Emission from Nd:YAG laser-produced tin plasmas

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J Colgan (LANL)
Laser-produced plasma for nanolithography

Laser

Collector mirror

Tin droplets

Industry: CO$_2$

ARCNL: Nd:YAG
Part I

Emission efficiencies of Nd:YAG plasmas: How to increase CE?

Part II

Spectral modelling: Comparison of opacity calculations done by James Colgan (LANL) with experiment
Nd:YAG laser-produced plasma for EUV light

Figures of merit

SP = \frac{E_{2\%EUV,2\pi}}{E_{EUV,2\pi}}

CE = \frac{E_{2\%EUV,2\pi}}{E_{laser}}

How to increase CE?
Limits to source efficiency

\[ \text{CE} \equiv \text{SP} \cdot \eta_{\text{rad}} \]

**Spectral purity:**

\[ \text{SP} = \frac{E_{\% \text{EUV}, 2\pi}}{E_{\text{EUV}, 2\pi}} \]

**Radiative efficiency:**

\[ \eta_{\text{rad}} = \frac{E_{\text{EUV}, 2\pi}}{E_{\text{laser}}} \]

‘Loss channels’:
- Plasma kinetics
- Non-absorbed light
- Light into other half-sphere
Experimental setup

Laser intensity \((I)\)

Droplet size \((D_0)\)

Laser pulse duration \((\tau)\)

2w = 96 \mu m

D_0 = 16 - 64 \mu m


M. Bayraktar, NEVAC blad 54, 14 (2016)
Effect of laser intensity on spectral emission

Identification of emission and optimal intensity

Intensities and optimal intensity levels are shown on the graph. The graph displays emission peaks at different wavelengths and intensity levels. The peak at 13 nm with an intensity of 1.3x10^{11} W/cm^2 is labeled as the best peak (SP). The graph also shows emission transitions from states like 8^+ to 15^+. The diagram compares intensities at different levels: 0.1, 0.3, 1.3, and 2.7. The data is taken from W. Svendsen and G. O’Sullivan, PRA 50, 3710 (1994) and F. Torretti, et al., Journal of Physics B 54 (4), 045005 (2018).
Effect of...

Reminder:

\[ CE = SP \cdot \eta_{\text{rad}} \]

Beamsize = 96\( \mu \text{m} \)
Radiative efficiency ($\eta_{\text{rad}}$)

$\eta_{\text{rad}} = \frac{\text{CE}}{\text{SP}}$

- **Radiative efficiency ($\eta_{\text{rad}}$)**: A measure of the efficiency of a radiant entity, typically used in physics to describe the proportion of radiant energy emitted by an object, relative to the maximum energy possible for that object.

- **Droplet size**: The size of the droplets produced by the laser pulse, measured in micrometers ($\mu$m).

- **Pulse duration (ns)**: The duration of the laser pulse in nanoseconds (ns).

- **Wavelength (nm)**: The wavelength of the laser light in nanometers (nm).

- **Intensity (norm.)**: The normalized intensity of the laser light.

- **SP, CE (%)**: The percentage of scattered or correlated events.

- **$\eta_{\text{rad}}$ (%)**: The percentage radiative efficiency.

- **Droplet size vs. Wavelength**: Graph showing the relationship between droplet size and wavelength.

- **Pulse duration vs. Wavelength**: Graph showing the relationship between pulse duration and wavelength.

- **SP, CE (%)** vs. Droplet size**: Graph showing the relationship between SP, CE percentage and droplet size.

- **$\eta_{\text{rad}}$ (%) vs. Droplet diameter (um)**: Graph showing the relationship between radiative efficiency and droplet diameter.

- **$\eta_{\text{rad}}$ (%) vs. Pulse duration (ns)**: Graph showing the relationship between radiative efficiency and pulse duration.

- **$\eta_{\text{rad}}$ (%) vs. Wavelength (nm)**: Graph showing the relationship between radiative efficiency and wavelength.

- **Droplet diameter (um)**: The diameter of the droplets produced by the laser pulse, measured in micrometers ($\mu$m).
Model for scaling of radiative efficiency

Plasma expansion during laser pulse increases laser light absorption

Free parameter

\[ \eta_{max} \]
\[ v \]
\[ t_h \]
\[ \eta_{\text{max}} = 49\% \]
\[ \nu = 0.9 \mu\text{m} \, \text{ns}^{-1} \]
\[ t_h = 0.35 \text{ ns} \]
Modelling of plasma emission

Los Alamos National Lab suite of atomic codes

1. COWAN based atomic structure calculations
2. Opacity calculated using ATOMIC code and assuming LTE
3. Apply radiation transport for LTE conditions to compare to experiment
Effect of configuration interaction (CI)

Taking into account more electronic configurations improves match with experiment.
Short-wavelength OOB

Slight shift in the short-wavelength OOB, feature shape is well captured

$\text{Experiment}$

$\text{Intensity (norm)}$

$I = 1.3 \times 10^{11} \text{W/cm}^2$

$\text{Wavelength (nm)}$

$6 \ 8 \ 10 \ 12 \ 14$

$0.0 \ 0.1 \ 0.2 \ 0.3$

$0.0 \ 0.1 \ 0.2 \ 0.3$

$\text{ATOMIC}$
Effect of change in density

Emission most likely from density regime of 0.002g/cc

![Graph showing emission intensity versus wavelength with different density regimes.](attachment:image.png)
Effect of change in temperature

Change in temperature correlates to experimental change in intensity

\[ I = 1.3 \times 10^{11} \text{W/cm}^2 \]
\[ I = 0.6 \times 10^{11} \text{W/cm}^2 \]
\[ I = 2.7 \times 10^{11} \text{W/cm}^2 \]

\[ \rho = 0.002 \text{g/cc} \]
Conclusions

Part I
• High SP for short-pulses and small droplets
• Radiative efficiency well described by simple geometric plasma expansion model

Part II
• State of the art opacity calculations
• Emission spectra from Nd:YAG LPPs well approximated by calculations for single density, single temperature plasma