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Ways to Discharge-Based Soft X-ray Lasers with the Wavelength λ < 15 nm

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Abstract Two basic ways to amplification of spontaneous emission in soft X-ray region are described. The first is based on electron-collisional recombination pumping scheme, which uses recombination of fully stripped ions into hydrogen-like ions to create (in the case of sufficiently fast cooling) a population inversion on energy levels belonging to Balmer-alpha transition. We test this scheme on nitrogen, for which the lasing wavelength is 13,4 nm. The second way to amplification of spontaneous emission is based on electron-collisional excitation pumping scheme: this uses for creation of population inversion a fast excitation of Ne- or Ni-like ions. However, for wavelength below 15 nm it is necessary to use Ni-like ions of some metal vapours. Feeding metal vapours into a capillary is difficult, and if being fed they deposit on the capillary wall and significantly reduce the capillary lifetime. That is why we prepare metal vapour plasma in a capillary with liquid wall – by wire explosion in water. For slowdown of the plasma-channel expansion a local-water-compression by linearly focused shock wave is being developed.

1. Introduction

At present there is a strong interest in shortening the wavelength of discharge pumped soft X-ray lasers. There are four possible ways [1], how to achieve population inversion with pulse power devices - namely with the help of recombination, of excitation by discharge itself, of combined excitation by discharge and pico-/femto-second laser pulse, and finally with the help of charge exchange; three of them seem to be passable even in the case of shorter wavelength.

The first way to population inversion is usually used in evacuated small diameter capillaries, where the discharge is initiated by a surface breakdown along the capillary wall. Such a breakdown does not ensure well-defined initial conditions (the number of from-wall-evaporated particles is uncontrolled), but plasma remains in good thermal contact with capillary walls and amplification of stimulated emission (usually during a cooling phase of the discharge - following **electron-collisional recombination pumping scheme** into hydrogen- or lithium-like ions) has been reported [2-6]. Later it was noticed [7] that lasing conditions according to recombination pumping scheme were approached in ultra-fast gas-filled micro-capillary discharge device with stored energy as small as 0.5 J: the gas is ionised along the capillary axis by electron beam (due to hollow cathode effect) and a one-nanosecond-discharge heats plasma to temperature >80 eV. Recently, following general consideration on Z-scaling (Z being

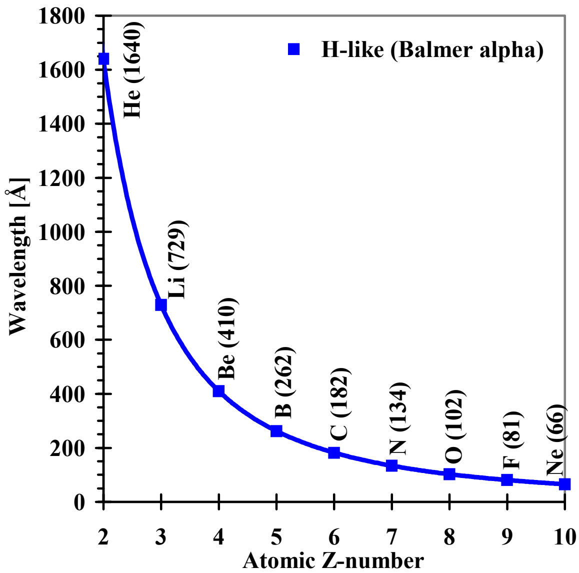

Fig. 1 Wavelengths of hydrogen-like ions (Balmer-alpha transition) for elements with different atomic numbers.

atomic number) of capillary gas-filling [8], an amplification on H-like N (Balmer-alpha-line, wavelength 13,4 nm – see Fig. 1) in N-filled capillary of larger diameter (~3 mm) has been predicted [9, 10, 11]. Experimental tests of these calculations are in progress [12].

The second way to population inversion in capillary discharge devices was found in gas filled capillaries with massive pre-ionization and a fast current rise-time. In this case the amount of material ablated from the capillary walls and, hence, the number of particles to be heated, is limited by a rapid detachment of plasma from the walls (by Z-pinch effect). Strong amplification [13, 14] (due to **electron-collisional excitation pumping scheme**, which prefers neon- or nickel-like ions), lasing [15-18] and achievement of saturation limit [19-22] with neon-like argon (46.9 nm) have been announced in a short time interval. Later lasing on neon-like sulphur (60.8 nm) [23, 24], and neon-like chlorine (52.9 nm) [25] were demonstrated. However, shortening of lasing wavelength has not yet been successful: it requires to use Ne-, or better Ni-like ions of metal vapours (see Fig. 2). While injection of metal vapour plasma into the capillary is difficult [26, 27], the delivery of Ag atoms into the capillary by ablation of its Ag_2S wall [28], or the delivery of Ti atoms into the capillary by ablation of segmented Ti ring structure within the capillary [29], or by Ti-wire explosion [30], might be feasible. However, in all these cases the metal vapour deposits on the capillary wall and significantly reduces its lifetime. Therefore, we suggest creating a metal vapour plasma channel with liquid wall by wire explosion in a liquid (water). A threat of channel fast expansion will be mitigated by a local liquid compression (to the GPa pressure range) by linearly focused cylindrical shock wave.

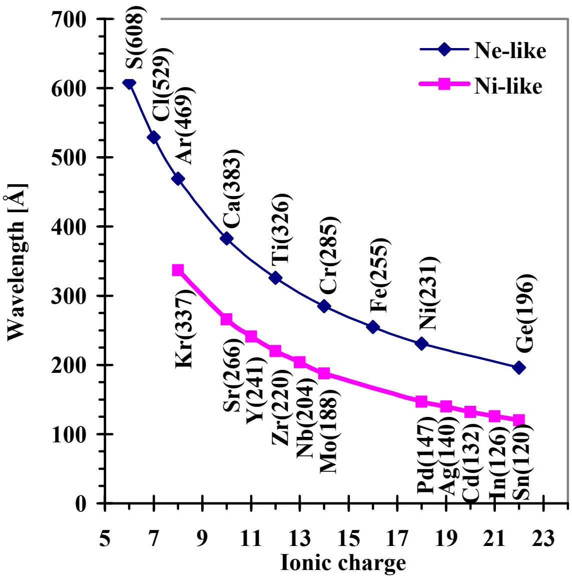

Fig. 2 Lasing wavelengths for Ne- and Ni-like ions as a function of ionic charge

The third approach to population inversion is **hybrid pumping scheme**, which combines generation and compression of plasma by discharge and build-up of population inversion by pico- or femto-second laser pulse. The wave-guiding of high intensity laser pulses in straight and curved plasma channels has been known for a few years [31-35], as well as the idea of amplification of a soft X-ray laser beam in active medium [36], but the feasibility of this scheme was demonstrated quite recently [37-39]. This approach is studied up to now both theoretically [40] and experimentally [41, 42]. We consider it very perspective; unfortunately, up to the present laser delivered the prevailing part of the energy. That disqualifies smaller laboratories. We think it is worth testing this scheme with a laser of the energy/power just slightly higher than that necessary for excitation of the upper laser level.

The fourth way to population inversion in capillary devices is **charge exchange pumping scheme** [43]. Because such a pumping is quite unusual – it was independently tested on two colliding plasma streams originating in two laser foci (0.75 mm apart) [44] and modelled [45]. Despite initial objections [46] (intensity enhancement in former experiments was interpreted in terms of guiding effect rather than by amplified spontaneous emission), the method of externally induced instability (by shaping inner capillary wall [47, 48, 49]) fully confirms amplification of spontaneous emission. Recently, the same effect was achieved by modulated return conductor [50]. However, we are afraid that general applicability of this scheme to scaling down the lasing wavelength is very small.

From this above given survey it is obvious that the experiments with excitation pumping scheme have the best results. They have the highest energy in pulse, peak power, and average power in repetitive regime, they demonstrated lasing at more wavelengths, their X-ray laser beam was examined (near and far field pattern, coherence) and used for the first applications. However, because at laser transition of Ne- and Ni-like ions (excitation pumping scheme) the principal quantum number remains unchanged (in contrast to H- and Li-like ions for recombination pumping scheme), the scaling to shorter wavelength with nuclear charge Z is very slow. Therefore, both the excitation and the recombination pumping schemes remain in the focus of our interest.

2. X-ray Amplification Conditions

2.1. Power

If N_u and N_l are upper and lower laser state population densities and σ_{stim} and σ_{abs} are cross-sections for stimulated emission and resonance absorption, then the small signal gain coefficient

$$g = N_u\sigma_{stim} - N_l\sigma_{abs} \sim N_u\sigma_{stim} . \tag{1}$$

Cross section for stimulated emission [51]

$$\sigma_{stim} = \frac{c^2}{8\pi\nu^2}\frac{A_{ul}}{\Delta\nu} , \tag{2}$$

c being speed of light, ν line frequency and $\Delta\nu$ line width. Taking into account that Einstein coefficient for spontaneous emission A_{ul} scales along an isoelectronic sequence as λ^{-2} then [52]

$$g \approx \frac{1}{8\pi\Delta\nu} N_u . \tag{3}$$

For naturally broadened line $\Delta\nu \sim A_{ul} \sim \lambda^{-2}$ and hence,

$$g_{natural} \approx N_u\, \lambda^2 . \tag{4}$$

Maintenance of the upper laser level population density N_u requires pump power density P

$$P_{natural} = N_u A_{ul}\, hc/\lambda \sim N_u\, \lambda^{-3} \sim g_{natural}\, \lambda^{-5} . \tag{5}$$

For Doppler broadened line

$$\frac{\Delta\nu}{\nu} = \frac{\sqrt{kT_i/m_i}}{c} , \tag{6}$$

k being Boltzmann constant, T_i ion temperature and m_i ion mass. Combining (3) and (6) the gain is in this case

$$g_{Doppler} \approx \frac{1}{\sqrt{kT_i/m_i}}\frac{c}{\nu} N_u \approx \frac{\lambda}{\sqrt{kT_i/m_i}} N_u \tag{7}$$

and the "maintaining" pump power density is (using (7))

$$P_{Doppler} = N_u A_{ul}\, hc/\lambda \sim N_u\, \lambda^{-3} \sim g_{Doppler}\sqrt{kT_i/m_i}\; \lambda^{-4} . \tag{8}$$

Therefore, considering for illustration naturally broadened line and supposing that mirrorless operation increases power 100 times, then lasing at 50 nm requires 10^7 times higher power density than at visible 500 nm and each next reduction of wavelength for one order of magnitude adds to power density requirement next 5 orders of magnitude.

2.2 Refraction losses

Another effect limiting the gain is refraction, which bents the X-rays out of the amplifying volume, decreases the effective gain and might limit the maximum amplification length. It also increases beam divergence and in some cases it can cause sidelobes or annual beam profiles.

In one-dimensional case London [53] analysed refraction losses in the parabolic density profile. The characteristic refraction length L_r (distance in the direction of propagation z passed by X-rays before being bend out) is

$$L_r = L_x \sqrt{n_{ec} / n_{e0}} \ , \tag{9}$$

where L_x is a transverse plasma dimension, n_{ec} is the critical density $\{n_{ec} = \pi m_e c^2/(e^2 \lambda^2)\}$ and n_{e0} is the maximum electron density. Then effective gain coefficient

$$g_{eff} = g\text{-}(1/L_r) \ . \tag{10}$$

The new "refraction gain-length" parameter defined as

$$G_r = g L_r \quad (= g_{eff} L_r + 1) \tag{11}$$

then determines, whether exponential growth of laser power with length is maintained till saturation intensity ($G_r > 1$ - in this case $g_{eff} L_r > 0$) or not ($G_r < 1$). Chilla and Rocca [54] extended refraction analysis to 2 dimensions with cylindrical symmetry finding that the reduction of the effective gain coefficient is doubled

$$g_{eff} = g\text{-}(2/L_r) \ . \tag{12}$$

The refraction losses can be reduced in laser pumped experiments by a special geometry of a target or by pre-pulse, in discharge pumped experiments by longitudinal magnetic field [55] or by plasma waveguides [56].

3. Experiments aiming at recombination pumping scheme

3.1. Apparatus

A new apparatus CAPEX-U (CAPillary EXperiment – Upgrade) has been recently put in operation. It consists of oil-filled Marx generator (12.5 nF/600 kV/2.25 kJ), spacer (oil-filled), co-axial pulse forming line (∅550x∅426x730 mm/12.7 nF/1.7 Ω), laser-triggered spark gap (Nd:YAG laser Quantel Brilliant b, 850 mJ/6 ns, split into 4 channels), and capillary (alumina in a polyurethane mantel, ∅40x∅3x232 mm) – see in more detail [57] and Fig. 3.

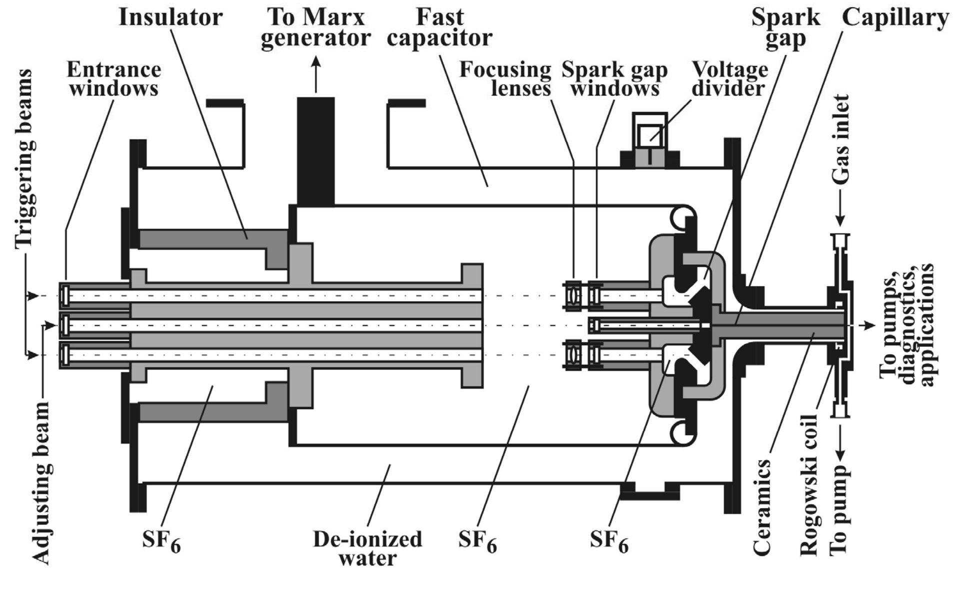

Fig. 3 CAPEX-U with a capillary

3.2. Preliminary results

The first type of experiments was performed according to Vrba's predictions [11] (inner capillary-diameter ~3 mm): the apparatus was aligned, tested with Ar-filling that Ne-like Ar laser works, carefully evacuated, and at each discharge-current-amplitude from ~20 to ~80 kA the filling nitrogen pressure was changed to find the optimum pinching (indicated by a short (~5-10 ns) intense X-ray radiation detected by vacuum photodiode with golden photocathode). Despite such regime was in many cases found, no sharp spike (as narrow as the apparatus function of our measuring apparatus – 1-2 ns) of X-ray radiation has been detected.

The second type of experiments was performed with small diameter (∅1 mm) capillary, where efficient cooling takes place. The capillary was filled with nitrogen in static regime (capillary and filling volume were separated from the detection part by a fast shutter), then the shutter was opened and a shot followed within ~1 ms. Unfortunately, even at medium current amplitude (~40 kA) the pressure in the capillary was so high that the fully ceramic capillary (wall thickness 19.5 mm) longitudinally cracked and exploded.

4. Experiments aiming at excitation pumping scheme

4.1. Apparatus

For these experiments the capillary will be removed from the CAPEX-U and substituted by the SHOW (SHOck Wave) device for wire explosion in water locally compressed by a focused cylindrical shock wave (see Fig. 4). This SHOW device consists of a separate capacitor bank 18 μF/50 kV (accumulated energy 22.5 kJ), pressurised triggerable spark gap, and water-filled experimental chamber that has insulating (polymethylmetacrylate PMM – plexiglas) flanges and cylindrical stainless steel shell ∅400x200 mm serving as a ground electrode. Its inner surface is covered by a porous ceramics (almandine) that (when voltage is applied) creates strong electric field at the output of pores and limits the current (reducing contact of metallic wall with conducting water). The second electrode is a co-axial mesh or a foil (if water between electrodes has a higher conductivity than the rest of experimental chamber) transparent for acoustical wave. When voltage is applied the corona-like multi-streamer discharge generates a strong cylindrical acoustic wave that propagates

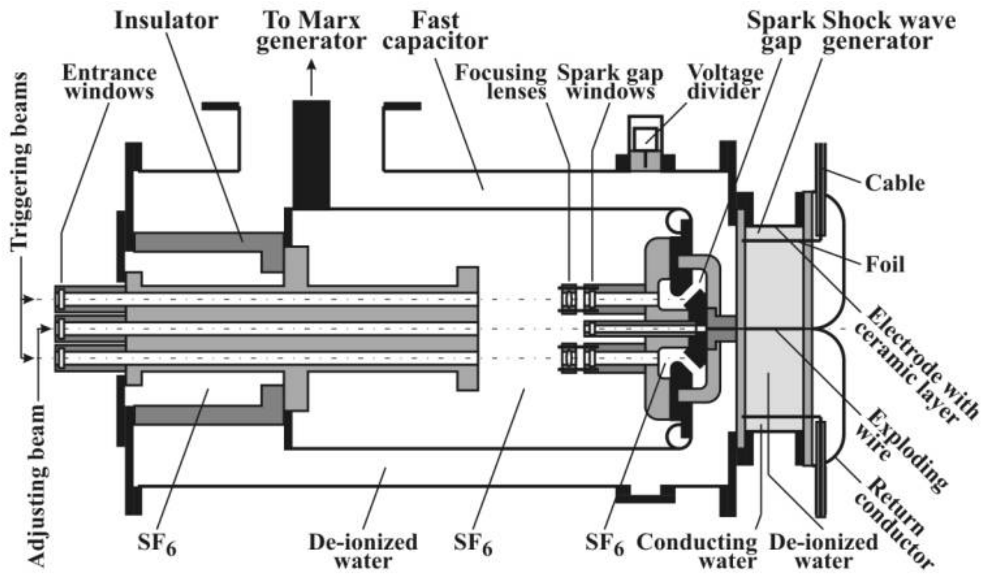

Fig. 4 CAPEX-U with the SHOW device

toward the second electrode and through it further to the chamber axis. Near the axis it changes into a shock wave with strongly increasing pressure amplitude.

4.2. Pressure measurement in/near the shock wave focus

Schlieren method was used for measurement of shock wave structure further from the shock wave focus. Unfortunately, the shock wave induced inhomogeneity at the focus was so large that the deflected beams went out of the schlieren lens aperture.

Off-axis shadowgraphy (newly developed technique) overcomes the above mentioned problem. The expanded laser beam (2nd harmonic of Nd:YAG) was directed along the axis of the separately staying SHOW device. The imaging lens (f=310 mm/∅80 mm) shielded by horizontal slit (57x20 mm) was placed in off-axis position to use for imaging the rays with higher deflections than in schlieren method (undeflected rays do not fall into lens-aperture at all (see Fig. 5)). Such measurements (an example is shown in Fig. 5, right) were repeated for a few off-axis positions and for a few delays to find the deflection, at which the signal disappears. From this deflection the maximum pressure in the inhomogeneity was inferred to be ~30 MPa at 20 kV charging voltage. A slight disagreement with pressure estimate made according to [58] (70 MPa) is attributed to boundary layer effects that were neglected during evaluation. The probing-laser-delay after the discharge and the radii of curvature of individual arcs on the shadowgrams gave

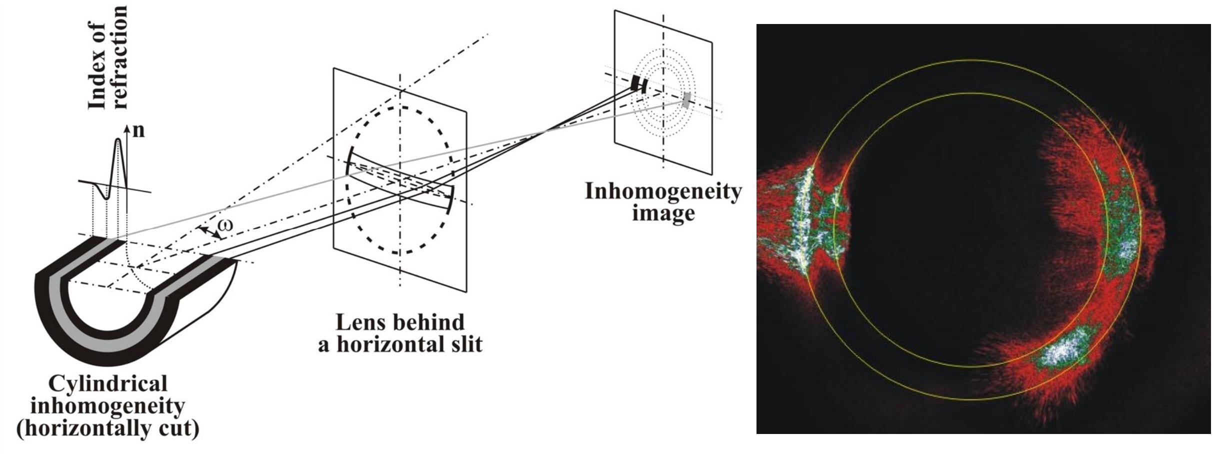

Fig. 5 Schematic diagram of the off-axis shadowgraphy. Right: shadowgram of the shock wave; double-arc on the left depicts rising parts of the index of refraction (from undisturbed to the maximum, and from the minimum to undisturbed), single arc on the right shows falling part of index of refraction (from its maximum to its minimum).

position of individual shock-wave-phases in the given time (see Fig. 6). From the graph the radius of shock wave focus 2,8 mm, and focusing time 122-125 μs after the multi-streamer discharge were determined.

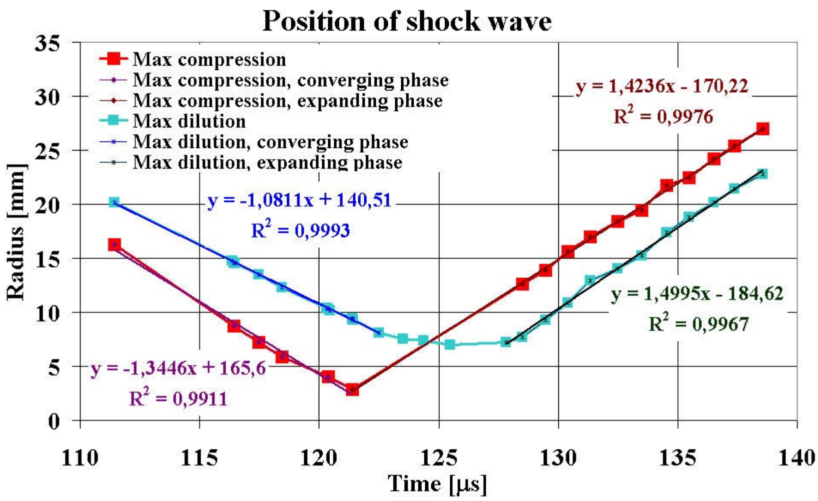

Fig. 6 Position of the shock wave

Piezoelectric pressure sensor was cut from silver-ink-metallised piezo-film sheet (MSI sensors), contacted by conducting stick, fixed on plastic (PMMA) rod of the diameter 10 mm and placed in the SHOW axis. This piezoelectric sensor was connected to high-impedance input of the near-staying battery-powered oscilloscope. The signals were smaller than it was expected (see Fig. 7 left), probably because the sensor thickness (110 µm) was small in comparison with characteristic dimension of the shock wave (~3,5 mm). The truncated signal is because of sparking.

Fibre-optic pressure sensor is based on idea of changed fibre transmission due to pressure-induced change of ratio of cladding/core index of refraction. The fibre (core: quartz, ∅210 µm, index of refraction n_{core}=1,457, cladding: plastic, ∅250 µm, index of refraction n_{clad}=1,41-1,44) was selected to have as close n_{core} to n_{clad} as possible. Fibre was elastically sealed in the axis of SHOW (to exclude fibre stretching due to pressure-induced axial movement of flanges). Fibre input was first illuminated through a chopper (for preliminary adjustment), then by continuous light of HeNe laser and the transmitted light was detected by the photomultiplier 65PK415. It turned out that initial fibre transmission at the shock wave compression phase falls and then (in the dilution phase) it rises (see Fig. 7, left). Unfortunately, sensitivity of this method to high pressures is very small (see Fig. 7, right). This method will be calibrated in a hydraulic press (in a quasi-static regime) as soon as it is available.

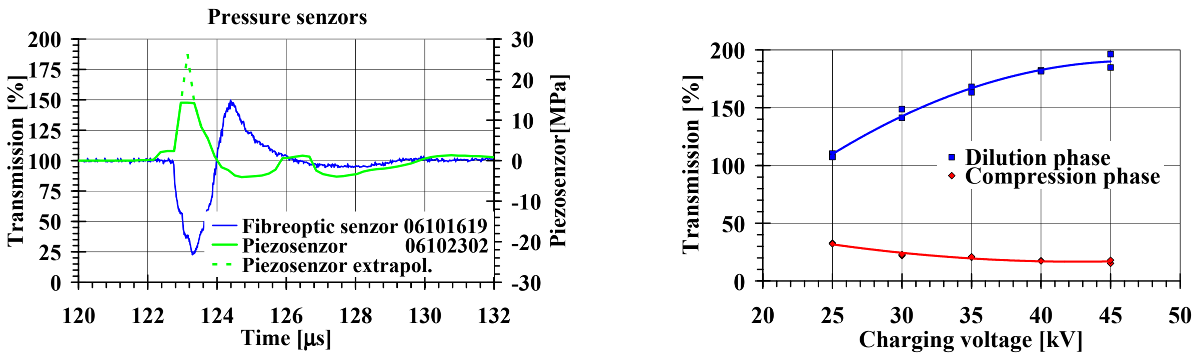

Fig. 7 Left: Signal of fibreoptic pressure sensor (blue curve) and piezo-sensor (green curve). Right: Transmission of pressure sensor as a function of charging voltage; red curve corresponds to the first extreme (minimum), blue curve corresponds to the second extreme (maximum) of the signal of the fibreoptic sensor.

4.3. Wire placed in uncompressed water and exploded by a slow driver

Cu wire of different diameters (∅ 0.1-0.3 mm) was exploded in the separately staying SHOW device. Explosion was performed by a slow driver (half period 4 µs) consisting of one or

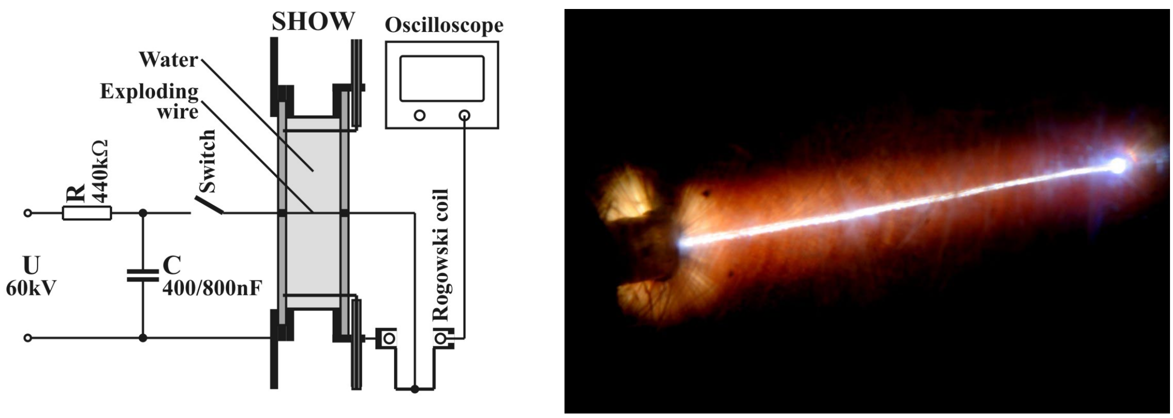

Fig. 8 Left: Schematic diagram of the wire explosion with slow driver. Right: Time-integrated picture of wire explosion

two condensers IK100-0.4/100 kV (400-800 nF charged to 60 kV), and a mechanical switch (see Fig. 8 left). The discharge current was "measured" by a Rogowski coil not optimised for this time-scale. Time-integrated pictures of wire explosion were taken in visible range by the Canon EOS 350D Digital CCD camera. It turned out that plasma channel created in water by wire explosion remains (even in the case of this slow driver) all the time perfectly stable (see Fig. 8 right). This is a good promise for further experiments.

5. Conclusion

In the case of hydrogen-like nitrogen laser (which uses recombination pumping scheme) there are two opened questions: 1) what is closer to reality: strongly pessimistic estimate of the chapter 2 of this paper (made on the bases of not fully justified prepositions: scaling leaves the rail of isoelectronic sequence) that predicts necessary discharge current >200 kA, or optimistic calculation of Dr. Vrba who predicts at least small gain even for the discharge current ~80 kA, 2) will be expansion cooling of previously pinched column sufficiently fast to ensure building of population inversion? The first time-resolved spectroscopic measurements should prompt the answer.

In the case of nickel-like metal vapour laser (excitation pumping scheme) both previous questions (1) question of sufficiently high power input, and 2) question of sufficiently fast compression that should guarantee detachment of the plasma column from the liquid wall) persist, but the third is added 3) if the wire (with solid-state density) ensures after its explosion a suitable plasma density/plasma density profile. The work is in progress.

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