Result of Optimization of the EUV Capillary Laser Source CAPEX

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Abstract. For any purposeful application of pulse EUV capillary discharge laser it is desirable to have as intense and simultaneously as reproducible laser signal as possible. For this purpose a working regime of the apparatus CAPEX, developed and located in Institute of Plasma Physics AS CR, v.v.i., was optimized. The main aim consisted in removing three substantial drawbacks, namely the laser intensity fluctuations, the short capillary lifetime and the emission of debris—particles of melted capillary wall material. All these three drawbacks have been significantly reduced by lowering the main current, and by setting a suitable preionisation regime.

Introduction

A very thin (diameter ≈ 0.2 mm), hot (electron temperature ≈ 100 eV) and dense (electron density ≈ 10^{20} cm^{-3}) plasma column created by the high current (≈ 40 kA) fast (≈ 10^{12} A s^{-1}) capillary discharge in argon at lowered pressure (≈ 50 Pa) serves as an extreme ultra violet (EUV) pulse (≈ 2 ns) laser source at a wavelength 46.9 nm. The first device of that type was created by J. Rocca and described in [Rocca et al., 1994]. On the same principle the device CAPEX (CAPillary EXperiment) was developed by Koláček’s group in the Institute of Plasma Physics AS CR, v.v.i. in Czech Republic [Schmidt et al., 2005]. A schematic drawing of CAPEX device is in Figure 1. High voltage (≈ 200 kV) pulse energy is supplied by Marx generator through Spacer to Fast capacitor (≈ 6 nF), which is connected by self breaking Spark gap to High voltage electrode of the Ar-filled ceramic Capillary. The pinching discharge in the Capillary closes the circuit to Grounding electrode with orifice for gas-filling and radiation output. In the Capillary created EUV laser pulse passes through the second Orifice/shutter to the vacuum chamber (≈ 10^{-2} Pa) where selected application can be placed. The most important parameter for lasing is a working gas (argon) pressure adjustable by needle valve. The value of argon pressure in the Capillary at steady state corresponds approximately to its value in Filling chamber, where it is formed an equilibrium between argon inflow through the needle valve and argon outflow through the Orifice/shutter to the vacuum space.

Another important condition for proper functioning of the device is argon preionisation, which is ensured by External driver connected to High voltage electrode through a water resistor and synchronized with the main discharge onset. The experience with the device CAPEX accumulated during years 2005–2011 arrive at two conclusions. On the one hand it is clear that this EUV laser is capable to serve for perspective applications, especially for nanopatterning or nanostructuring of solids. [Koláček et al., 2011]. On the other hand it is clear that further improvement is necessary. It concerns mainly reproducibility of laser pulses, purity of radiation and error-free operating time.

Weaknesses of the CAPEX system before its optimization

For visualisation of the EUV signal from the CAPEX capillary laser a semitransparent luminescent “phosphor” screen was used (in fact zinc sulphide doped by silver). The screen was placed perpendicularly to the capillary axis at a distance of 1 m from the capillary mouth and shielded by 0.8 μm thin Al filter against the visible radiation component. As we can see in Figure 2 dominating effect is not the EUV radiation (barely visible light spot in the middle of each snap), but intensive tracks of some hot debris reflected from the detector and chamber walls (after perforating the Al-filter).

It turned out that a temporarily plausible solution would be to insert a mechanical high speed shutter in a reasonable distance (≈ 0.5 m) from the capillary mouth. The shutter succeeded to stop all the debris just immediately after passing the laser pulse through it. This arrangement enabled to make a lot of interesting experiments, not affected by debris.
However, the debris emission is also closely connected with melting of the capillary wall material (Al₂O₃ specifically) due to dissipation of a part of discharge energy in it [Straus et al., 2006]. Each successive shot intensifies the damage of the wall, and its profile becomes too rough for a proper stabilization of the pinching process. At this time the laser effect fades away and during several shots disappears at all. For this reason the capillary lifetime is very limited, typically to ≈ 200 shots in case of successful cleaning after first ≈ 100 shots.

Another negative effect of debris production is clogging of the output orifice serving for laser radiation extraction from the gas-filled capillary to the vacuum chamber and of the grounding electrode with orifice—see Figure 3. In usual regime it takes only about ≈ 100 shots to block a half of the orifice area by the deposited material. That is usually one of the main reasons for servicing.

The last problem consists in an axial rupture of the capillary, usually along nearly the whole its length, with surprisingly smooth rupture plane (see Figure 4). This was observed after about 200 shots, depending on a working regime of the whole CAPEX system, especially on a preplasma quality in the capillary volume at the time of the main current onset.

**Result of optimization: CAPEX-LS (Capillary EXperiment-Laser Source)**

At first a triggering system was re-arranged to allow the main current onset after a preionisating prepulse only. The reason is that each shot executed without any prepulse rapidly destroys the capillary wall possibly due to uncoordinated discharge process in non-conducting neutral gas,
Figure 3. Grounding electrode with orifice diameter 2.5 mm (left) and the second orifice diameter 1 mm (right)—both made of heavy-melted metal (alloy W–Cu), partially clogged by melted debris emitted from the capillary during approximately 100 shots. View in direction to the capillary.

Figure 4. Axially ruptured and for inspection cut capillary after approximately 200 shots. Capillary is made from alumina pipe of inner diameter 3 mm, outer diameter 6 mm, length 232 mm and polyurethane resin coat of diameter 38 mm. On the left and right sides there are signs of cutting. Perfect flat quarry of both materials is apparent in the middle, but it proceeds along almost the whole capillary length. Black, degraded surface of ceramics is apparent on its quarry and on the inner capillary wall.

necessarily accompanied by massive energy dissipation. After introducing that remediation, the capillary lifetime significantly increased.

The second step was the decrease of the main current from approximately 40 kA to 20 kA, to reduce the load of capillary wall. This completely stopped the debris emission, which previously accompanied each laser shot, and substantially suppressed the capillary wall degradation. This also significantly enhanced a total operation ability of the capillary and increased shot to shot stability of laser signal as well. Nevertheless, simultaneously the laser intensity decreased ≈ 2–3-times.

For its compensation the prepulse-current influence on the ionisation stage of Ar was spectroscopically investigated in range of UV, VIS and IR spectra [Straus et al., 2010]. It was proved, that the suitable value of prepulse current, which generates an abundance of at least one-times ionized Ar ions, is on the level of about 10-times higher than commonly accepted, i.e. about 100 A. Application of that prepulse regime significantly increased the laser intensity near to its original level—see Figure 5.

In Figure 6 there is a typical footprint of laser pulse from the optimized laser source CAPEX LS. After introduced changes, no debris emission was observed.

In Table 1 we can follow the approximate development of the basic quality characteristics of the capillary Ar\(^{8+}\) laser source CAPEX as a result of individual parametric changes.

Conclusion

Two substantial changes in working regime of Ar\(^{8+}\) capillary laser CAPEX were practically tested. It was achieved a significant improvement of most of followed quality characteristics at the expense of slightly decreased laser intensity. The optimized device CAPEX LS is suitable for applied research.
Figure 5. Typical pressure dependence of laser shot level measured on the device CAPEX by Au vacuum photodiode placed at the distance of 150 cm from the capillary end. Dashed line corresponds to the originally used prepulse 10 A, full line to the intensified prepulse 100 A. The main discharge current was 15 kA.

Figure 6. Debris-free laser footprint on the phosphor screen behind Al 0.4 μm thin filter at the distance 130 cm from the capillary mouth. Reproducible result from the optimized CAPEX LS device. (Oblique line at the top right is induced by visible light from ruptured Al-filter).

Table 1. Approximate effect of optimized parameters on the quality characteristics of CAPEX device.

<table>
<thead>
<tr>
<th>Quality characteristics</th>
<th>Total operation ability for one capillary (number of shots)</th>
<th>Servicing free operation ability (number of shots)</th>
<th>Debris-free laser signal</th>
<th>Laser shot level (Au vacuum photodiode 150 cm distanced) (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BEFORE optimization</td>
<td>200</td>
<td>100</td>
<td>NO</td>
<td>5</td>
</tr>
<tr>
<td>Main current decreased from 40 to 20 kA</td>
<td>1000</td>
<td>250</td>
<td>YES</td>
<td>2</td>
</tr>
<tr>
<td>Prepulse current increased from 10 to 100 A</td>
<td>1000</td>
<td>250</td>
<td>YES</td>
<td>4</td>
</tr>
<tr>
<td>AFTER complete optimization</td>
<td>1000</td>
<td>250</td>
<td>YES</td>
<td>4</td>
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</table>
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