Atomic models and hydrodynamic simulation for laser-plasma EUV source

Takeshi Nishikawa,
Dep't Electrical & Electronic Eng., Okayama Univ.
Akira Sasaki,
Advanced Photon Research Center, JAERI
Hiroyuki Furukawa and Atsushi Sunahara,
Institute for Laser Technology
Katsunobu Nishihara,
Institute of Laser Engineering, Osaka Univ.

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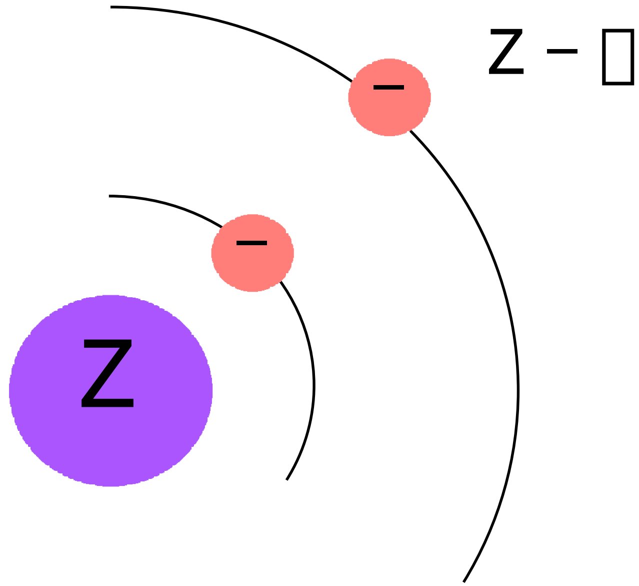
Why Average Ion Model & Screened Hydrogenic Model?

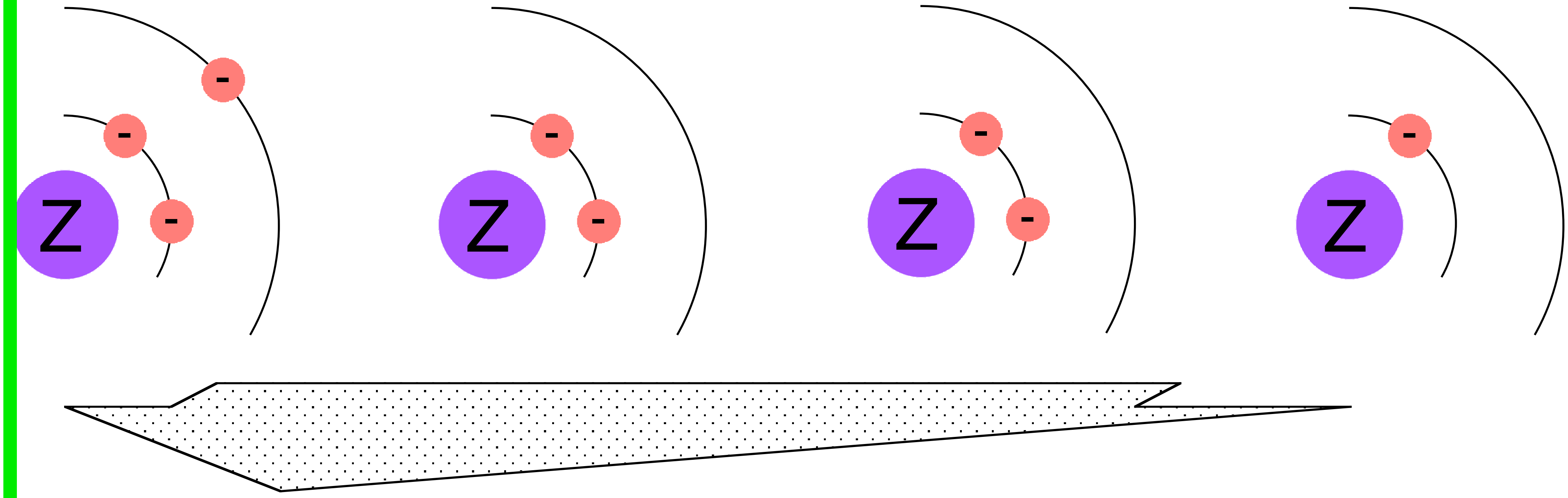
Hydrodynamic simulation including radiation transport and atomic process with less computation resources
→Average Ion Model

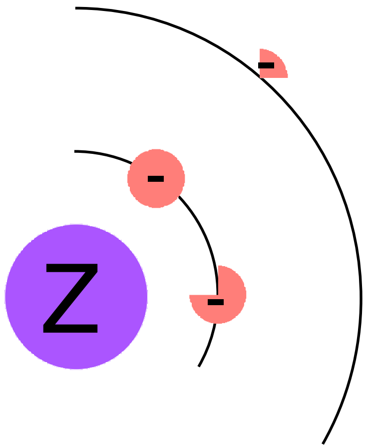
- Simple and physically intuitive
- Models (formalism) including equation of state are available
- Many tests have already done
- average ion model usually used with screened hydrogenic model



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

Average Ion Model





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

Rate equation is solved only <u>for the average ion</u>

New Screened Hydrogenic Model with l-splitting

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

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

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

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

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

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

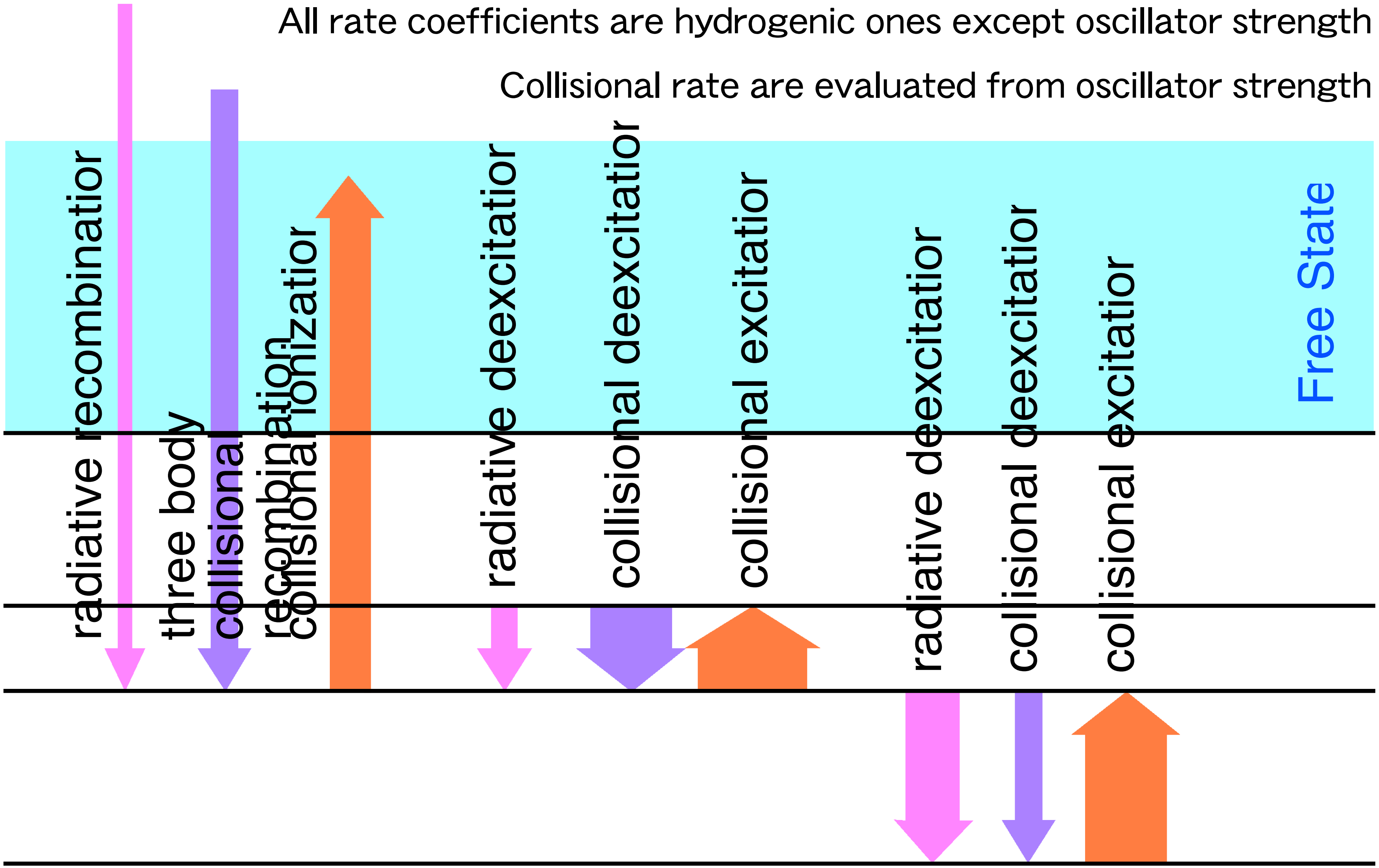
Energy Level Calculation of Sn: SHM/HULLAC (A)

Charge State	4d-4f	4p-4d	4d-5p	4d-5f
13	128.3/130.5	127.0/128.1	122.9/123.7	73.5/77.6
12	127.6/129.8	130.7/128.1	131.2/133.2	77.9/82.9
11	128.5/130.1	134.0/129.6	141.1/145.9	83.0/89.8
10	131.2/131.7	136.6/131.7	153.2/159.6	89.2/96.3
9	135.8/135.3	138.6/134.6	168.3/159.9	96.9/104.3
8	142.8/140.9	139.8/141.2	187.3/174.8	106.4/113.4
7	152.9/150.2	140.3/146.8	212.2/175.6	118.6/124.2
6	167.3/167.6	139.9/140.5	246.0/255.5	134.8/137.1
5	188.1/191.1	138.8/145.7	294.6/300.8	157.2/155.8
4	219.8/228.2	137.0/	370.2/369.6	189.9/186

Collisional Radiative Equilibrium (CRE) Model

All rate coefficients are hydrogenic ones except oscillator strength

Collisional rate are evaluated from oscillator strength



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,

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

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

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

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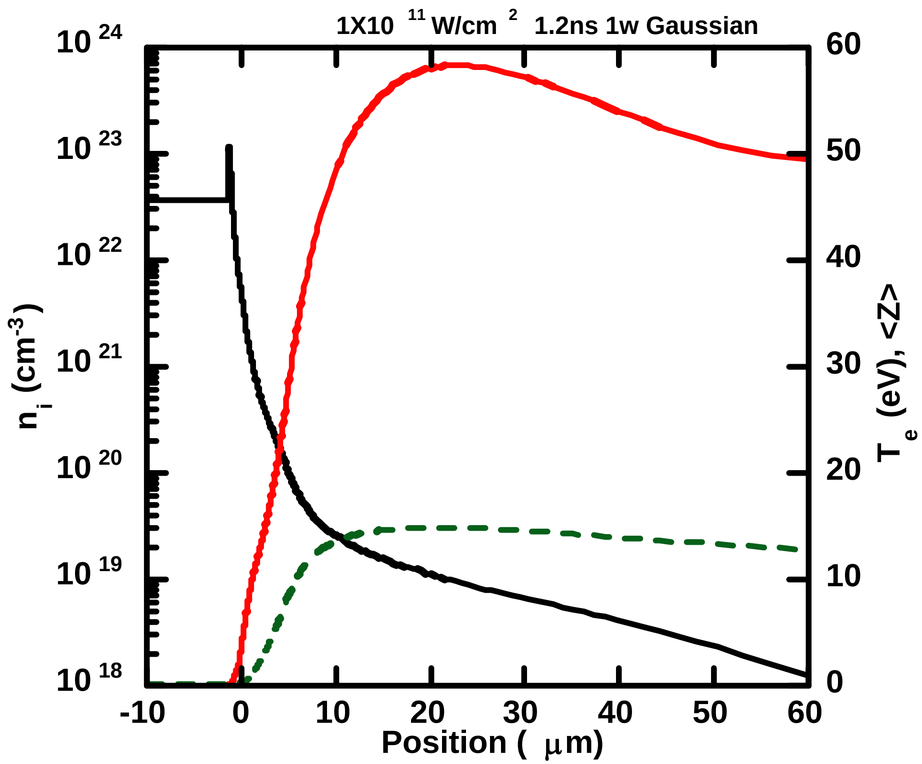
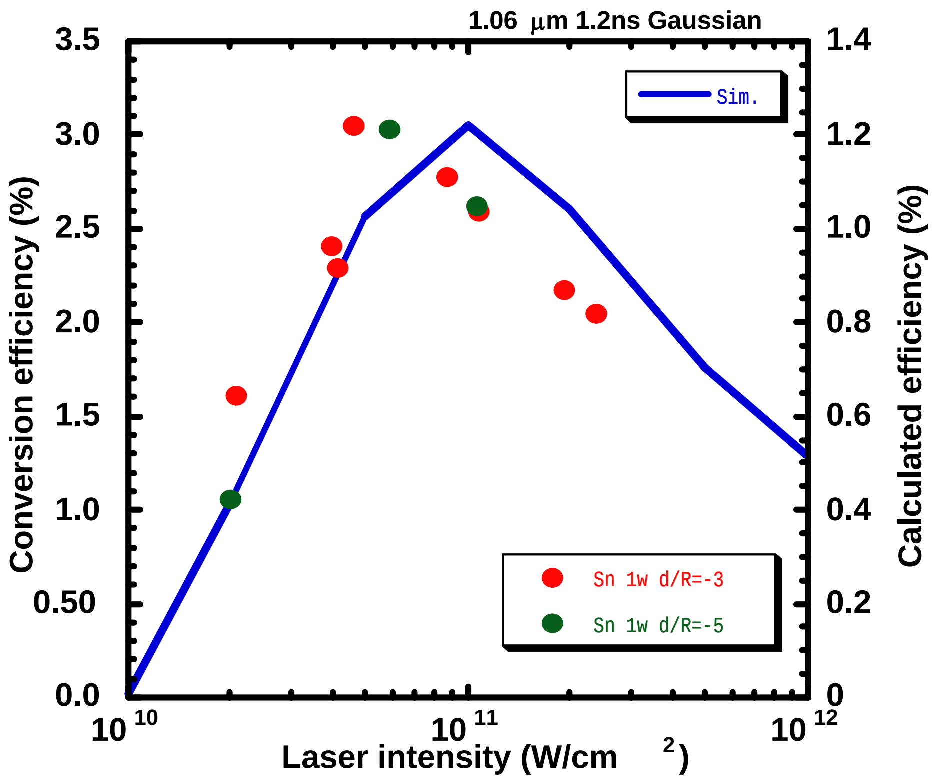
Here, $x_j = P_j / D_j$
D_j: Statistical weight of state *j*
P_j: Population of state *j* given by average ion model

Dependence on the conversion efficiency estimated by simulations are roughly agreed with the experimental result.





Summary

We have developed a simple atomic code which is based on

- Average ion model
- Screened hydrogenic model

! which can predict energy level HULLAC's results.

- Statistical approach is used

! in estimating chage 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)

After solving radiation transport with hydro-motion,
rough EUV spectra can be reproduced.
Sorry to say, predicted conversion efficiency from laser to EUV
of 2 % bandwidth of 13.5 nm is about 3 times smaller than
experimental ones.