Xenon Filled Fast Capillary Discharge as a Source of Intense EUV Radiation

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Experiments - GREMI. MHD code – ITEP. IONMIX code – IPP CAS
Experimental Setup

**Fig. 1:** Experimental set up (GREMI-ESPEO Orleans)

1 - Knob capacitors, 2 - Gas inlet, 3 - Capillary,
4 - Fast switch, 5 - to Detection chamber

Xenon filled **Alumina capillary**

Two capacitors banks configured in a Blumlein fashion pulse forming line
Measured X-ray emission spectra

Time resolved spectra from 1.0 mm dia 10 mm long alumina capillary at 0.5 Torr Xenon without conductance at 15 kV
Current waveforms

Electric current profiles measured for Charging voltages 28, 24, 18, 15 kV.

Fitting formula entered to MHD code:

\[ I(t) = I_0 \sin\left(\frac{\pi t}{2t_0}\right) \exp\left(-\frac{t}{t_1}\right) \]
# NPINCH Code

Input parameters to **1d - MHD code one-fluid** and **two-temperature plasma** model of capillary discharge

<table>
<thead>
<tr>
<th>Case</th>
<th>Initial Voltage [kV]</th>
<th>Initial Pressure $p_0$ [mbar]</th>
<th>Initial Density [g/cm³]</th>
<th>$I_0$ [kA]</th>
<th>$t_0$ [ns]</th>
<th>$t_1$ [ns]</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>U28</td>
<td>28</td>
<td>0.66</td>
<td>3.474e-6</td>
<td>6.605</td>
<td>85</td>
<td>867.1</td>
<td></td>
</tr>
<tr>
<td>U24/p66</td>
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<td>0.66</td>
<td>3.474e-6</td>
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<td>85</td>
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<td>/p53</td>
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<td>/p33</td>
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<tr>
<td>/p13</td>
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<tr>
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<td>4.314</td>
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<td>723.4</td>
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<td>85</td>
<td>182.9</td>
<td>Spectra</td>
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<td>6.948e-7</td>
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</tr>
</tbody>
</table>
$p(t)/p_0$

$N_e \text{ (cm}^{-3}\text{)}$

$T_e \text{ (eV)}$

$p_0 = 0.66 \text{ mbar}$
$U_0 = 15$ kV
Dependence of the Plasma Properties on the Charging Voltage and Filling Pressure

Overview

<table>
<thead>
<tr>
<th>Case</th>
<th>Initial Voltage [kV]</th>
<th>Energy stored [J]</th>
<th>Maximum Current $I_{\text{max}}$ [kA]</th>
<th>Initial Pressure $p_0$ mbar</th>
<th>Initial Density $\rho$ [g/cm$^3$]</th>
<th>Initial Concentration $I_0$ [kA]</th>
<th>$t_0$ [ns]</th>
<th>$t_1$ [ns]</th>
<th>Pinch Time $t_1$[ns]</th>
<th>Compression ratio $\rho/\rho_0$</th>
<th>Electron Temperature $T_e$ [eV]</th>
<th>Electron Density $N_e$[cm$^{-3}$]</th>
<th>Average Ionisation State $Z$</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>28</td>
<td>6.3</td>
<td>6</td>
<td>1.0</td>
<td>5.263e-6</td>
<td>2.4 10^{16}</td>
<td>6.53</td>
<td>85</td>
<td>48 (62)</td>
<td>2.89</td>
<td>21.8</td>
<td>9.30 10^{17}</td>
<td>13.2</td>
<td>double pinch</td>
</tr>
<tr>
<td>B</td>
<td>28</td>
<td>6.3</td>
<td>6</td>
<td>0.2</td>
<td>1.0526e-6</td>
<td>4.8 10^{15}</td>
<td>6.53</td>
<td>85</td>
<td>38</td>
<td>12.75</td>
<td>95.1</td>
<td>1.83 10^{18}</td>
<td>29.7</td>
<td>high compression, hot</td>
</tr>
<tr>
<td>C</td>
<td>12</td>
<td>1.2</td>
<td>2.6</td>
<td>1.0</td>
<td>5.263e-6</td>
<td>2.4 10^{16}</td>
<td>4.80</td>
<td>85</td>
<td>30</td>
<td>1.97</td>
<td>18.4</td>
<td>4.33 10^{17}</td>
<td>9.0</td>
<td>low compression, cold</td>
</tr>
<tr>
<td>D</td>
<td>12</td>
<td>1.2</td>
<td>2.6</td>
<td>0.2</td>
<td>1.0526e-6</td>
<td>4.8 10^{13}</td>
<td>4.80</td>
<td>85</td>
<td>37 (51)</td>
<td>2.71</td>
<td>37.3</td>
<td>2.42 10^{17}</td>
<td>16.7</td>
<td>low compression,</td>
</tr>
</tbody>
</table>
The peak value of compression ratio increases with increasing current (initial voltage) and with decreasing filling pressure. The highest value is 12, the lowest about 2. The pinch effect is the most profound for low pressures and high voltage (case B).
Local plasma electron temperature increases with the increasing current density. Peak temperatures are higher than \textbf{20 eV} in all investigated cases. The highest
Thermodynamic and Radiative Plasma Properties

IONMIX Code

Input parameters: plasma temperature, nuclei densities, ionization potentials

Ionization state is sensitive to changes of plasma temperature not to initial pressure. If plasma temperature is 20 eV the ions Xe$^{8+}$ prevail, for 50 eV Xe$^{11+}$, Xe$^{12+}$, Xe$^{13+}$ ions are expected.
Bohr-like Model for Xe Ions

Energy of any ion with outermost electron residing in shell $n$: $E_{n,j} = - \Phi_j \left( \frac{n_0}{n} \right)^2$, $n \geq n_0$

$n_0$ is principal quantum number of outermost electron in its ground state, $\Phi_j$ is the ionization potential of the $j^{th}$ ion.

Wavelength corresponding to Lyman– and Balmer- like transitions for various Xe ions

<table>
<thead>
<tr>
<th>Ion</th>
<th>Xe$^{6+}$</th>
<th>Xe$^{7+}$</th>
<th>Xe$^{8+}$</th>
<th>Xe$^{9+}$</th>
<th>Xe$^{10+}$</th>
<th>Xe$^{11+}$</th>
<th>Xe$^{12+}$</th>
<th>Xe$^{13+}$</th>
<th>Xe$^{14+}$</th>
<th>Xe$^{15+}$</th>
<th>Xe$^{16+}$</th>
<th>Xe$^{17+}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Phi_j$ [eV]</td>
<td>98</td>
<td>112</td>
<td>170</td>
<td>202</td>
<td>233</td>
<td>264</td>
<td>294</td>
<td>325</td>
<td>358</td>
<td>389</td>
<td>421</td>
<td>452</td>
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<tr>
<td>$n_0$</td>
<td>5</td>
<td>5</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
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</tr>
<tr>
<td>$\lambda_L$ [nm]</td>
<td>41.4</td>
<td>36.1</td>
<td>20.2</td>
<td>17.1</td>
<td>14.8</td>
<td>13.3</td>
<td>11.7</td>
<td>10.6</td>
<td>9.6</td>
<td>8.8</td>
<td>8.1</td>
<td>7.6</td>
</tr>
<tr>
<td>$\lambda_B$ [nm]</td>
<td>68.6</td>
<td>59.9</td>
<td>37.1</td>
<td>31.4</td>
<td>27.3</td>
<td>24.1</td>
<td>21.5</td>
<td>19.5</td>
<td>17.7</td>
<td>16.3</td>
<td>15.1</td>
<td>14.0</td>
</tr>
<tr>
<td>$\lambda_{Edge}$</td>
<td>12.6</td>
<td>11.04</td>
<td>7.25</td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>
**Spectral Emissivity**

*Kirchhoff – Planck” law:*

\[ \eta(\lambda) = k(\lambda) \cdot w(\lambda) \]

\( k(\lambda) \) is the **spectral emission coefficient** (line part calculated by IONMIX code) and **continuous part** for plasma temperature \( T \):

\[ w(\lambda) = \frac{1}{2\pihc} \frac{1}{\lambda^5} \frac{1}{\exp\left(\frac{hc}{kT} \cdot \frac{1}{\lambda}\right) - 1} \]

Maximum value of \( w(\lambda) \) corresponds to \( \lambda_{max}[\text{nm}] = 442 / T[\text{eV}] \).

For \( \lambda_{max} = 13 \text{ nm} \), should be \( T = 34 \text{ eV} \).
Calculated Spectral Emissivity for various temperatures

Temperatures $T = 20-70$ eV and initial atom density $N = 3.10^{17}$ cm$^{-3}$ according to the experiment and results of N-pinch code

Lyman-like transitions $\lambda_L = 14.8, 13.1, 11.7$ nm are identified for ions $\text{Xe}^{10+}-\text{Xe}^{12+}$ at temperatures $35-60$ eV. The higher is the plasma temperature the shorter wavelength of Lyman-like transition for higher ionized ions is seen.

For lower temperatures the recombination edges (free-bound transitions) at $\lambda_{\text{Edge}} = 12.6$ and $11.0$ nm, corresponding to $\text{Xe}^{6+}$ and $\text{Xe}^{7+}$ are apparent.
Measured Spectral Intensity for various time delays

Three emission peaks at 11.7, 13.5 and 14.7 nm correspond to Lyman-like $\alpha$ transitions of $\text{Xe}^{12+}$, $\text{Xe}^{11+}$, $\text{Xe}^{10+}$ ions.

The time evolutions of their amplitudes are interpreted as the time changes of the ion concentrations.

The highest concentration of $\text{Xe}^{12+}$ (highest peak at 11.7 nm) observed at $t_{\text{exp}} = 75$ ns. corresponds to $T_e = 50$ eV.
Conclusion

For experimental values of electrical peak currents $I_{\text{peak}} = 2.6 - 6.3 \text{ kA}$ and Xe pressure $p_0 = 0.2 - 1 \text{ mbar}$

- The evaluated pinch effect is weak,
- Temperature varies in the range $T_e = 36 - 167 \text{ eV}$,
- Three observed emission peaks at 11.2, 13.5 and 14.7 nm correspond to the similar quantum transitions of adjacent $\text{Xe}^{12+}$, $\text{Xe}^{11+}$, $\text{Xe}^{10+}$ ions,
- Time changes of peak values of spectral lines during a shot correspond to the simulated plasma temperature evolution.