Potentiality of Magnetically Confined Plasma as an Efficient Extreme Ultraviolet Source

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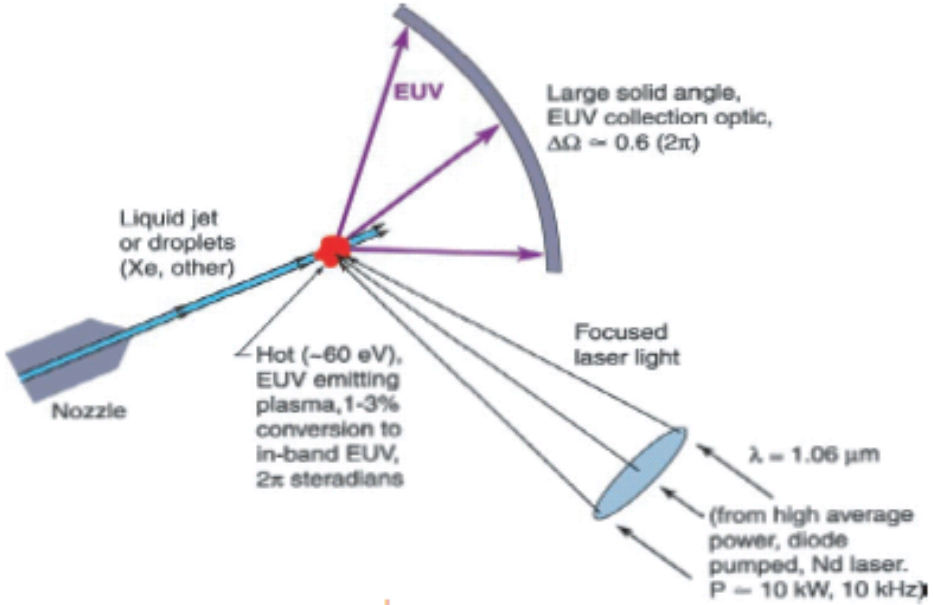
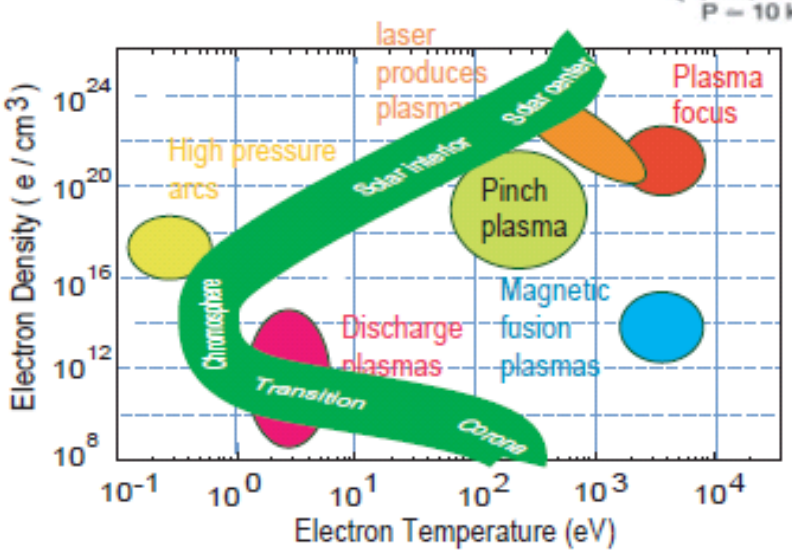
Outline

- DPP -EUV (Extreme-Ultraviolet) source is dominated by the plasma dynamics
- DPP Plasma conversion efficiency (CE) is evaluated using time-dependent atomic model
- Results indicate that prolonging the life-time of the radiating plasma is essential for efficient EUV source
- Magnetically confined long-life plasma can increase CE order of magnitude compared with that of fast pinched plasma

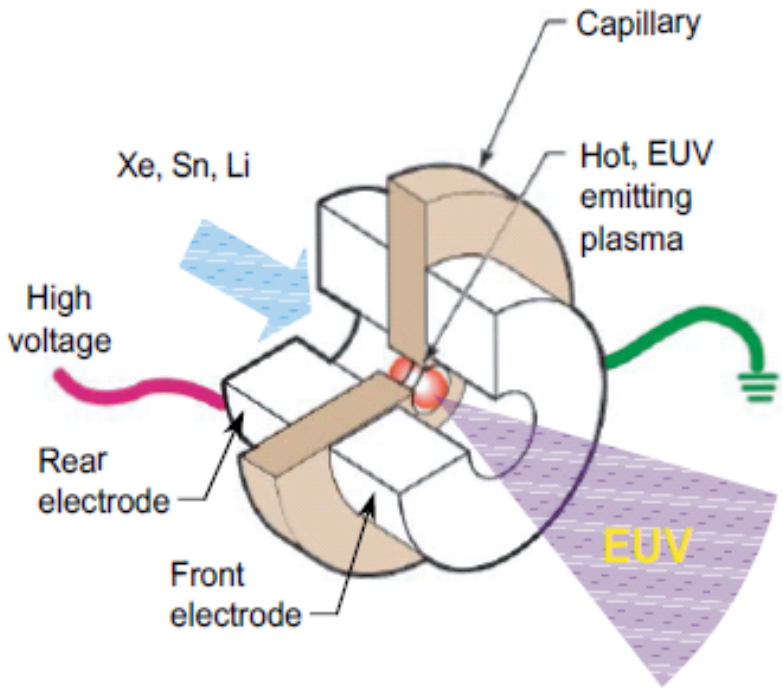
LPP and DPP EUV source

Typical laser produced plasmas





Typical discharge produced plasmas



* laser produced plasmas have so many advantages but expensive

* Discharge produced plasmas are cheap

Requirements

* Wavelength region

In-band radiation 13.5 ± 0.135 nm

* Some industrial requirements for discharge-produced plasmas (DPPs)

EUV power (2% bandwidth) At source about 1kW in 2π sr

U. Stamm, EUV Source Workshop, Feb. (2005)

Etendue of source output Maximum 3.3 mm^2sr

(For example: radius=0.03, length=0.4 cm, collection solid angle 1.33 sr)

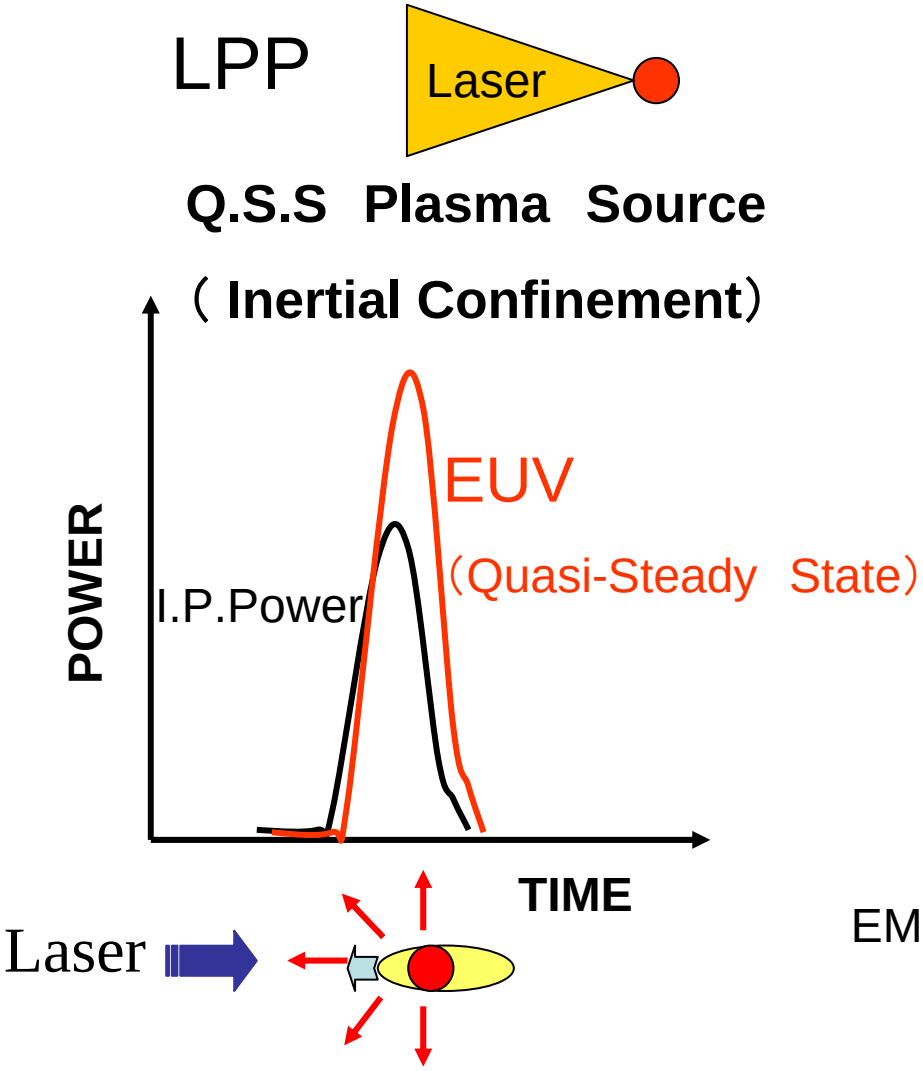
Y. Watanabe, EUV Source Workshop, Feb. (2005)

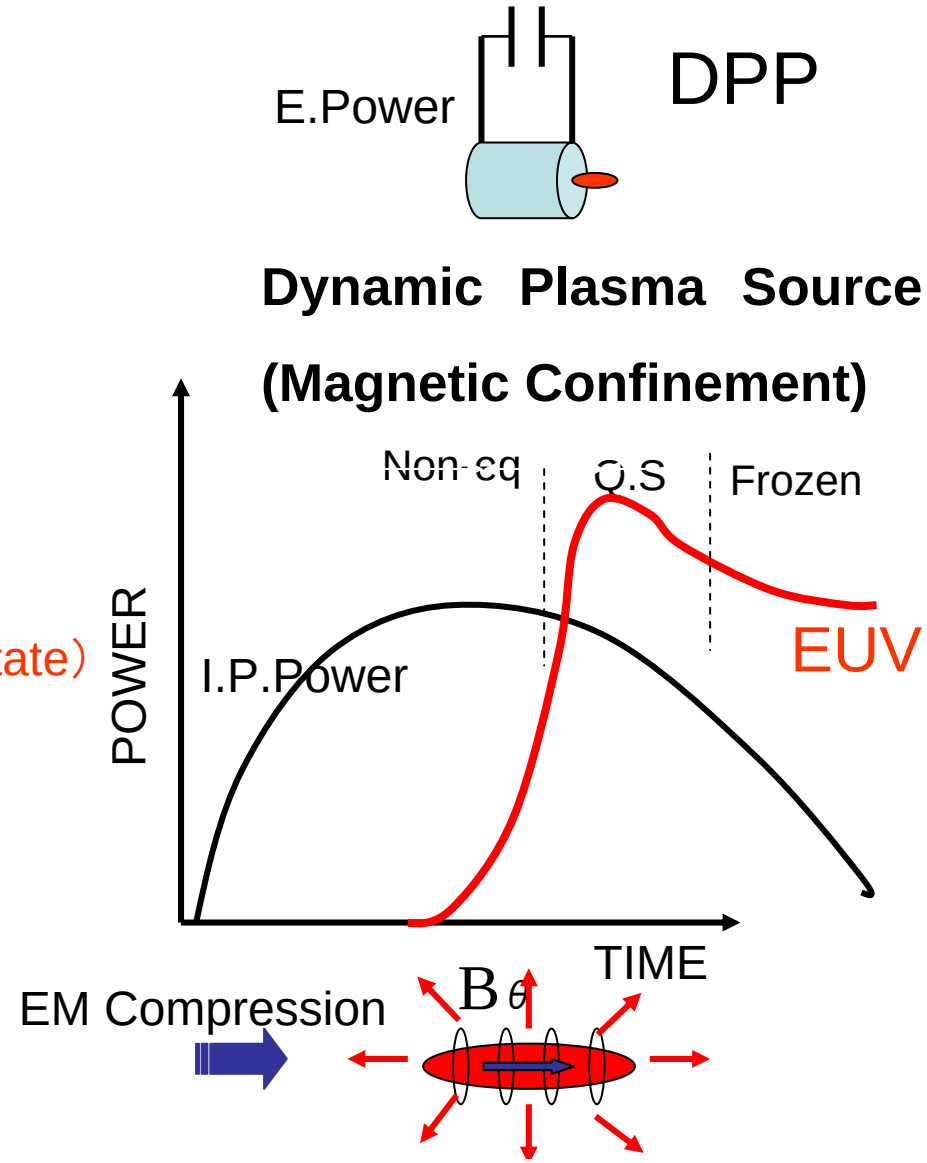
* Critical limitation in DPPs

Heat removal from discharge tube, On the roadmap: (< 40 kW)

U. Stamm, EUV Source Workshop, Feb. (2005)

Comparison of LPP and DPP EUV source





Plasma conversion efficiency of
DPP source depends on;
the geometry, parameters,
and life-time of radiating plasma

Controlling the plasma dynamics;
density distribution, electrode geometry,
and the shape of driving current

Assumptions

- The intensity of radiation field $I_\lambda d\lambda = L_\lambda d\lambda$, where L_λ is the spectral radiance - a quantity which characterizes the surface angular radiant flux density. So, the intensity

$$L_{ul}^{q^+} = \frac{C}{\lambda_{ul}^4}\left(\frac{\widetilde{\Delta\lambda_{ul}}}{\lambda_{ul}}\right)\left(\frac{g_u n_l^{q^+}}{g_l n_u^{q^+}} - 1\right)^{-1}, (\mathrm{W/cm^2srHz})$$

- $C = 2hc^2 = 1.2 \times 10^{16}$, if λ in nm
- $\widetilde{\Delta\lambda_{ul}}$, low-density plasmas: Doppler & opacity broadening; line-profile function: Gaussian
- Lambert's law: the radiant exitance $M_{ul}^{q^+}$ $(\mathrm{W/cm^2Hz}) = \pi L_{ul}^{q^+}$

- Steady-state rate equation

$$\frac{d}{dt}n_i^{q^+} = n_e \sum_{j\neq i} n_j^{q^+} Q_{ji}(T_e) + \sum_{j>i} n_j^{q^+} \Re_{ji} A_{ji} - n_i^{q^+}\left[n_e \sum_{j\neq i} Q_{ij}(T_e) + \sum_{j<i} \Re_{ij} A_{ij}\right] = 0$$

- $\Re_{ij}$ is escape factor normal to cylinder, in which calculated based on optical thickness at static plasma

Opacity and ionization degree

- $\Re_{ij}$: the Doppler-profile escape factor normal to cylinder, a=1.0010796, b=2.3212136, and c=0.22335545. *A. K. Bhatia and S. O. Kastner, JQSRT 58 (1997) 347*

$$\Re_{ij} = a/\{1 + \exp\left[b\left(\log(\tau_{ij}) - c\right)\right]\}$$

- The escape factor applied between all the excited levels
- Actually, in rate equation, the relative level populations, namely, $n_j^{q^+}/n^{q^+}$, where n^{q^+} represents the total (summed over all of the levels of the ion) number density q^+ ion is calculated. This can easily related to ionization balance by writing

$$n_j^{q^+} = \left(\frac{n_j^{q^+}}{n^{q^+}}\frac{n^{q^+}}{n_i}\frac{n_i}{n_e}n_e\right) \simeq \left(\frac{n_j^{q^+}}{n^{q^+}}\frac{\delta^{q^+}}{Z_{\rm ave}}n_e\right)$$

- The ionization balance is calculated based on effective rate coefficients which they include the effect of excited states based on Griem's boundary. *T. Fujimoto, Plasma Spectroscopy (Clarendon, New York, 2004), Chap. 5, pp 150-204.*

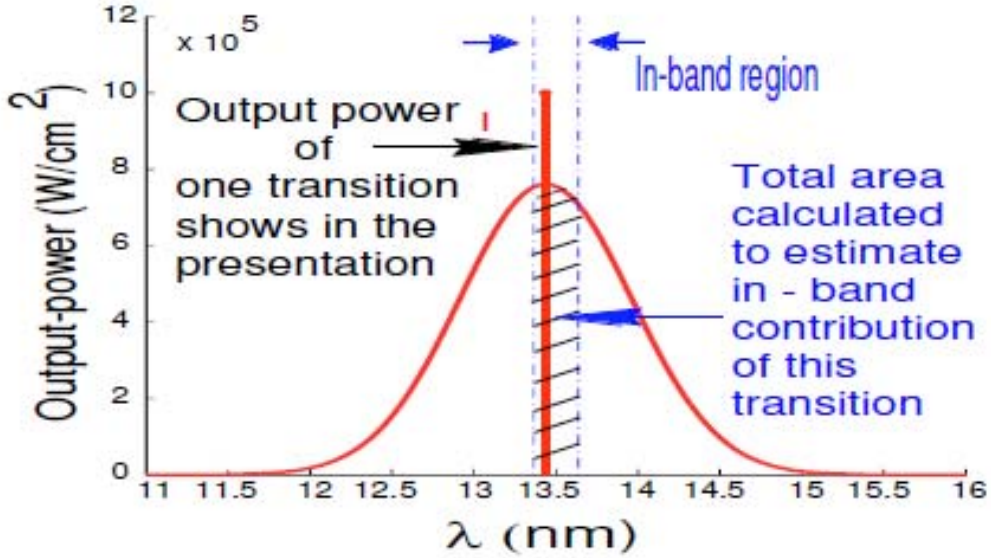
$$S^{\rm eff}_{(q-1)^+}\delta^{(q-1)^+} = \alpha^{\rm eff}_{q^+}\delta^{q^+}$$

In-band Power

- Therefore, for each of the electron density and the electron temperature, the ionization fraction, population of excited states including opacity, the spectral radiance and the radiant exitance are calculated. Second the the intensity is Gaussian distributed based on

$$\Delta\overline{\lambda} = 2919.6\overline{\sigma}/\overline{E}^2$$

- where FWHM of wavelength is in nm, energy and variance (width) are in eV
- Finally, the contribution of each lines in 2% bandwidth is calculated using integration

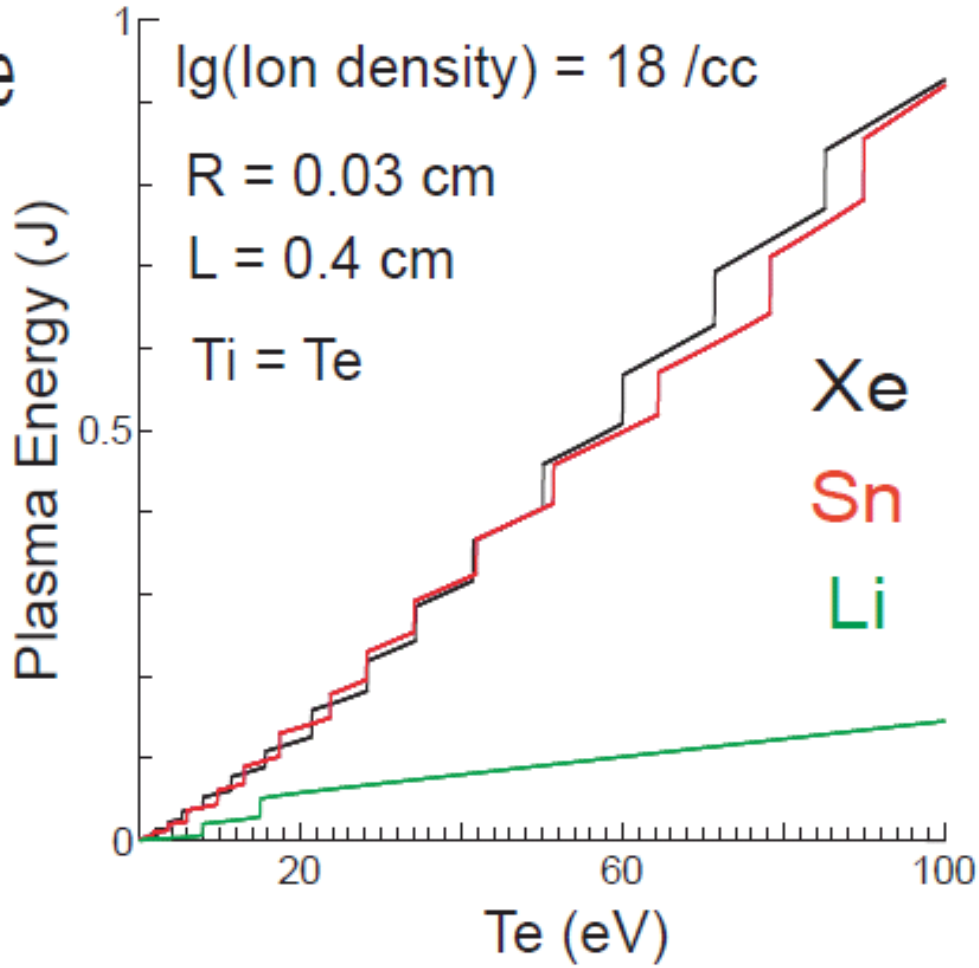


Plasma energy & Emission duration

* Plasma energy =
  Thermal energy (electrons + ions) + Ionization potentials

* Li: lower energy needs to make

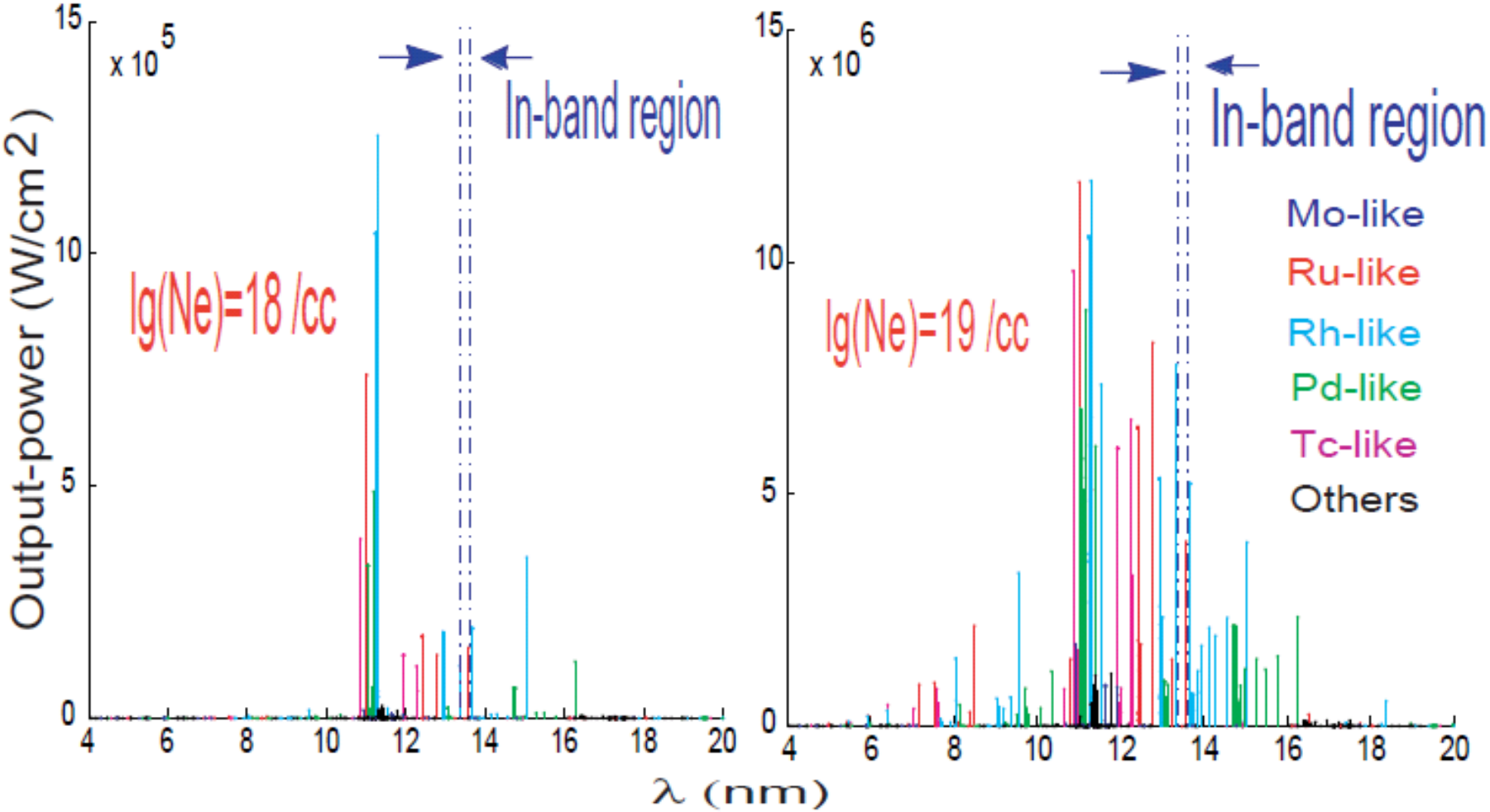
* Emission duration (dt)
  shortest time among
  (i) Ionization time
  (ii) Inertia confinement time
  (iii) The time which total plasma energy converts to total radiation



Collisional-radiative model, Xenon

* Typical spectrum of output power (Xe 5+ - Xe 15+)

Opacity effect increases in-band radiation

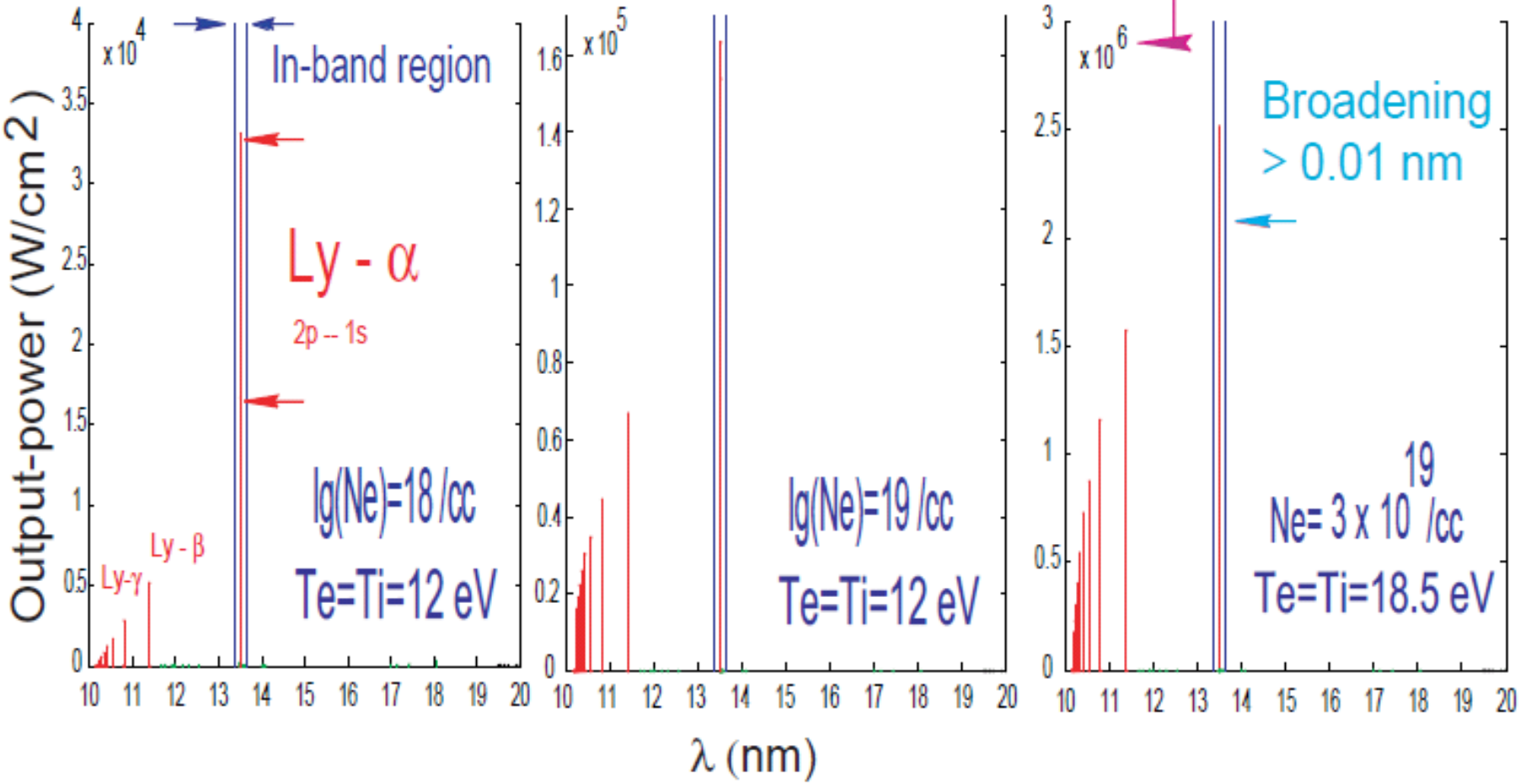


Collisional-radiative model, Lithium

* Typical spectrum of output power

Opacity effect increases the out of band radiation

Output-power is extremely higher in high Te



Plasma Conversion Efficiency of DPP should be estimated by a Time-Integrated Criterion

In-band Power

$$CE_{DPP} = \frac{\int_0^{\tau} P_{euv} dt}{\int_0^{\tau} \left\{ P_{kin} + P_{ion} + P_{ex} + P_{rad} \right\} dt}$$

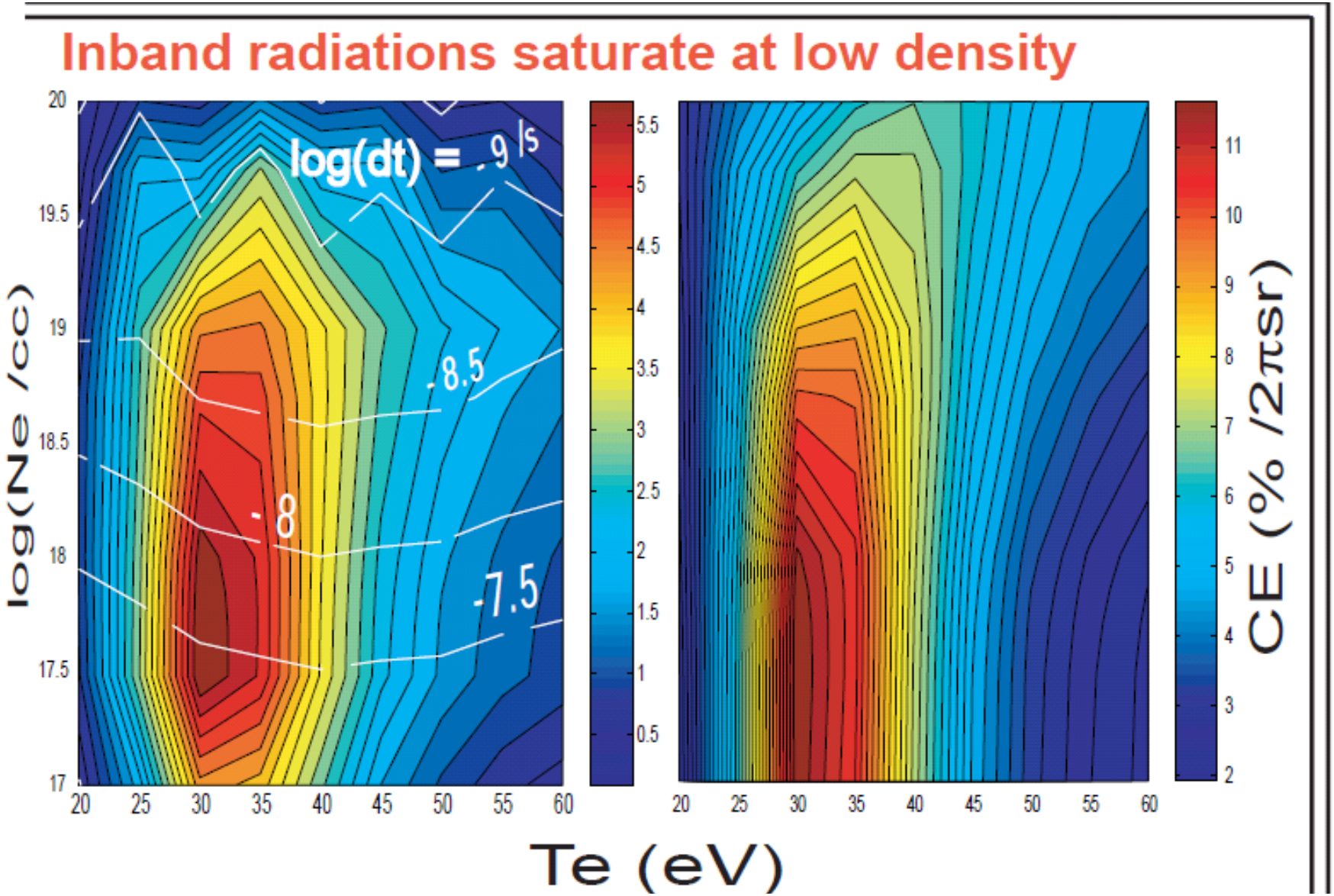
Total Radiation

Conversion Efficiency of DPP reduces to spectrum efficiency for magnetically confined, long-life plasma

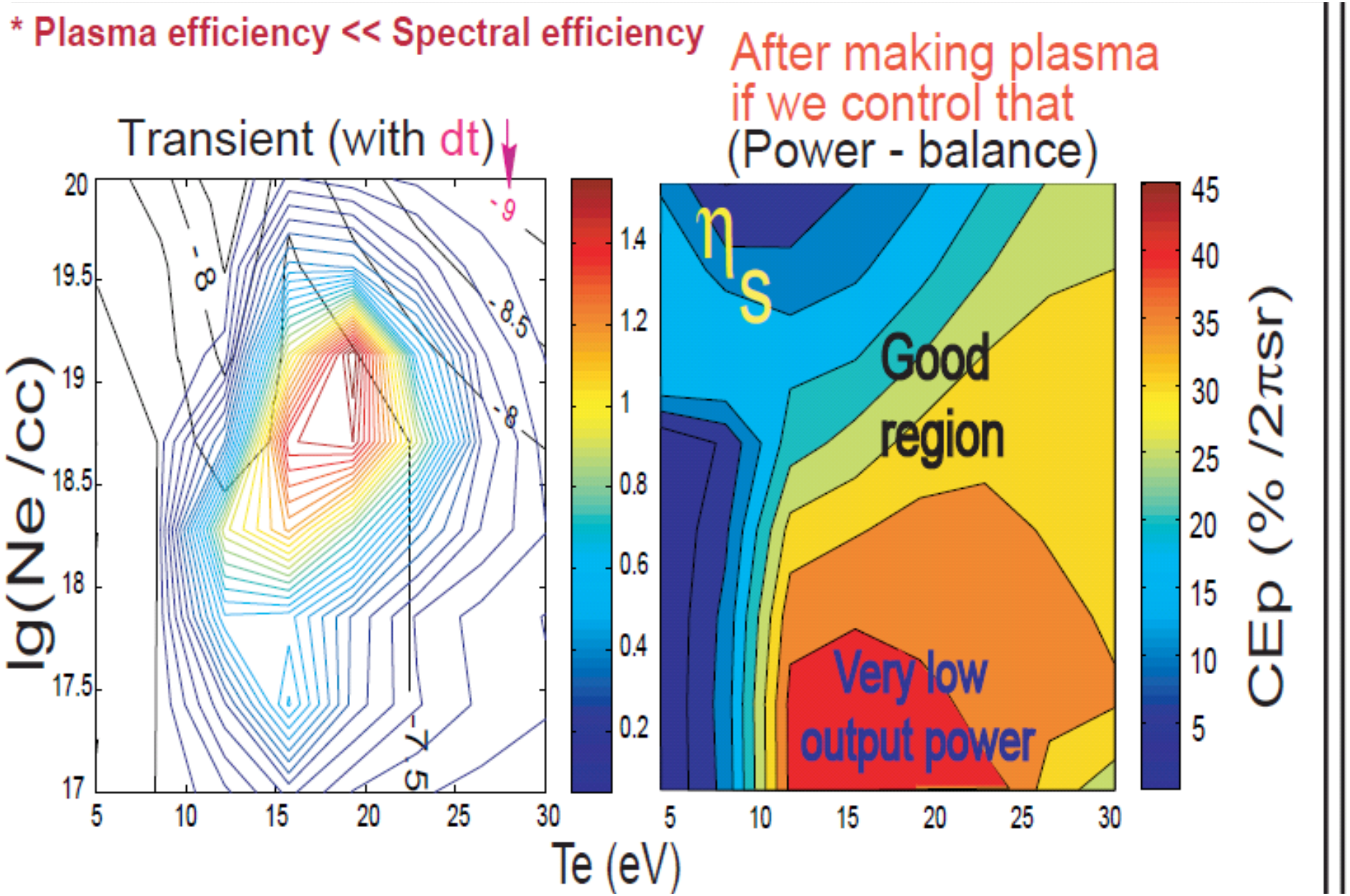
$$CE_{DPP} = \frac{\int_0^{\tau} P_{euv} dt}{\int_0^{\tau} \left\{ \cancel{P_{kin}} + \cancel{P_{ion}} + \cancel{P_{ex}} + P_{rad} \right\} dt} \Rightarrow \frac{P_{euv}}{P_{rad}}$$

Spectrum Efficiency

Plasma Conversion Efficiency and Spectrum Efficiency for Sn



Plasma Conversion Efficiency and Spectrum Efficiency for Li



Summary

- Opacity effect is important factor for DPP plasma source
- Maximum efficiency can be obtained in low density region
- Optimum density-temperature region of steady plasma is broader than the transient plasma
- Plasma efficiency ;
  - Li(1.5%), Sn(1.6%)/2 π sr for transient plasma
  - Li(>20%), Sn(3.3%)/2 π sr for steady state plasma

Conclusions

- Controlling the plasma, in particular, prolonging the life-time of the radiating plasma is essential for efficient EUV source

- Magnetically confined DPP plasma can improve CE order of magnitude compared with that of conventional pinched plasma source

References

- M.Masnavi, M.Nakajima, A.Sasaki, E.Hota, K.Horioka; Applied Physics Letters, Vol.87, No.11, pp.111502-111502-4 (2005)
- M.Masnavi, M.Nakajima, A.Sasaki, E.Hotta, K.Horioka; Applied Physics Letters, Vol.89, NO.3, 031503 (2006)