Prospects for scaling towards shorter wavelengths of capillary-discharge based soft X-ray lasers

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Historical remarks

- 1980 - X-ray lasing experiment at Nevada Test Site
- 1984-1990 – laser plasma based sources
- 1991 – gas-filled devices (W. Hartmann et al.)
- 1996 – Li-like oxygen (O⁵⁺) laser (52 nm, 49.8 nm) (recombination scheme) GL ~ 2.5

amplification in Ne-like argon (Ar$^+$) at 46.9 nm laser in 1994, saturation in 1996 (in polyacetal capillary)

from 1998 – ceramic (alumina) capillaries

2001-2003 several groups realized the lasing in argon-filled capillary
2001, 2002 E. Hotta and K. Horioka studied the role of predischarge (preionization) current.

2002 group of L. Reale and G. Tomassetti showed lasing in a capillary discharge pumped by “long” current pulse.

From 1990s – modeling activities (MHD, ablative/non-ablative discharges) N.A. Bobrova, V.N. Shlyaptsev.
Capillary-discharge based Ne-like Ar soft X-ray laser

- Preionization pulse (3 - 6 µs, ~20 A)
- Current pulse:
  - Amplitude 17-20 kA, half-cycle duration 130 - 180 ns
  - Slope 3 x 10^{11} A/s, 4.5 x 10^{11} A/s (rise-time 45-60 ns)
- Capillary – alumina (Al_2O_3) up to 45 cm long
- Ar pressure 0.25 – 0.6 Torr (flowing gas system)
Applications

- Soft X-ray reflectrometry (J.J. Rocca, 1999)

- Dense plasma shadowgraphy (J.J. Rocca, 2000)

- Dense plasma interferometry (J.J. Rocca, 2002)

- Material ablations (J.J. Rocca, 2003)

- Testing the LiF detector (L. Reale, G. Tomassetti, 2003)

- Creating of a plasma waveguide (J.J. Rocca, 2004)
Comparison of compact laser-plasma based and capillary-discharge based lasers

<table>
<thead>
<tr>
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<tbody>
<tr>
<td>Pulse length</td>
<td>2-30 ps</td>
<td>&lt; 2 ns</td>
</tr>
<tr>
<td>Repetition rate</td>
<td>~ 1 kHz (pump-laser limited)</td>
<td>&lt; 10 Hz</td>
</tr>
<tr>
<td>Wavelength</td>
<td>10-60 nm</td>
<td>46.9 nm</td>
</tr>
<tr>
<td>Coherence</td>
<td>20-30 µm transverse¹</td>
<td>5.4 µm transverse¹</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Longitudinal (10⁴-10⁵)λ/2 [1]</td>
</tr>
<tr>
<td>Divergence</td>
<td>1-10 mrad</td>
<td>0.6 mrad [3]</td>
</tr>
<tr>
<td>Energy/pulse</td>
<td>1-15 µJ</td>
<td>0.88 mJ (at 4 Hz)</td>
</tr>
<tr>
<td>Average/Peak power</td>
<td>-</td>
<td>3.5 mW/0.6 MW</td>
</tr>
<tr>
<td>Peak spectral brightness photons / (s mrad² mm² 0.01% bandwith)</td>
<td>10²⁴</td>
<td>2 x 10²⁵</td>
</tr>
<tr>
<td>Linewidth</td>
<td>(10⁻⁴ – 10⁻⁵) λ</td>
<td>&lt; 10⁻⁴ λ [1]</td>
</tr>
</tbody>
</table>

¹ For the transverse coherence the diameter of the equivalent incoherent source is given [1]

Efforts to decrease the wavelength


The NaF plasma was created by a 60 kA, 3.4 µs prepulse inside the capillary and the emerging plasma jet was subsequently excited with a high-current (1.2 MA) main pulse. A peak power of 25 GW in a 20 ns pulse was measured for the He-like sodium (Na$^{+9}$) 1s2 - 1s2p1P transition at 1.1 nm (He-α line). The 1.1 nm radiation from He-like sodium can resonantly populate the $n=4$ to $n=1$ transition in He-like Ne with potential for lasing on the 4-3, 4-2, and 3-2 transitions at wavelengths of 23 nm, 5.8 nm, and 8.2 nm, respectively.
Efforts to decrease the wavelength


Colloquium, 2004 Prague, Czech Republic
Efforts to decrease the wavelength

From 1999 the team of J.J. Rocca is building an apparatus (200 kA/10 ns) for amplification at shorter wavelengths using Ni-like ions (pumping intensity can be reduced respect to the Ne-like scheme). They are mainly interested in lasing line for Ni-like cadmium at 13.17 nm and Ni-like silver at 13.9 nm. The appropriate Ni-like spectra have been characterized for cadmium and silver in 2003 and 2004, respectively. However, for example the 13.2 nm Ni-like cadmium-line (Cd$^{20+}$) is clearly visible in the EUV spectrum convincing evidence of lasing on these elements was not yet presented.

How their set-up is working?
Efforts to decrease the wavelength

- ICOPS 2004 - Rahman A. - personal communication
  - They are using plastic (polyacetal) capillaries
    (in ceramic capillaries conductive metal layer forms after few shots on the capillary wall)
  - The metal vapor is created by electrode ablation utilizing $\mu$s discharges.
  - The desired electron density and temperature is reached by a subsequent main discharge (z-pinch compression).
How to remain “table-top”?

Experimental arrangement of the Livermore’s COMET (compact multipulse terawatt) tabletop X-ray laser. The rendering shows the laser system and the target chamber.

http://www.llnl.gov/str/Dunn.html

Efforts to decrease the wavelength

Generation of pure, high density and homogenous metal and dielectric vapor plasma by capillary discharge.


Double pulse excitation of x-ray capillary lasers.

Efforts to decrease the wavelength

- Recombination / charge exchange pumping schemes.

Only relatively small gain-length product was reported ($GL < 7$). In order to utilize these soft X-ray sources for application, further investigation is needed.

- Discharges in methane or nitrogen filled ($N^{6+}$, 13.4 nm) non-ablative capillaries are considered.

- Optical field ionization and inner-shell transition schemes.
Efforts to decrease the wavelength

- Incoherent EUV sources
  - Main fields of applications (sub-)micro lithography, (sub-)micro machining.
- System requirements: high collectable in-band power, low debris production, high-repetition rate and pulse-to pulse repeatability.
- The spectral range of possible EUV sources for microlithography is greatly determined by the available highly reflecting optics in the EUV region. Mo:Si and Mo:Be mirrors attain their highest reflectivity (70%) in the 13-14 nm and 11-12 nm wavelength region, respectively.
- Good results utilizing short, Xe-filled capillary discharges.
Efforts to decrease the wavelength

- Hybrid X-ray lasers.

Experimental arrangement of the hybrid X-ray laser. The concave electron density distribution with minimum on the capillary axis, which is necessary for guiding of the pumping laser pulse, is shown on the left.

- Gas-filled or ablative capillaries are creating a medium, which can be pumped longitudinally by external laser pulse.

- Successful experiment on Ne-like sulfur at 60.8 nm (J.J. Rocca, K.A. Janulewicz in 2001).

- Important to further investigate the waveguiding properties of the created plasma inside the capillary.
Conclusions

- Desired spectral range 11-14 nm (or water-window 4.4-2.2 nm).
- Competitive on size and price.

- Electrically pumped sources

- Metal vapor (collisional excitation scheme, Ni-like ions)
- Gas filled devices (recombination scheme, N$^6^+$)

- Hybrid soft X-ray lasers.

- Non-coherent sources

Acknowledgements

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