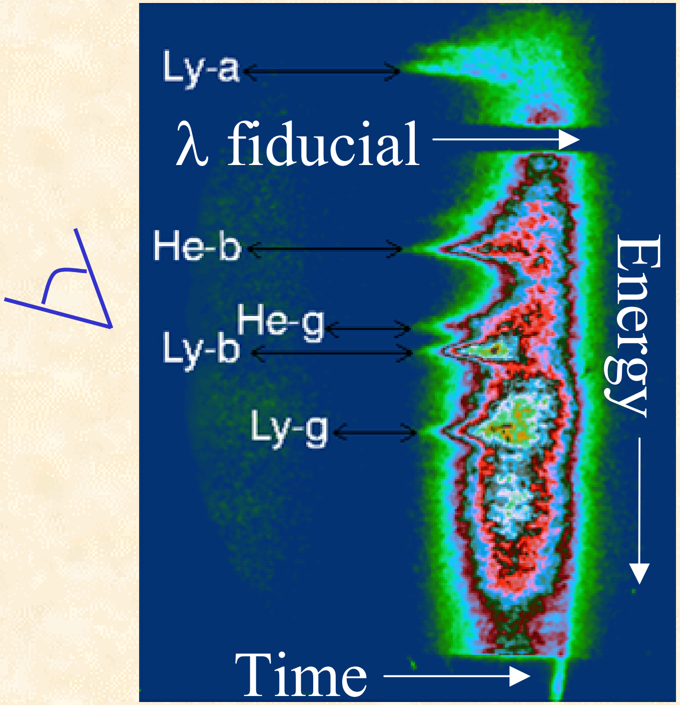
In a series of campaigns using the Omega Laser System at the University of Rochester's Laboratory for Laser Energetics, Prof. Hooper's group at UF has observed plasma-induced line shifts in directly-driven spherical implosions

23 kJ
in a
1ns square pulse

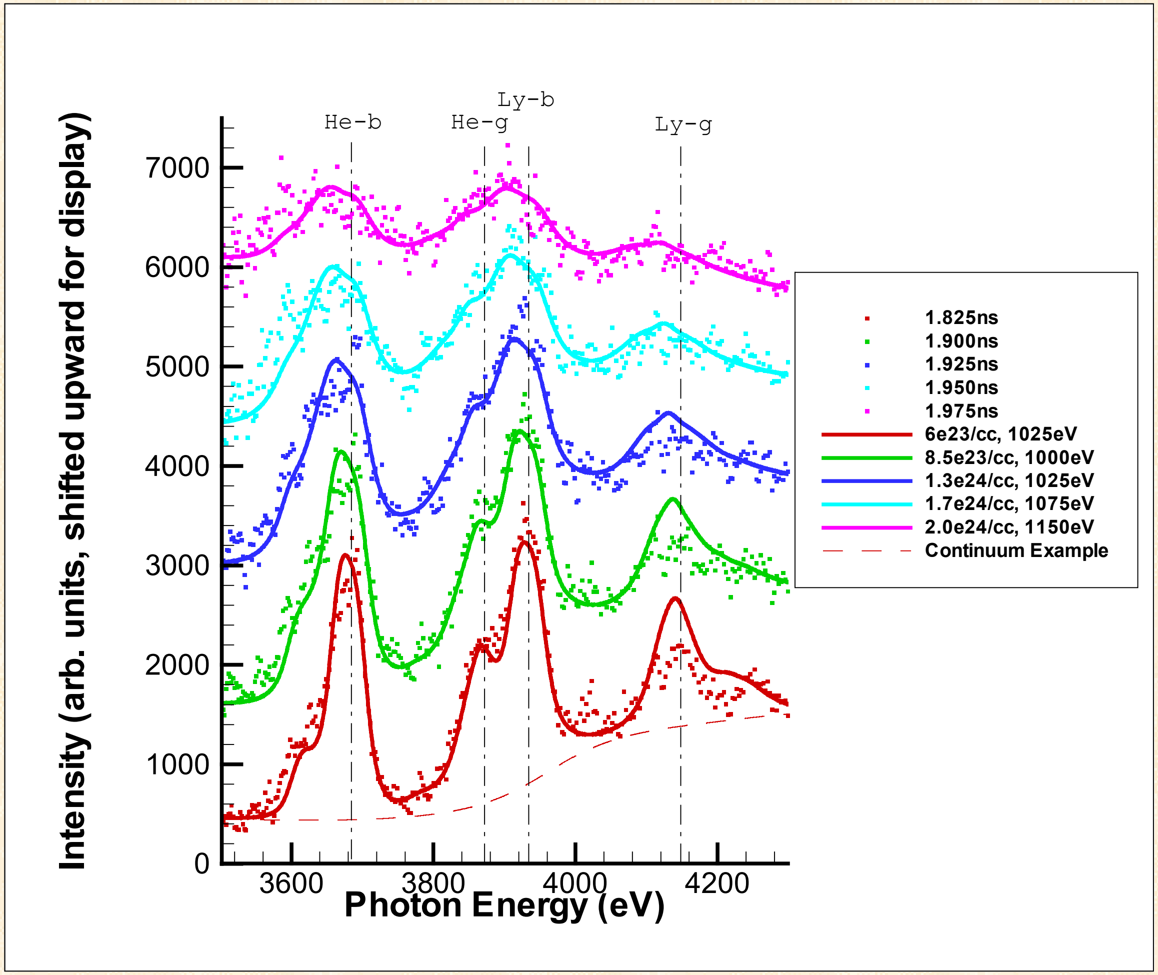


During the implosion, the time-dependent **Ar K-shell** spectrum was recorded by a flat crystal spectrometer attached to an x-ray streak camera





Thus constituted, the spectral model of ArFIT provides a useful tool for the inference of emissivity averaged core conditions for microballoon implosions doped with Ar



- 1% Ar in 15Atm D_2, 20μm thick, 450μm inner diameter CH capsule imploded using 23kJ in a 1ns square pulse

- The plasma induced line shift is apparent in this data, as is the lowered photorecombination edge into He-like Ar

- The intensity of the Ly-γ line is not as well modeled as the other features of the spectrum, and we continue to investigate the possibility that dense plasma effects are causing this discrepancy.

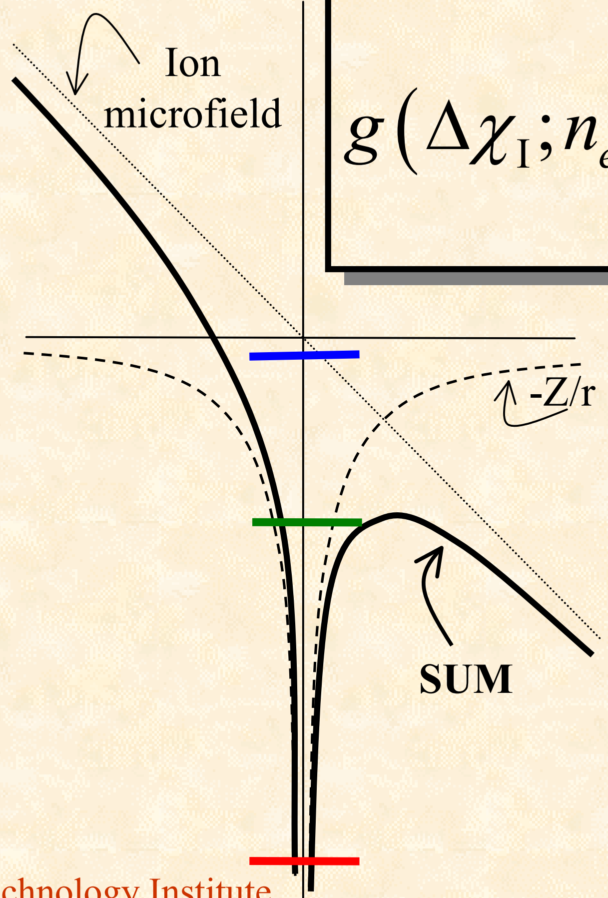
- The investigation of higher density effects was discussed in Prof. Hooper's talk on Tuesday.

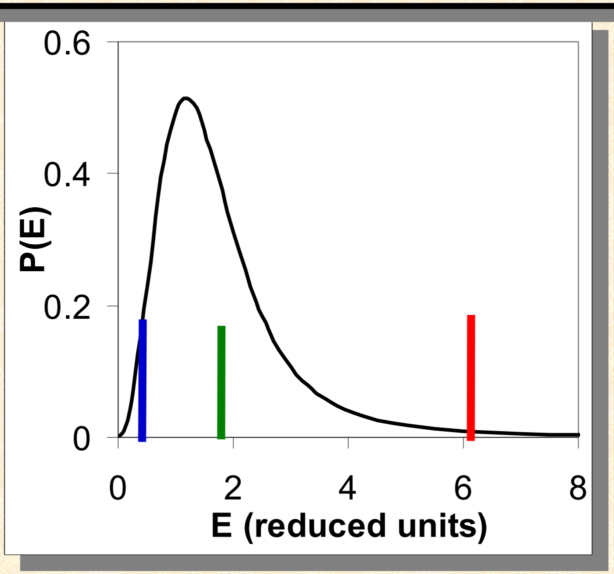
- The spectral model in ArFIT was used to create look-up tables used by LLE in their analysis of recent implosion experiments.

Given level shifts on the order of the observed line shifts, level population calculations relying on degeneracy lowering models should, in principle, include the effects of these shifts.

Though the line shifts we have observed are much smaller than kT, level shifts on the order of the observed line shifts will effect temperature inferences from line ratios calculated using degeneracy lowering models.

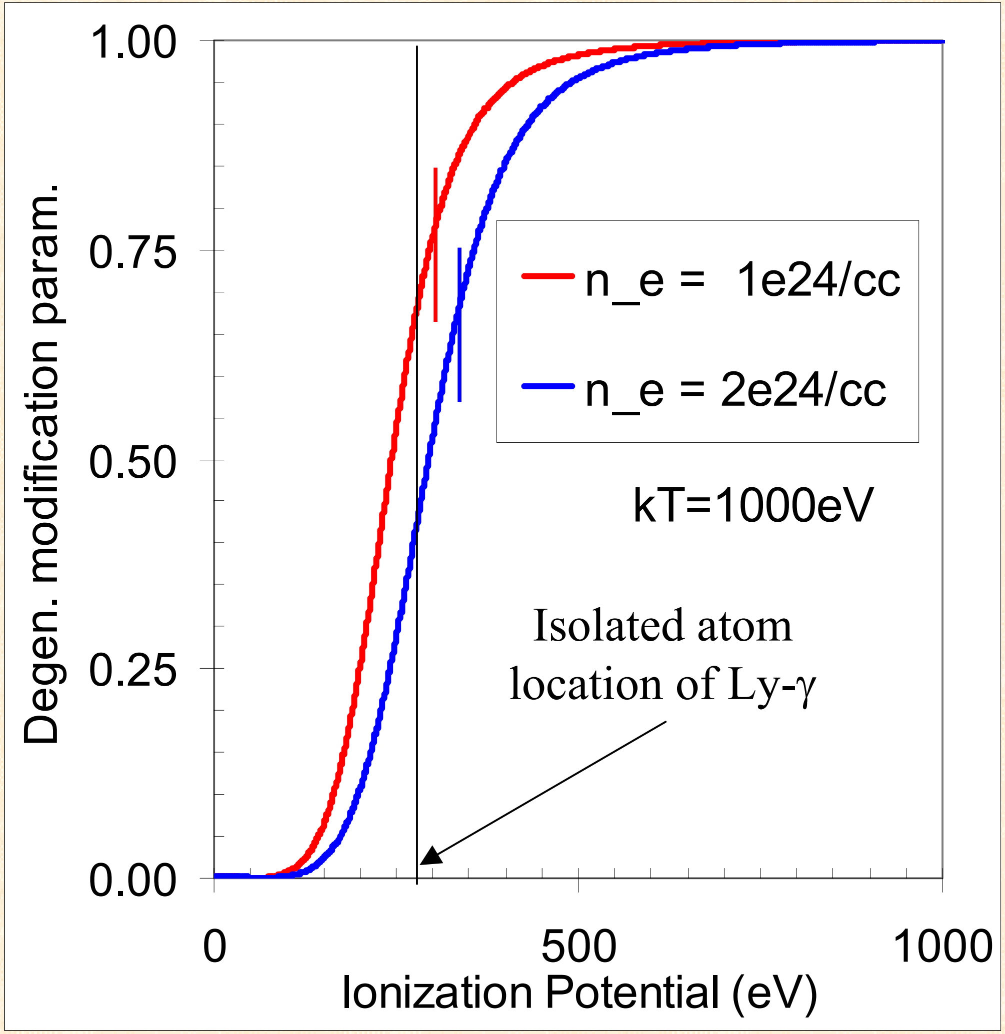
$$\boxed{g\left(\Delta\chi_{\mathrm{I}};n_e,kT\right)=g_0\left[1-\int_{E(\Delta\chi_{\mathrm{I}})}^{\infty}dE\,P\left(E;n_e,kT\right)\right]}$$





The dependence of the degeneracy lowering parameter on binding energy in, *e.g.*, the Mihalas-Hummer approximation is sufficiently strong so that shifts ~ 0.1kT can have large effects on the population of the upper states of transitions.

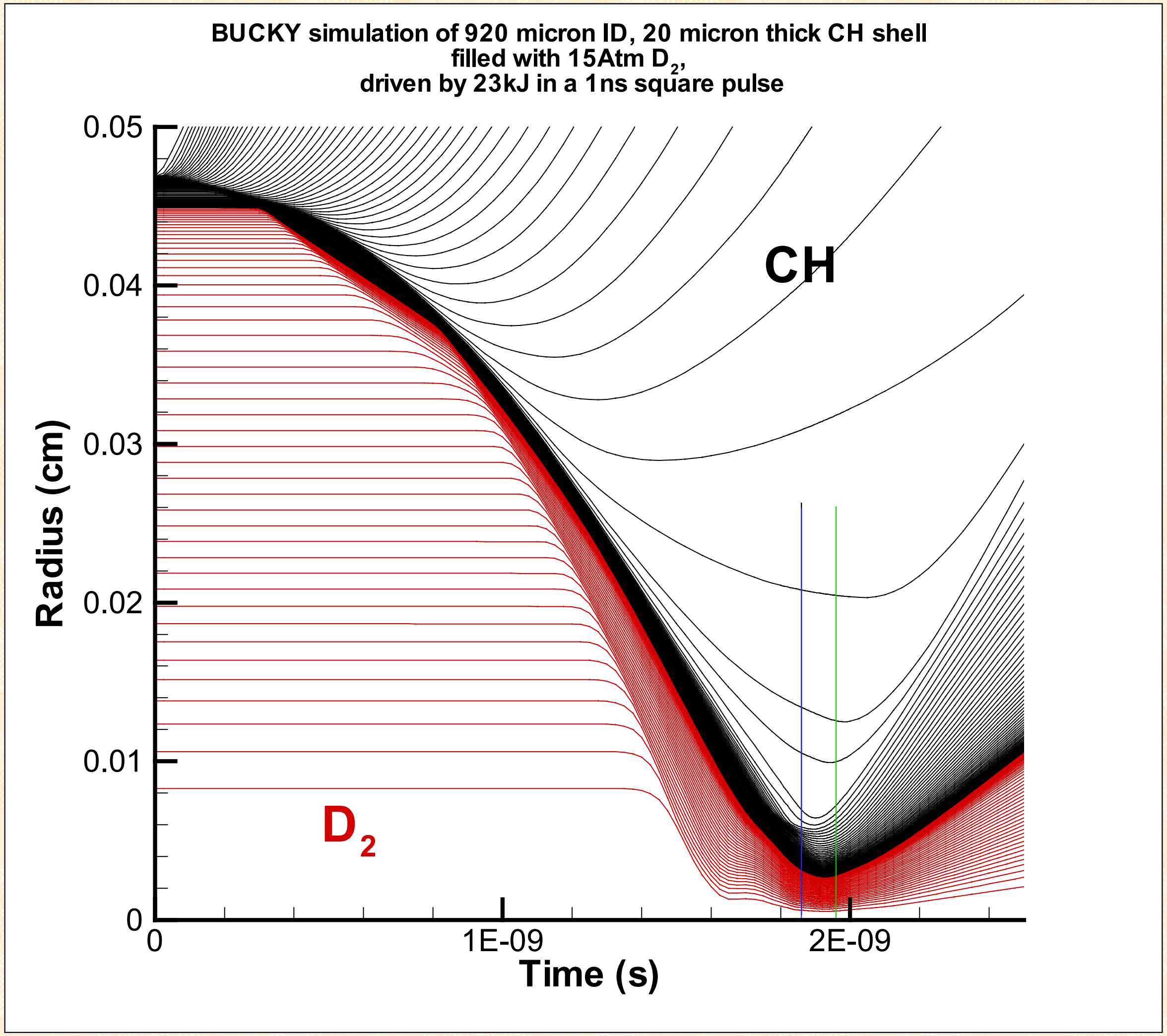
A naïve implementation of plasma-induced line shifts into a CRE population kinetics calculation would change the degeneracy lowering parameter of the n=4 $^3P_{½}$ level by 12% and 33% for plasma with electron densities of 1e24/cc and 2e24/cc, respectively.



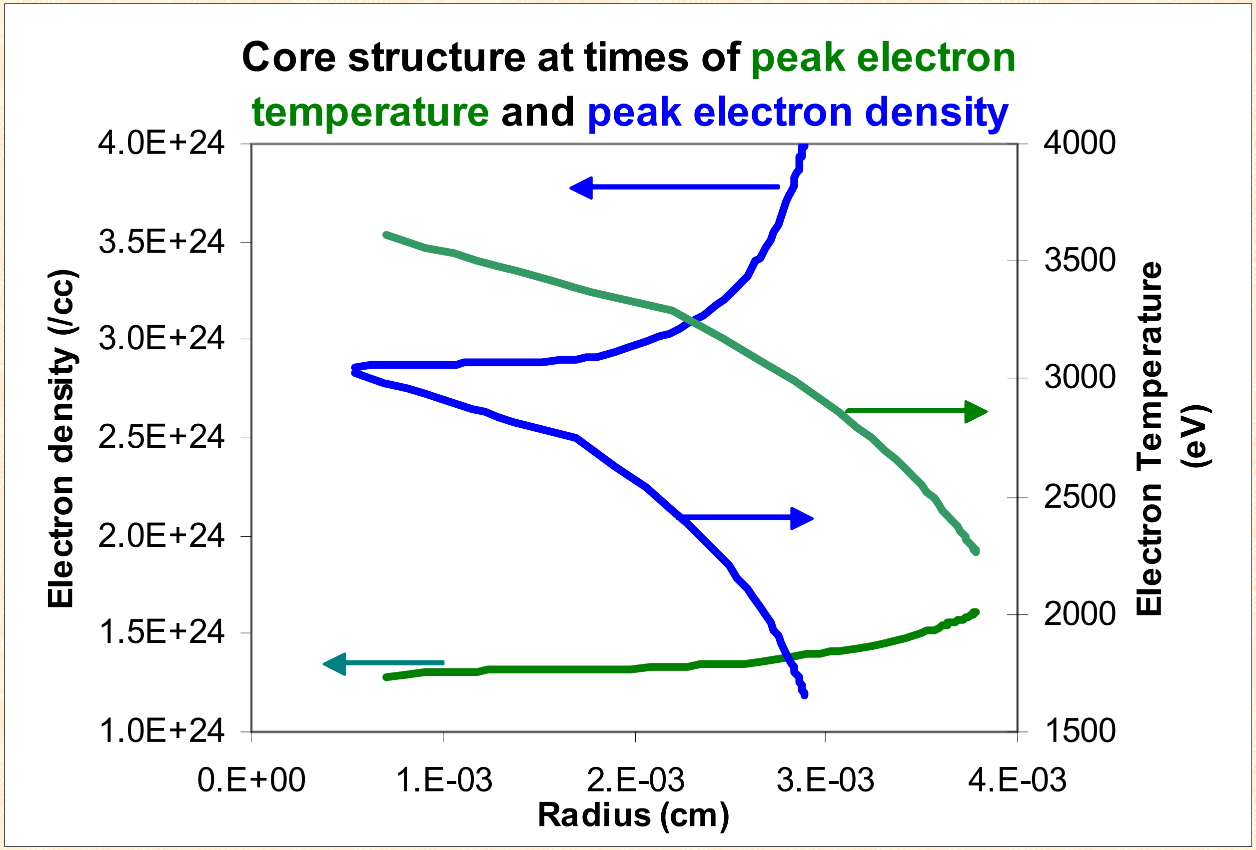
BUCKY is a Flexible 1-D Lagrangian Radiation-Hydrodynamics Code

- 1-D Lagrangian MHD (spherical, cylindrical or slab).
- Thermal conduction with diffusion.
- Applied electrical current with magnetic field and pressure calculation.
- Radiation transport with multi-group flux-limited diffusion, method of short characteristics, and variable Eddington.
- Non-LTE CRE line transport.
- Opacities and equations of state from EOSOPA or SESAME.
- Equilibrium electrical conductivities
- Thermonuclear burn (DT,DD,DHe3) with in-flight reactions.
- Fusion product transport; time-dependent charged particle tracking, neutron energy deposition.
- Applied energy sources: time and energy dependent ions, electrons, x-rays and lasers.
- Moderate energy density physics: melting, vaporization, and thermal conduction in solids and liquids.
- Benchmarking: x-ray burn-through and shock experiments on Nova and Omega, x-ray vaporization, RHEPP melting and vaporization, PBFA-II Kα emission, …
- Platforms: UNIX, PC, MAC

To assess the impact that the uniform core approximation has on the inference of core conditions, BUCKY was used to simulate recent OMEGA experiments



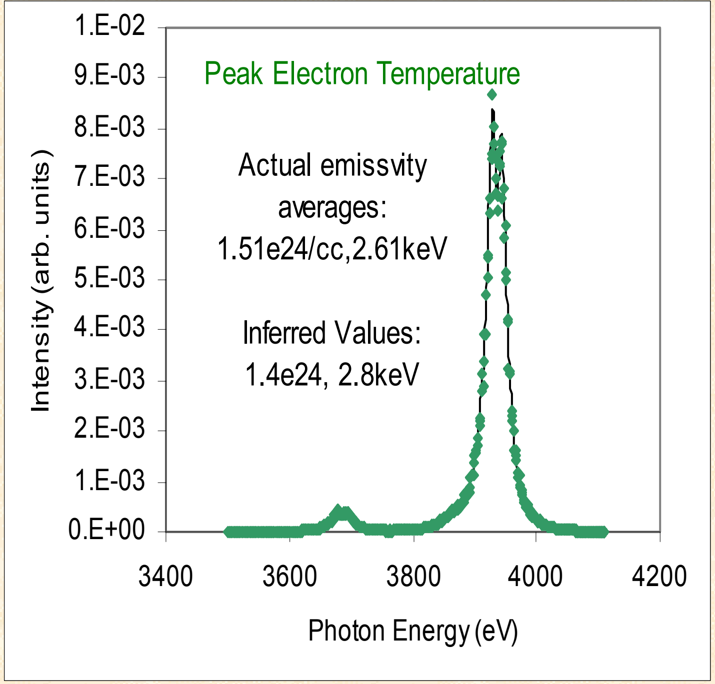
The 1d simulations predict the presence of gradients in temperature and density in the core. We sought to estimate the effect of these gradients on the quality of core condition inferences using ArFIT's uniform sphere approximation



N.B.-This graph shows the quantities varying as a function of radius, and thus exaggerates the importance of the contributions at small r to volume averages.

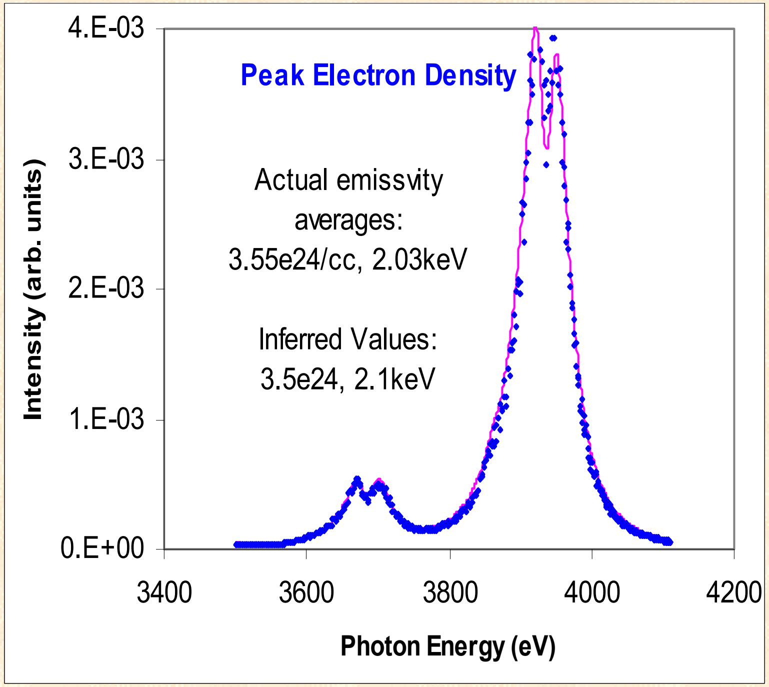
For these predicted core gradients, the effect of the uniform core approximation in the inference of emissivity averaged core temperature and densities is that the density is under-inferred , and the temperature is over-inferred, **though in each case by less than 10%**

High-order satellites and plasma gradients effects on Ar Heb line opacity and intensity distribution, Golovkin, I E; Mancini, R C, JQSRT, 65, p.273-286 (2000)


Peak Electron Temperature

Actual emissvity averages: 1.51e24/cc,2.61keV

Inferred Values: 1.4e24, 2.8keV


Peak Electron Density

Actual emissvity averages: 3.55e24/cc, 2.03keV

Inferred Values: 3.5e24, 2.1keV

For the times of peak electron temperature and density the predicted core structures were input into a full solution of the transfer equation using detailed Stark broadened line profiles and atomic kinetics. 10% white noise is added to the resulting model spectrum, and the results fit with a uniform core approximation.

Conclusions/Summary

- The strong density dependence of Stark broadened line profiles and the temperature- and density-sensitive relative intensities of the Ar K-shell lines in recent Ar-doped microballoon implosions provides a useful means of inferring emissivity averaged core conditions.

- Radiative transfer effects on the population distribution and on the observed lineshape are approximated using a uniform core approximation.

- The effects if this approximation were investigated using post-processed 1D radiative hydrodynamics simulation of directly driven microballoon implosions. For the low concentrations of Ar currently being used for diagnostic purposes, the uniform core approximation yields inferences of emissivity averaged core conditions within 10% of the correct values.

ArFIT provides a highly detailed model of Ar K-shell emission from hot, dense plasmas. This model is useful for the extraction of time-dependent emissivity- averages of electron temperature and density from Ar-doped cores of ICF relevant implosions.