Physics of laser ablation and the quest for maximum CE

M. M. Basko

Keldysh Institute of Applied Mathematics, Moscow, Russia
RnD-ISAN, Troitsk, Moscow, Russia

2016 International Workshop on EUV and Soft X-Ray Sources, Amsterdam, November 7-9, 2016
Spectral purity (SP) of the EUV emission from Sn plasmas

\[
SP = \frac{\text{Emission power into the 2\% band at 13.5 nm into } 4\pi}{\text{Total EUV emission power into } 4\pi}
\]

SP inferred from the atomic physics (Sn plasma emissivity):

KIAM (V. Novikov, A. Solomyannaya, A. Grushin et al., 2012)
SP degradation due to self-absorption in band (RALEF-2D)

A static Sn-plasma cylinder cools down due to spectral radiative energy transport.

**Initial Sn-plasma state:** \( \rho_0 = 10^{-4} \text{ g/cc} \ (N_i = 5 \times 10^{17} \text{ cm}^{-3}), \ T_0 = 50 \text{ eV} \)

**What is learned:**
(i) the peak spectral purity is \( \sim 42\% \),
(ii) the timescale of thermal inertia is \( \sim 0.5 \text{ ns} \),
(iii) the optimum size of the EUV emitting region is \( \leq 100 \mu\text{m} \).
Absolute theoretical maximum of CE

\[ \text{CE} = \frac{\text{Emission power into the 2% band at 13.5 nm into } 2\pi}{\text{Total power of the heating laser}} \]

If a plasma cloud with SP≈40% could be maintained in a static state at no cost, and if the radiation losses were compensated by laser heating at a 100% efficiency,

\[ \Rightarrow \text{one would obtain } \text{CE} \approx 20\% ! \]

Optimum Sn-plasma parameters for the “working” zone:

- density: \( N_i \leq 10^{18} \quad (N_e \leq 10^{19}) \text{ cm}^{-3} \) [CO\(_2\) laser!]
- temperature: \( T = 30 \sim 40 \text{ eV} \)
- size: \( \tau_{uv} \leq 0.1 \sim 0.3 \) \[\text{SP} \rightarrow 1.5\% \text{ as } \tau_{uv} \rightarrow \infty\]

\[ k_{uv} \approx 70 \left( \frac{n_e}{10^{19} \text{ cm}^{-3}} \right) \left( \frac{30 \text{ eV}}{T} \right)^{3.5} \text{ cm}^{-1} \] [Novikov et al., 2012]
**Statement of the problem**

*Question addressed:* how closely can one approach CE=20% under realistic conditions?

Once the static plasma is excluded as unrealistic, the best close to reality theoretical idealization appears to be a steady ablation plasma flow.

To ensure the main-pulse (MP) laser access to the “working” zone, the plasma flow must have a diverging pattern ⇒ in this study we concentrate on a steady quasi-spherical ablation from a spherical droplet.

For more details see [M.Basko, Phys. Plasmas, 23, 083114, 2016].
Optimization tasks

The general optimization problem for maximum CE can be split into two separate tasks:

**Task 1:** find the maximum possible CE for a preconditioned Sn density profile $\Rightarrow$ maximum possible instantaneous CE!

**Task 2:** find the maximum possible steady-state CE for the self-consistent (i.e. consistent with a steady MP laser pulse) density profile.

**General guidelines for maximizing CE:**

i. The MP laser pulse must be fully absorbed in the ablated plasma $\Rightarrow$ no steep gradients of $n_e$ can be tolerated!

ii. As much as possible of the MP energy must be absorbed near the optimum temperature $T \approx 30\text{-}40 \text{ eV}$ where the SP peaks.

$\Rightarrow$ The “working” zone, where most of the MP is absorbed, must be fairly uniform in what concerns the $n_e$ and $T$ distributions.
Task 1: density profile preconditioned by a “slave” laser

One of the ways to generate a smooth quasi-spherical flow might be to employ an independent short-wavelength “slave” laser at a low power level [Nishihara et al., Proc. SPIE 6921, 2008].

After about 30–50 ns, the radial density profile stabilizes at $\rho \propto r^{-2}$!
Task 1: optimization strategy

Once the MP laser \((\lambda_{ml} = 10.6 \mu m)\) is fixed, we are left with only two independent parameters to perform the full optimization, namely, with

- the spatial scale \(R_{mc}\) of the preconditioned density profile

\[
n_e(r) = n_{mc} \left(\frac{R_{mc}}{r}\right)^2, \quad n_{mc} = \text{the MP critical density}; \tag{1}\n\]

\[
R_{mc} \approx R_{dr} 0.63 \lambda_{ml} \lambda_{sl}^{-0.75} I_{sl,9}^{-0.08} \ [\mu m], \quad R_{dr} = \text{droplet radius in \(\mu m\)};
\]

- the intensity \(I_{ml}\) of the MP, which controls the temperature \(T\) in the “working” zone

\[
T \propto (\lambda_{ml} I_{ml})^{0.4}, \quad \text{[Basko et al., Phys. Plasmas, 22, 053111, 2015]}
\]

The full optimization of \(\text{CE} = \text{CE}(I_{ml}, R_{mc})\) has been performed with the 2D RHD code RALEF.
The role of self-absorption in band

- A preferred optimum $T$ value $\Rightarrow$ $CE = CE(I_{ml}, R_{mc})$ has a maximum versus $I_{ml}$ (for each $R_{mc}$);
- Interplay between the laser ($\tau_{ml}$) and the in-band ($\tau_{uv}$) absorption $\Rightarrow$ $CE = CE(I_{ml}, R_{mc})$ has a maximum with respect to $R_{mc} \Rightarrow$ there is an optimum EUV source size!

$$\frac{\tau_{uv}}{\tau_{ml}} \approx \frac{36}{z_i \ln \Lambda_{ml}} \left(\frac{30 \text{eV}}{T}\right)^2 \left(\frac{R_{wz}}{R_{mc}}\right)^2 \approx (0.3 \div 0.5) \left(\frac{R_{wz}}{R_{mc}}\right)^2 \quad (2)$$

- For too small $R_{mc}$ the $CE$ drops because $\tau_{ml} << 1$, the radius of the “working” zone $R_{wz} = R_{mc}$, and the MP laser is poorly absorbed (mostly reflected).
- For too large $R_{mc}$ we have $\tau_{ml} \sim 1$, $R_{wz} >> R_{mc}$, and the $CE$ drops because $\tau_{uv} >> 1$ and the in-band emission is quenched by the self-absorption.
- The $CE$ is maximum at $\tau_{ml} \approx 0.5$ and $R_{wz} \approx R_{mc}$, that is when the “working” zone is adjacent to the critical surface of the MP.
Optimization results for Task 1

**CO\textsubscript{2} MP turned on at t = 35 ns**

**Task 1:** on a preconditioned $\rho$-profile, **maximum CE = 11.5%**.

**Causes of degradation from 20%:**

(i) about 2.5% – lost as the kinetic energy of the plasma flow;
(ii) the rest – due to the non-uniformity of $T$ across the “working” zone and because of the in-band reabsorption.
Once turned on, the MP laser deforms the preconditioned density profile – the result being a higher laser reflection and a smaller CE.

The optimization strategy remains the same as in Task 1!
Optimization results for Task 2

**CO$_2$ MP only (no “slave” laser)**

Task 2: with the self-consistent $\rho$-profiles, maximum CE = 9.0%.

At a practically 100% laser absorption, the degradation of CE from 20% to 9% is mainly caused by a combination of self-absorption and temperature non-uniformity across the laser-absorption zone.
Conclusions

- For a fixed wavelength $\lambda_{ml}$ of the MP laser, full optimization of CE under the conditions of steady-state laser ablation is equivalent to a two-parametric study with respect to the MP intensity $I_{ml}$ and the plasma flow scale $R_{mc}$.

- Fully optimized realistic CE values from the Sn ablation plasmas (11.5% in the transient peak, and 9% in the steady state) are still well below the absolute theoretical maximum of 20% suggested by the atomic physics – primarily due to a combined effect of the reabsorption in band, and non-optimal temperature profile imposed by the laser absorption physics.

- For sufficiently large values of $\lambda_{ml}$ (like that of the CO$_2$ laser), the fully optimized CE becomes insensitive to $\lambda_{ml}$ (because of saturation of the peak SP at low densities).
Appendix: SP from different KIAM opacity tables

Partially LTE: black-body in 10% around 13.5 nm

Tables version: v07, newGrid. Rad. field: Planck [86 eV; 96 eV]

CRE with spectral leakage from a 300-µm Sn layer

Tables version: v12n. Rad. field: flat layer L = 300 µm

Courtesy of A. Grushin, June 2016.