Physics of laser-produced Li plasma EUV light source

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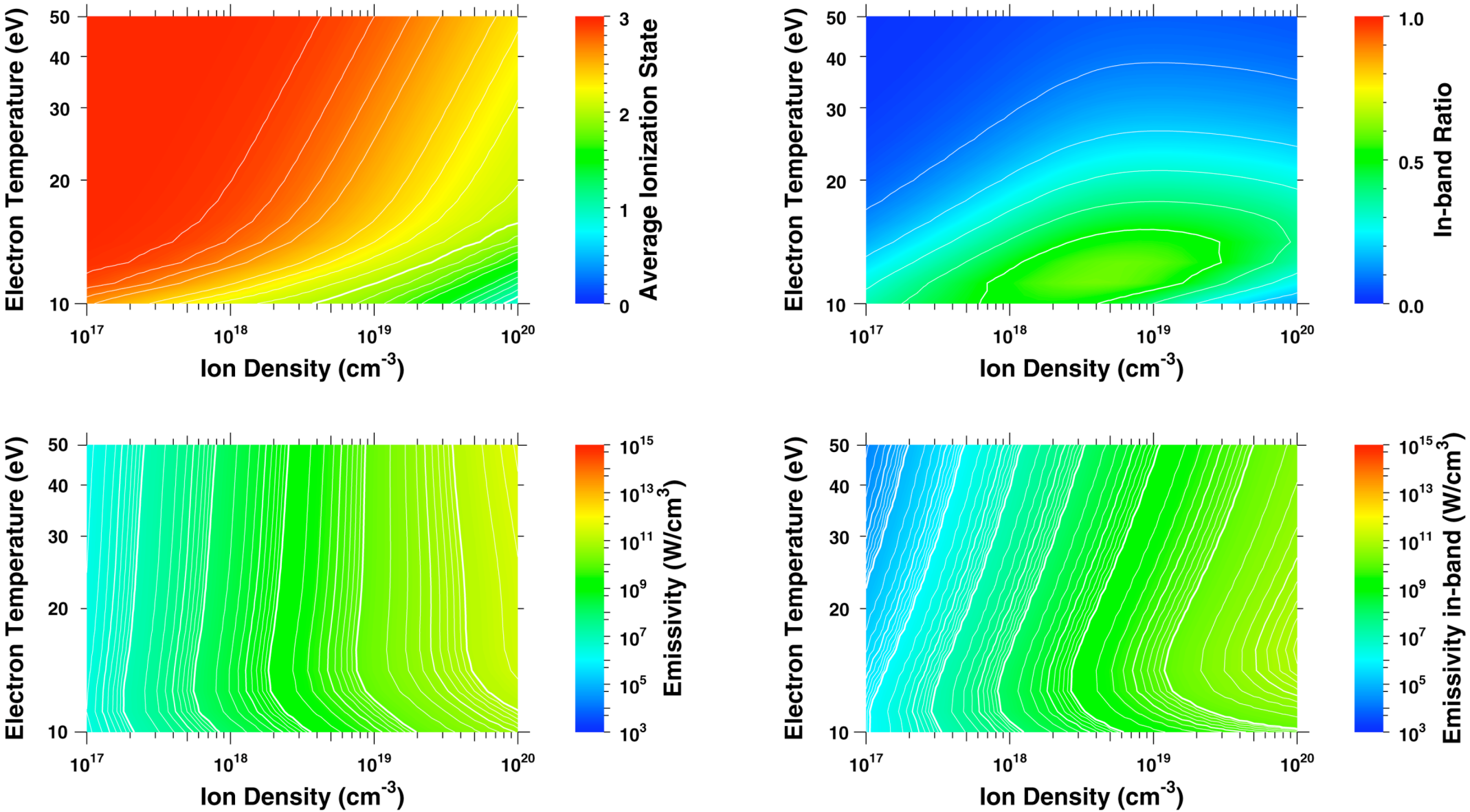
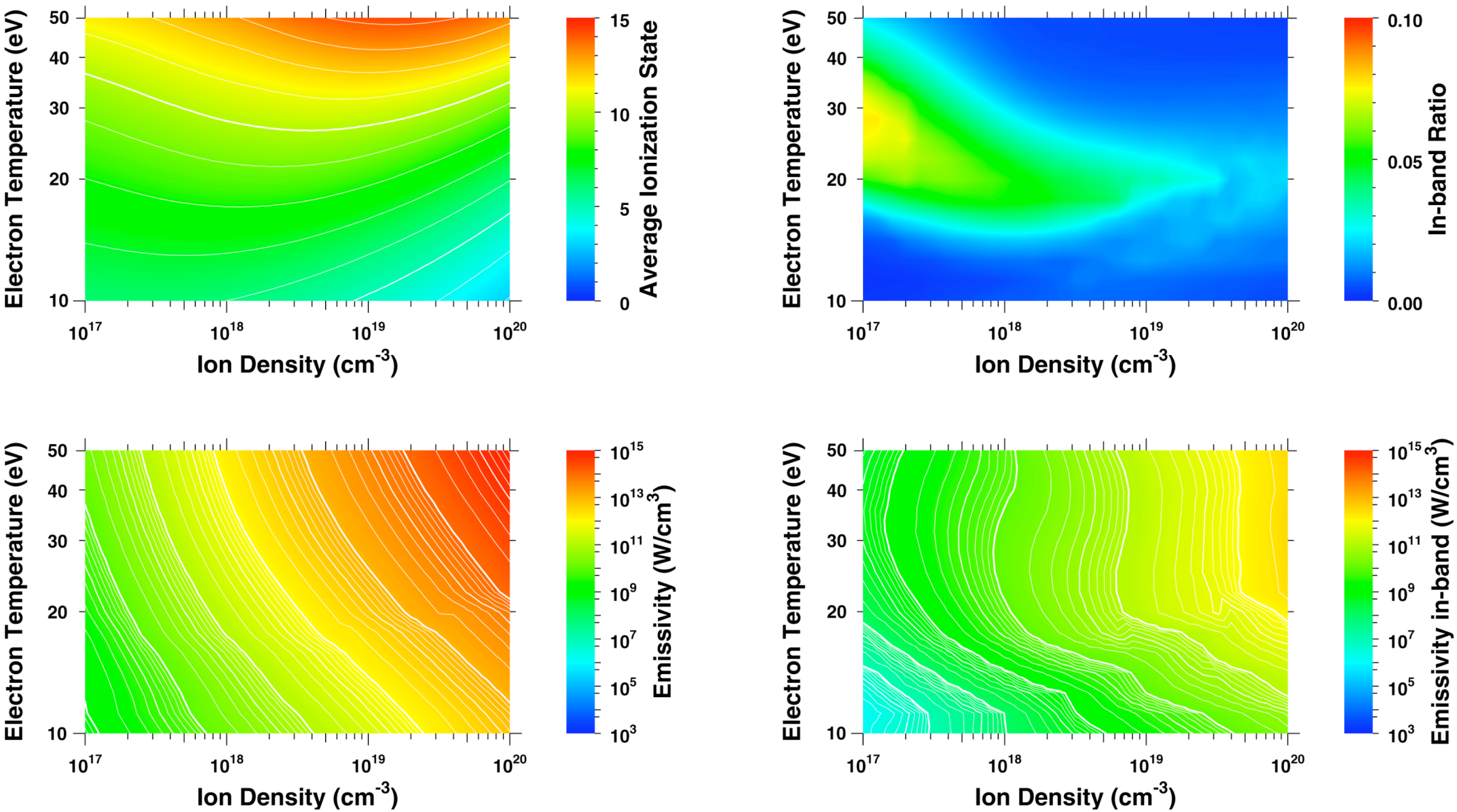
2005 International Symposium on Extreme Ultraviolet Lithography
November 7-9, 2005
San Diego, USA

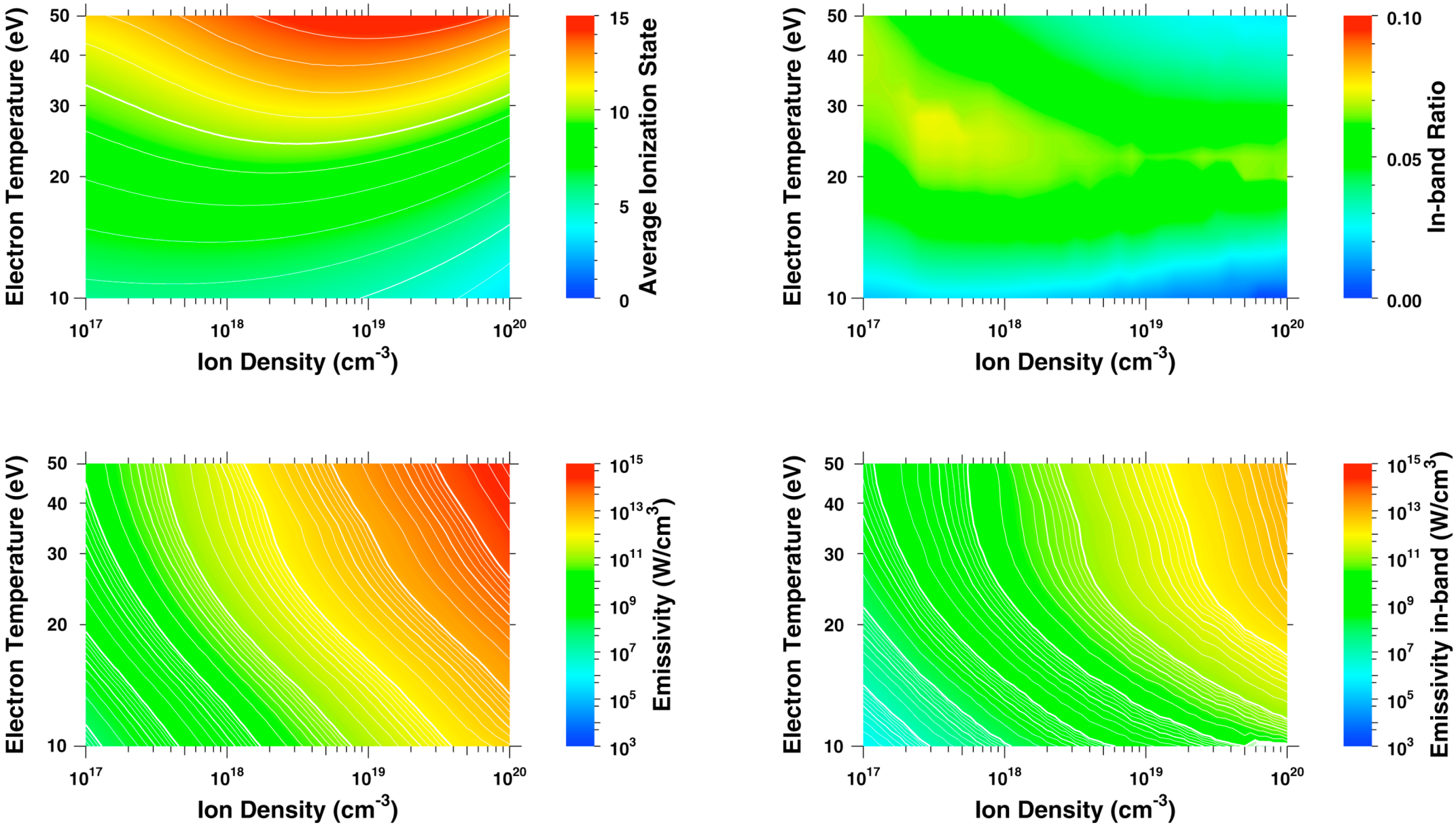
Basic Radiative Properties of Lithium



Basic Radiative Properties of Xenon



Basic Radiative Properties of Tin



Difference among Li(Z=3), Sn(Z=50), and Xe(Z=54) (A Coefficients)

$$A(p,q) = \frac{8\pi^2 e^2 \omega^2}{mc^3} \frac{g(q)}{g(p)} f_{qp} \approx 4.34 \times 10^7 E_{(\mathrm{eV})}{}^2 \frac{g(q)}{g(p)} f_{qp}$$

Same transition energy of 92 eV (13.5nm)

Emission oscillator strength $\frac{g(q)}{g(p)} f_{qp}$

0.4 - 0.6 for Sn

0.06 for Xe

0.1 for Li (A = 3.7×10^{10} /s -> 27 ps)

Difference among Li, Sn, and Xe (Ionization Potential)

Required Ionization energy to emit 92 eV (13.5nm)

Xe => 1000 eV (11+)
Sn => 162 eV (5+)～ 1800 eV (14+)
Li => 202 eV (Fully ionized)

Plus plasma kinetic energy of 30～50 eV (×2)

=> Li needs less Ionization loss
Electron density becomes one-thirds to -fourths

Difference on Energy Level

Ionization energy for 92 eV transition energy

Li: 122eV
Xe 10+, for example: 228 eV

Li's upper level is close to ionization threshold
Sn, Xe are relatively wide

=>Li's upper population easily escape
via electron collisional process
=> High density (=short wavelength) is

Rate Coefficients (/s) of Li

20	2	3	4	5	free	
	91.8	108.8	114.75	117.504	122.454	
	4.59	5.44	5.7375	5.8752	6.1227	
	0.4162	0.0791	0.029	0.0139		
1e+17	3.25e+6	2.23e+5	5.76e+4	2.35e+4	1.72e+5	
1e+18	3.25e+7	2.23e+6	5.76e+5	2.35e+5	1.72e+6	
1e+19	3.25e+8	2.23e+7	5.76e+6	2.35e+6	1.72e+7	
1e+20	3.25e+9	2.23e+8	5.76e+7	2.35e+7	1.72e+8	
1e+21	3.25e+10	2.23e+9	5.76e+8	2.35e+8	1.72e+9	
	1	3	4	5	free	1
	91.8	17	22.95	25.704	30.6135	91.8
	4.59	0.85	1.1475	1.2852	1.530675	4.59
	0.4162	0.6407	0.1193	0.0447		0.4162
1e+17	8.01e+7	1.14e+9	1.17e+8	3.40e+7	1.72e+5	3.79e+10
1e+18	8.01e+8	1.14e+10	1.17e+9	3.40e+8	1.72e+6	3.79e+10
1e+19	8.01e+9	1.14e+11	1.17e+10	3.40e+9	1.72e+7	3.79e+10
1e+20	8.01e+10	1.14e+12	1.17e+11	3.40e+10	1.72e+8	3.79e+10
1e+21	8.01e+11	1.14e+13	1.17e+12	3.40e+11	1.72e+9	3.79e+10

Emissivity & Opacity Code of Li

Population: Saha-Boltzmann

=> Opacity effect is most optimistic one due to the assumption of LTE population

=>CRE(collisional radiative equilibrium) is in progress (also radiation effect)

>Opacity & Emissivity is based on H-like (He-like)

>But, for oscillator strength, detailed calculations for isolated ion have been installed

>Main contribution for Line Profile is Stark effect

>Present estimation is rough, factor of 2 deviation might includes in optical thickness

Modeling of EUV-LPP (Power balance)

Consider following energy losses

- kinetic energy loss due to expansion, I_k
- ionization loss, I_i
- radiation loss, I_R ,

and assume a sum of the losses equals to laser flux.

$$I_L = I_k + I_i + I_R$$

Assume isothermal expansion in corona

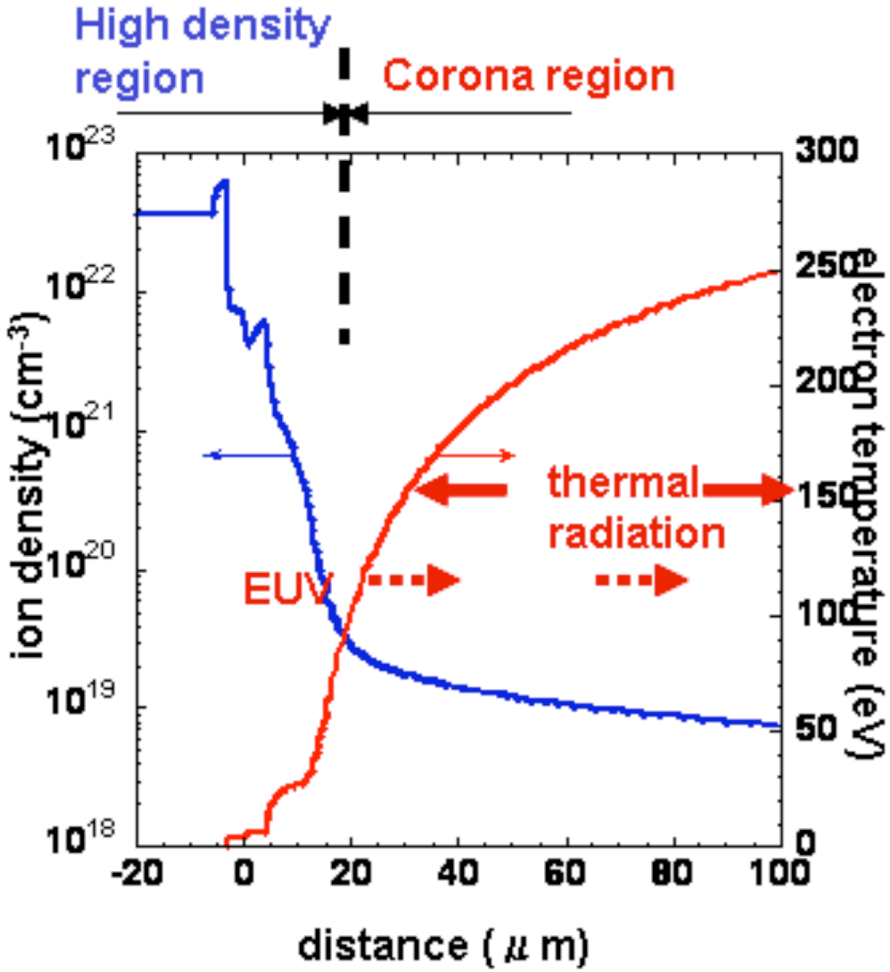
$$n = n_o \exp(-x/c_s t), \quad v = c_s + x/t$$

$$I_k = 3Z^*(n_0, T_e) n_0 T_e c_s,$$

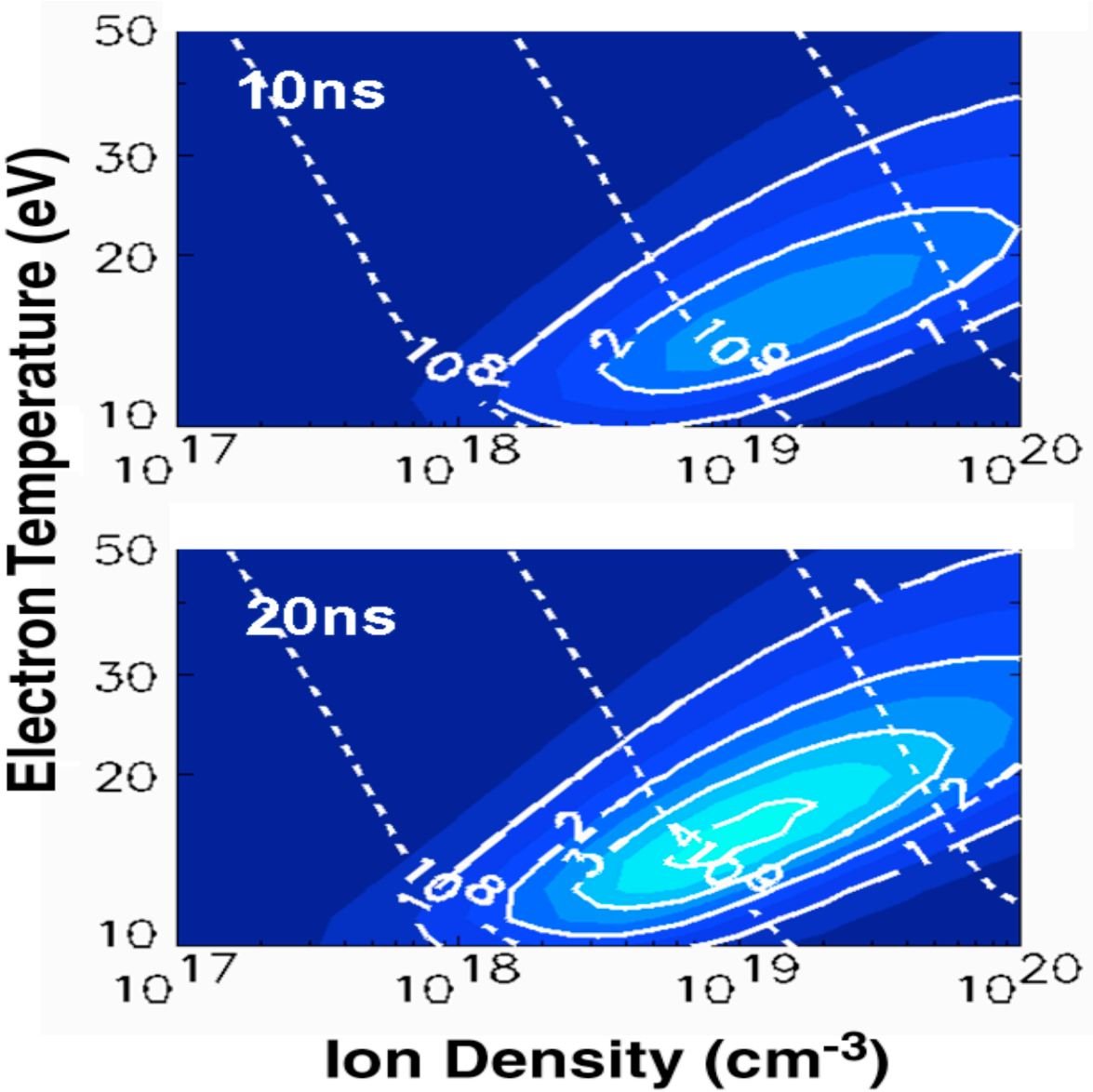
$$I_i = \left[E_{ion}(n_0, T_e) + \frac{3}{2} Z^*(n_0, T_e) T_e \right] n_0 c_s,$$

$$I_R = \int j_\nu(n_i(x), T_e) \exp\left[-\int_x^\infty k_\nu(n_i(x'), T_e) dx' \right] dx d\nu,$$

where Z^* : ionization state, n_i : ion density, T_e : electron temperature, c_s : sound speed

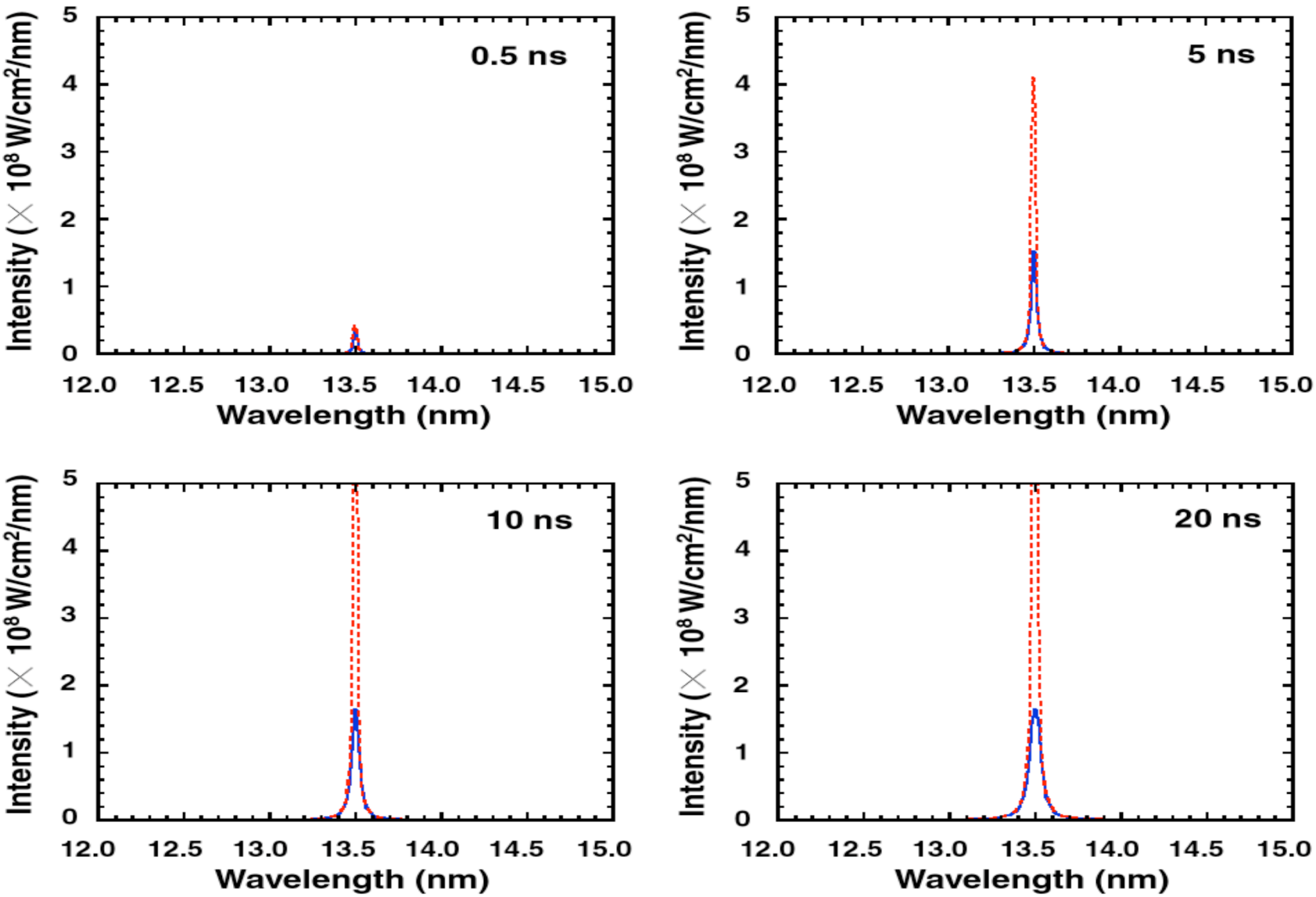


Conversion Efficiency of Li Plasmas



Longer laser pulse gives higher conversion efficiency

Planck's law suppress head of the Lyman-α



But optical thickness play an important role on spectral broadening!

Design for 115 W EUV light source

For example,

CE = 3 % at 10^{10} W/cm^2 is possible

10^{10} (W/cm^2: Laser Intensity)

0.03 (Conversion Efficiency)

20×10^{-9} (s: Pulse width)

3.14×0.04^2 (area)

= 15 mJ/shot

To achieve 115 W, at least 8 kHz repetition rate is necessary

(Figures are most optimistic) => higher rate is required

Maybe, no solution on 10 kHz laser operation

Conclusions

Lithium can achieve high conversion efficiency,
but available intensity per shot is small.

Required laser for lithium target
>high repeatiton rate
>long wave length

>high conversion efficiency (-3%)
>merit on debris mitigation
(light ion, low temperature, if heated mirror)
is expected