4th EUVL Symposium
2005. Nov. 7th in San Diego

Optimized parameters for generating a laser-produced tin plasma as a source for high volume production

Toshihisa TOMIE

National Institute of Advanced Industrial Science and Technology (AIST)
Advanced Semiconductor Research Center (ASRC)

This work is supported by NEDO

Content

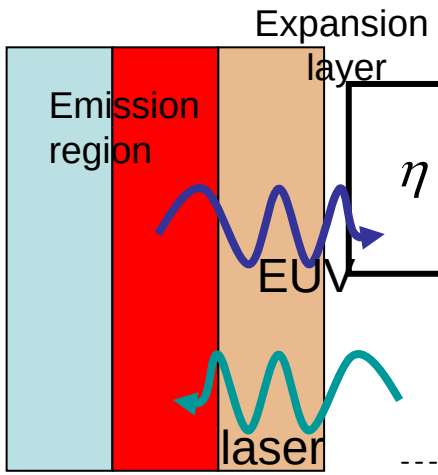
1. CE of a LPP can be estimated analytically by calculating
    1. laser absorption efficiency
    2. radiation efficiency
    3. spectral efficiency
2. The radiation efficiency is estimated by calculating
    2-1. the energy for sustaining a plasma
    2-2. Radiation energy
3. spectral efficiency is determined by opacity
4. Optimum parameters to maximize 3 efficiencies
5. CE of Sn LPP can be **4% /2πsr**

Conversion Efficiency (CE) is
a product of
Three efficiencies

1. laser absorption efficiency
2. radiation efficiency
3. spectral efficiency

CE can be calculated analytically !!

Conversion efficiency η



$$\eta = A_{abs} \times \frac{\Sigma E_{rad}}{\Sigma E_{rad} + E_{plasma}} \times \eta_{spect,intrinsic} \times T_{hot} \times T_{cool} \quad \text{---(1)}$$

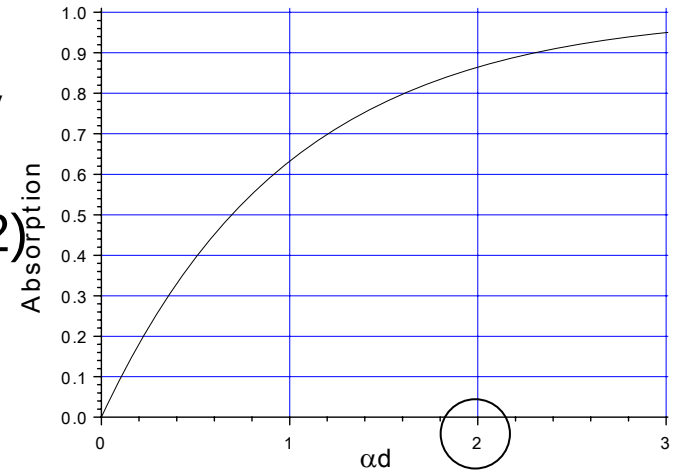
Radiation efficiency

Spectral efficiency

$$A_{abs} = 1-\exp(-\alpha d) \quad \text{---(2)}$$

$$\alpha = 6E\text{-}37\ Z n_e^2\ \lambda_{laser}(\mu m)^2 / T_e(eV)^{3/2}$$

αd needs to be around 2



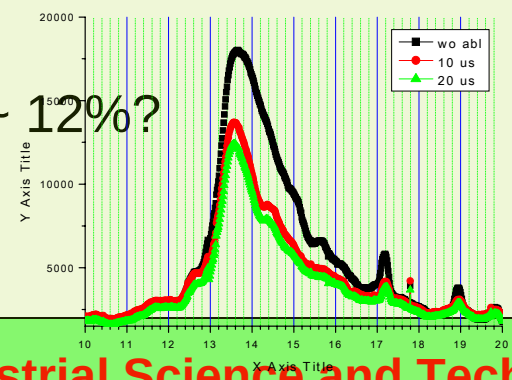
$$\frac{\Sigma E_{rad}}{\Sigma E_{rad} + E_{plasma}} \sim (1 - E_{plasma} / \Sigma E_{rad}) \quad \text{---(3)}$$

when $E_{plasma} / \Sigma E_{rad} << 1$

$$\eta_{spect} = \eta_{spect,intrinsic}\ T_{hot}\ T_{cool}$$

Needs to be 5-6 %

$\eta_{spect,intrinsic} \sim 12\%$?



To calculate the radiation efficiency, the energy for sustaining a plasma (E_{plasma}: plasma energy) is calculated as follows.

Radiation efficiency 1: Plasma energy 1

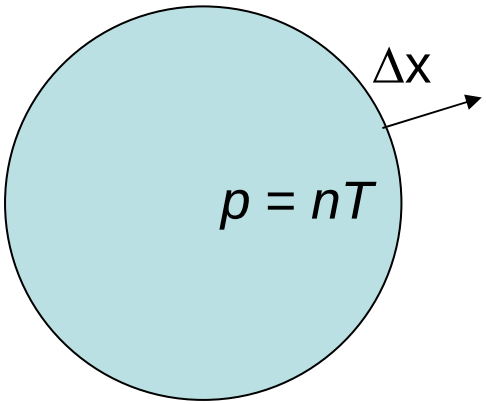
Expansion energy

Plasma: uniform density and temperature

Expansion velocity: constant

(for simplicity of calculation)

$$V_{exp} = (Z/M)^{1/2}\, T_e(eV)^{1/2}\ 1.6E6\ \text{cm/sec}$$



$$\Delta E_k = p\, S\, \Delta x \qquad P = nT$$

$$S = 4\pi(r_0+vt)^2$$

$$n = (r_0/(r_0+vt))^3\, n_0$$

$$dE_k = r_0^3\, n_0\, 4\pi\, T\, v\, dt/(r_0+vt))$$

$$E_k = \int dE_k$$

$$= r_0^3\, n_0\, 4\pi\, T\, v \int dt/(r_0+vt))$$

$$= r_0^3\, n_0\, 4\pi\, T \ln(1+vt/r_0)\Big|_{t=0}^{t=t}$$

Ratio to $E_{thermal}$(thermal energy)

$$E_{thermal} = (4\pi/3) r_0^3\, n_0 T$$

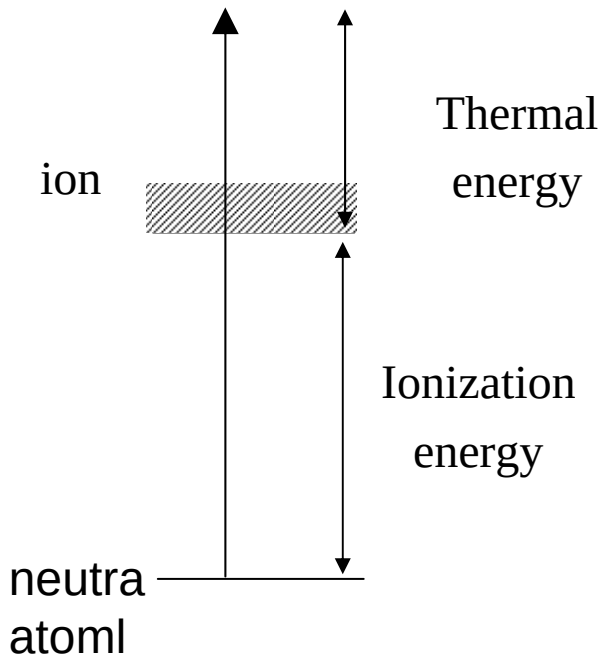
$$\boldsymbol{E_k/E_{thermal}} = r_0^3\, n_0\, 4\pi\, T \ln(1+vt/r_0)/\ (4\pi/3) r_0^3\, n_0 T$$

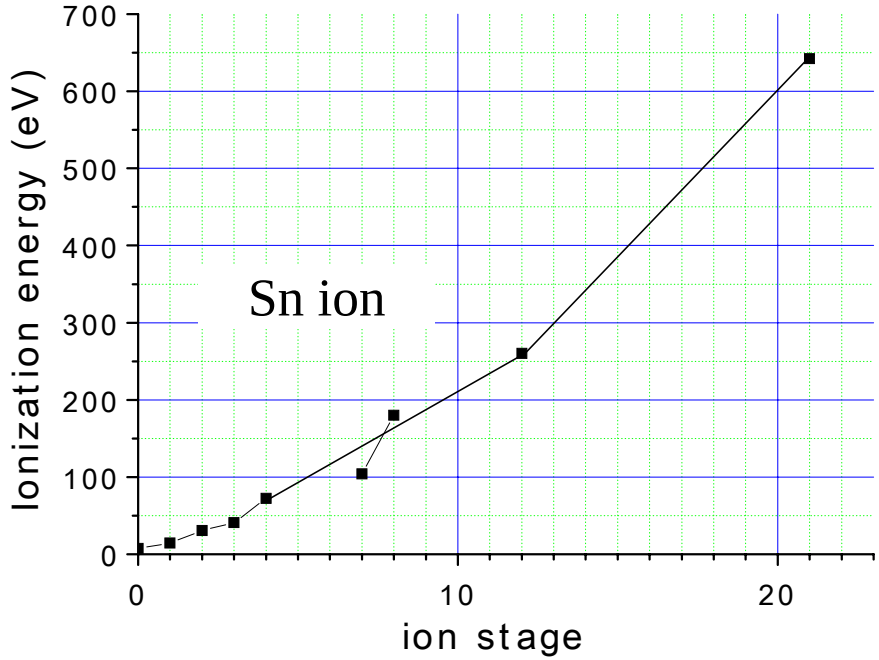
$$= 3 \ln(1+vt/r_0) \fallingdotseq 2.1 \quad \text{for } vt=r_0$$

(**= 1.2** for $vt=r_0/2$ (when density becomes 1/3 of the initial)

Radiation efficiency 2: Plasma energy 2

Ionization energy





Sn^{+5} =>average 33eV/electron

Sn^{+10} => 85eV/electron

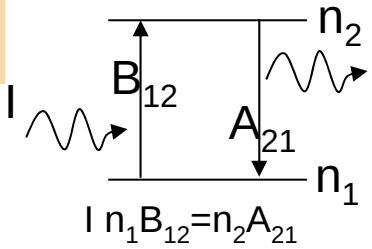
Sn^{+15} => 137eV/electron

$$E_{plasma} = \text{ionization} + \text{thermal} + \text{expansion}$$
$$\sim (90\ \text{eV} + 3T_e)\ /\text{electron}$$

(When CE is large, $E_{plasma} << \Sigma E_{rad}$ => accuracy of E_{plasma} can be low)

Radiation energy

Radiation efficiency 3: radiation energy



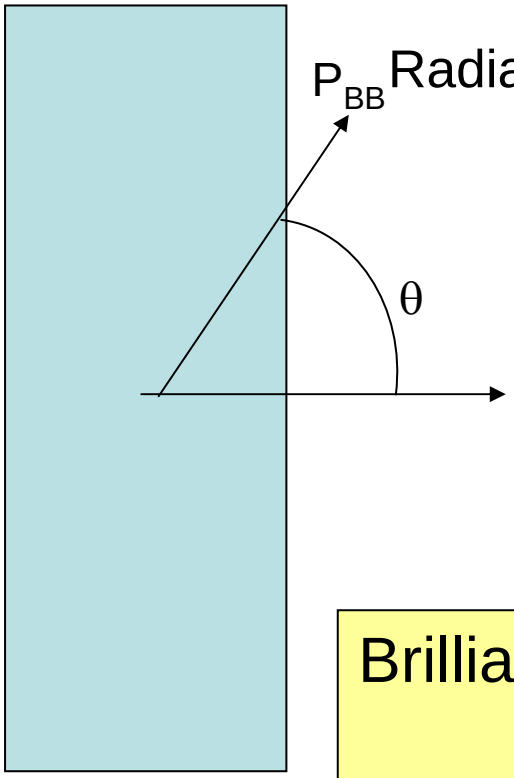
Blackbody brilliance is the limit for any sources

P_{BB} $=(A_{21}/B_{12}) \times (n_2/n_1) = (A_{21}/B_{12}) \times \exp(-\Delta E/kT_R)$

$= 3.73\times10^{12}\ (\Delta\lambda/\lambda)/\ (\lambda\ (10\text{nm})^4 \times (\exp(h\nu/k_BT_R)-1))$ (W /(cm^2 π sr))

$= 7.41\times10^{19}/\ (h\nu(\text{eV})\ \lambda\ (10\text{nm})^4 \times(\exp(h\nu/k_BT_R)-1))$

(photons /(sec 0.1% mm^2 mrad^2))



P_{BB} Radiation flux per unit area

$$\int P_{BB} \cos\theta\, d\Omega$$

$$= P_{BB}\, 2\pi \int \cos\theta \sin\theta\, d\theta$$

$$= \pi P_{BB}$$

$= 3.73\text{E}12\times 2\% / (1.35^4 \times(\exp 2.3 - 1)$ <= 40eV

$=$ **2.5E9** W/cm^2 **For a infinite thick plasma**

(4.2E9 W/cm^2 @50eV, 6.2E9 W/cm^2 @60eV)

Brilliance for a finite thickness (opacity τ_{hot}) plasma

$P_{BB}(1-\exp(-\tau_{hot}))$

Radiation efficiency 4

$$\Sigma E_{rad} = (P_{BB}(1-\exp(-\tau))/\eta_{spect,})t_{rad}$$

emission duration

For large CE => $\Sigma E_{rad} >> E_{plasma}$

Sn^{+10} electron density

$$(P_{BB}(1-\exp(-\tau))/\eta_{spect})\, 4\pi r^2\, t_{rad} >> (90\text{ eV} + 3T_e)(4\pi r^3/3)\, n_e$$

$t_{rad} \sim r/V_{exp}$ plasma surface plasma volume

$$P_{BB}(1-\exp(-\tau_{hot}))/\eta_{spect,} >> (90\text{ eV} + 3T_e)(V_{exp}/3)\, n_e$$

Condition 1: when T_e~40eV => P_{BB}=2.5E9W/cm^2, V_{exp} ~3E6 cm/sec

Condition 2: if η_{spect} =10% is required

=>7.4E20 (1-exp(-τ_{hot})) >>n_e(/cm^3) → **Solid&liquid target & short wavelength laser =>not acceptable**

Condition 3: for τ_{hot}<<1, 1-exp(-τ_{hot}) ~ $\tau = \sigma\, n_i\, r$

For large CE => $P_{BB}\, \sigma\, r/Z\eta_{spect,} >> (90\text{ eV} + 2T_e)(V_{exp,}/3)$

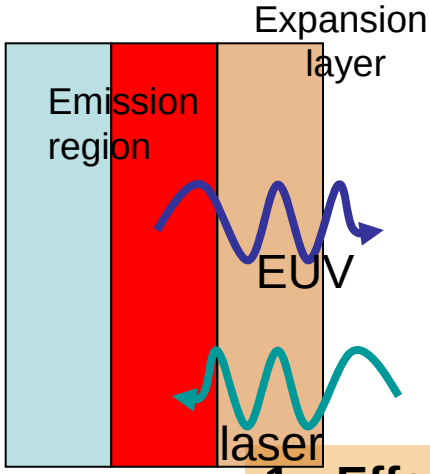
$\sigma(\nu)$=2E-17cm^2:for Sn@13-14nm、1 order small for Xe@13nm

=> r>>7μm → **Thin plasma & sub-ns laser => not acceptable**

Transmission of EUV light through a plasma

EUV transmission affects the spectral efficiency

(spectral efficiency can be evaluated experimentally



Opacity reduces spectral efficiency

$$\tau(\nu) = \tau_0 \exp(-((\nu-\nu_0)/\Delta\nu)^2)$$

$$\tau(\nu) = \sigma(\nu)\, Ni\, d;$$

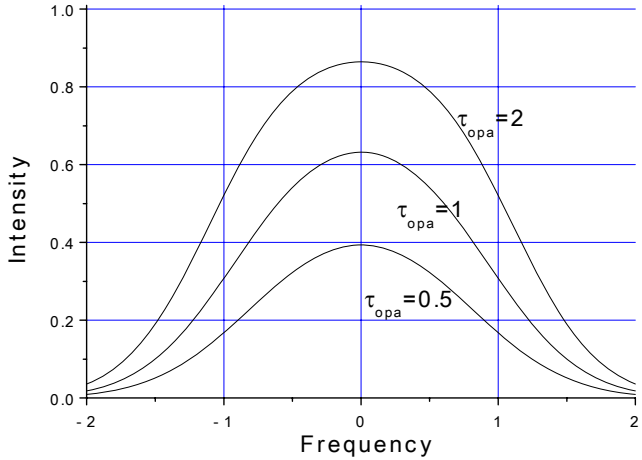
τ: opacity, σ: absorption cross section

1. Effect of opacity of the emitting region

$$I(n) = P_{BB}(1-\exp(-\tau_{hot}(\nu))) \quad \text{---(4)}$$

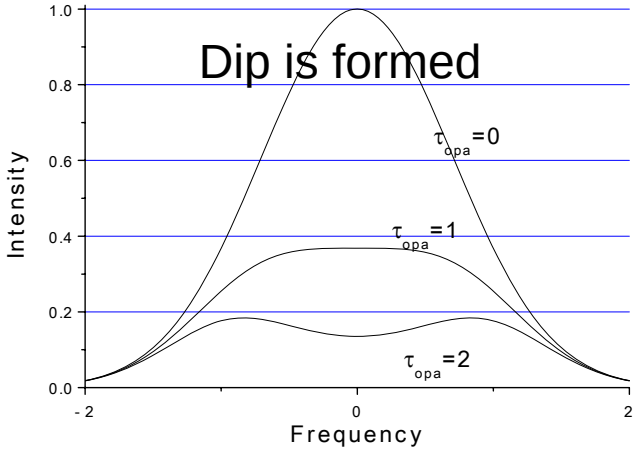
Spectrum is broadened

$(\ln(\tau_0/\ln(2/(1+e^{-\tau_0})))^{1/2} \quad \sim(\ln\tau_0)^{1/2}$



2. Effect of opacity of the expanding region

$$T_{cool} = \exp(-\tau_{cool}(\nu)) \quad \text{---(5)}$$



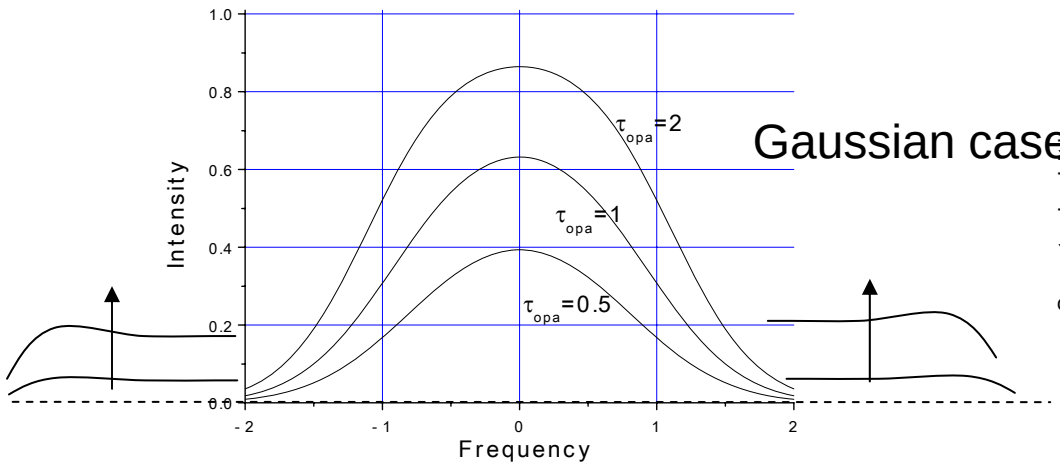
Important: τ_{cool} should be zero

=> 1. long pulse has a bad effect

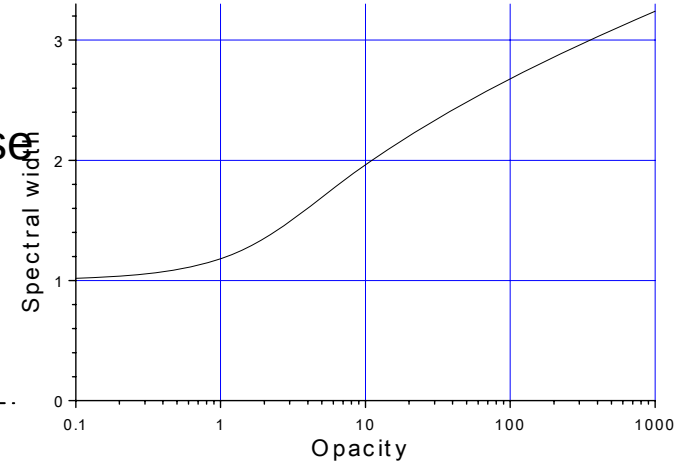
2. steep gradient is required

Effect of opacity of the emitting region

Spectrum is broadened by the amount of $(\ln(\tau_0/\ln(2/(1+e^{-\tau_0})))^{1/2}$ $\sim(\ln\tau_0)^{1/2}$

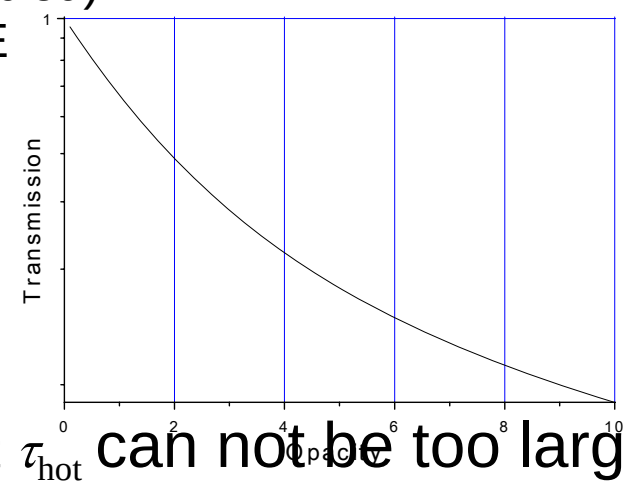


Gaussian case



Broadening is not significant (even when τ_{hot}=10, doubled)

If the emission is a single line=>no degradiation of CE



1. Many emission lines

$\Rightarrow$relative intensity is reduced

$\Rightarrow \eta_{spect,}$becomes low

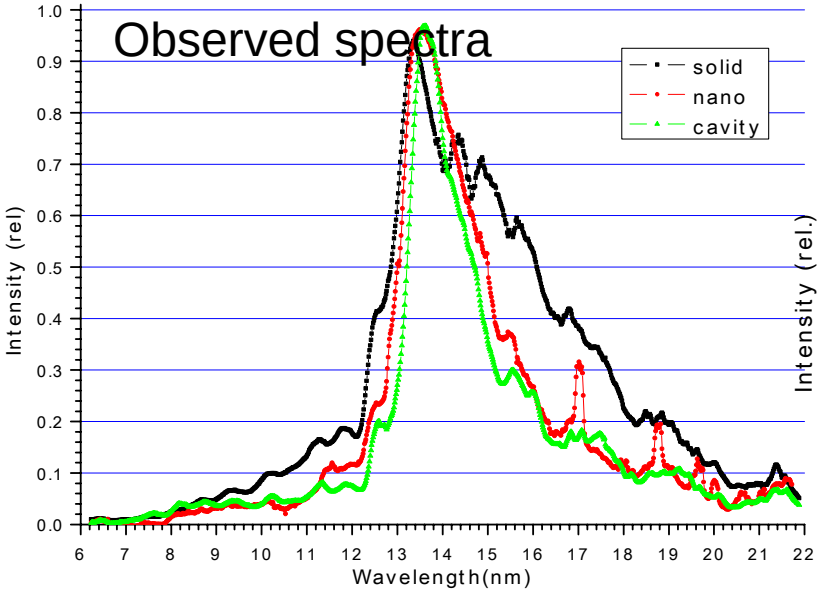
2. $E_{plasma}/\Sigma E_{rad}$ is degradiated

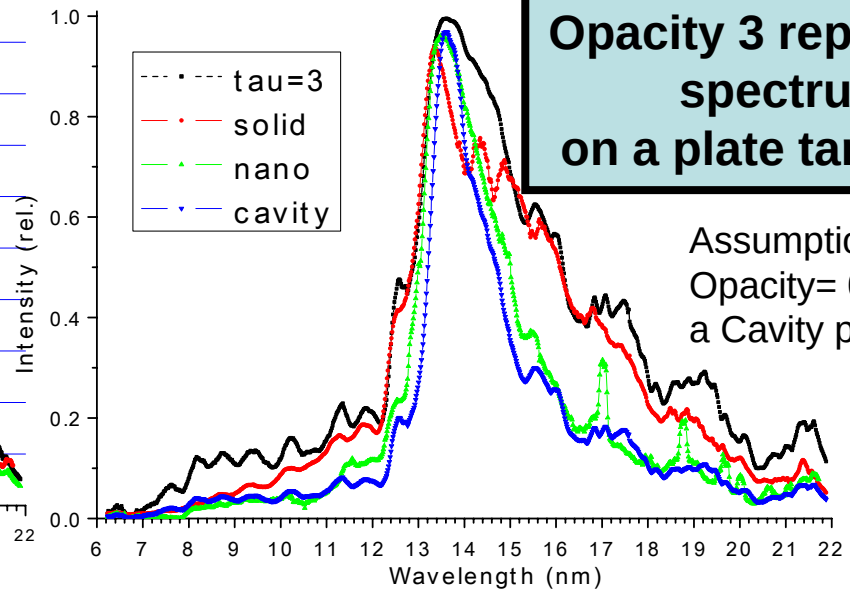
$\eta_{spect,}$becomes low

(not so serious as the opacity of expanding layer) but τ_{hot} can not be too large

$\tau_{hot} \sim 1$

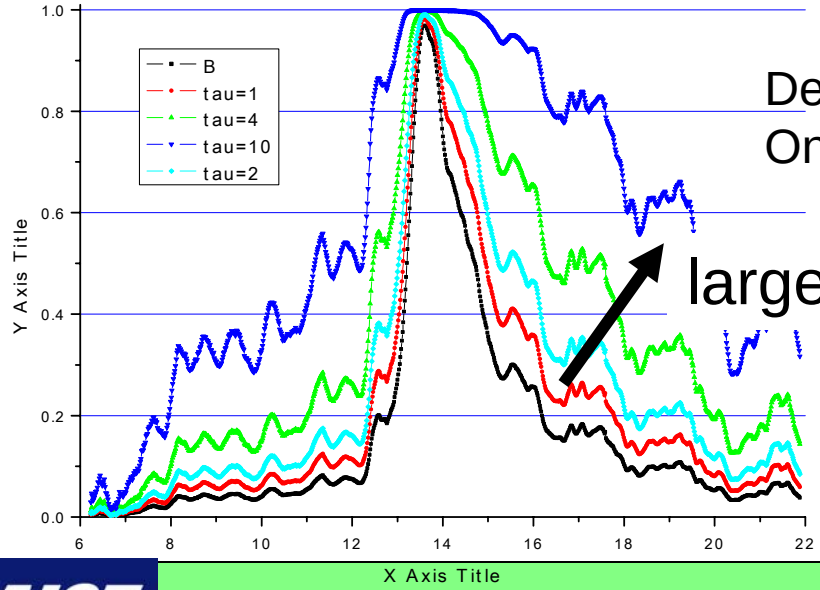
Effect of opacity of the emitting region 2





Opacity 3 reproduces spectrum on a plate target！！

Assumption:
Opacity= 0 for
a Cavity plasma



Dependence of emission spectrum
On opacity

larger τ

Spectral efficiency
8.9% =>5.5% (tau=2)
=>4.6% (tau=3)

Spectral Efficiency of Blackbody, BB, (=infinite opacity)

$P_{BB} = 3.73\text{x}10^{12}\ (\Delta\lambda/\lambda)/\ (\lambda\ (10\text{nm})^4 \text{ x } (\exp(h\nu/k_B T_R)-1))$ (W /(cm^2 π sr))

$\int P_{BB} \cos\theta\ d\Omega$

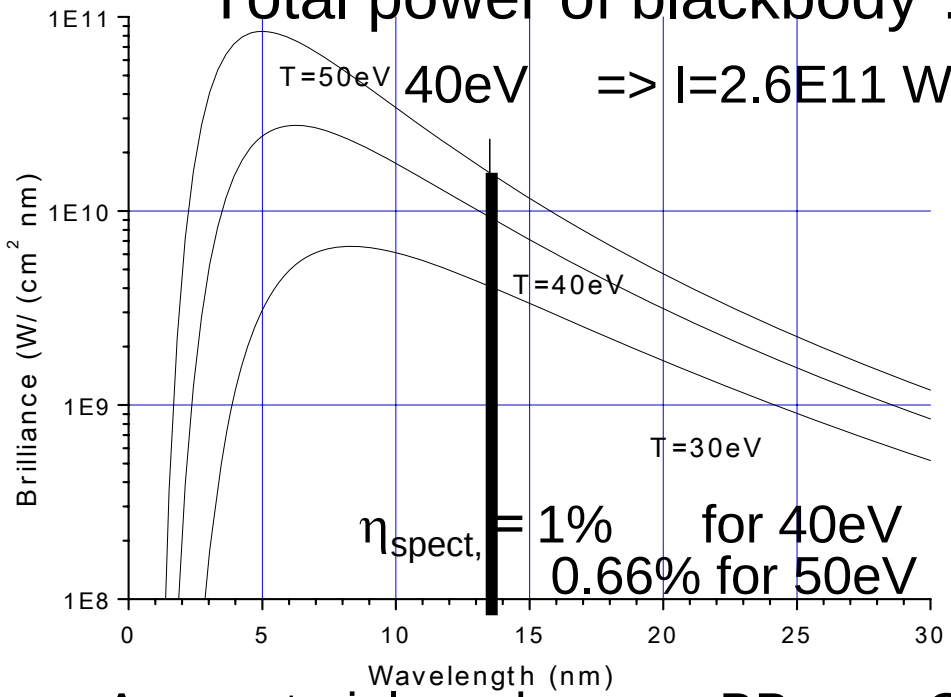
$= P_{BB}\ 2\pi \int \cos\theta \sin\theta\ d\theta \qquad = \pi P_{BB}$

$= 3.73\text{E}12\text{x } 2\% / (1.35^4 \text{ x}(\exp 2.3 - 1)$

$= \mathbf{2.5E9}$ W/cm^2

Total power of blackbody : $I=\sigma(\kappa T)^4$

40eV => I=2.6E11 W/cm^2



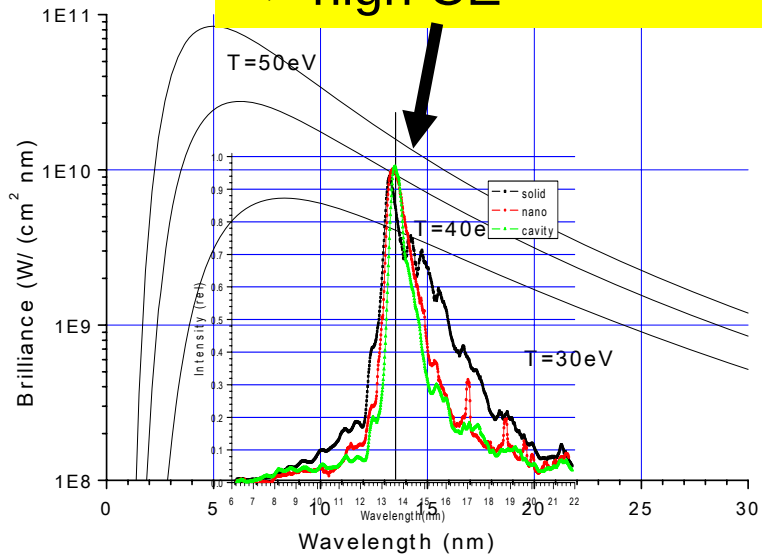
$\eta_{spect,}$ = 1% for 40eV

0.66% for 50eV

low opacity τ~1

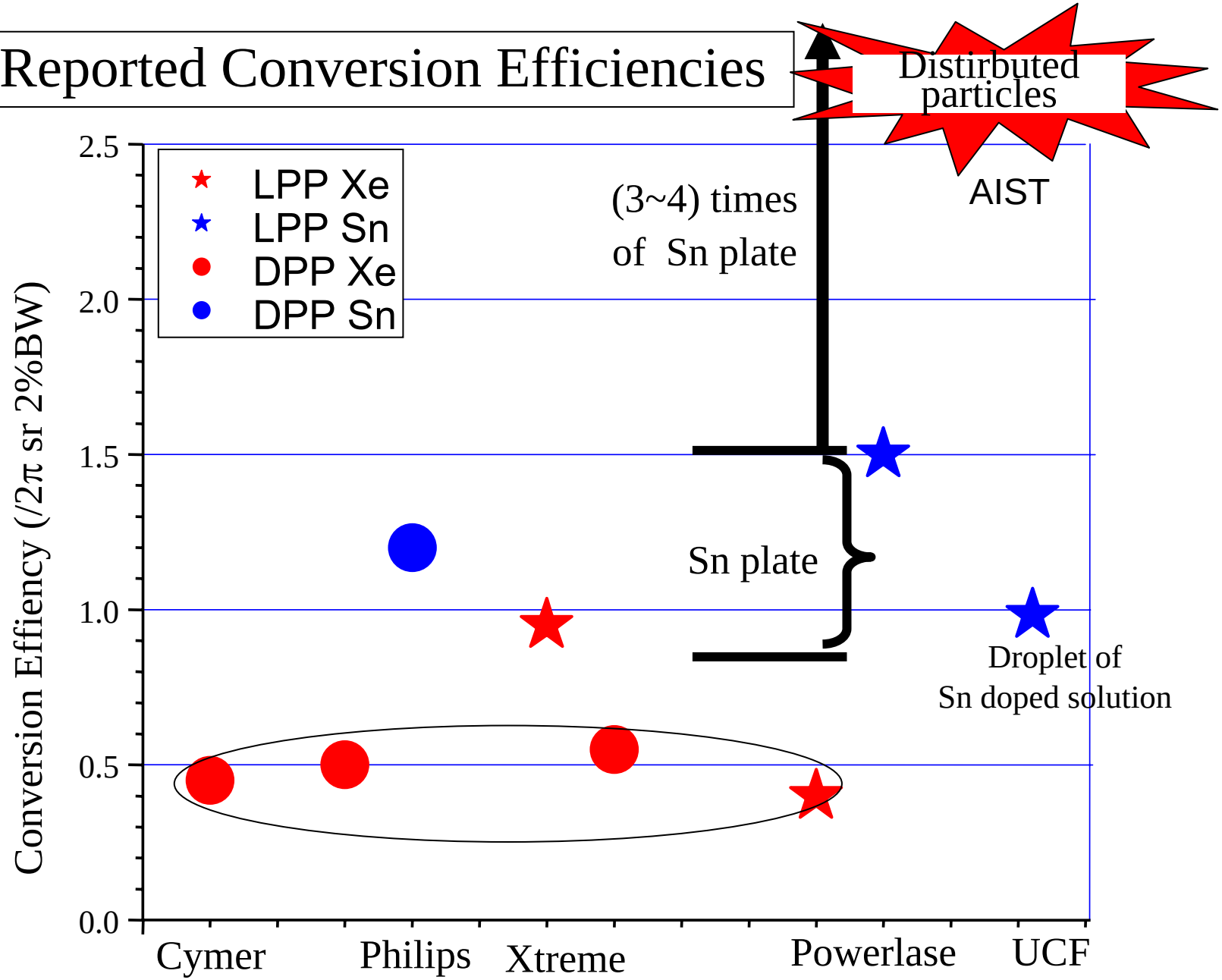
=>high spectral efficiency

=> high CE



=> Any material can become BB => CE~ 1 %/2πsr

Reported Conversion Efficiencies



Optimum parameters

Specific values 1

Low limit of opacity τ_{hot} for EUV power of 115 W

P_{BB} = 7.5E10x 0.02 / 2π x (1.35^4 x(exp2.3 - 1)=7.2E7/(exp2.3 - 1)

= 8 x10^6 W / (mm^2 sr) ---------- (4-6)

When duty ratio of a pulse laser is 5x10^{-5} (10kHz、5ns pulse)

Limit brilliance B_{limit}(for 40eV) is

B_{limit} = 8×10^6×5×10^{-5} W/(mm^2 sr)

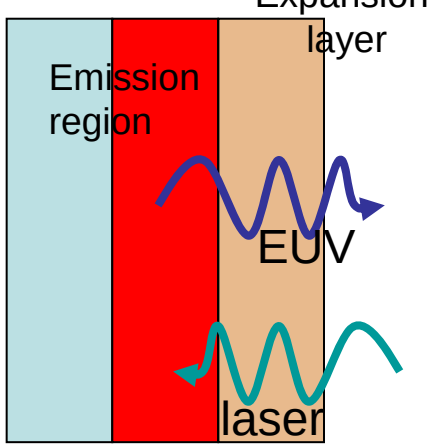
= 400 W/(mm^2 sr) ---------- (4-7)

For 50eV =>(exp2.3-1)/(exp1.84-1)=8.97/5.30=1.69

115W / (reflectivity=0.5x debris mitigation=0.7) =>330W

3.3 mm^2 sr	=>330/1300= 1-exp(-τ_{hot})	=> τ>0.3
1 mm^2 sr	=>330/400= 1-exp(-τ_{hot})	=> **τ>1.7**

Specific values 2



Opacity: $\sigma (n_e/Z)\, d = \tau$, σ= **2E-17/cm^3**

By specifying diameter and opacity, τ

d =0. 5mm, τ = 2 => n_e= 4E19/cm^3

For large laser absorption

$$A_{abs} = 1\text{-}\exp(-\alpha d)$$

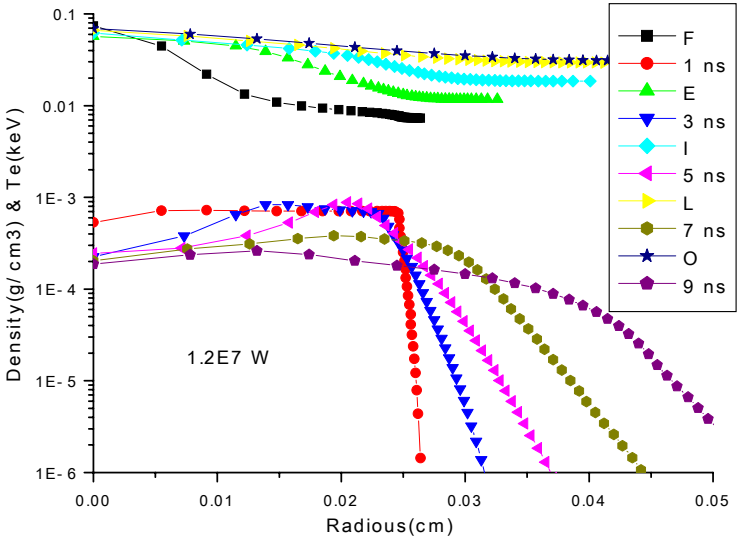
$$\alpha = 6\text{E-}37\, Z n_e^2 \lambda_{laser}(\mu\text{m})^2 / T_e(\text{eV})^{3/2}$$

αd=2 d=0.5mm

$$\Rightarrow 3\text{E-}38 \times 10 \times n_e^2 \lambda_{laser}(\mu\text{m})^2 / T_e(\text{eV})^{3/2} = 2$$

$$\Rightarrow \boxed{n_e(/\text{cm}^3)\, \lambda_{laser}(\mu\text{m}) = 2.6\text{E}18 \times T_e(\text{eV})^{3/4}}$$

=4.1E19 for 40eV, 4.9E19 for 50eV



When n_e= 4E19/cm^3 => λ_{laser} = 1 μm

(For detailed design, numerical simulation is required because density is reduced by expansion and absorption efficiency changes)

Expected efficiency

1.Laser absorption A_{abs} = 1-exp(-2)= 0.86

2.Radiation efficiency

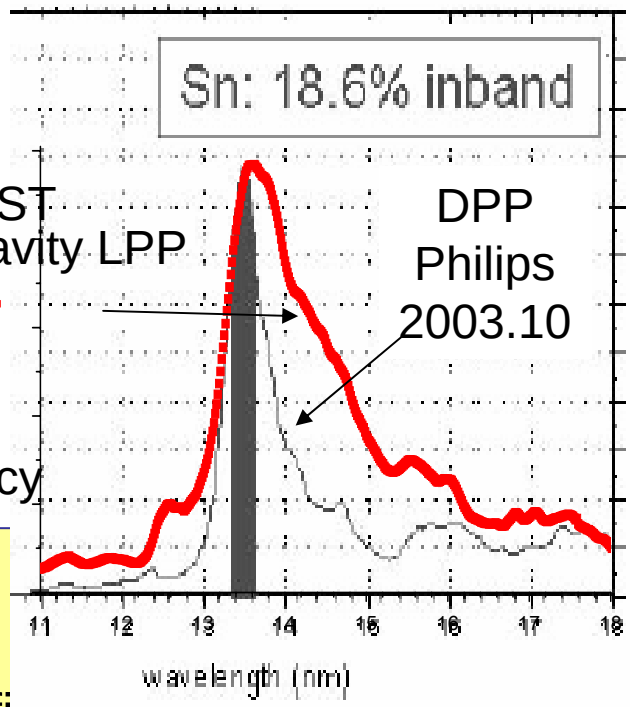
ΣE_{rad} = 2.5E10 W/cm^2 (1-exp(-2)) x 4π(0.025cm)^{2}x(0.025cm/3E6cm/sec)
=1.4 J (= 8 ns)

E_{plasma} = 210eVx 4E19/cm^{3}x (4π/3)(0.025cm)^3
=0.088 J

$$\frac{\Sigma E_{rad}}{\Sigma E_{rad} + E_{plasma}} = 1.4/(1.4+0.088) = 0.94$$

3.Spectral efficiency **10%?**

Then=> CE = 10%/2 x 0.86 x 0.94 = **4% /2πsr**



Laser absorption & radiation efficiency can be > 90%
=> CE is determined almost by spectral efficiency

Most Important parameters to be clarified :

1. Spectral shape for τ_{hot} =0
2. Electron temperature for maximizing spectral efficiency

Summary

1. η~1%/2π sr can be achieved by any materials

2. Max in-band EUV power is 2.5E9W/(cm^{2}2%BW) for Te=40eV.
   => 1. optimum irradiation power is around 4E10W/cm^2
   2. CE is lower for a higher irradiation power

3. For a large CE: **n_e<<7.4E19 (1-exp(-τ_{hot}))/η_{spect}**

CE of LPP can be = **4% /2πsr**

Opacity determines CE and power

4. No absorbing layer (τ_{cool}=0)
   => high density target & long pulse are not accepted

5. Opacity of the emitting region **τ_{hot}~1**
   for 100W @IF100W within etendue of 1mm^2 sr

6. Optimum parameters; radius *r*, opacity τ & laser absorption

n_e= 5**E19cm^2** & λ_{laser} ~ 1 **μm**