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

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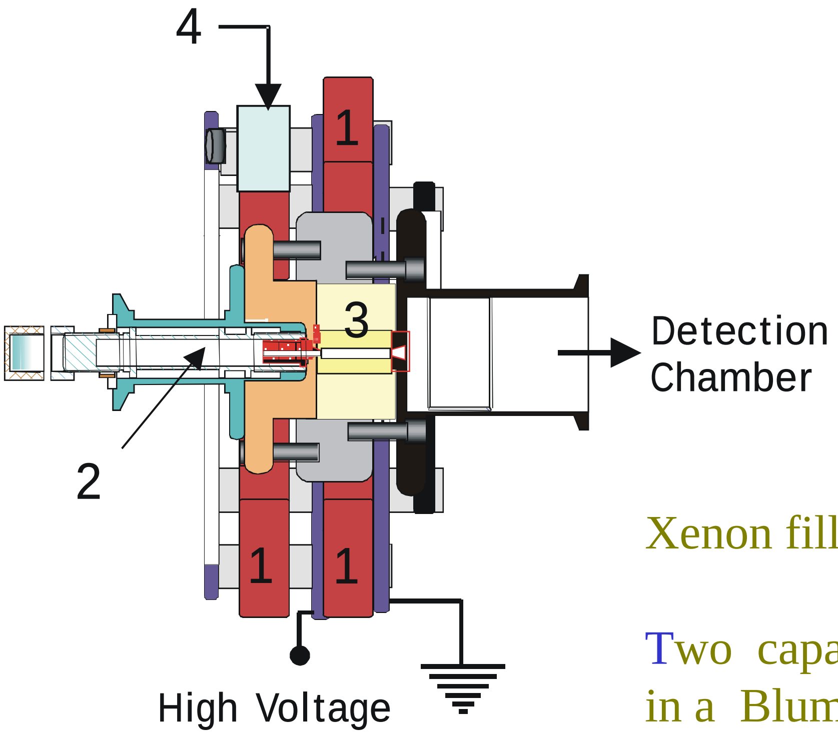
Experiments - GREMI. MHD code – ITEP. IONMIX code – IPP CAS

Experimental Setup

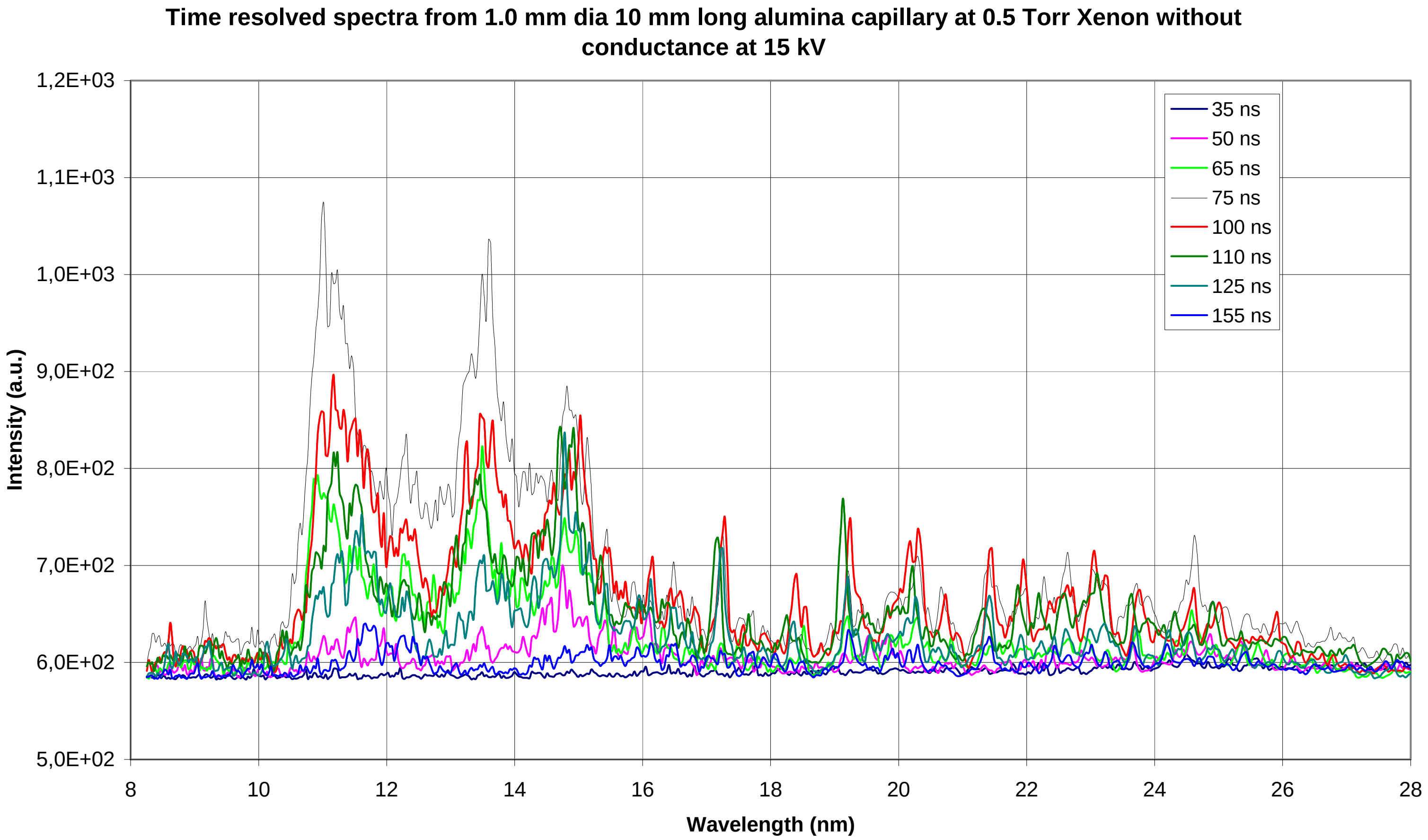


Xenon filled **Alumina capillary**

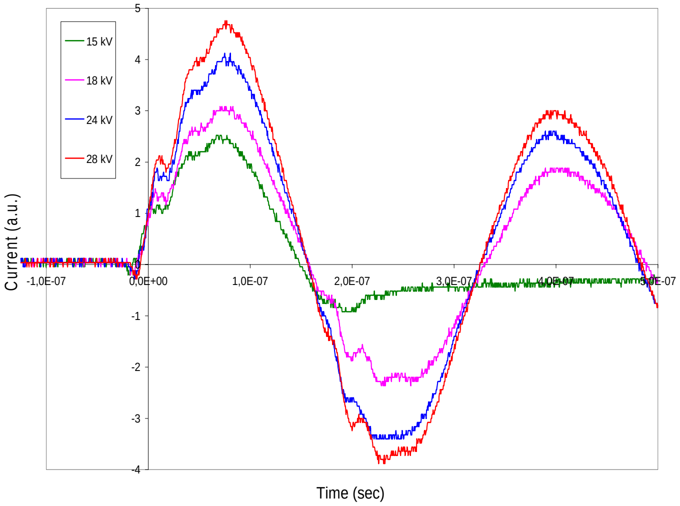
Two capacitors banks configured
in a Blumlein fashion pulse forming line

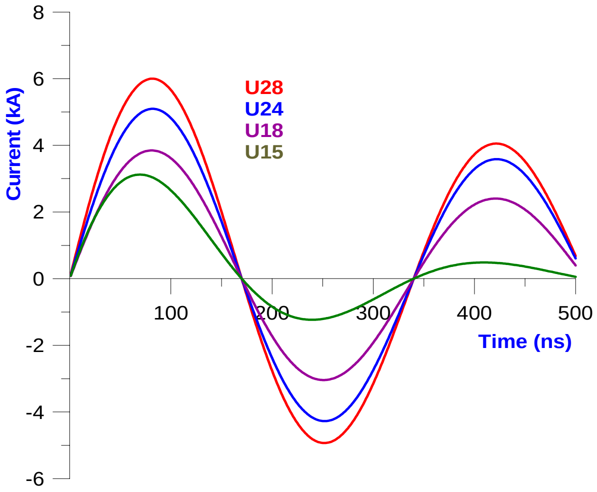
Fig. 1: Experimental set up (GREMI-ESPEO Orleans)
1 - Knob capacitors, 2 - Gas inlet, 3 - Capillary,
4 - Fast switch, 5 - to Detection chamber

Measured X-ray emission spectra



Current waveforms





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

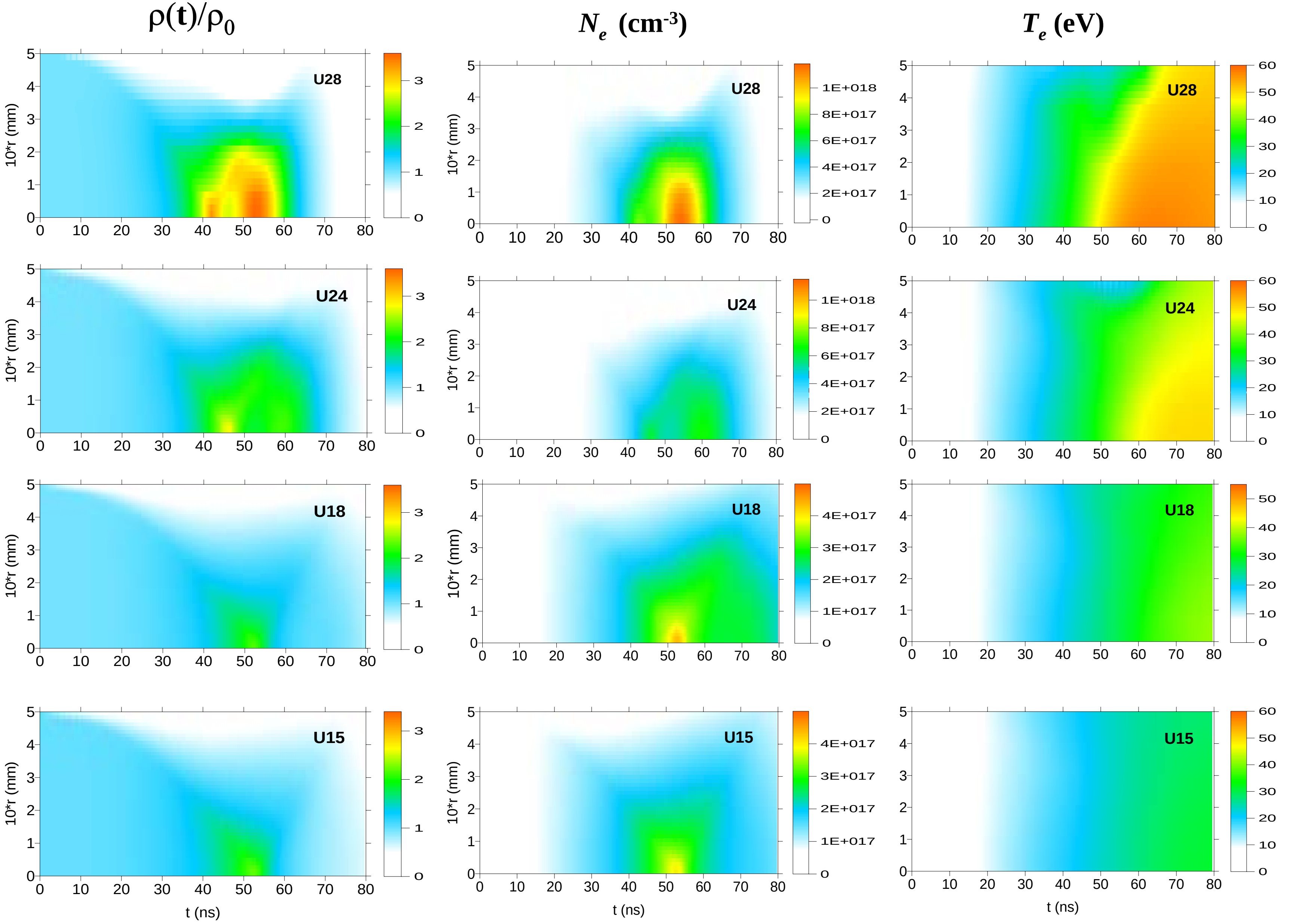
Fitting formula entered to **MHD code:**

$$I(t) = I_0 \sin\left(\frac{\pi t}{2t_0}\right) \exp\left(\frac{-t}{t_1}\right)$$

NPINCH Code

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

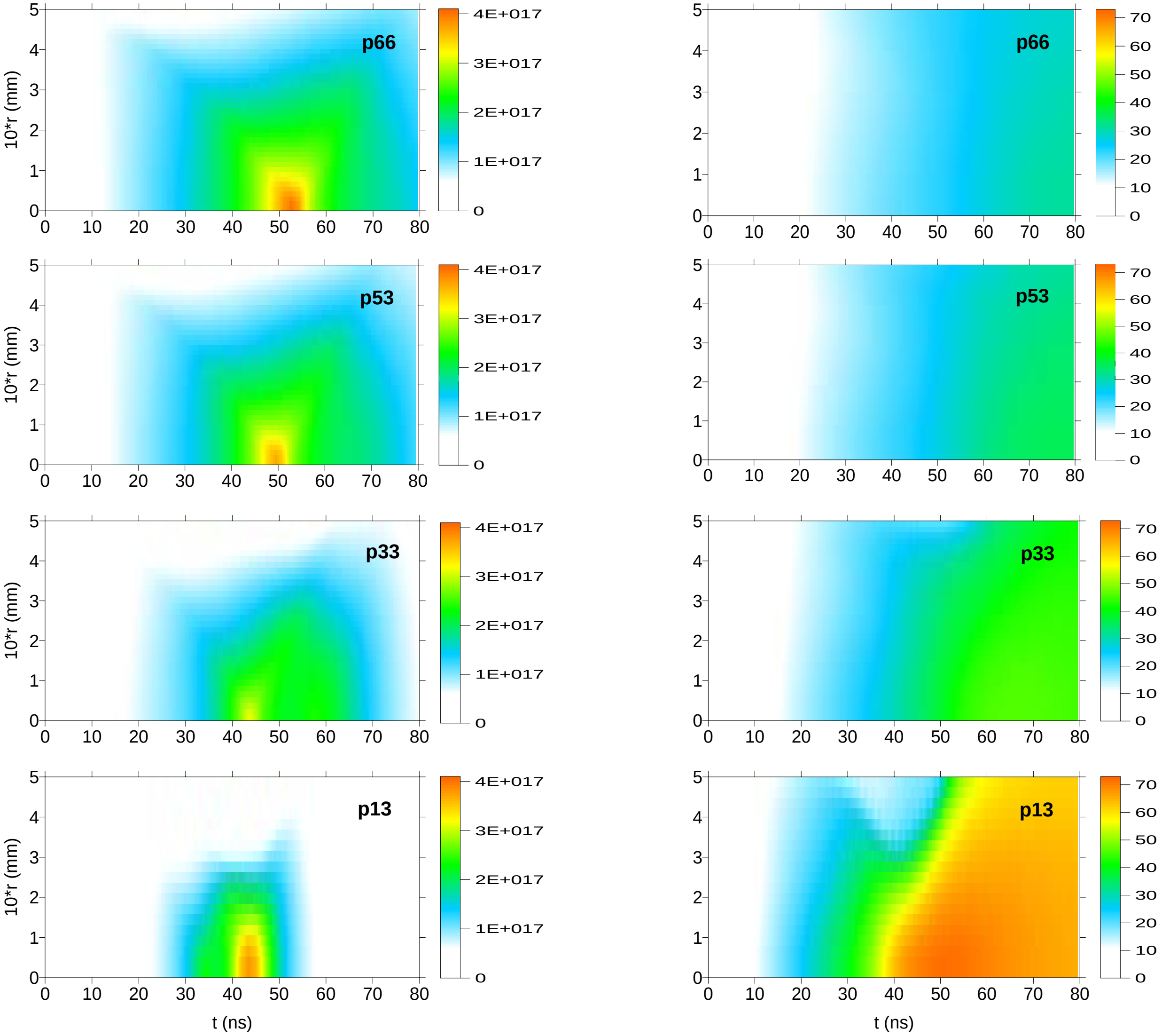
Case	Initial Voltage [kV]	Initial Pressure p_0 [mbar]	Initial Density [g/cm^3]	I_0 [kA]	t_0 [ns]	t_1 [ns]	Re marks
U28	28	0.66	3.474e-6	6.605	85	867.1	
U24/p66	24	0.66	3.474e-6	5.556	85	966.5	***Spectra***
/p53		0.53	2.782e-6				
/p33		0.33	1.737e-6				
/p13		0.13	6.948e-7				
U18	18	0.66	3.474e-6	4.314	85	723.4	
U15/p66	15	0.66	3.474e-6	4.761	85	182.9	***Spectra***
/p53		0.53	2.782e-6				
/p33		0.33	1.737e-6				
/p13		0.13	6.948e-7				


ρ(t)/ρ0
Ne (cm-3)
Te (eV)
U28
U24
U18
U15
10*r (mm)
t (ns)
0
10
20
30
40
50
60
70
80
0
1
2
3
4
5
2E+017
4E+017
6E+017
8E+017
1E+018
1E+017
3E+017
4E+017

p_0 = 0.66 mbar

N_e (cm^{-3})

T_e (eV)



U_0 = 15 kV

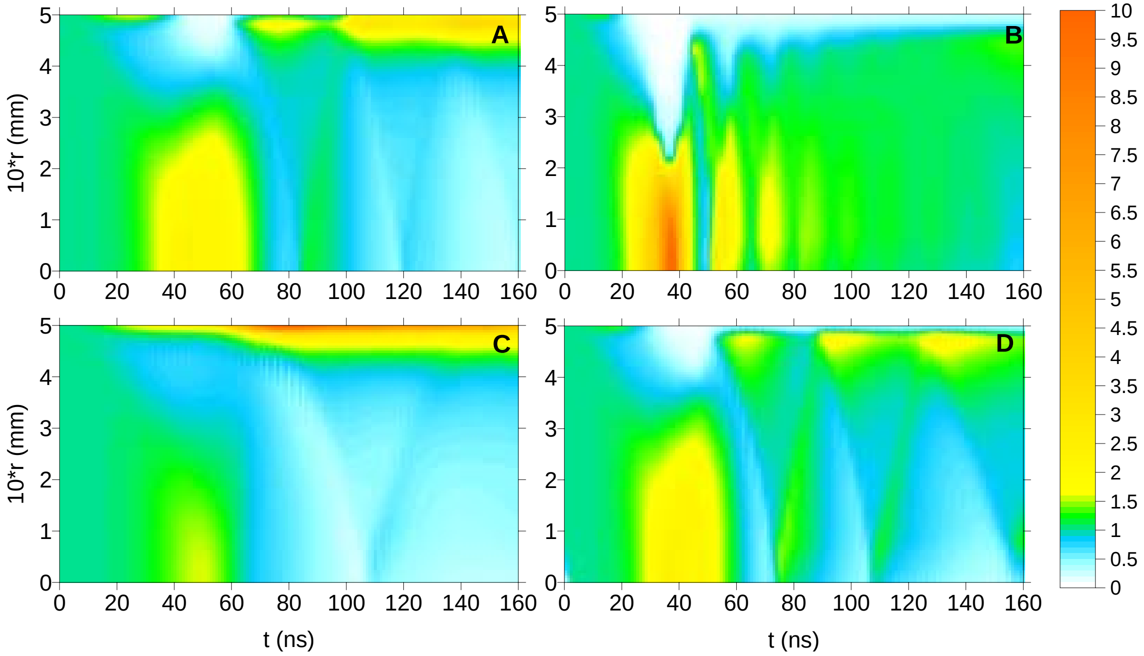
Dependence of the Plasma Properties on the Charging Voltage and Filling Pressure

Overview

Case	Initial Voltage [kV]	Energy stored [J]	Maximum Current I_{max} [kA]	Initial Pressure p_0 mbar]	Initial Density ρ [g/cm^3]	Initial Concentration [cm^{-3}]	I_0 [kA]	t_0 [ns]	t_1 [ns]
A	28	6.3	6	1.0	5.263e-6	2.4 10^{16}	6.53	85	986.4
B	28	6.3	6	0.2	1.0526e-6	4.8 10^{15}	6.53	85	986.4
C	12	1.2	2.6	1.0	5.263e-6	2.4 10^{16}	4.80	85	123.1
D	12	1.2	2.6	0.2	1.0526e-6	4.8 10^{15}	4.80	85	123.1

Case	Pinch Time t_1[ns]	Compression ratio ρ/ρ_0	Electron Temperature T_e [eV]	Electron Density N_e[cm^{-3}]	Average Ionisation State Z	Remarks
A	48 (62)	2.89	21.8	9.30 10^{17}	13.2	double pinch
B	38	12.75	95.1	1.83 10^{18}	29.7	high compression, hot
C	30	1.97	18.4	4.33 10^{17}	9.0	low compression, cold
D	37 (51)	2.71	37.3	2.42 10^{17}	16.7	low compression,

Space-time Dependences of Compression Ratio ρ/ρ_0



High current

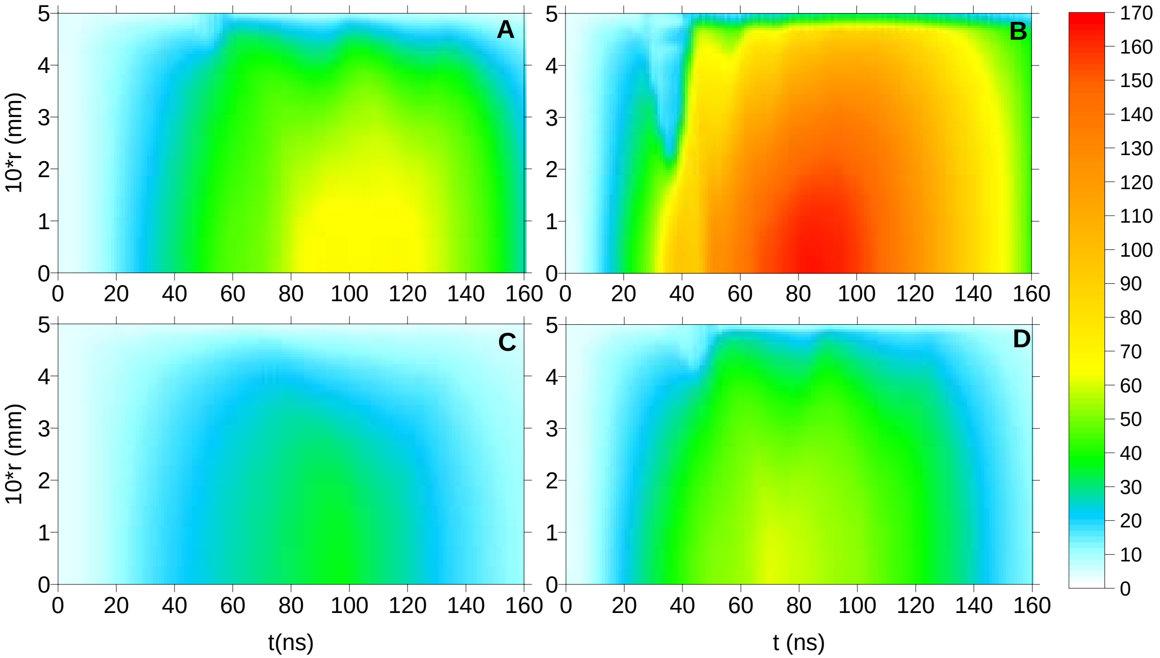
Low current

High pressure

Low pressure

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***).

Space-time Dependences of Electron Temperature T_e



High current

Low current

High pressure

Low pressure

Local plasma electron temperature increases with the increasing current density.

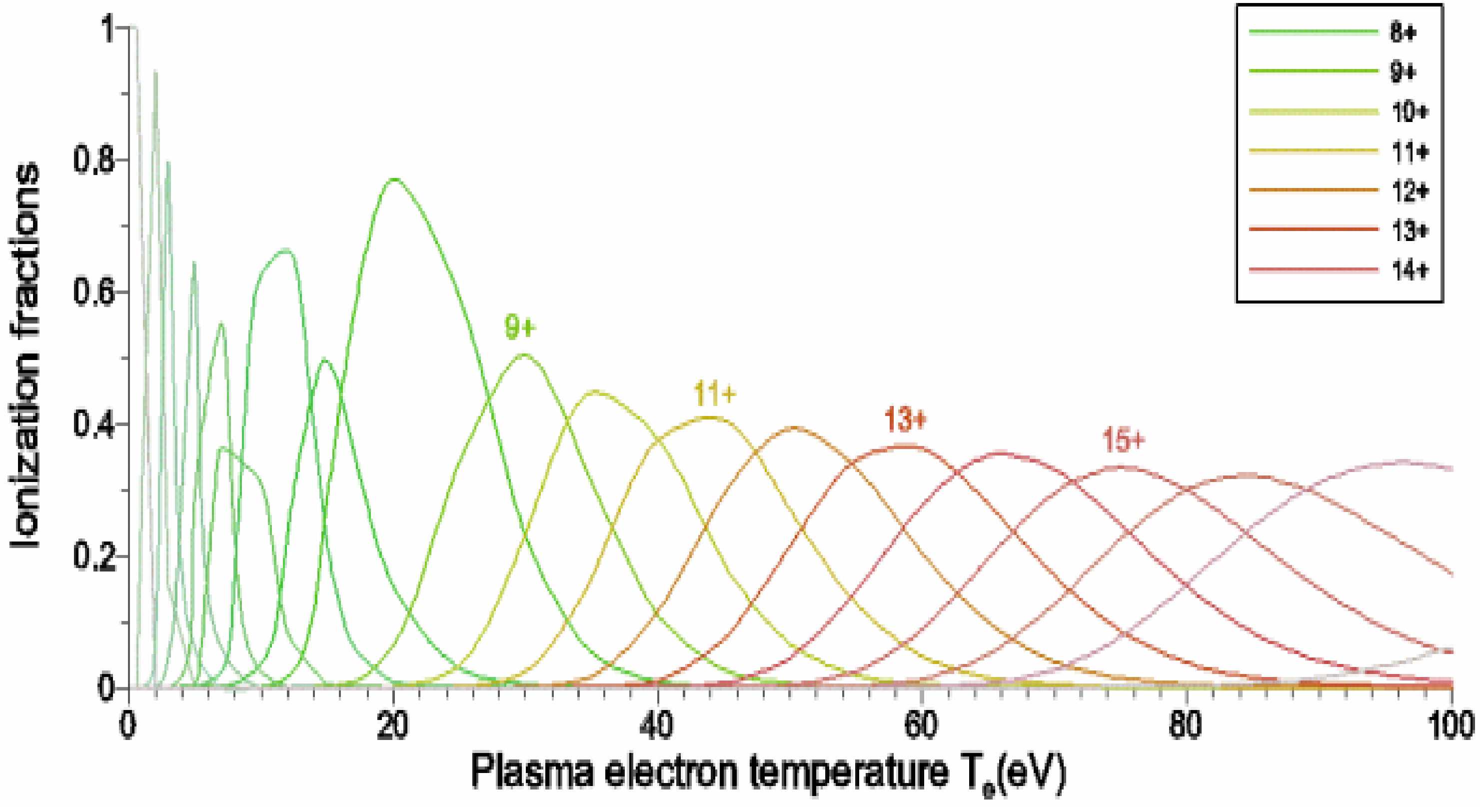
Peak temperatures are higher than **20 eV** in all investigated cases. The highest

Thermodynamic and Radiative Plasma Properties

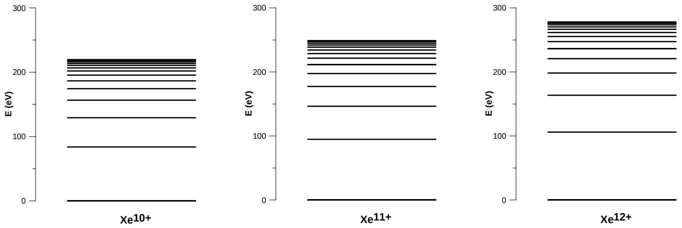
IONMIX Code

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: $E_{n,j} = -\Phi_j (n_0/n)^2$, $n \geq n_0$

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

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

Ion	Xe^{6+}	Xe^{7+}	Xe^{8+}	Xe^{9+}	Xe^{10+}	Xe^{11+}	Xe^{12+}	Xe^{13+}	Xe^{14+}	Xe^{15+}	Xe^{16+}	Xe^{17+}	Xe^{18+}
Φ_j [eV]	98	112	170	202	233	264	294	325	358	389	421	452	572
n_0	5	5	4	4	4	4	4	4	4	4	4	4	4
λ_L [nm]	41.4	36.1	20.2	17.1	14.8	13.1	11.7	10.6	9.6	8.8	8.1	7.6	6.0
λ_B [nm]	68.6	59.9	37.1	31.4	27.3	24.1	21.5	19.5	17.7	16.3	15.1	14.0	11.1
λ_{Edge}	12.6	11.04	7.25										

Spectral Emissivity

Kirchhoff – Planck” law:

$$\eta(\lambda) = k(\lambda)\,.\,w(\lambda)$$

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

$$w(\lambda) = 8\pi hc\frac{1}{\lambda^5}\frac{1}{\exp(\frac{hc}{kT}.\frac{1}{\lambda}) - 1}$$

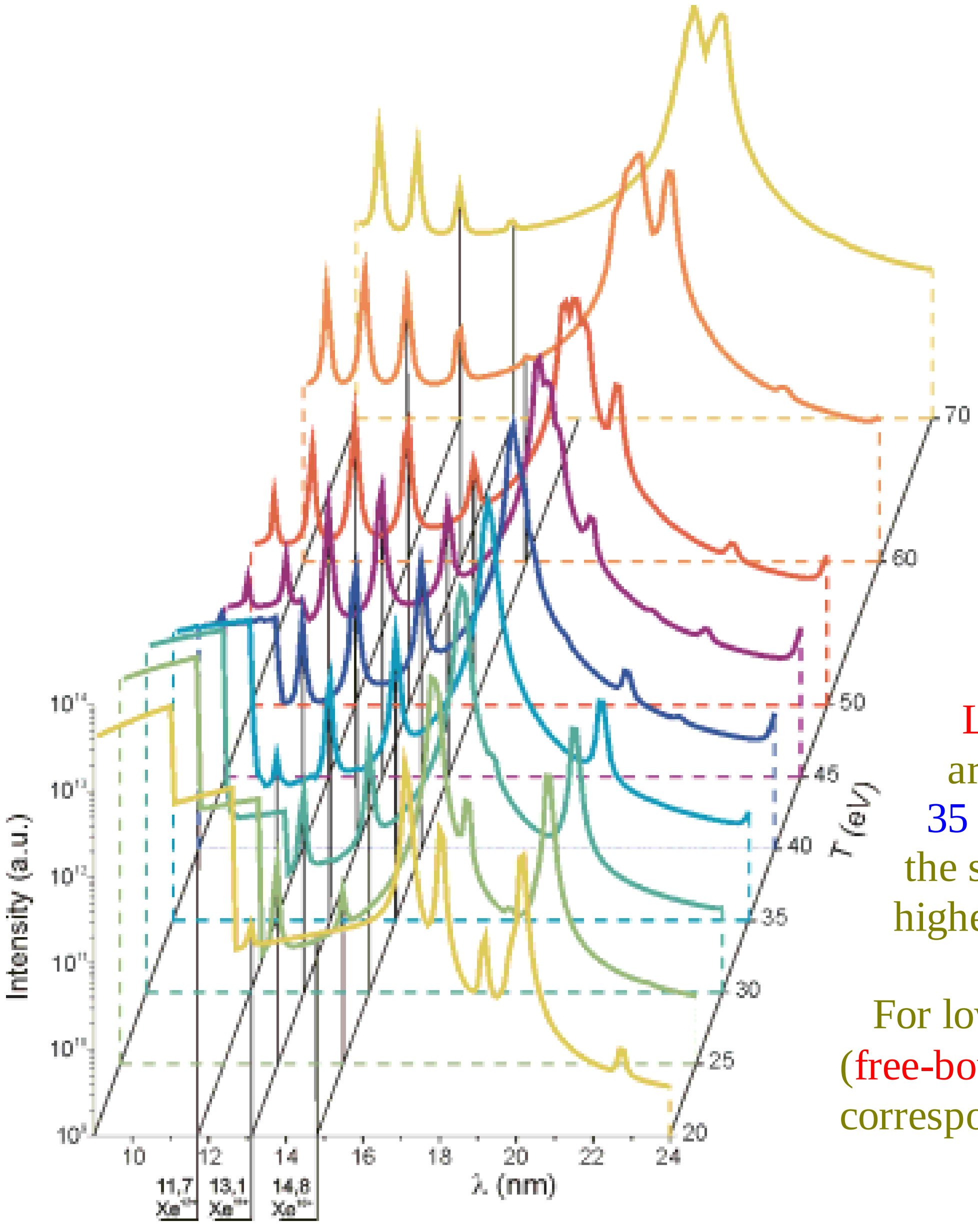
.

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

For λ_{max} = 13 nm, should be T = 34 eV.

Calculated Spectral Emissivity

for various temperatures



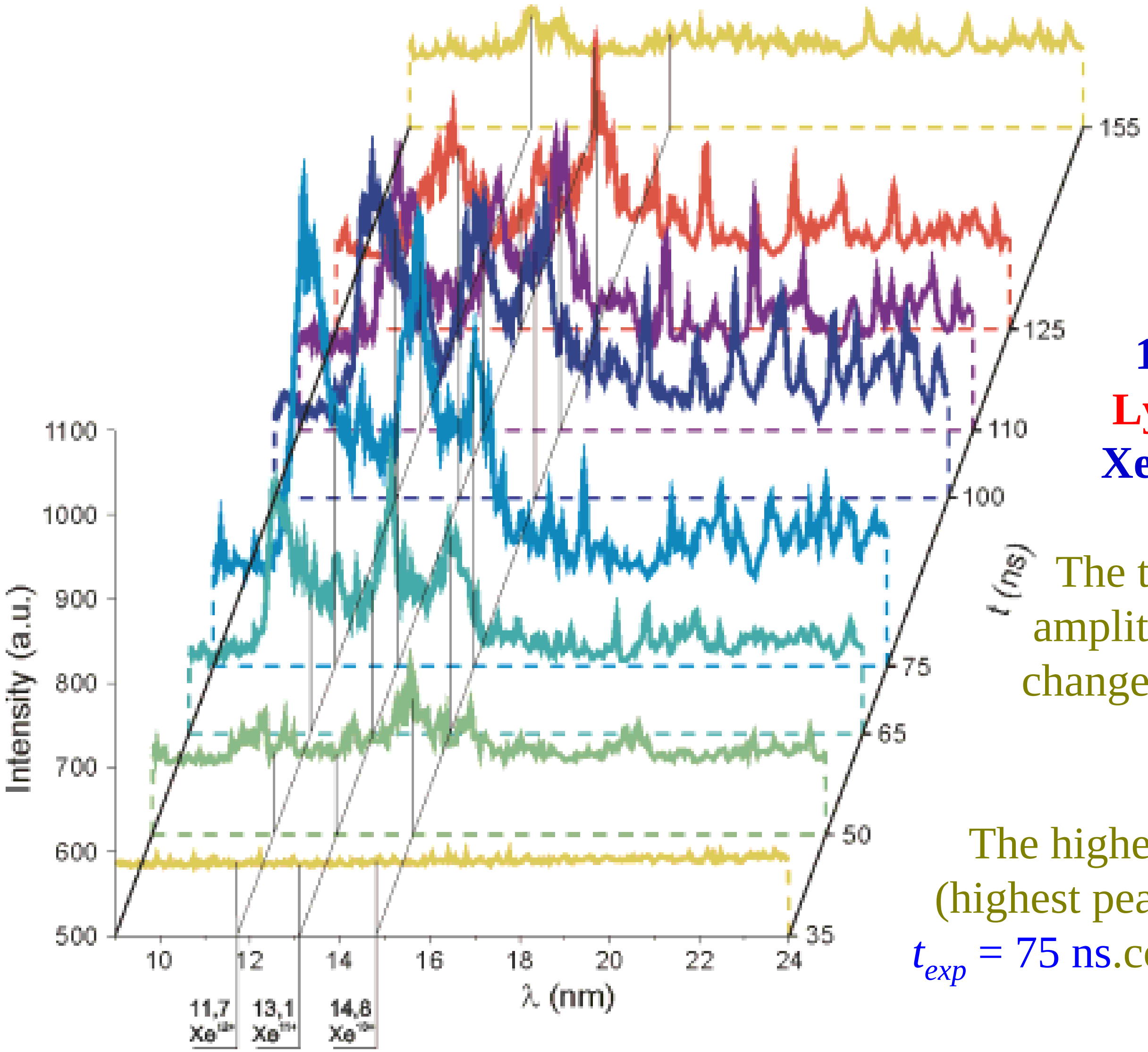
Temperatures T= 20-70 eV and initial atom density N = 3.10^{17} cm^{-3} according to the experiment and results of N-pinch code

Lyman-like transitions λ_L = 14.8, 13.1, 11.7 nm are identified for ions Xe^{10+} - 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 λ_{Edge} = 12.6 and 11.0 nm, corresponding to Xe^{6+} and 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 α transitions** of **Xe^{12+}, Xe^{11+}, Xe^{10+}** ions.

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

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

Conclusion

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

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

References

[1] Cachoncinlle C. et al.: Cpillary Discharge Sources of Hard UV Radiation, Proc.of XXV ICPIG Nagoya, Japan 2001, vol. 4, 345.
[2] Bobrova N.A., Bulanov S.V., Razinkova T.L., Sasorov P.V., Plasma Physics Reports 22 (1996), 387-402
[3] MacFarlane J.J., Comput. Phys. Commun. 56 (1989) 259-278.