Atomic models for radiation transport in laser plasma hydrodynamic simulation of EUV light source

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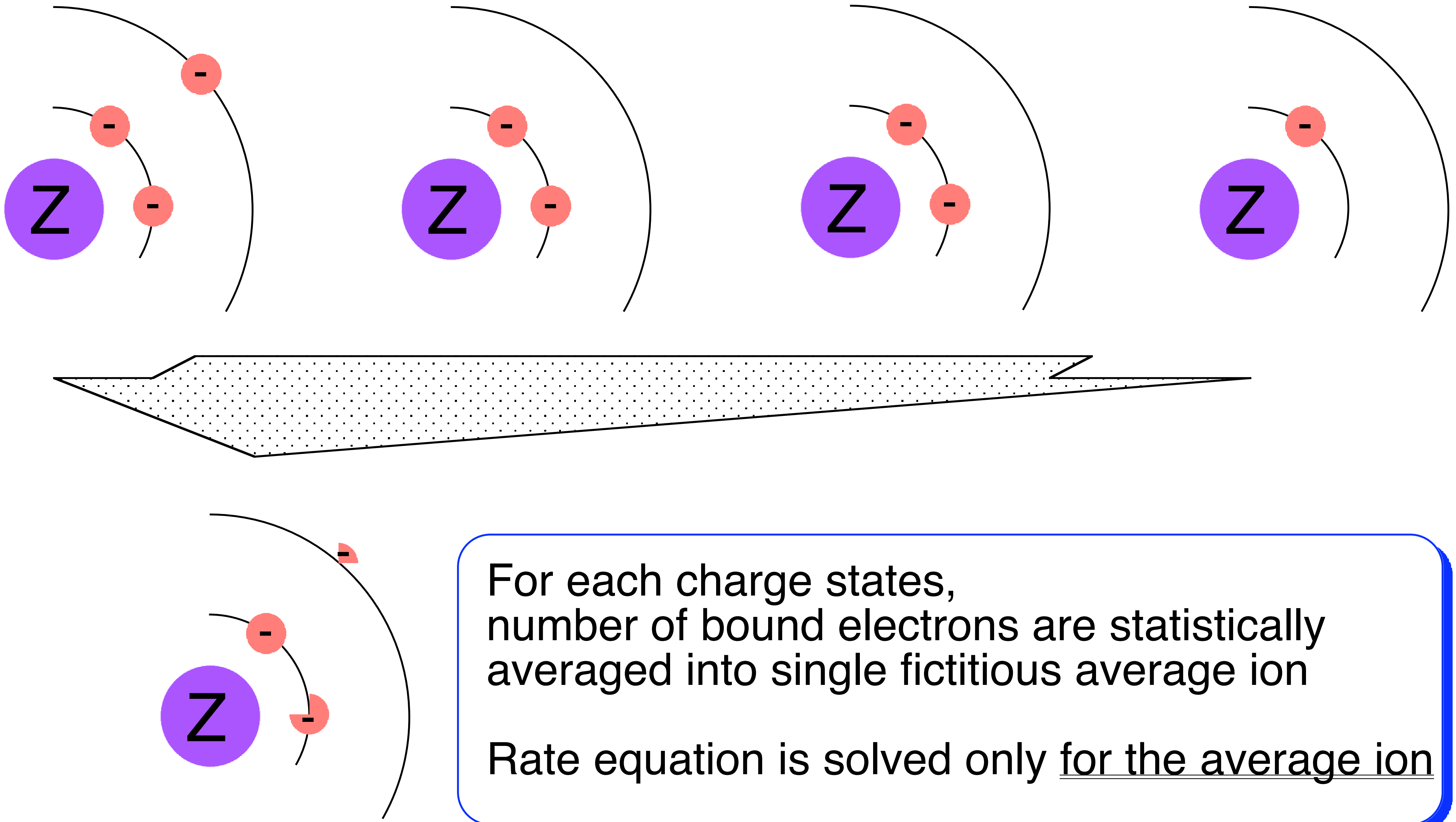
Average Ion Model



For each charge states,
number of bound electrons are statistically averaged into single fictitious average ion

Rate equation is solved only for the average ion

Why Average Ion Model?

Hydrodynamic simulation requires not only opacity and emissivity tables but also requires equation of state;
pressure & specific heat
→Average Ion Model

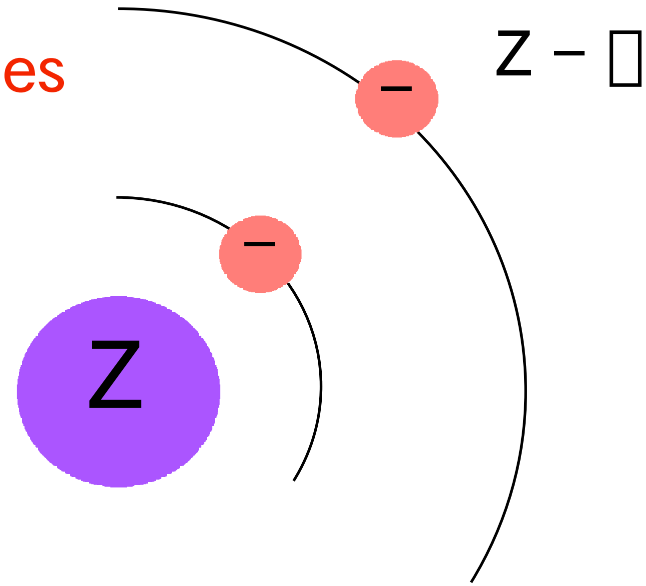
- Simple
- Models (formalism) including equation of state are available
- Many tests have already done

But Why Screened Hydrogenic Model?

Average ion model is usually used with screened hydrogenic model? No. but・・・

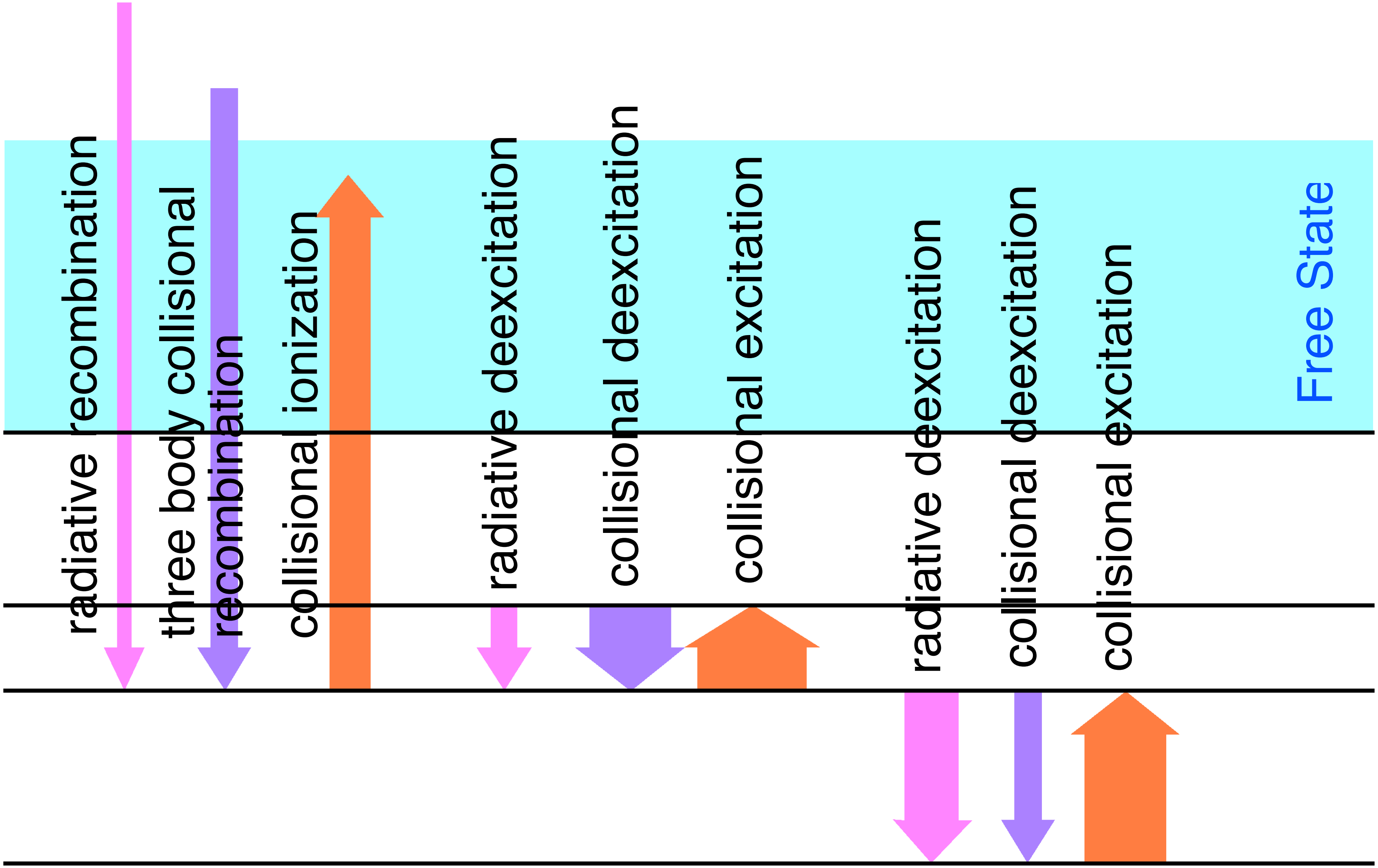
Even if we use self-consistent calculation,
we can't predict experimental transition energies
of complex Xenon or Tin ions

But using Screened Hydrogenic Model,
we can fit transition energy!
by tuning a set of screening constant.



Moreover we can use Average ion model & SHM,
hydrodynamic simulation becomes with less difficulties.

Collisional Radiative Equilibrium (CRE) Model



New Screened Hydrogenic Model with l-splitting

$$\langle H \rangle = -\sum_j P_j \frac{Q_j^2}{2n(j)^2}\left[1+\frac{\alpha^2 Q_j^2}{n(j)^2}\left(\frac{n(j)}{k}-\frac{3}{4}\right)\right]+\sum_j \sum_{m(j')<m(j)} P_j P_{j'} \frac{Q_j^2}{n(j)^2}\sigma_{jj'} + \max\left[P_j-1,0\right]P_j \frac{Q_j^2}{n(j)^2}\sigma_j$$

$$Q_j = Z - \sum_{m(j')<m(j)} P_{j'}\sigma_{jj'} - \max\left[P_j-1,0\right]\sigma_{jj}$$

$$E_j = -\frac{Q_j^2}{2n(j)^2}\left[1+\frac{\alpha^2 Q_j^2}{n(j)^2}\left(\frac{n(j)}{k}-\frac{3}{4}\right)\right]\left[1-\max\left[P_j-1,0\right]\left(\frac{4\sigma_{jj}}{Q_j}+\frac{6\sigma_{jj}^2}{Q_j^2}+\frac{4\sigma_{jj}^3}{Q_j^3}+\frac{4\sigma_{jj}^4}{Q_j^4}\right)\right]$$

$$+\sum_{m(j')>m(j)} \frac{P_{j'}}{2n(j')^2}\left[2Q_{j'}+\sigma_{j'j}+\frac{\alpha^2 Q_{j'}^3}{n(j')^2}\left(\frac{4}{Q_{j'}}+\frac{6\sigma_{j'j}}{Q_{j'}^2}+\frac{4\sigma_{j'j}^2}{Q_{j'}^3}+\frac{4\sigma_{j'j}^3}{Q_{j'}^4}\right)\right]\sigma_{j'j}$$

$$E_{ion} = -\sum_j P_j \frac{Q_j^2}{2n(j)^2}\left[1+\frac{\alpha^2 Q_j^2}{n(j)^2}\left(\frac{n(j)}{k}-\frac{3}{4}\right)\right]$$

$$m(1,0), m(2,0), m(2,1), m(3,0), m(3,1), m(3,2), m(4,0), m(4,1), m(4,2), m(5,0), m(5,1), m(4,3), \cdots$$
$$= 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15,$$

Energy Level Calculation of Sn: SHM/HULLAC (nm)

Charge	4d-4f	4p-4d	4d-5p	4d-5f
13	12.8/13.1	12.7/12.8	12.3/12.4	7.4/7.8
12	12.8/13.0	13.1/12.8	13.1/13.3	7.8/8.3
11	12.9/13.0	13.4/13.0	14.1/14.6	8.3/9.0
10	13.1/13.2	13.7/13.2	15.3/16.0	8.9/9.6
9	13.6/13.5	13.9/13.5	16.8/16.0	9.7/10.4
8	14.3/14.1	14.0/14.1	18.7/17.5	10.6/11.3
7	15.3/15.0	14.0/14.7	21.2/17.6	11.9/12.4
6	16.7/16.8	14.0/14.1	24.6/25.6	13.5/13.7
5	18.8/19.1	13.9/14.6	29.5/30.1	15.7/15.6
4	22.0/22.8	13.7/-	37.0/37.0	19.0/18.6

In order to solve Collisional Radiative Equilibrium

All rate coefficients are hydrogenic
except oscillator strength
for n = 1, Hydrogenic, for n = 2, Li-like, for n = 3, Na-like, for n = 4, Cu-like are installed
Collisional ionization rates are Seaton's formula.
Collisional excitation rate are evaluated from oscillator strength; dipole-allowed transitions are only adopted.

Statistical Approach Predicting Charge State Distribution

Assume population given by the average ion model
as the probability of electron occupying the level *j*
For example,

$$F_{P_{1s}=2, P_{2s}=2, P_{2p}=6, P_{3s}=2, P_{3p}=6, P_{3d}=10, P_{4s}=2, P_{4p}=5, P_{4d}=8, P_{4f}=0, \cdots} =$$

$$x_{1s}{}^{2} x_{2s}{}^{2} x_{2p}{}^{6} x_{3s}{}^{2} x_{3p}{}^{6} x_{3d}{}^{10}$$

$$x_{4s}{}^{2} \frac{6!}{(6-5)!5!} x_{4p}{}^{5} (1-x_{4p})^{6-5} \frac{10!}{(10-8)!8!} x_{4d}{}^{8} (1-x_{4d})^{10-8} (1-x_{4f})^{14}$$

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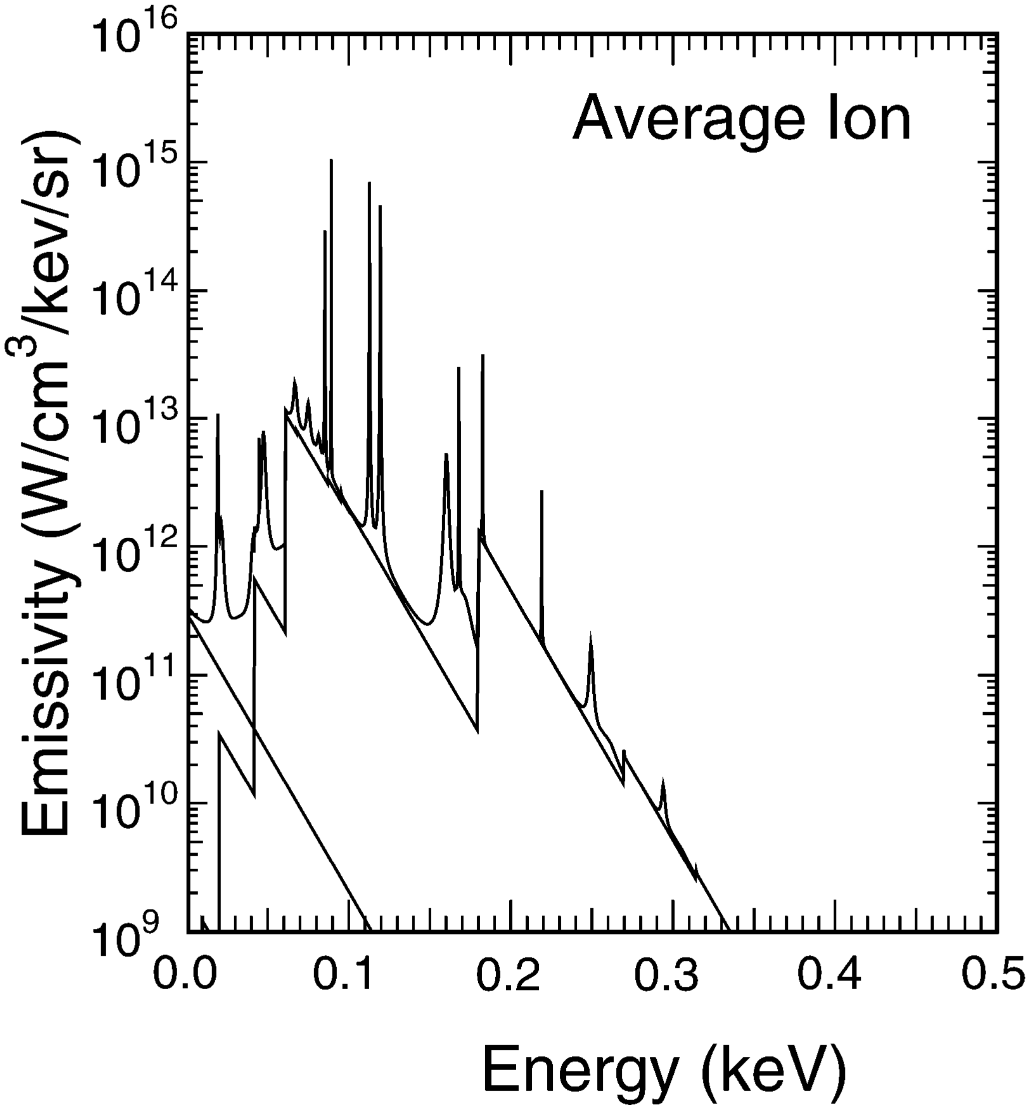
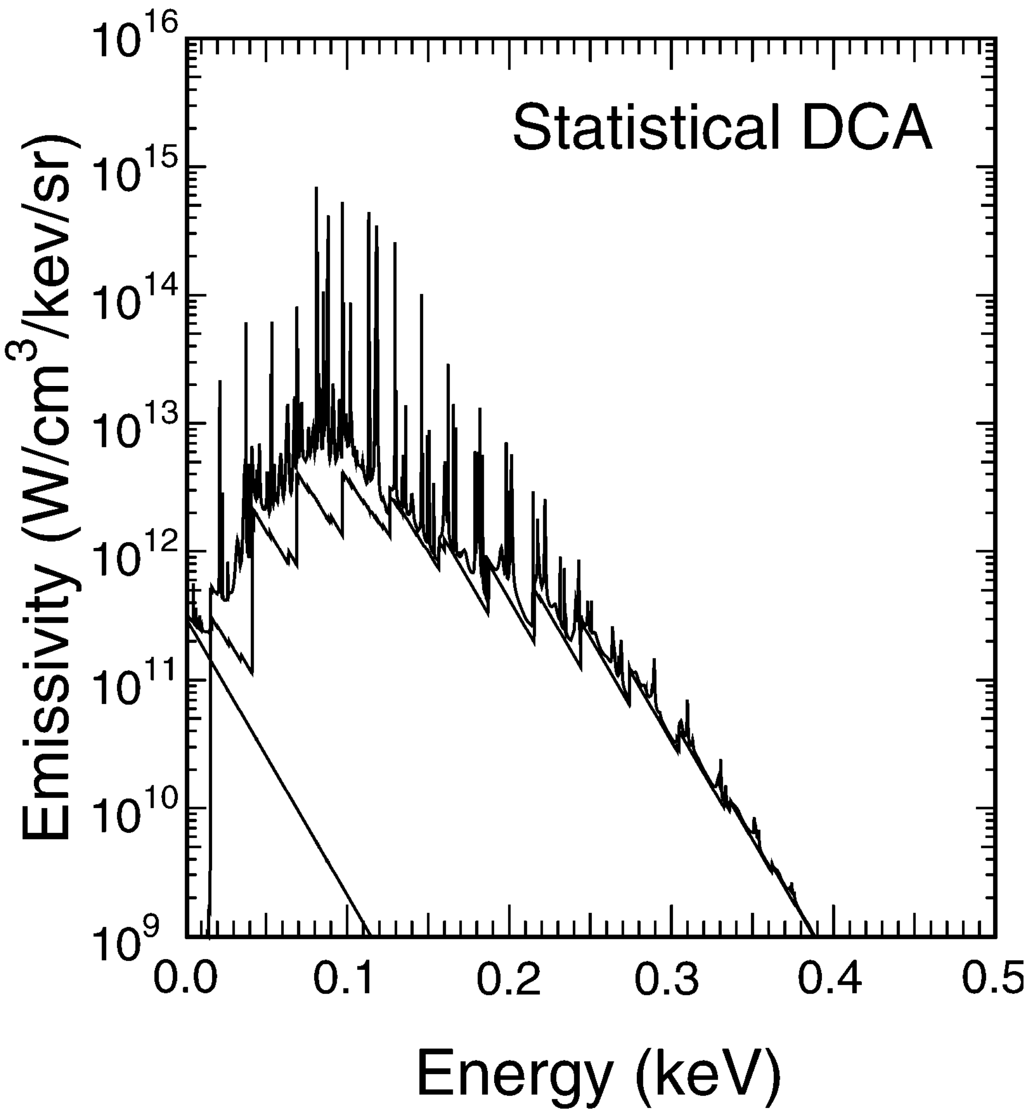
Here, $x_j = P_j / D_j$
D_j: Statistical weight of state *j*
P_j: Population of state *j* given by average ion model

Emissivity of Xenon plasma

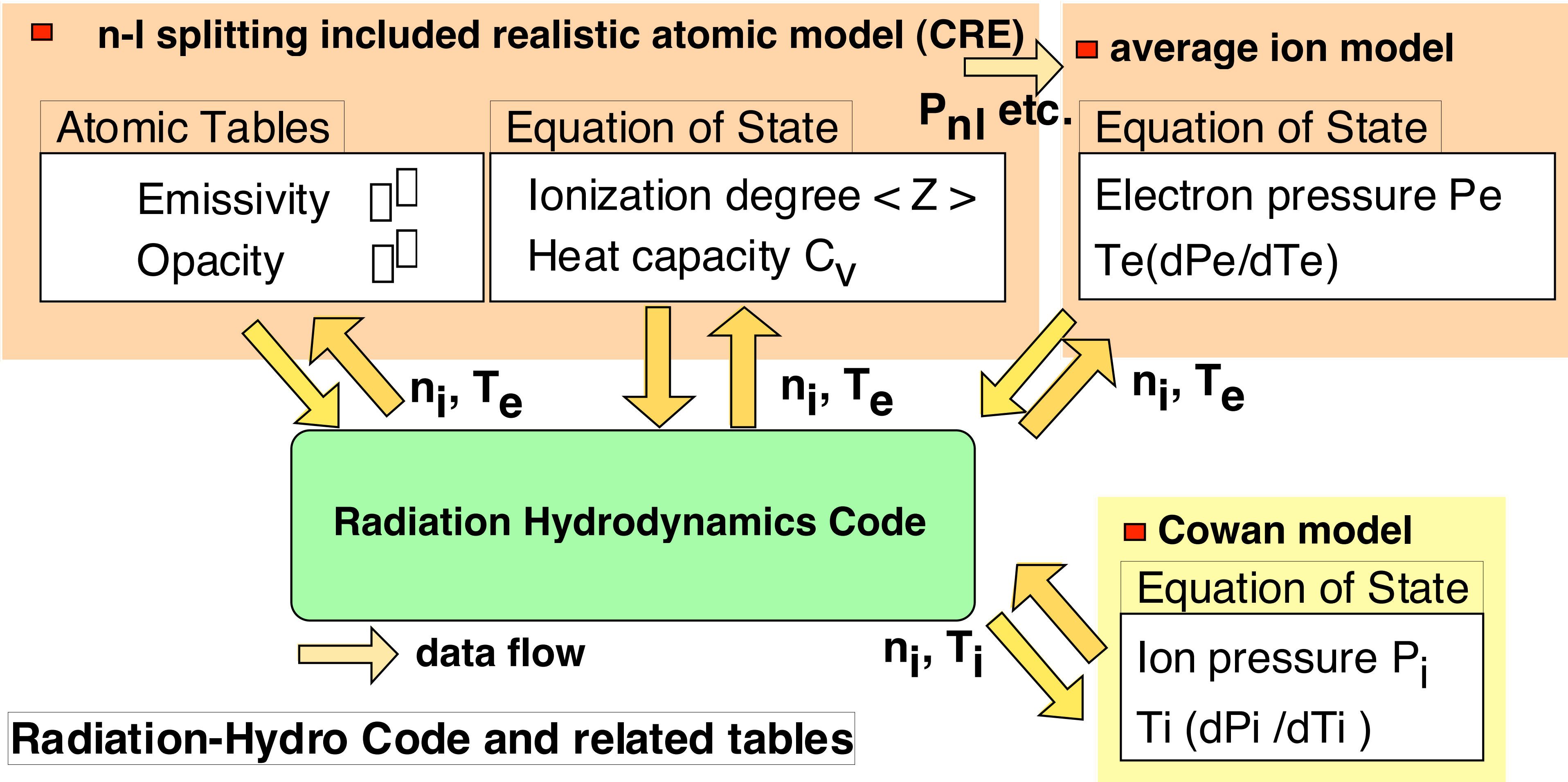
Temperature = 20 (eV)
Density = 0.01 (g/cm3)





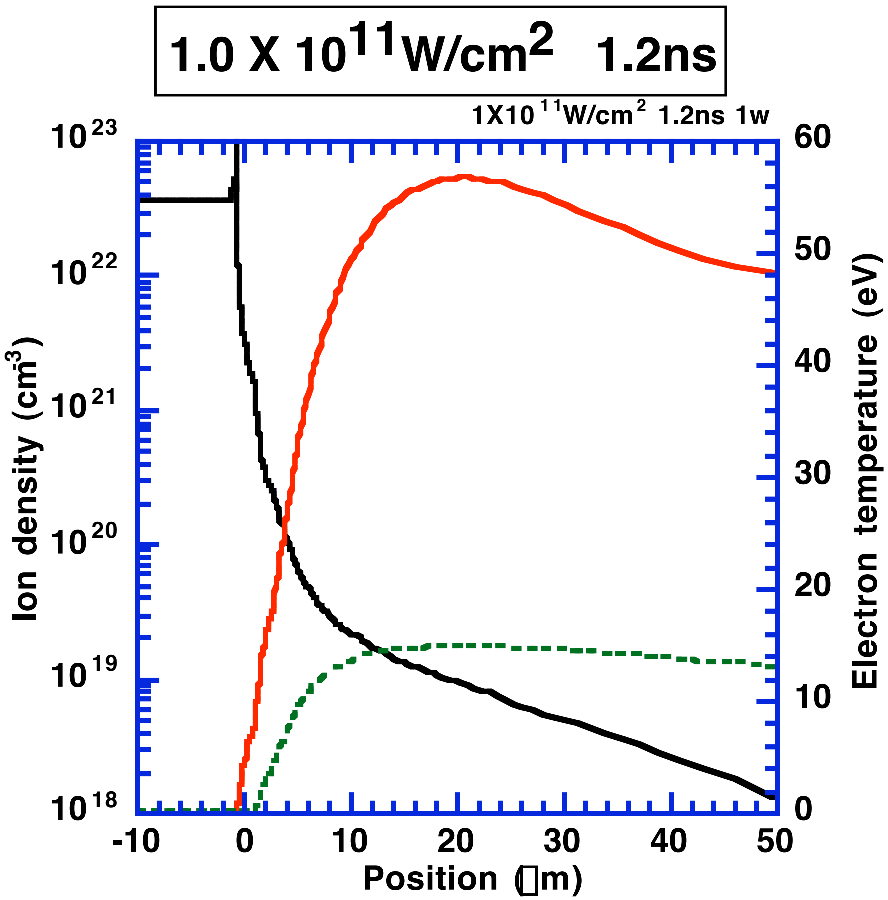
1-D Hydrodynamic Simulation

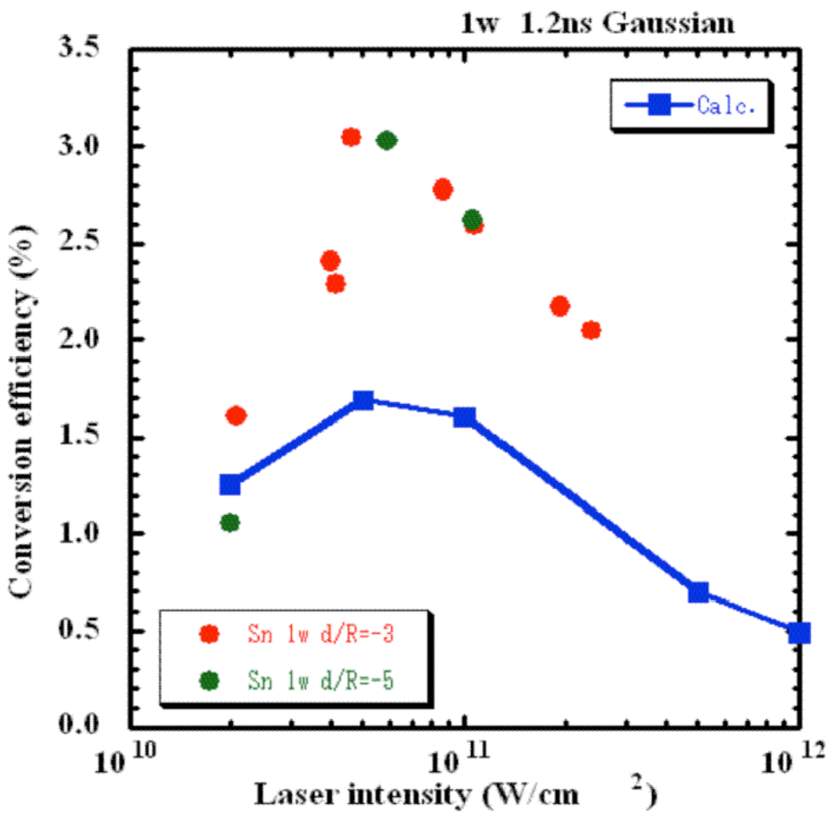
- Electron and ion conduction by Spitzer-Harm and Braginskii
- Electron and ion energy relaxation
- Laser absorption by the inverse-bremsstrahlung with ray-tracing
- Multi-group diffusion approximated x-ray transport



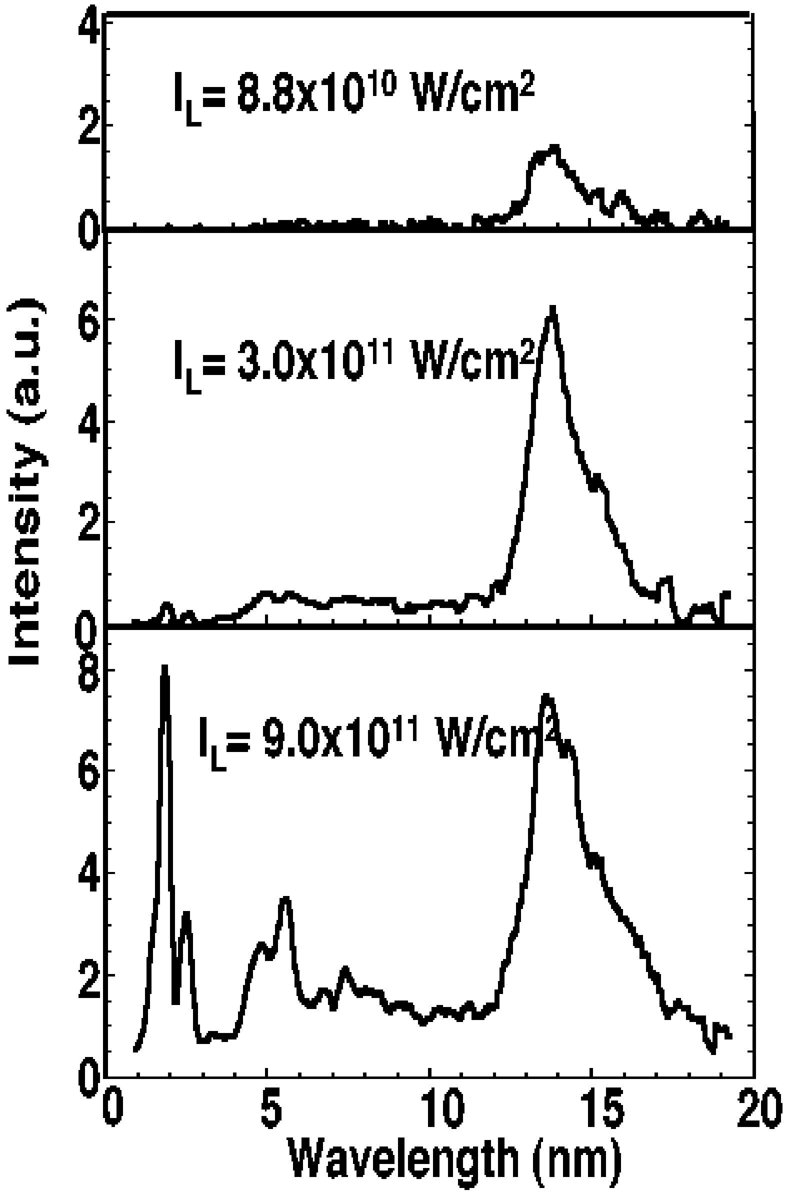
Hydrodynamic Simulation can roughly predict experimental conversion efficiencies

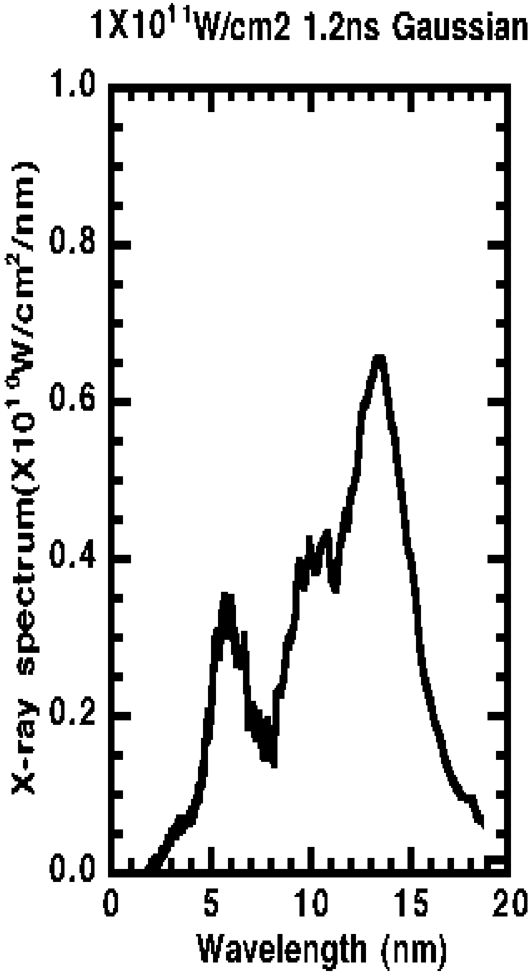
Absolute values are under ...

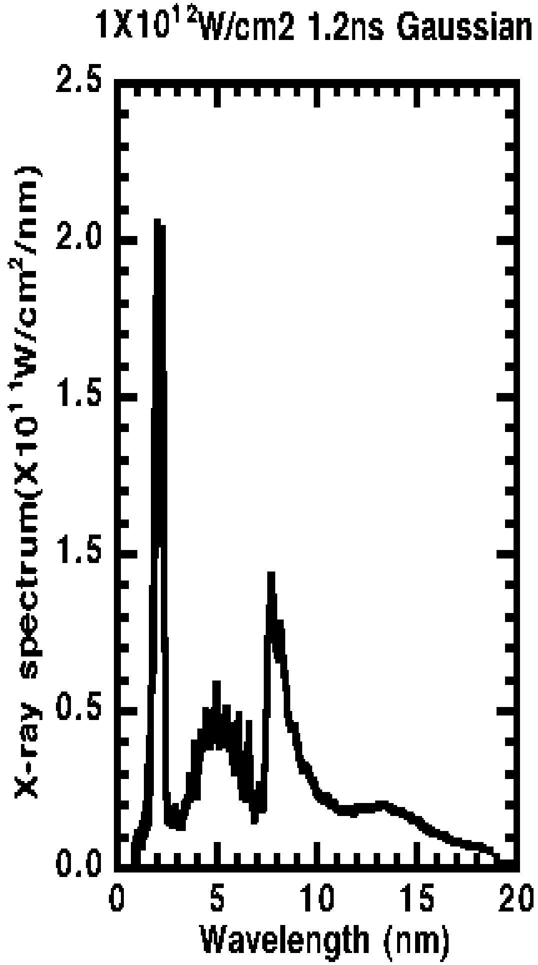




EUV Spectra Prediction by Radiation Transport with Hydromotion







Summary

We have developed a simple atomic code which is based on

- Average ion model
- Screened hydrogenic model
! which can predict energy level of HULLAC's results.
- Statistical approach is used
! in estimating charge state distribution in spectral calculation.
- Line broadening due to term-splitting estimated by HULLAC
! code is used for calculating spectral emissivity and opacity.
! (But gaussian shape in n,l-splitting)

Predicted conversion efficiency from laser to EUV of 2 % bandwidth of 13.5 nm is about half of experimental values.