Water window radiation from 40 kA Z-pinching capillary discharge plasma

M. Nevrkla, A. Jančárek
DISCHARGE DRIVERS DEVELOPED AT FNSPE CTU since 2009

2009
- lasing at 46.9 nm
- inspired by design of J.J. Rocca’s group
- $\sim 10^{12}$ ph/Sr at 2.88 nm
- 5 Hz

2011
- modification for 2.88 nm
- $\sim 10^{13}$ ph/Sr at 2.88 nm
- multiple Z-pinch
- 5 Hz

2013
- driver for 13.4 nm laser
- full-rate current not reached yet
- $\sim 10^{14}$ ph/Sr at 2.88 nm
- 1 Hz
Z-PINCHING CAPILLARY DISCHARGE

- Plasma heating by **shock thermalization**
- Plasma cooling by fast **adiabatic expansion**
- Long (~ 10s cm) **thin** (~ 100s um) **plasma column**
- Stabilization by **pre-ionization** discharge
- **ASE** - No mirrors -> high gain needed \( G \sim 1 \)

---

3B-RECOMBINATION PUMPING SCHEME OF 13.4 NM LASER

- **Electron temperature** $T_e$
  - $>50\%$ abundance of fully stripped ions $\rightarrow$ initial $T_e > 140$ eV
  - high 3b-recombination rate $\rightarrow$ drop of $T_e < 60$ eV

- **Electron density** $N_e$
  - $N_e > 10^{19}$ cm$^{-3}$ to ensure high 3b-recombination rate
  - limited to $N_e \approx (5 \div 10) \times 10^{19}$ cm$^{-3}$ (to reduce collision excitation into lower laser level 2)

- **Cooling time**
  - faster than 3-b recombination rate $\beta^{-1}(T_e = 60$ eV, $N_e = 4 \cdot 10^{19}$ cm$^{-3}) \approx 5$ ns

---

Optimized discharge condition for ASE at 13,4 nm – Jakub Hübner
Slab water capacitor design with pulse compression:

- **Table top** size of the driver
- **Well shielded capillary**
  
  22.4 cm long capillary (20.4 cm shielded!)...\( L \approx 60-80 \text{ nH} \)
- Both sides of **capillary opened**.
- Complex design
- High voltage at capillary ends.

CAD model of discharge driver. 1 – spark-gaps, 2 – capillary, 3 – water capacitor
ASSEMBLY

- spark-gap triggering cable
- water line charging cable
- voltage dividers
- capillary gas inlet
- Rogowski coil integration circuit
- pre-ionization coil

Dimensions: 600 x 600
CAN THE DRIVER BE USED AS W-W RADIATION SOURCE?

- At present the driver operates at 55% of expected full-rate current.
- The driver is designed to produce N6+ and N7+ ions at \( N_e \sim 10^{19} \text{ cm}^{-3} \).
- But we need only N5+ ions.

😊 high current ≡ high XUV energy/pulse

😊 long capillary
   low efficiency (self-absorption)
   complex design

😢 low rep-rate (1 Hz)
DISCHARGE CURRENT AND XUV INTENSITY

<table>
<thead>
<tr>
<th>Pressure [Pa]</th>
<th>Peak power (kW/Sr)</th>
<th>Brightness (ph/Sr)</th>
<th>Brightness (ph/Sr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>300</td>
<td>9.5</td>
<td>1.4e14</td>
</tr>
<tr>
<td>80</td>
<td>250</td>
<td>7.3</td>
<td>1.0e14</td>
</tr>
<tr>
<td>120</td>
<td>300</td>
<td>12.0</td>
<td>1.7e14</td>
</tr>
<tr>
<td>180</td>
<td>320</td>
<td>10.7</td>
<td>1.5e14</td>
</tr>
<tr>
<td>220</td>
<td>390</td>
<td>8.6</td>
<td>1.3e14</td>
</tr>
<tr>
<td>400</td>
<td>480</td>
<td>8.4</td>
<td>1.2e14</td>
</tr>
</tbody>
</table>

Values without filter
400 nm Al filter

500 nm Ti filter

SPECTRA
- Pinhole image
- FWHM = 280 μm
BEAM PROFILE AND DIVERGENCE

θ_{FWHM} \approx 10 \text{ mrad} 
\left( \Omega_{FWHM} \approx 8 \times 10^{-5} \text{ sr} \right)

FWHM \approx 6.2 \text{ mm} 
FWHM \approx 9.1 \text{ mm}

510 mm 
880 mm

W \approx 770 \text{ nJ} 
(1 \times 10^{10} \text{ ph})

CCD counts (a.u.)

position (mm)
<table>
<thead>
<tr>
<th></th>
<th>2009</th>
<th>2013</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max. current</td>
<td>27 kA</td>
<td>40 kA*</td>
</tr>
<tr>
<td>Rise-time</td>
<td>46 ns</td>
<td>25 ns</td>
</tr>
<tr>
<td>Capillary diameter</td>
<td>3.2 mm</td>
<td>3.2 mm</td>
</tr>
<tr>
<td>Capillary length</td>
<td>11.3 mm</td>
<td>22.4 mm</td>
</tr>
<tr>
<td>source size FWHM</td>
<td>360 μm</td>
<td>270 μm</td>
</tr>
<tr>
<td>Beam divergence</td>
<td>30 mrad (7 \times 10^{-4}) Sr</td>
<td>10 mrad (8 \times 10^{-5}) Sr</td>
</tr>
<tr>
<td>Peak intensity</td>
<td>87 kW/Sr</td>
<td>480 kW/Sr</td>
</tr>
<tr>
<td>Brightness (at 2.88 nm)</td>
<td>4 mJ/Sr</td>
<td>12 mJ/Sr</td>
</tr>
<tr>
<td></td>
<td>(5.5 \times 10^{13}) ph/Sr</td>
<td>(1.7 \times 10^{14}) ph/Sr</td>
</tr>
<tr>
<td>Energy in the beam</td>
<td>2.24 μJ ((3 \times 10^{10}) ph)</td>
<td>770 nJ ((1 \times 10^{10}) ph)</td>
</tr>
</tbody>
</table>

Radiance values without filter

* 55% of expected full-rate current
CONCLUSION AND FUTURE PLANS

- Discharge driver for 13.4 nm laser research still in development
- Meanwhile tested as a source at 2.88 nm
  - High peak intensity, low beam divergence
  - Far from optimal design for 2.88 nm (long capillary)

Plans

- Increase discharge current
- Time-resolved discharge plasma diagnostics
- Looking for ASE at 13.4 nm
THANK YOU FOR ATTENTION

ACKNOWLEDGEMENT

This work was supported by the MEYS of the Czech Republic grant no. LG13029.