Time resolved measurements of a capillary discharge dedicated to a soft X-ray amplifier

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Introduction and prospecting

Experiment Objectives

- Bright soft X-ray source generated by a highly ionized carbon plasma created in an ablative capillary discharge

- Study of the feasibility of a coherent soft x-ray source. Investigation on the Balmer-α line of CVI at 18.2 nm.

- Understanding of the plasma formation and dynamics

- Plasma parameter measurements to determine if the required conditions of amplification are satisfied.

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Discharge conditions for the recombination scheme

Plasma of C^{6+}

High electron temperature for the creation of fully stripped carbon atoms

Magnetic Compression

Increase of Ne and Te at the maximal compression

Small volume capillaries

High power density, High Te and Ne

Brutal and fast cooling

Activation of the 3-body recombination process

Expansion phase and/or contact with the capillary wall during the expansion phase

Cooling by thermal diffusion to the wall

3- Populating of the Balmer line upper levels by efficient recombination

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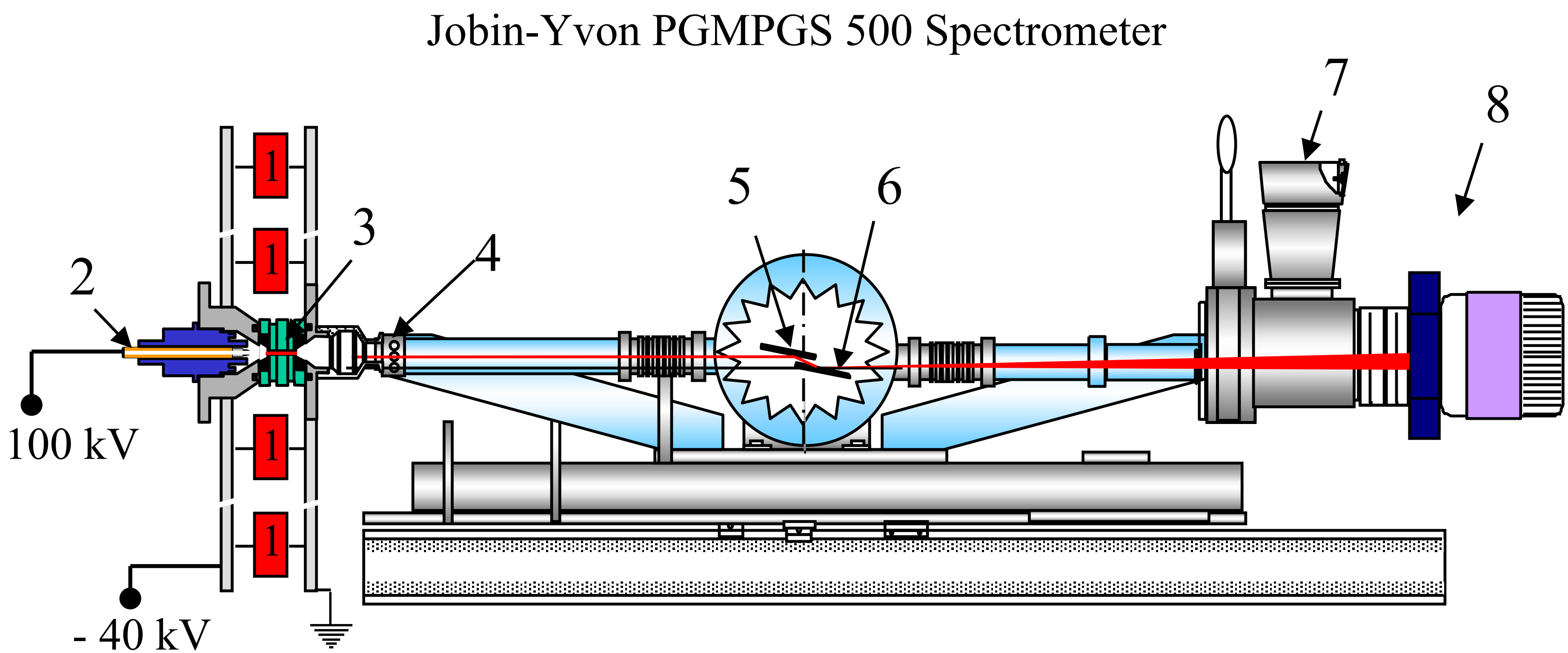
Experimental Arrangement

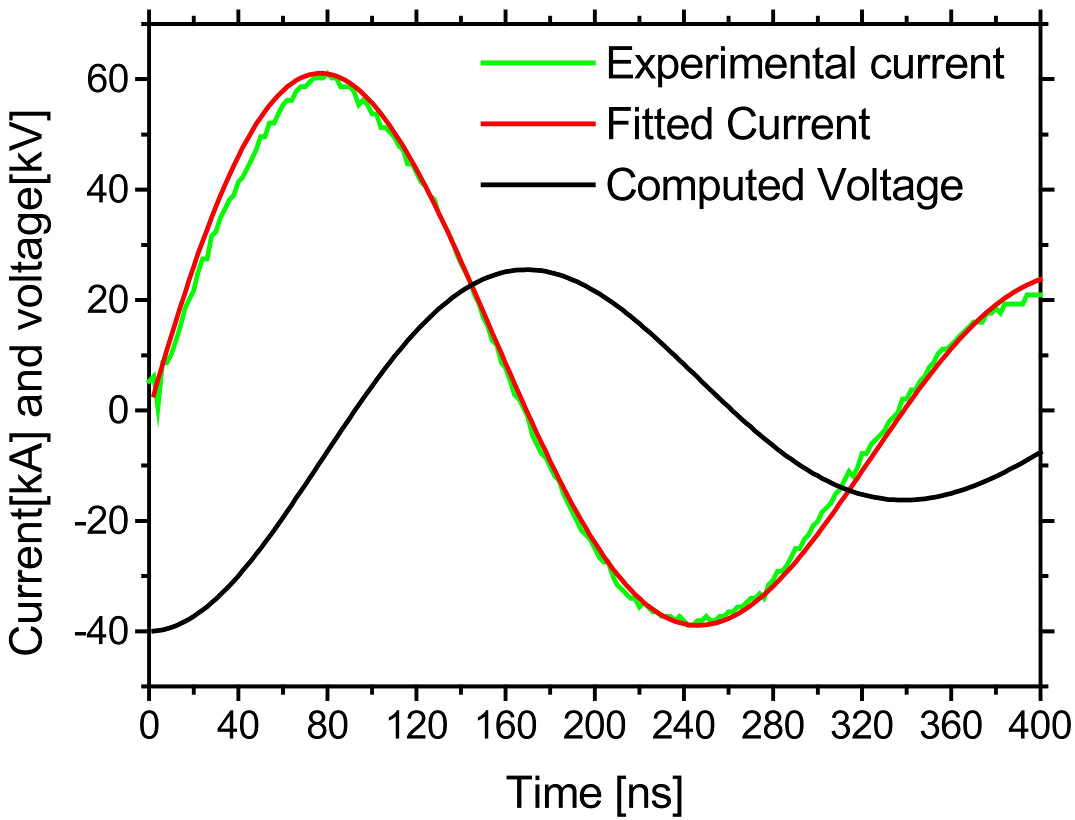


1. 50 knob capacitors of 2 nF
2. Pre ionization electrode
3. Polyethylene Capillary $(CH_2)_n$
4. Entrance slit of the spectrometer
5. Torroidal mirror
6. Reflective grating (800 $l.mm^{-1}$)
7. Turbo molecular pump
8. Gated MCP and ICCD camera

Electrical Characteristics

Measurements for a 16 mm long, 1 mm diameter capillary

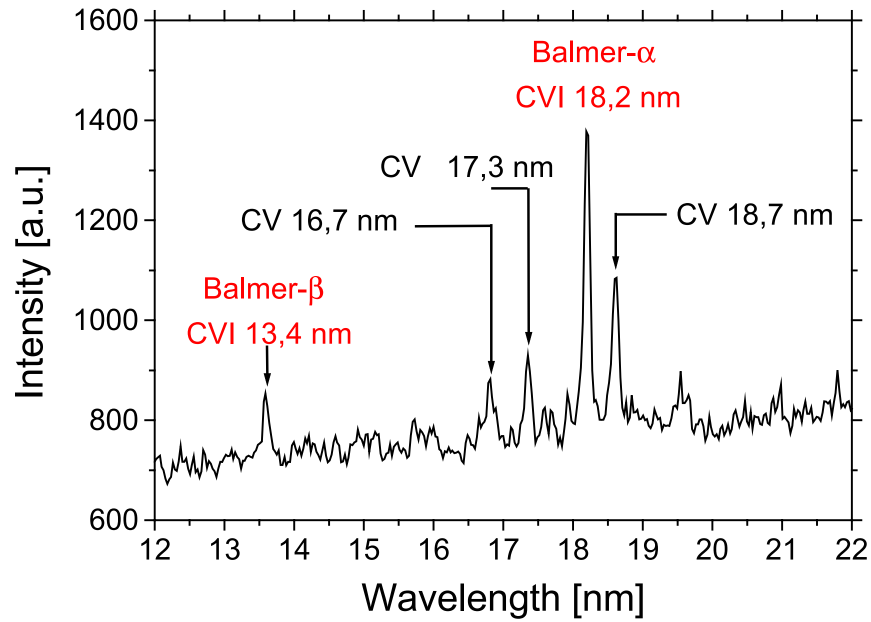
- Maximum applied voltage : **40 kV**
- Total capacity : **100 nF**
- Total inductance : **30 nH**
- Average resistance : **0.15 Ω**
- Peak current rise time : **50 ns**
- Maximum peak current : **60 kA**
- Power density : **70 GW.cm^{-3}**



Time integrated spectrum

obtained with the Jobin-Yvon

spectrometer

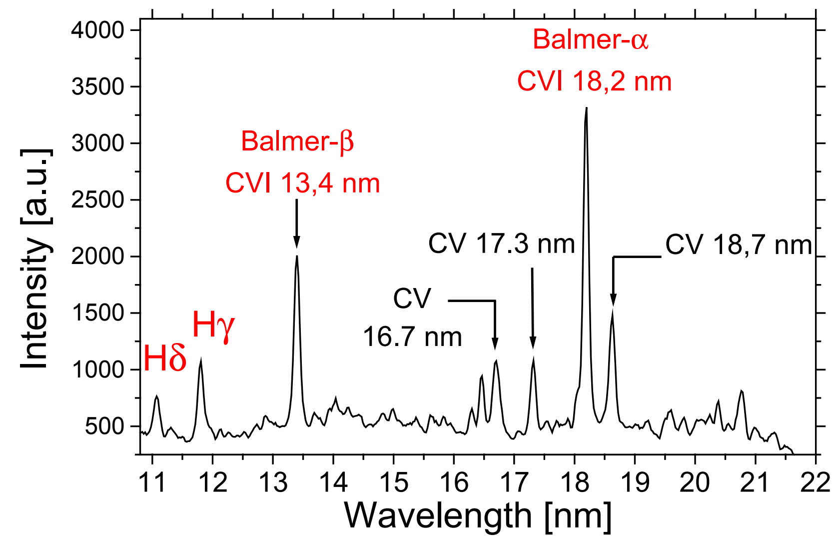


Time resolved spectrum

obtained with the Jobin-Yvon

spectrometer a few ns after

the current pulse maximum



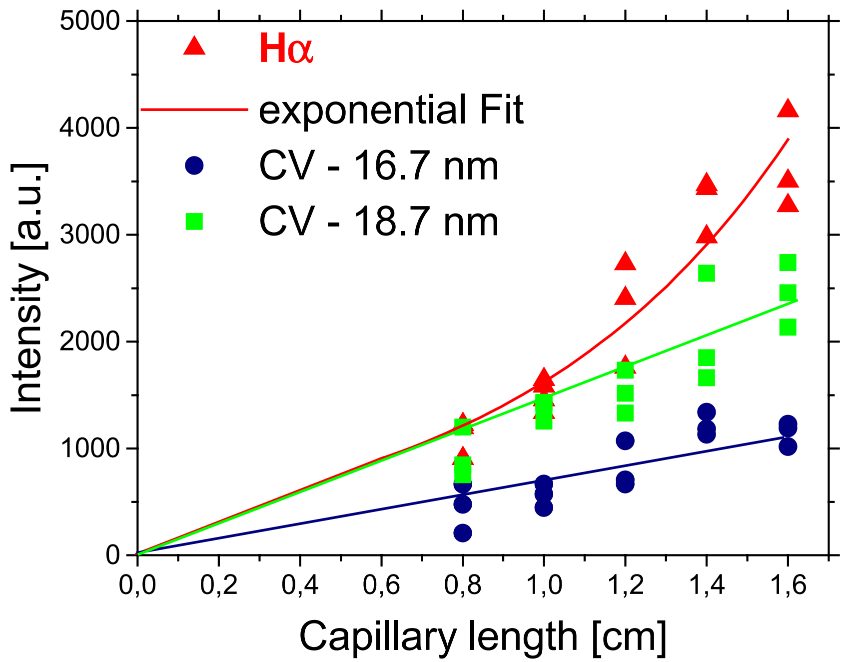
In both cases, the Hα line dominates the spectrum

Gain Measurements

Gain Measurements

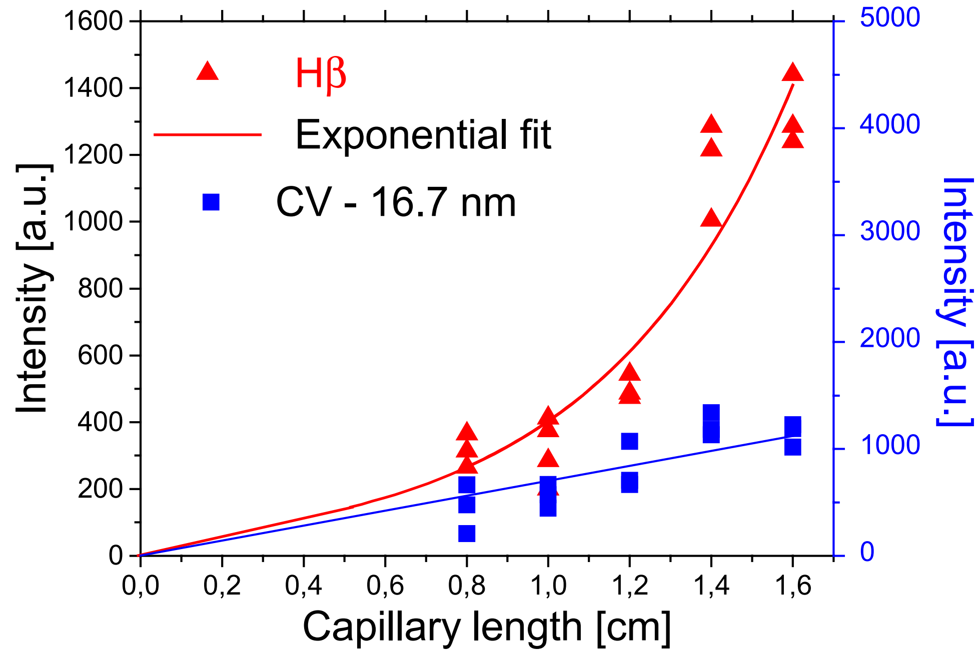
Injected power density : 70 GW·cm^{-3}

G.L = 2.6 ± 0.6



Hα

G.L = 3.4 ± 0.8



Hβ

Gain Measurement Comments

- Measurements obtained from time integrated spectra

- Very reproducible spectra, but difficulties estimating the gain by time resolved measurements

- Gain-length product still under 5

- Difficulties maintaining amplification for longer capillaries

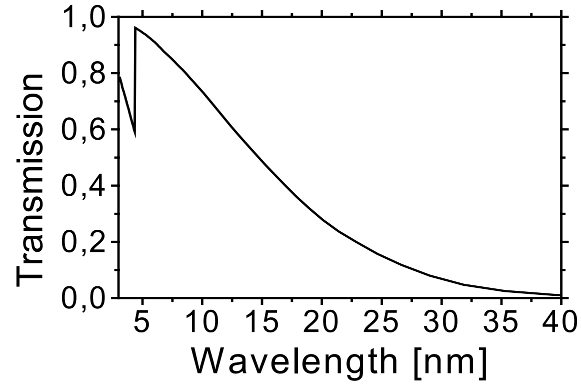
→ **Study of the plasma time evolution**

Study of the Plasma Time Evolution

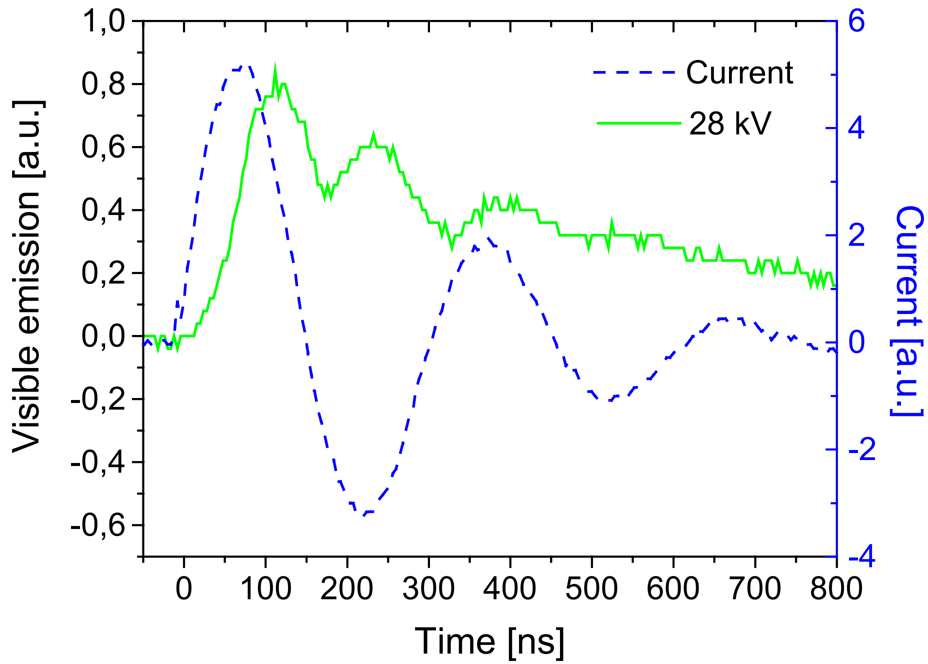
- Plasma integrated radiation using a photodiode
- Spectra dynamics
- Time resolved imaging using a pinhole camera
- Determination of the electron temperature and density

Plasma integrated emission using a Photodiode

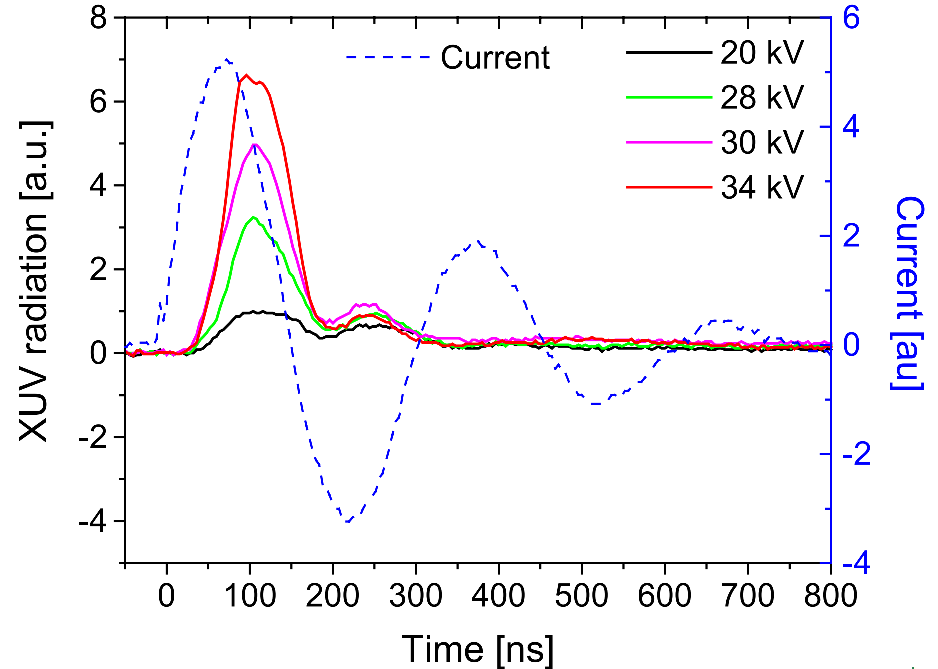
- XUV emission analysis using a polyimide filter, which allows photon transmission below 20 nm



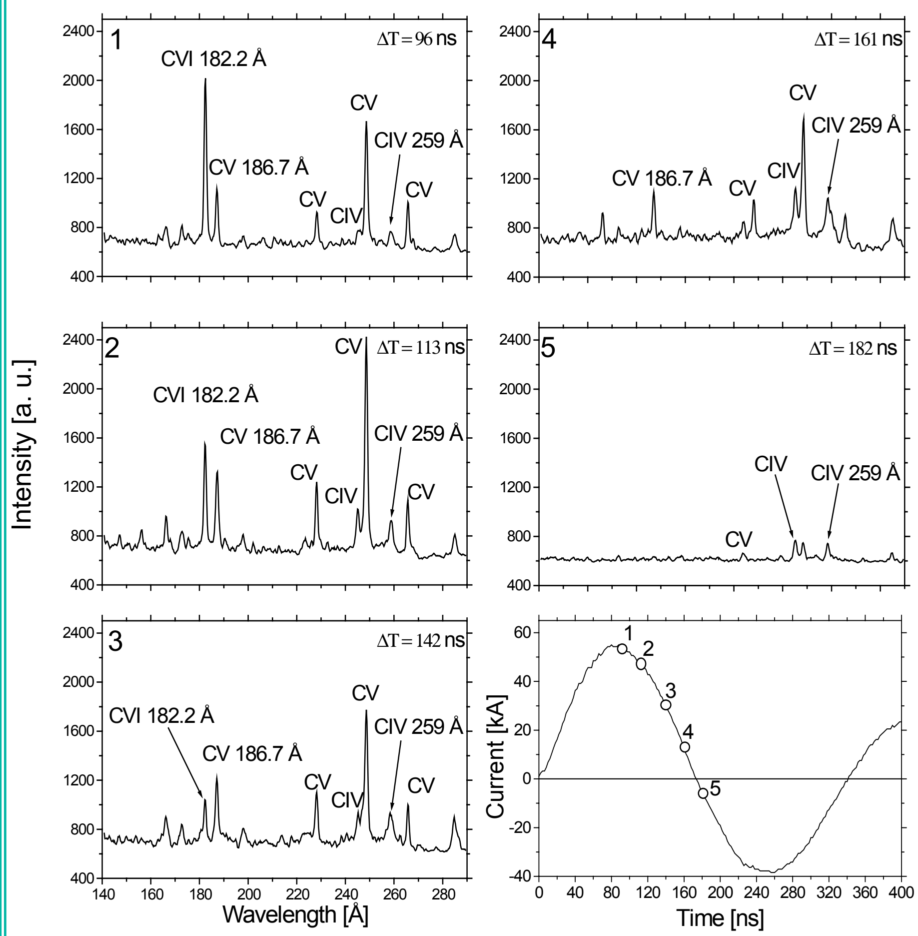
Visible Emission



XUV-Emission



Spectrum dynamics



U = 40 kV

Diameter = 1mm

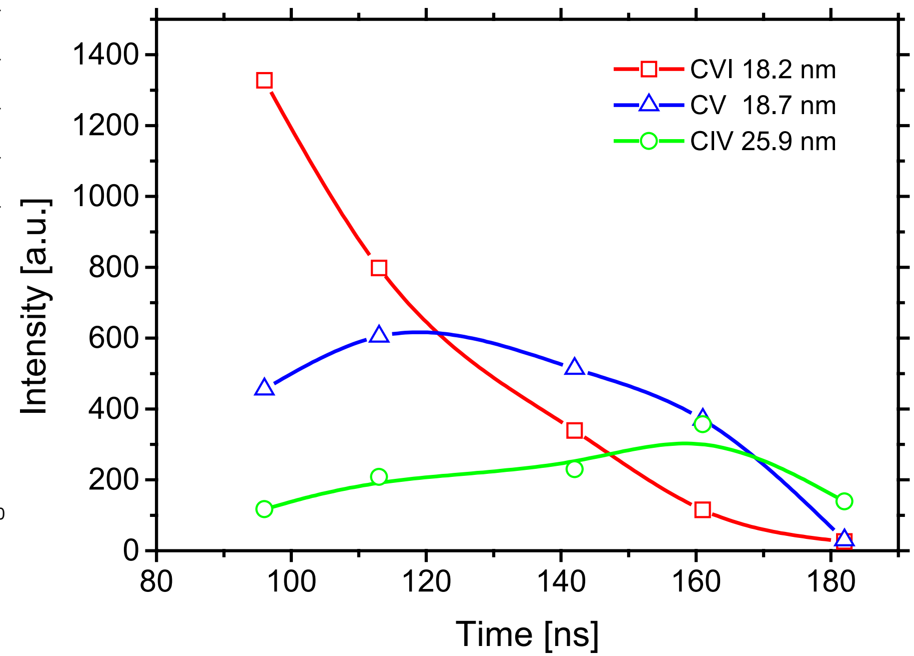
C = 100 nH

l_{Capil} = 16 mm

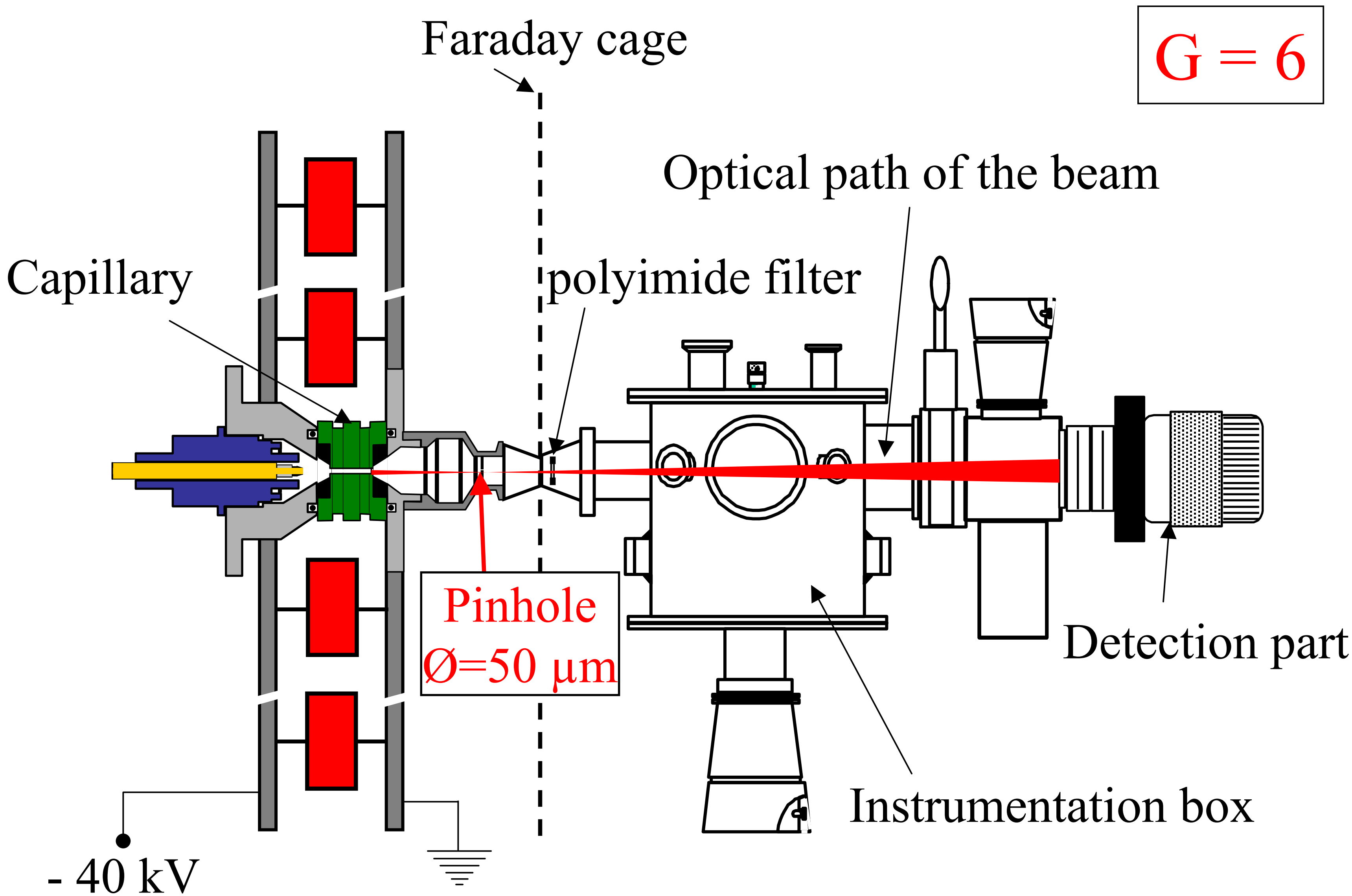
L = 30 nH

Period = 350 ns

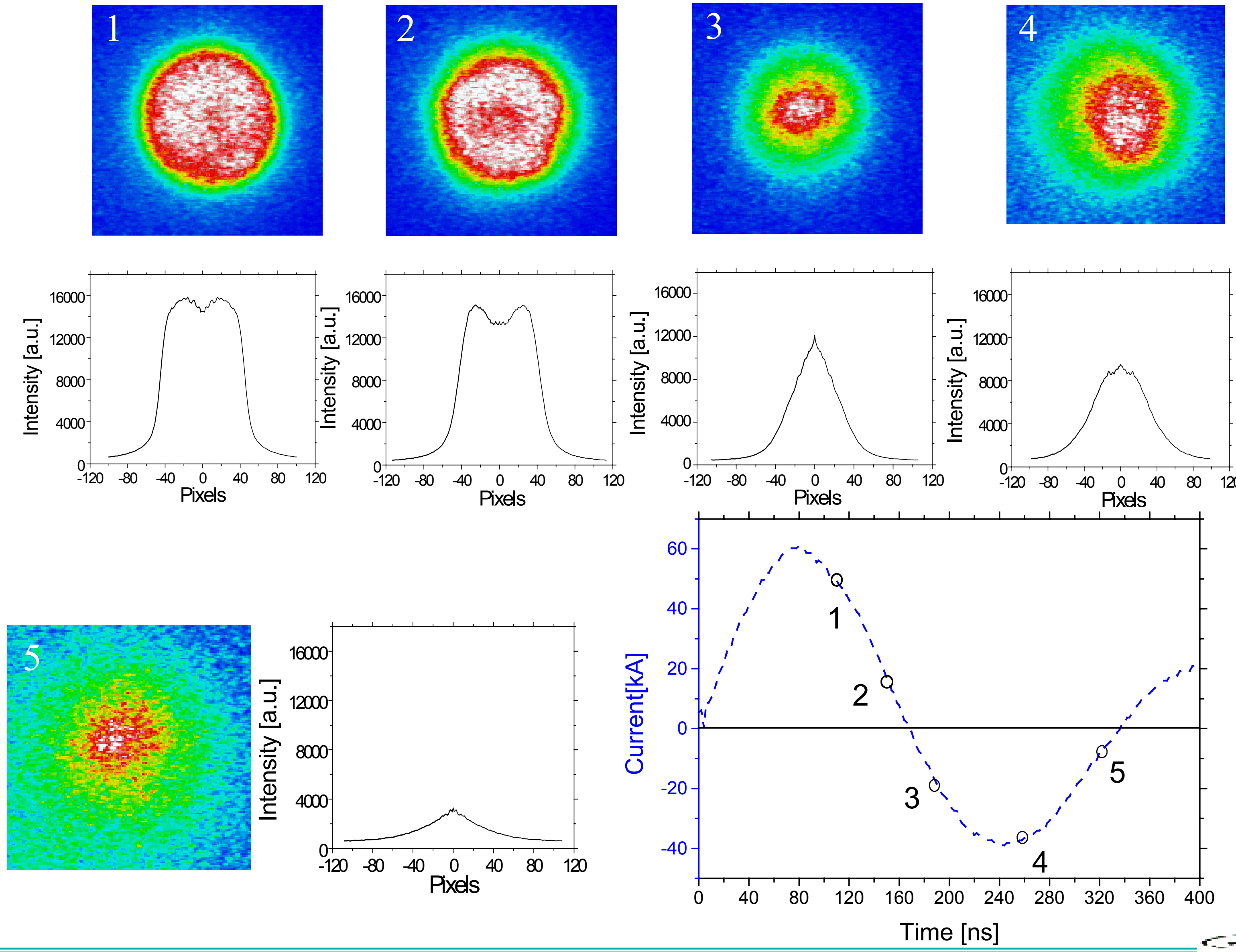
Power density = 70 GW.cm^{-3}



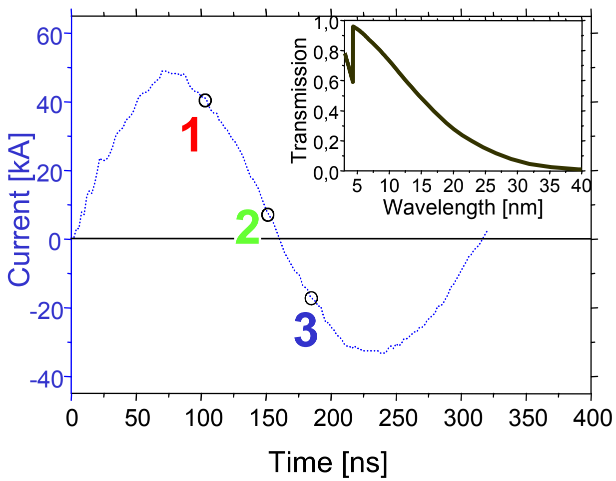
Setup of pinhole camera experiment

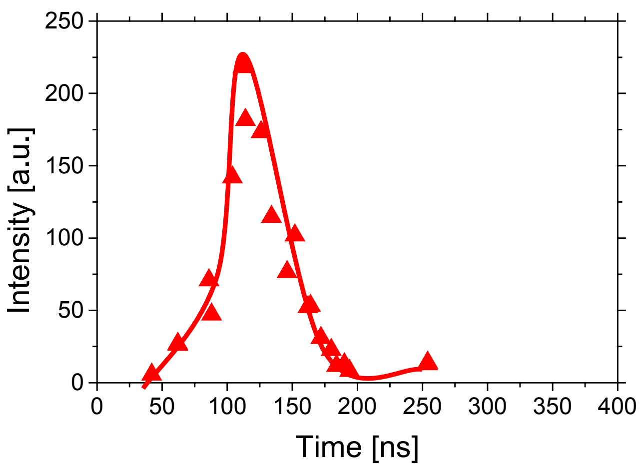


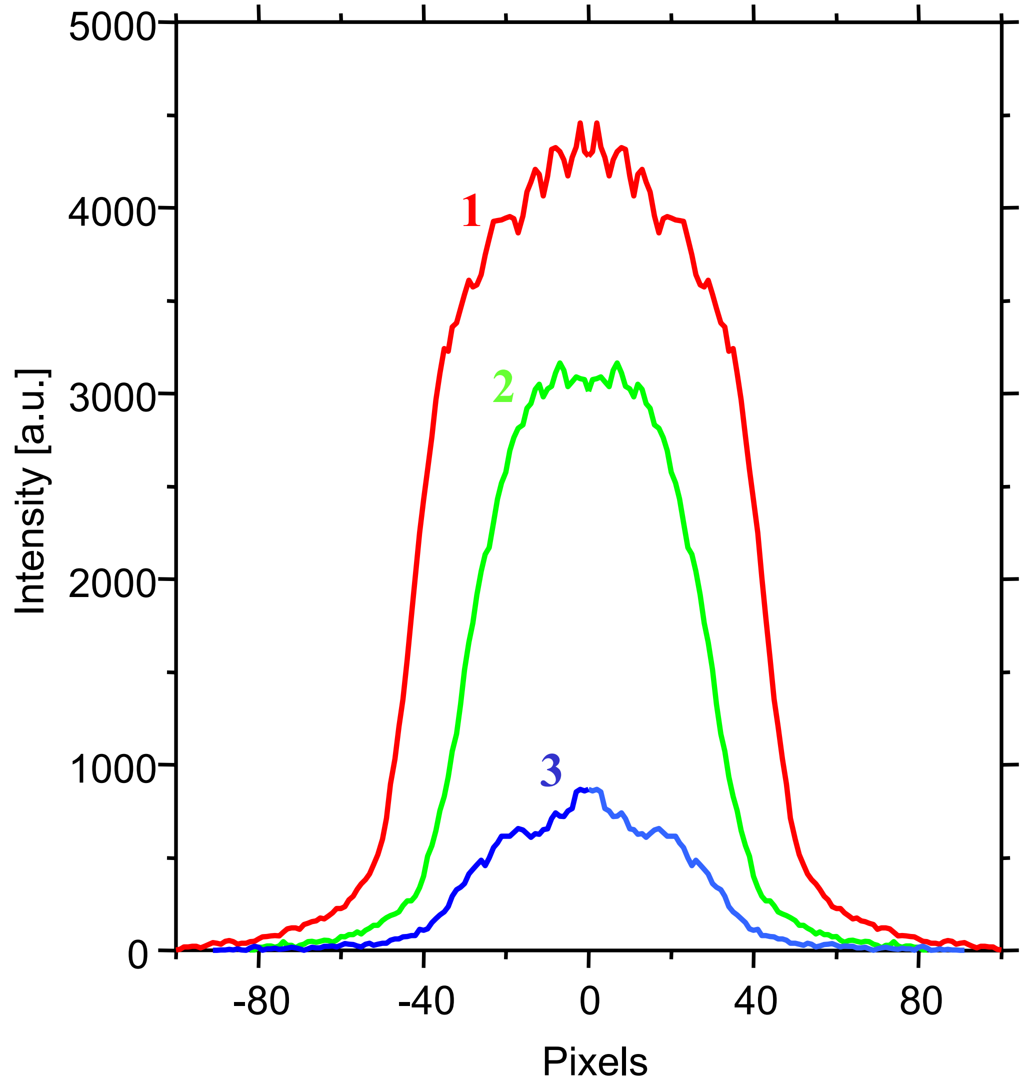
Time evolution of the plasma



Soft X-ray production regions



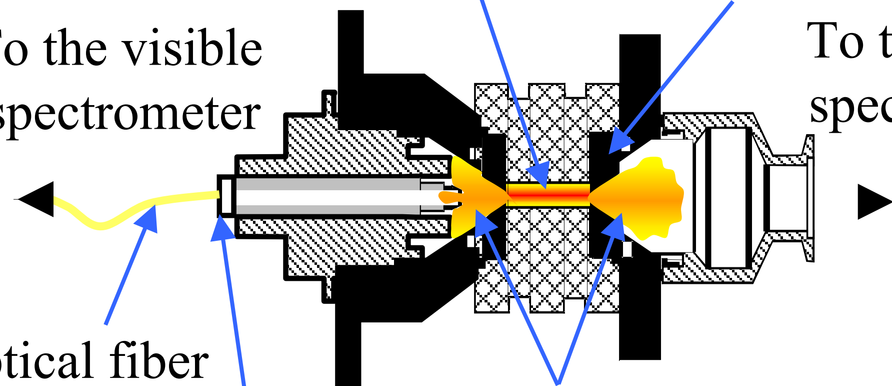




Electron density measurements

✓ Analysis of the light emitted by the plasma extended **outside** the capillary channel

✓ Spectroscopy in the visible



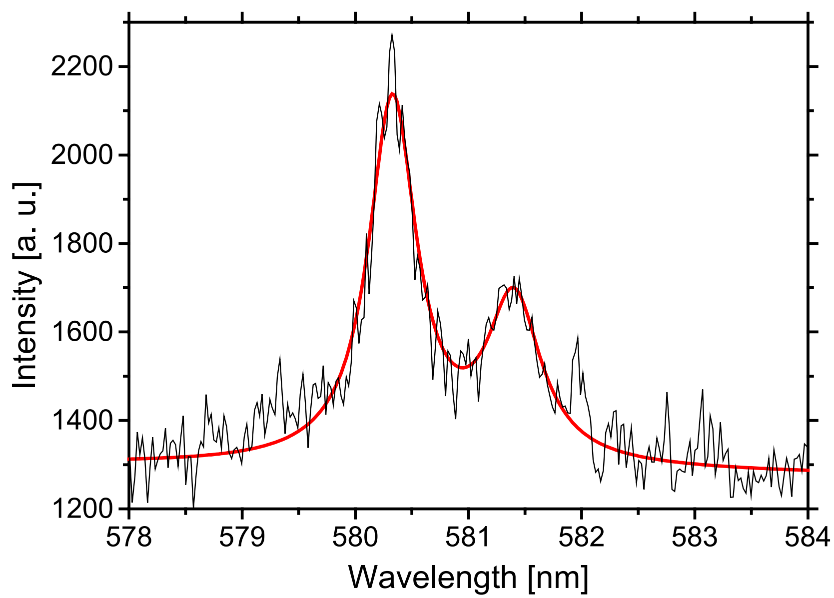
Stark broadening of the multiplet $3s^2S\text{-}3p^2P^0$ of the CIV lines at **580.29 nm** and at **581.36 nm**

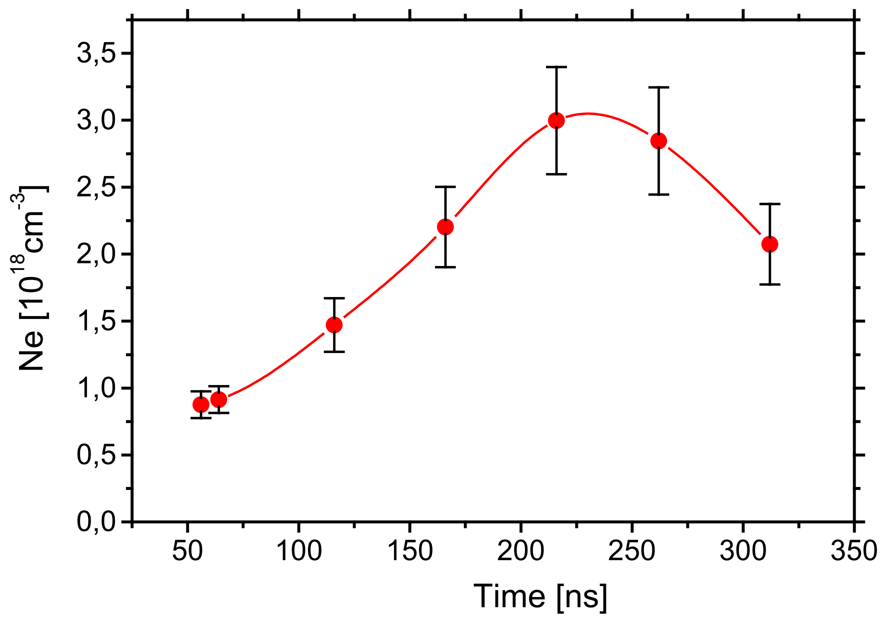
Electron density

✓ Lines fitted by a Lorentzian profile

✓ Ne=1-3.10^{18} cm^{-3} **outside** the capillary

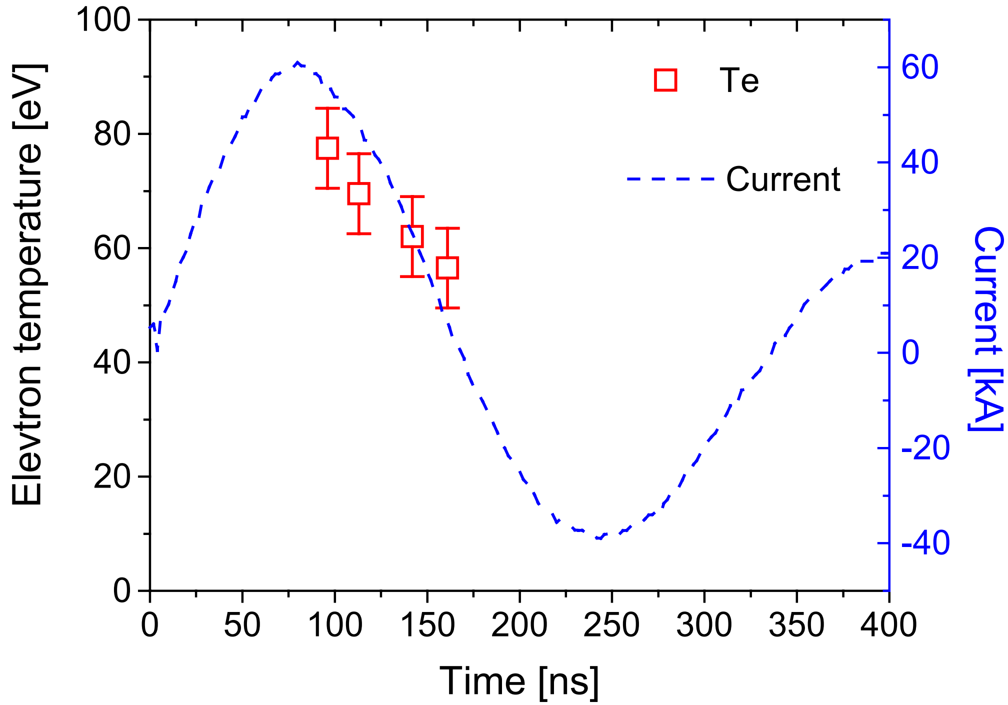
✓ 12 kV applied voltage





Electron temperature

- ✓ Radiative collisional FLY code used to determine the temperature from the intensity ratio between the Balmer-α line at 18.2 nm and the CV line at 18.7 nm
- ✓ Plasma mixture composed of 33% of carbon and 66% of hydrogen
- ✓ Temperature averaged on the diameter of the capillary
- ✓ Electron density assumed to be 10^{19} cm^{-3} in the capillary channel



Results

- ✓ Te=80 eV at the maximum XUV emission, when recombination from C^{6+} to C^{5+} occurs
- ✓ Not brutal enough cooling to create an efficient 3-body recombination

Simulation of the ablative capillary discharge

Simulation using the code CADILAC*

Brief presentation of the code :

- 0 dimensional collisional-radiative model. Plasma composed of C^{4+}, C^{5+} and C^{6+}
- Capillary wall ablation taken into account.
- Energy balance between ohmic plasma heating and plasma cooling by thermal conductivity and radiation losses
- 6 He-like and 15 H-like states

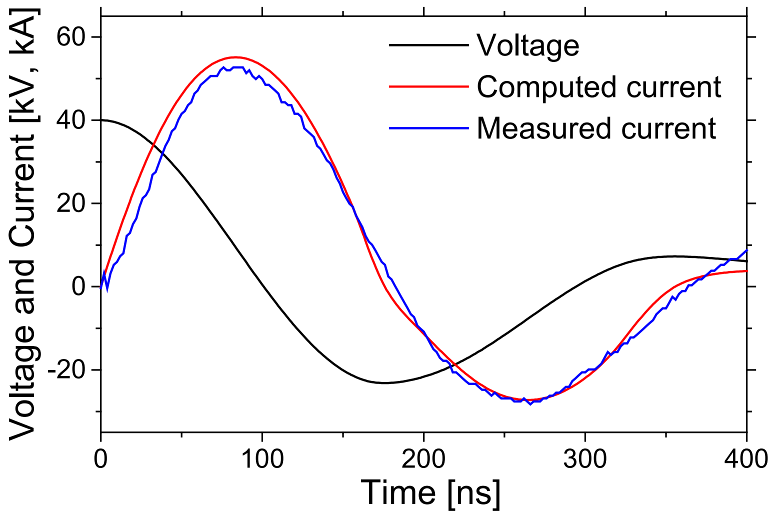
Presentation of two performed simulations

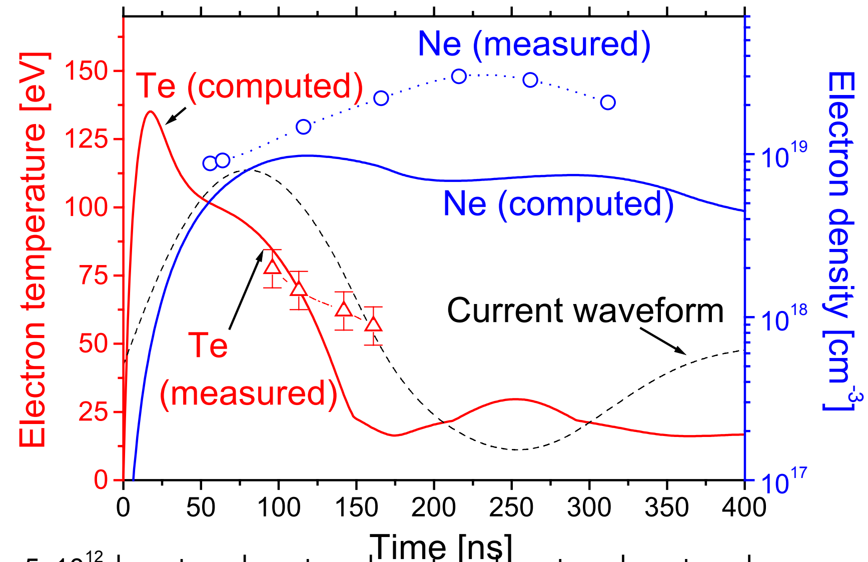
Energy of 80 J for both cases

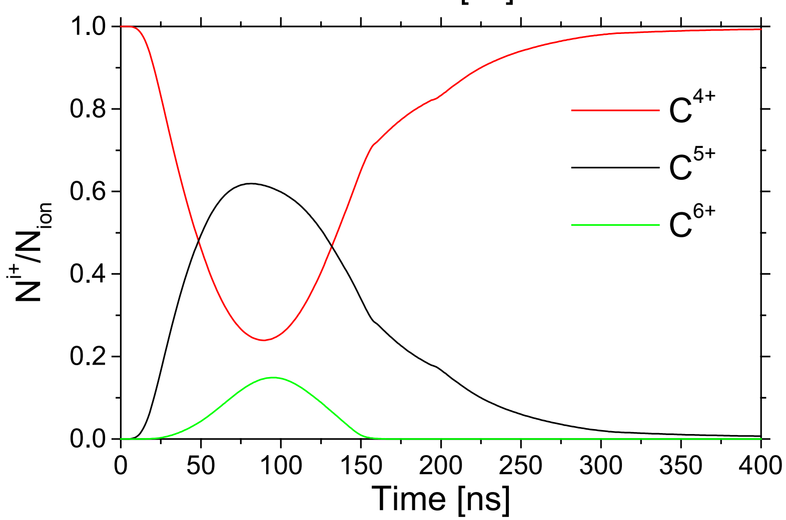
40 kV 100 nF	57 kV 50 nF
Experimental conditions : $P = 70\ GW.cm^{-3}$	Faster current pulses : $P = 100\ GW.cm^{-3}$

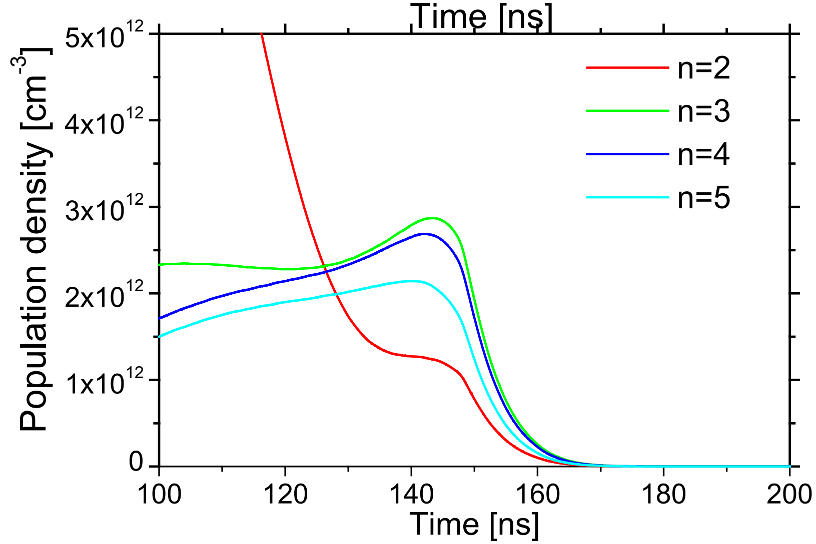
* Author : **Manfred Pöckl** from the « Institut für Allgemeine Physik », Technische Universität at Wien, Austria

First simulation : P = 70 GW.cm^{-3}



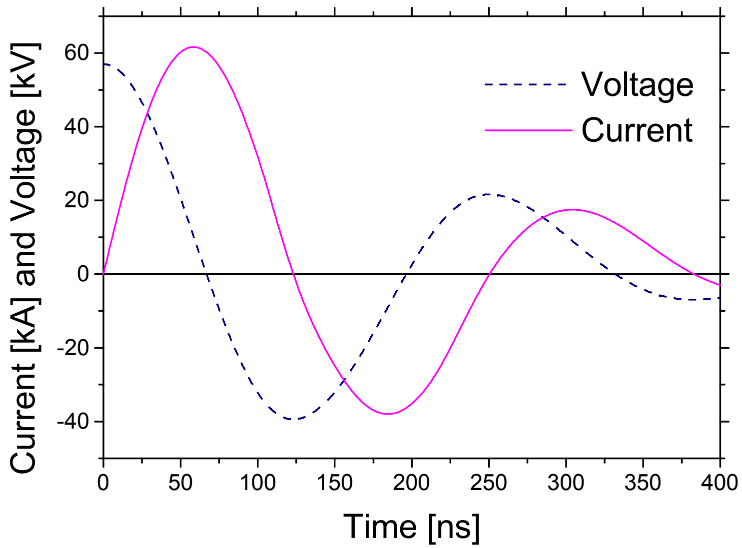


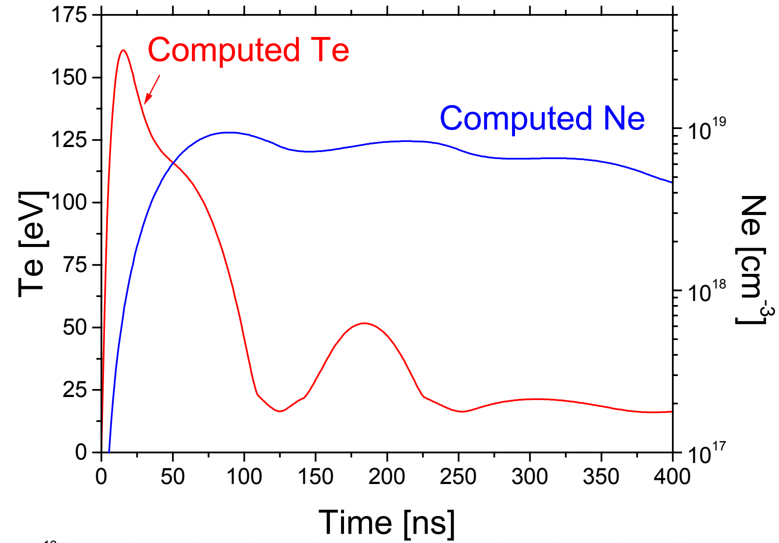


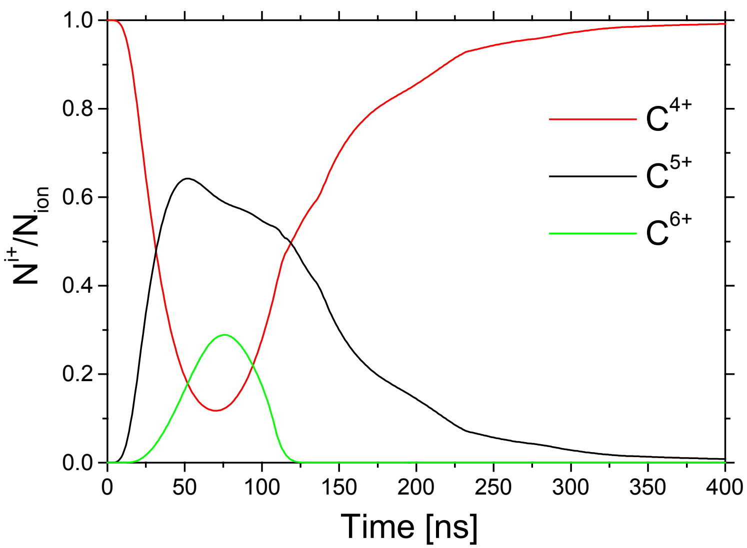


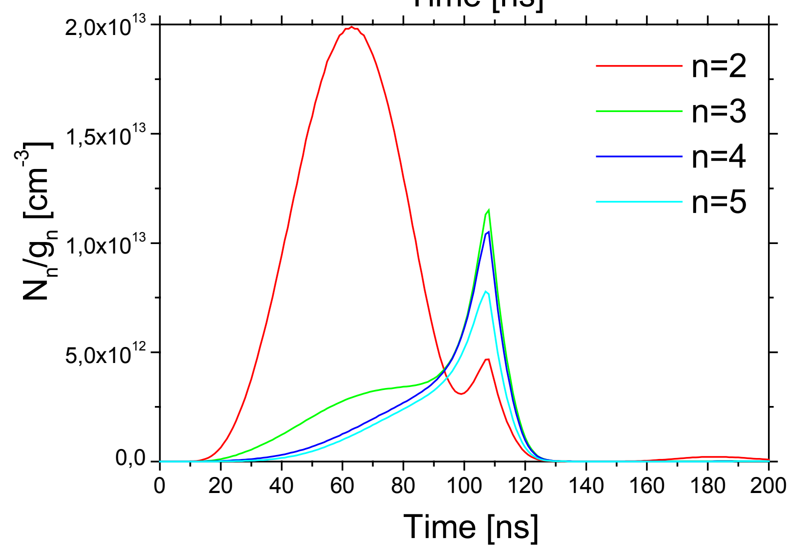
- Results from the simulation quite close to those obtained by measurements
- Population inversions on several Balmer lines as observed experimentally

Second simulation : P=100 GW.cm-3









- Population inversions are accentuated : the computed gain is increased by a factor of 4

Conclusions and prospects

- Very good and high emission of the Balmer-α and -β lines, on which we have observed an amplification as it was predicted by the code CADILAC.

- To increase the gain value, we need a faster cooling of the plasma. Cooling by thermal diffusion to the wall occurs too late after the recombination of CVI to CV.

- Development of pulse generators (BLUMLEIN) to create faster current pulses and fill the conditions for increasing the amplification of the Balmer lines as it is predicted by the code CADILAC.